Geomorphic, Engineering, and Ecological Considerations When Using Wood in River Restoration

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This chapter provides an overview of wood in rivers, focusing on wood stability in rivers and design considerations for the reintroduction of wood to larger alluvial channels. Wood debris is a common component of the particulate matter in streams and rivers and has been recognized throughout most forested portions of the globe as an important factor influencing stream geomorphology and ecology. The stability and preservation of wood in large channels is primarily a function of its embedment in the streambed. The ecological benefits of wood are evident at several scales ranging from the wood surface to the complex interstitial space of wood accumulations (logjams), to the role of wood on altering bed textures and bed forms, to the influence of wood on channel planform, particularly creating multichannel systems. A logjam can increase available surface area for invertebrates and cover for fish by more than four orders of magnitude. A logjam can split flow and increase edge habitat severalfold. Logjams create pools and bars and raise water elevations to increase floodplain connectivity and have been placed in rivers with basal shear stress values of 166 Pa. Regardless of whether wood is included in a restoration design, as long as riparian trees grow along a stream, wood will end up in the channel; hence, it is also important to understand how naturally recruited wood behaves in rivers. Reintroducing wood to rivers brings up many other issues, from flood conveyance to public safety, all of which should be considered in the design process.

1. INTRODUCTION

Wood is a common component of the particulate matter in streams and rivers throughout the world. In many areas, wood comprises the largest individual particles found in the stream. 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 majority of the vertical drop of a channel [e.g., *Keller and Tally*, 1979; *Montgomery et al.*, 1995, 1996; *Montgomery and Buffington*, 1997; *Abbe*, 2000; *Abbe and Montgomery*, 2003]. In larger-order channels, a piece of 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

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[e.g., *Abbe and Montgomery*, 1996, 2003]. Recognition of the geomorphic and ecologic role of wood has led to large-scale efforts to restore riparian forests and reintroduce wood into restoration and bank protection projects. Understanding the mechanics, dynamics, and persistence of wood in the fluvial environment is critical, not only in understanding how the system will respond to wood placements but also for the consequences to riparian forests and carbon storage in alluvial valleys. What then are the key variables contributing to the stability of wood debris? Understanding wood stability is central to understanding the ultimate fate of trees once they fall into a stream.

The geomorphology of a fluvial system is largely a function of its flow regime and sediment load. Of all the components of the particulate load, wood debris remains the least predictable with regard to the implications of how changes in the size distribution and supply of wood debris influence the system. We know that when individual pieces of wood are large enough, they can form stable obstructions that alter a river's course and can last for centuries [e.g., *Muir*, 1878; *Wolff*, 1916; *Guardia*, 1933; *Montgomery and Abbe*, 2006]. However, it is well established that wood alters rivers on a range of scales (Plate 1) and that changes in wood loading can alter sediment transport capacity, bed textures and channel morphology, and sediment transport [e.g., *Lisle*, 1995; *Abbe and Montgomery*, 1996, 2003; *Buffington and Montgomery*, 1999a, 1999b; *Manga and Kirchner*, 2000; *Brooks and Brierley*, 1997, 2004; *Cordova et al.*, 2006; *Magilligan et al.*, 2007]. Also, extensive literature exists on the role instream wood plays on aquatic ecosystem dynamics (see *Harmon et al.* [1986] and *Maser and Sedell* [1994] for an overview) and on some of the indirect relationships among channel morphology, wood, and processes such as hyporheic exchange flow [*Boulton*, 2007; *Stofleth et al.*, 2008; *Wondzell et al.*, 2009].

Since the 1990s, wood has become a significant component of river rehabilitation efforts [*Gerhard and Reich*, 2000; *Brooks et al.*, 2006; *Chin et al.*, 2008]. However, with the increased interest in wood reintroductions as a core river management activity within many government agencies come increasing concerns about appropriate design principles and appropriate monitoring of wood reintroduction activities and, indeed, all river management activities [*Dolloff*, 1994; *Bernhardt et al.*, 2005; *Wohl et al.*, 2005; *Mehan et al.*, 2006].

This chapter will review some of the attributes of wood in rivers before describing some of the key aspects of wood debris to consider in river restoration. Drawing on over a decade of experience in reintroducing wood to rivers on two continents, we will outline the basic elements of wood stability and design for controlling stream grade and flow patterns, present several large river examples, and offer guidelines for the reintroduction of wood into rivers, including its role in carbon sequestration. The approach to wood reintroduction that we outline is one that is strongly founded in understanding the role that wood has played in natural systems. However, we also show that it is possible to understand and analyze the role and performance of individual logs and log accumulations (logjams) through the common language of mathematics and physics.

1.1. Geologic and Human History of Wood in Rivers

The affinity between trees and rivers predicates the delivery of wood debris to the channel network. Wood, or evidence of wood, can be found in fluvial sediments deposited since trees appeared about 360 million years ago. 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 forming from the time woody plants first evolved [e.g., *Gastaldo and Degges*, 2007], contributing to the vast deposits of fossil fuels upon which human civilization is built. The fluvial sediments containing evidence for ancient wood also demonstrate that some of the wood stays within the fluvial system where it gradually breaks down or is preserved over long periods of time [e.g., *Hyatt and Naiman*, 2001; *Montgomery and Abbe*, 2006; *Guyette et al.*, 2008].

Trees found in both modern and ancient alluvium demonstrate that wood debris has been a part of fluvial systems at least through the Pleistocene and potentially has been a key mechanism for long-term carbon sequestration. *Guyette et al.* [2008] radiocarbon dated 200 tree boles exposed in eroding banks of eight streams in North Missouri, United States, 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 3515 years B.P. They found that the mean residence time for carbon was about 1960 years due to decreases in wood density over time as a result of reductions in cell wall thickness. The implications from this and other work documenting the longevity of wood in alluvium [e.g., *Brakenridge*, 1984; *Nanson et al.*, 1995; *Brooks and Brierley*, 2002; *Abbe*, 2000; *Montgomery and Abbe*, 2006] are important for considering the carbon-sequestering role of wood debris in floodplain management and wood reintroduction projects.

1.2. Influence of Wood Debris on Alluvial Systems

Integrating wood into river restoration involves an understanding of all aspects of fluvial geomorphology that

Plate 1. Wood debris acts on a wide range of scales from substrate and cover to channel planform and floodplain morphology.

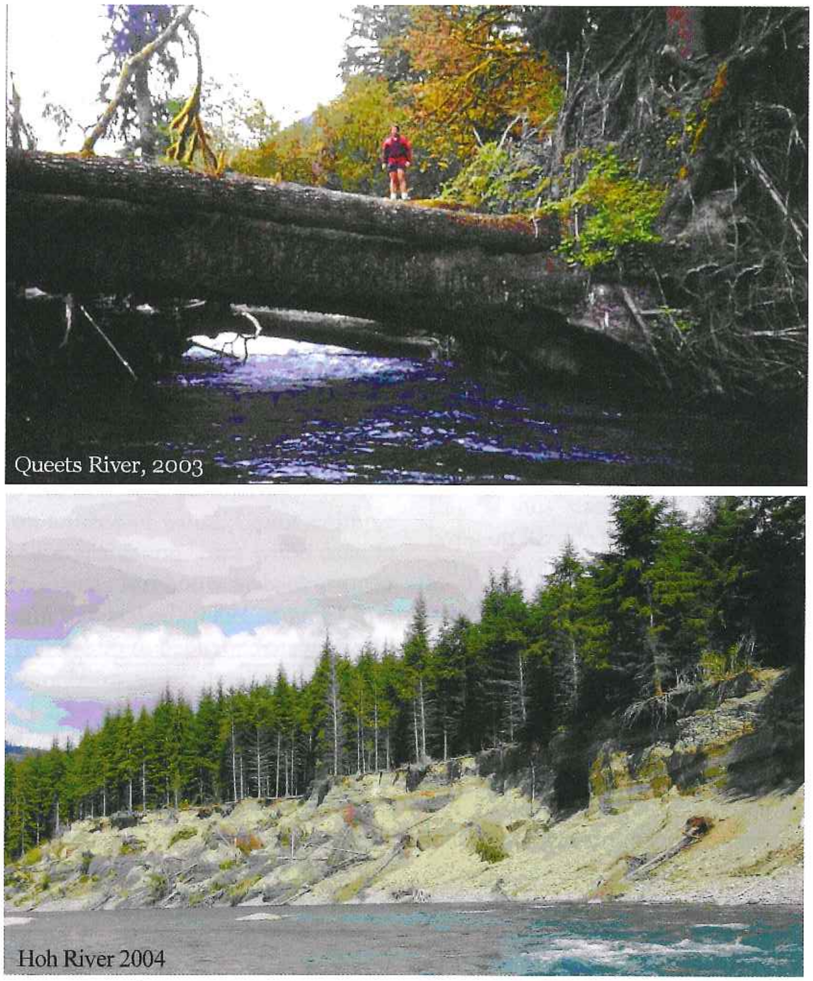

Plate 2. Changes in the size of wood recruited to rivers influence geomorphic processes. (top) Recruitment of old growth along the Queets River in Olympic National Park introduces key pieces capable of redirecting flow. (bottom) Trees falling in the river from a forest plantation along the Hoh River outside Olympic National Park are easily washed away by the river. Both photos are looking upstream. The recruitment of key members provides a means of increasing bank roughening that reduces shear stress and erosion.

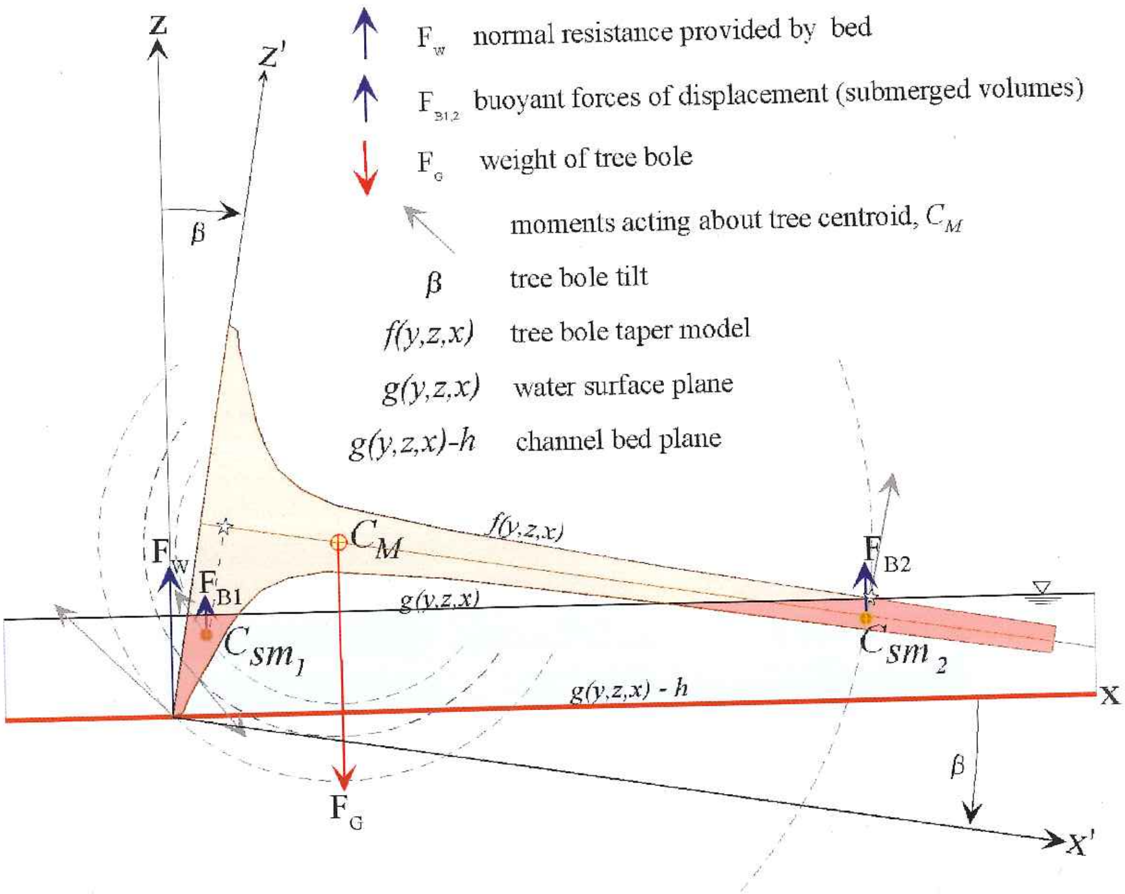

Plate 3. Free-body diagram for a snag. A root wad does several important things: (1) raises the center of mass, (2) increases the normal stress imposed on the streambed by reducing the log's footprint area, and (3) creates a bluff body flow obstruction that creates scour around the root wad that begins embedment in the streambed.

influence the recruitment, stability, transport, and effects of wood, including basin hydrology, channel hydraulics, sediment transport, channel dynamics, and riparian vegetation.

It has long been recognized in fluvial geomorphology that flow and sediment supply control channel morphology [e.g., *Lane*, 1955], but it has become increasingly apparent in some rivers that wood debris can be the dominant factor controlling channel morphology. Observations of early European settlers in North America did recognize the important role of wood debris, such as the large complex logjams of the southeastern United States that often created vast networks of impounded waters and bayous [e.g., *Lyell*, 1830; *Catlin*, 1832; *Veatch*, 1906; *Russell*, 1909; *Dacy*, 1921] to the role of a single fallen *Sequioadendron giganteum* log in creating the habitat that nurtured these trees high in the Sierra Nevada of California [*Muir*, 1878]. A great deal of effort was exerted by the U.S. government over more than a century to clear wood from rivers [e.g., *Ruffner*, 1886; *Sedell and Frogatt*, 1984; *Collins and Montgomery*, 2002]. Similar efforts were expended in other New World countries such as Australia, where active wood removal programs persisted from the 1800s up to the 1990s [*Erskine and Webb*, 2003; *Brooks et al.*, 2006]. The impact of these actions was to alter the energy gradient and morphology of rivers subjected to this treatment [e.g., *Guardia*, 1933; *Hartopo*, 1991; *Brooks et al.*, 2003].

The wood from riparian forests was an essential resource in the development of every human civilization, providing energy and the fundamental building material for shelter, transportation, and industry [e.g., *Williams*, 2003]. Human development was often focused in river valleys, and riparian forests were often the first to be cleared. In a wide range of climates, it is these areas along streams and rivers where trees thrived and attained the most impressive size. It was these same trees that were the source of timber recruited to streams and rivers via a range of mechanisms [*Abbe*, 2000; *Collins and Montgomery*, 2002; *Abbe and Montgomery*, 2003; *Benda et al.*, 2002; *Fox and Bolton*, 2007]. Hence, not only has wood been historically removed from channels for navigation and flood conveyance, but riparian sources of wood have been significantly altered or eliminated. Historic changes in the characteristics of riparian trees recruited to rivers have also had an influence on the stability of wood in rivers, with the general trend of much smaller, more mobile large wood debris (LWD) loading (Plate 2). Stable LWD accumulations directly affect the retention of smaller mobile LWD and, thus, the overall wood budgets of rivers.

2. WOOD STABILITY

About 100,000 species of trees, making up 25% of all vascular plants [*Raven and Crane*, 2007], are estimated. The vast range of trees come in many shapes and sizes and have adapted to a wide range of environmental conditions. Trees are the largest individual pieces of debris entering most streams and rivers and can have a pronounced influence on the conveyance of water and sediment. The shape and size of wood is a key attribute that contributes directly to its stability and function in streams and rivers [*Abbe and Montgomery*, 1996; *Abbe*, 2000; *Braudrick and Grant*, 2000; *Manners et al.*, 2007]. So how is it that a material that often has a specific gravity of less than unity (i.e., it floats) can remain stable in a river for long periods of time?

In circumstances where single-stem trees dominate, simplifying the shape of the tree can be a useful way of evaluating the forces that act on a piece of wood. Using a simple cylinder may be adequate for evaluating some wood used in restoration projects, but all trees have a tapered trunk (or bole) due to buttressing near the ground (Plate 3). Tree trunk buttressing can have a significant influence on the shape of a log and the centroid location of a snag [*Abbe et al.*, 1997; *Abbe*, 2000]. The presence of a root wad is one of the most important factors influencing wood stability. A simple expression for a snag taper exponent, a, using the bole radius, R_b, measured distance X_i from the base of the root wad with a radius of R_{rw} is given in equation (1):

$$a = \frac{\log(R_b/R_{\mathrm{rw}})}{\log(X_i - 1)}. \tag{1}$$

To estimate how far the bole's center of mass is from the root mat (distance along x axis, x_c) the moment of volume with respect to x (M_x) is divided by bole's volume, V:

$$x_{c_m} = \frac{M_x}{V} = \frac{(2a+1)(x^{2a+2} - 1)}{(2a+2)(x^{2a+1} - 1)}, \tag{2}$$

$$M = \pi \int_{x=1}^{x_n} x (R_{\mathrm{rw}} x^a)^2 \mathrm{d}x = \frac{\pi R_{\mathrm{rw}}^2}{2(a+1)} (x_n^{2(a+1)} - 1), \tag{3}$$

$$V = \pi \int_{x=1}^{x_n} (R_{\mathrm{rw}} x^a)^2 \mathrm{d}x = \frac{\pi R_{\mathrm{rw}}^2}{2a+1} (x_n^{2a+1} - 1). \tag{4}$$

Assuming the log is resting on a level surface, its tilt will be a function of its length and radii at either end (root wad, R_{rw}, and crown, R_n). The centroid elevation, z_{c_m}, for this simple model is

$$z_{c_m} = \left\{ R_n \left(\frac{R_{\mathrm{rw}} - R_n}{x_n - 1} \right) x_n - x_{C_m} \right\} \sin \left\{ \tan^{-1} \left(\frac{R_{\mathrm{rw}} - R_n}{x_n - 1} \right) \right\}. \tag{5}$$

Centroid locations of submerged portions of a log upon which buoyant forces act can be determined through a numerical integration of the volume defined by the log's intersection with the relevant water surface elevation. A basic hydrostatic analysis is the first step in evaluating the stability of a piece of wood or tree bole. The water depth at which a log becomes fully buoyant, $F_B = F_G$, is referred to as the buoyant depth, h_{b}, and commonly corresponds to the log's maximum draft, d_m. The draft of the log relative to a particular flow depth is critical since it will influence the frictional resistance the log encounters along the channel boundaries. A bed form or roughness element upon which a log comes in contact can provide a resisting force equal to the driving forces, thus stabilizing the log. The hydrostatics of a tree lying on its side is a very different situation than a tree stump sitting upright. In the case of a tree stump, a large portion of the wood volume is displaced with relatively little water depth and the centroid (center of mass) is relatively low to the ground. Thus, a tree stump has a relatively shallow buoyant depth. But in the case of a snag with an intact root wad lying on its side, the centroid is typically situated higher above the ground. In the latter case, rising water displaces a relatively small volume of the snag because the root wad elevates the bole above the ground, so a snag has a greater buoyant depth when lying on its side versus sitting upright. The relatively high buoyancy and low potential for embedment make stumps a poor choice for LWD placements.

With the stem or bole taper determined, the volume of the buttressed end of the snag can be estimated:

$$V_{\mathrm{rw}} = \frac{\pi R_{\mathrm{rw}}^2}{2a+1} (X_i^{2a+1} - 1). \tag{6}$$

This estimate of volume can work for the "stump" portion of the logs. For a single-stem straight tree the volume (V_b) above the stump (above the basal radius of the bole, R_b) can be estimated assuming a truncated cone or frustum of length L_b:

$$V_b = \frac{\pi L_b}{3}(R^2 + Rr + r^2). \qquad (7)$$

The total snag volume, V_w, is the sum of V_{rw} and V_b. The dry weight of a snag is determined using the dry density of the wood.

$$W_{wd} = g\rho_w V_w \qquad (8)$$

where

W_{wd} weight of log;
g gravitational constant;
ρ_w wood density;
V_w volume of wood.

Buoyancy will be defined on the submerged volume of the snag, Vs_w, which can be used to estimate the snag's buoyancy relative to the amount of submergence.

$$W_{ws} = g[(\rho_w V_w) - (\rho_f Vs_w)], \qquad (9)$$

where W_{ws} is submerged weight of log, ρ_f is fluid density, and Vs_w is submerged volume of wood (displacement).

A negative value for the submerged weight indicates the log is buoyant. As the size of wood increases, so do its weight, strength, and the height of its centroid. Thus, it takes deeper water to float it and stronger currents to drag or break it. But size also means greater buoyant forces, and thus, a greater extent of burial is required if the snag is to remain stable. Since buoyancy depends on the weight of the water displaced, a large tree can exert significant buoyant forces if submerged, depending on its specific gravity (if greater than 1, the tree will sink). Even if buoyant, a tree may not move down the river if it encounters sufficient resistance along the riverbed, just like a grounded ship. The partially buried root wad of a buoyant tree (just like the keel of a sailboat) will encounter passive earth pressures that can be sufficient to halt its movement [*Abbe et al.*, 2003a].

After a tree falls into a river, the key to its stability will rely on whether it becomes embedded into the channel. Thus, the snag has to remain stable after bed load transport has been initiated and have sufficient weight to sink into the riverbed. The presence of a root wad and elevated centroid are critical for this process to proceed. A snag is most stable with its root wad facing upstream, forming a bluff body in the river flow. The root wad of a snag adds significant draft to the wood and, thus, drags upon the riverbed. The floating tip of a snag will be most stable in the lee of the root wad [*Abbe and Montgomery*, 1996]. Thus, the stable configuration of a snag with the root wad facing upstream forms a bluff body to incident flow [*Abbe*, 2000]. A bluff body is the opposite of an aerodynamic form. As flow goes around a bluff body, it separates around the edges to form a turbulent zone called a Von Karmen vortex street. Between each vortex street is the flow separation envelope commonly referred to as an eddy. Within this eddy, bed material can accumulate and begin to bury the back side of the root wad, adding passive earth pressure resistance to the drag acting on the snag. If a snag remains stable under the flow conditions (depth and velocity) that mobilize the substrate, the root wad will settle into the adjacent scour hole. Only a small amount of burial is required for the snag to become stable in flows that would otherwise have caused mobilization [*Abbe*, 2000; *Abbe et al.*, 2003b]. Since the stems of the key pieces initiating a wood accumulation [*Abbe and Montgomery*, 1996] are typically located within the flow separation envelope, they become buried (Plate 4). A buried snag initiates a flow obstruction that can trap mobile debris and lead to bar formation that can go on to develop into a floodplain island [*Abbe and Montgomery*, 1996]. The natural process by which a snag embeds itself into the riverbed is fundamental for understanding wood stability in large channels [*Abbe*, 2000; *Abbe et al.*, 2003a].

Despite the vast number of tree species, the range of specific gravity is relatively low when compared to rock. The specific gravity of all woods can never exceed cellulose and lignin creating the solid wood material, which is 1.54 [*Skaar*, 1988]. Since wood originates as living tissue, it must have some porosity to transmit water and nutrients. Thus, the specific gravity of the densest woods (dry) does not exceed 1.37 for Lignum vitae (*Guajacum sanctum*) and can be as low as 0.16 for balsa (*Ochroma lagopus*). The relatively low specific gravity of wood (often <1) when compared to rock (>1) is one of the principal perceptions that can influence the application and management of wood in rivers. To assume that all wood floats, however, would be a mistake, just as equating buoyancy with instability would be a mistake.

The specific gravity of a piece of wood depends on its porosity and moisture content. If wood is completely saturated, the specific gravity must of course be greater than water and less than the wood substance. Moisture content varies the greatest within the long cell cavities (lumen) and the least in the cell walls that comprise the wood or xylem. The maximum possible moisture content is dependent on density of the wood structure, which is reflected in the basic specific gravity of different species (Figure 1). Determining the weight, volume, specific gravity, and moisture content of wood is a fundamental step in designing with wood.

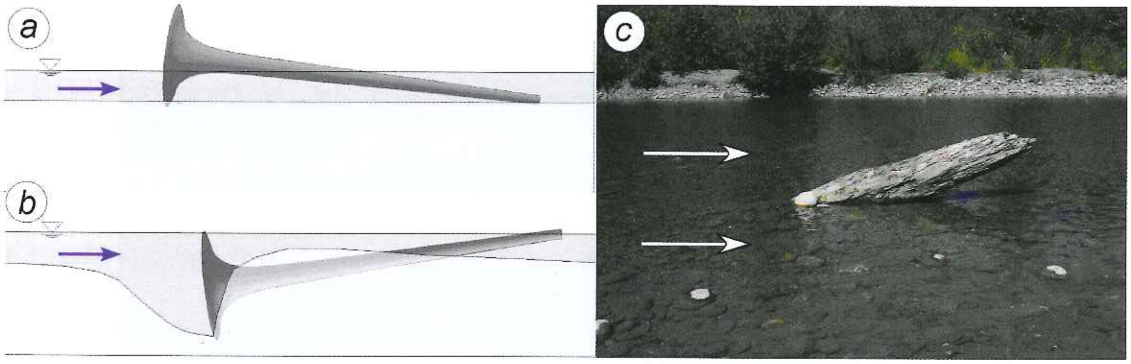

Plate 4. (a) If a snag remains stable after bed load transport has been initiated, (b) scour can begin process by which the snag is buried into the streambed. (c) Buried snags will always have their tips pointed downstream and create formidable obstructions within the river.

$$W_g = W_d\left(1 + \frac{M}{100}\right) \tag{10}$$

$$M = \left(\frac{W_g}{W_d} - 1\right)100, \tag{11}$$

where W_g is weight of green wood, W_d is oven dry weight of wood, and M is moisture content of wood.

Wood density, ρ_w, is determined by

$$\rho_w = \left(\frac{W_d}{V_g}\right)\left(1 + \frac{M}{100}\right), \tag{12}$$

$$G_b = \left(\frac{W_d}{V_g}\right)\left(\frac{1}{p_w}\right), \tag{13}$$

$$\rho_w = G_b\rho\left(1 + \frac{M}{100}\right), \tag{14}$$

where ρ is density of water, V_g is green volume of wood, and G_b is "basic" specific gravity [*Simpson*, 1993].

The maximum moisture content (%), $M_{\max}$, is expressed as a function of the wood porosity ($1 - \gamma_b/\gamma_w$). Thus, the denser the wood, the lower the maximum moisture content.

$$M_{\max} = (100/\gamma_b)(1 - \gamma_b/\gamma_w), \tag{15}$$

where γ_b is basic specific gravity of tree species and γ_w is specific gravity of the wood material (cellulose and lignin) equal to 1.54.

The maximum moisture content for western red cedar (*Thuja plicata*) has a relatively low specific gravity (γ) of about 0.35 and has maximum moisture content of about 220%. Douglas-fir (*Pseudotsuga menziesii*) has a specific gravity of about 0.55 and a maximum moisture content of about 120%. Australian red mahogany (*Eucalyptus resinifera*) has a maximum moisture content of only 40% due to its high specific gravity of 0.96. The maximum moisture content of one the world's hardest woods (γ = 1.35) Lignum vitae (*Guaiacum* spp.) is only 10%. When saturated, even low-density woods can sink, as reflected in the many logs found at the bottom of mill ponds throughout the world. When designing with wood, the conservative assumption is to use the dry or green density of the wood in force balance calculations. If it is known that the timber will remain submerged; a stability analysis can be undertaken using a less conservative value for the timber density.

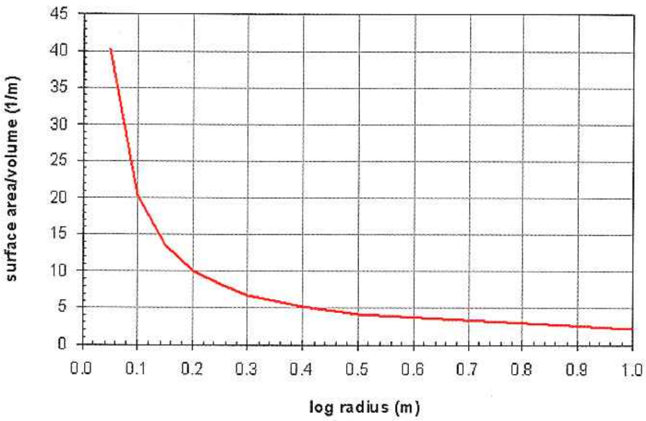

Plate 5. The ratio of surface area to volume declines dramatically as a function of the log radius (independent of log length). The greater the surface area to volume, the more rapid the exposure of the log to decay.

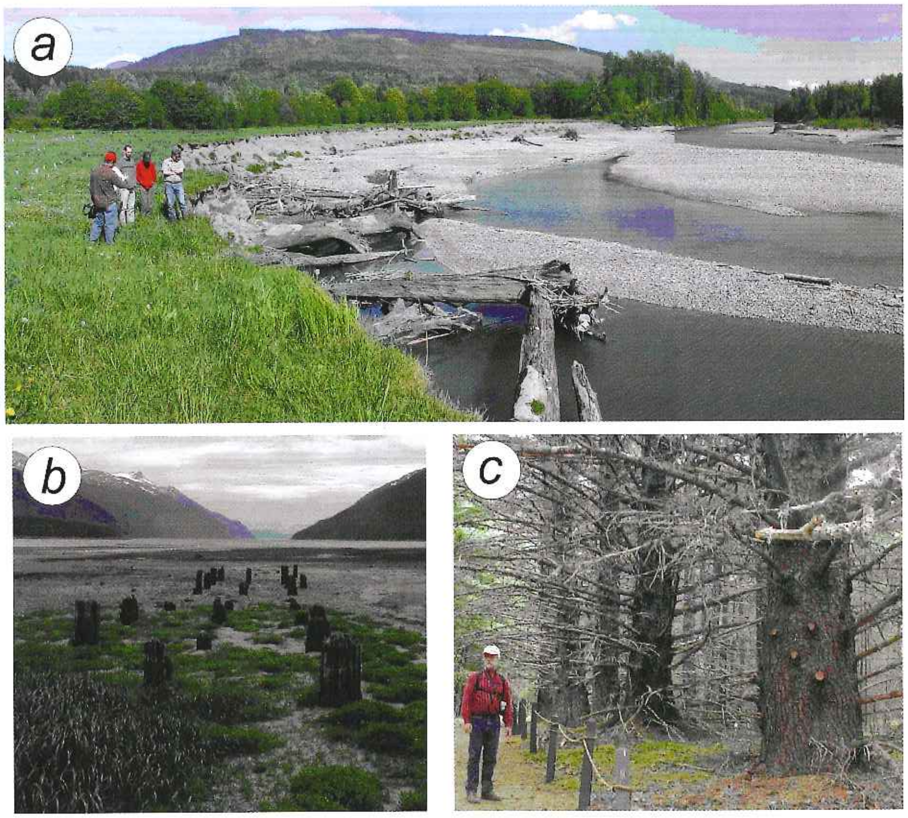

Plate 6. Examples of wood longevity: (a) 2003 exposure of buried logjam along South Fork Nooksack, Washington, over 118 years old based on the fact that a river never historically occupied this area [*Collins and Sheikh*, 2004], (b) remains of 110 year old timber piles in Dyea, Alaska, at outlet of Taiya River (2002), and (c) 110 year old Sitka spruce trees in Dyea (2002).

It should also be recognized that wood density will vary through time, both on short time scales of hours to weeks, with wetting and drying cycles, and over periods of years as the timber decays. The short-term variation in density is a function of the difference in the moisture content of the wood, which is a function of the proportion of intercellular pore spaces that contain either water or air. The longer-term variation in density associated with timber decay is a function of an increase in porosity as the lignin and cellulose decays. Figure 2 shows some experimental data using pieces of river red gum (*Eucalyptus camaldulensis*) showing the wood density under field conditions during drought (considered to be the worst-case conditions) and then after oven drying for 24 h (the basic dry density) as well as the following 6 and 18 h saturation. These data show that even in the case of relatively dense Australian eucalypts, when it dries out in the field, this timber can become buoyant. However, even after 6 h of immersion, it is possible for these timbers to increase their specific gravity to the extent that they are no longer buoyant. Hence, it is clear that the moisture content is a critical variable for understanding the stability of individual logs in a river. Furthermore, the same species of timber might behave very differently in two rivers depending on the hydrologic regime. Timber within a river having a stable base flow and in which flood waters rise gradually may never dry out and will consequently be more stable than the same tree in a very flashy ephemeral channel where a piece of wood may be completely dry and then completely submerged in a matter of hours.

3. WOOD LONGEVITY

Two types of stability exist with regard to wood: mechanical and biogeochemical. The first involves the ability of a piece of wood to resist the forces that would move or break it. The second involves the decay or breakdown of the wood material. Both types of stability lead to common and legitimate questions in river engineering and restoration, and both can be addressed. Mechanical stability can be evaluated using a force balance approach. Decay can be addressed based on a set of assumptions. The certainty to which predictions can be made regarding either condition depend on

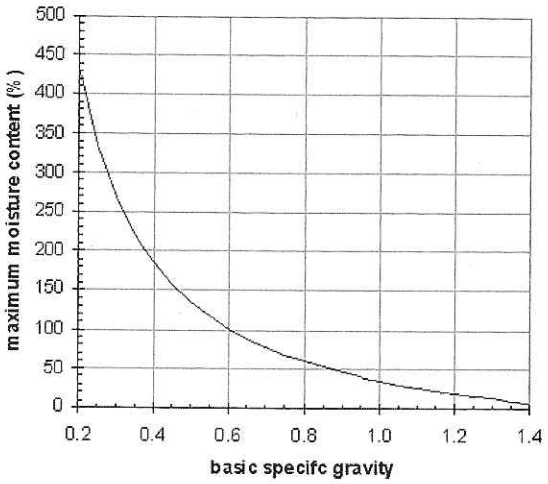

Figure 1. Maximum moisture content as a function of basic specific gravity [*Simpson*, 1993].

the quality of the input data and validity of the assumptions. An individual piece of wood ("log") is stable in fluvial environments under one of two conditions: (1) the wood is large enough to be locked into place within the channel either between banks or against preexisting obstructions such as boulders or trees or (2) the wood is embedded within alluvial sediments.

In the first case, the wood must be situated such that it cannot rise above the obstruction during high water or break under the drag force imposed by flowing water. The first condition is commonly found in low-order headwater areas where wood is large relative to the channel. The second condition is found in large alluvial channels where an individual piece of wood is small relative to the channel geometry.

An important question in any wood debris restoration work regards the longevity of the wood. Wood can last virtually indefinitely under two scenarios, when kept under anaerobic (submerged) condition or perfectly dry. Obviously, the latter condition will not be found in rivers, but the former does occur, although the most common state is likely to be one of wetting and drying. When wood is saturated year round, it can be remarkably well preserved and lasts for hundreds and even thousands of years and plays an important role in structuring alluvial rivers and forested floodplains [e.g., *Nanson et al.*, 1995; *Abbe*, 2000; *O'Connor et al.*, 2003; *Montgomery and Abbe*, 2006; *Fox and Bolton*, 2007; *Magilligan et al.*, 2007]. Because wood floats and is subject to decay, it is often believed that wood should not be put in rivers; this common perception has hampered the integration of wood in restoration. This perception fails to take into account the geologic history of wood in rivers, including the last 6000 years in which wood has been an integral part of aquatic environments. Wood in rivers can last for a very long

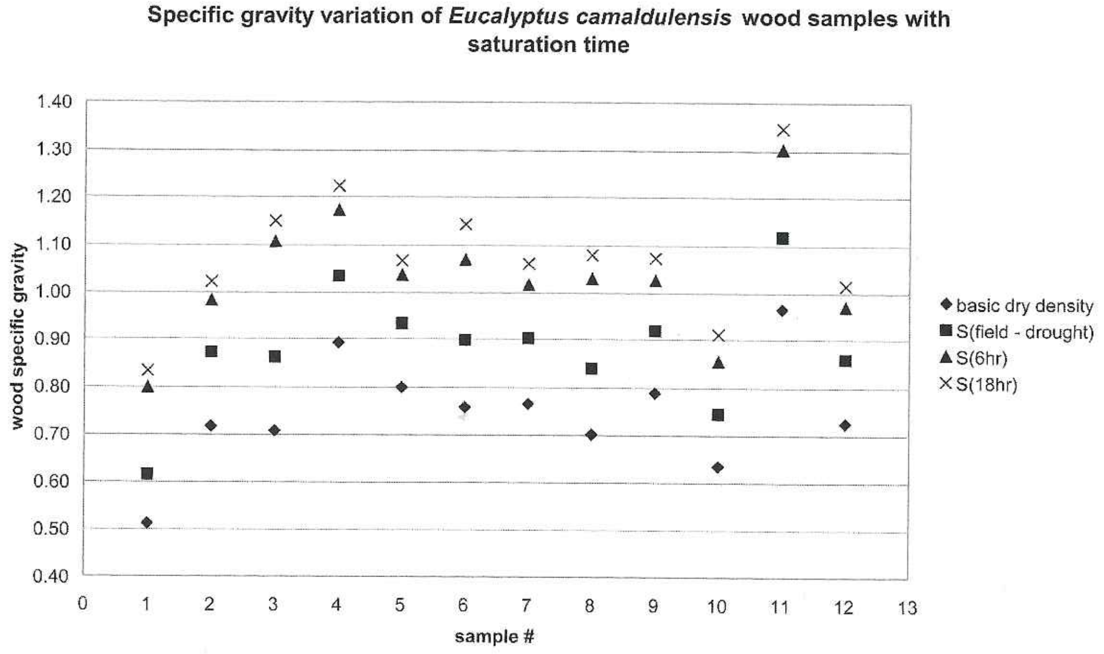

Figure 2. Some experimental data using pieces of river red gum (*Eucalyptus camaldulensis*) showing the wood density under field conditions during drought (considered to be the worst-case conditions) and then after oven drying for 24 h (the basic dry density) as well as the following 6 and 18 h saturation.

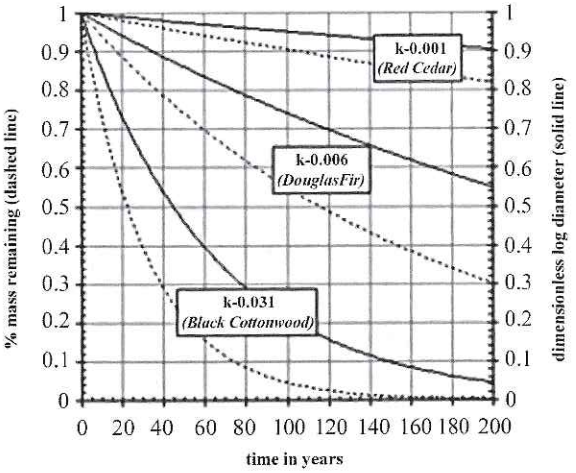

Figure 3. Simple decay model for cylindrical logs with spatially uniform decay. Decay rates (k) are taken from *Harmon et al.* [1986] for forest floor logs and thus are conservative for timber situated in a stream or river. The curves are for three common tree species in the Pacific Northwest that show a wide range in susceptibility to decay, ranging from western red cedar (*Thuja plicata*) to Douglas-fir (*Pseudotsuga menzisii*) to black cottonwood (*Populus trichocarpa*). After 120 years, a Douglas-fir log would lose about 50% of its mass and have an effective diameter of about 70% of its original.

time, depending on the tree species and the conditions of preservation. Wood situated above the base water surface will be subjected to biological decay and physical breakdown associated with wetting and drying and abrasion by transported sediment. Thus, the type of wood and size of log play a dominant role in its decay. Certain woods are chemically predisposed to excellent preservation. In general, however, the larger the log, the greater the longevity, since the ratio of surface area to volume decreases as log diameter increases (Plate 5). Conversely, the higher the ratio of surface area to volume, the faster the decay [e.g., *Spanhoff et al.*, 2001], so it is always advantageous to use larger logs for the structural foundation of any in-stream wood structure.

Many examples can be found throughout the world to illustrate the preservation of wood relative to the water table. Wood in alluvial sediments can be subjected to a wide range of decay agents that can break down the structural integrity of a log. But in the right depositional conditions, wood debris can last for thousands of years. In the case of restoration, field inspections within a project area can reveal evidence of relic logjams exposed in eroding banks (Plate 6a). These ancient structures typically consist of the key pieces that initially formed the logjam. The piles beneath St. Mark's in Venice, Italy, were so well preserved below the ground water level after 1002 years; they were left in place to support the reconstructed tower and determined to have an "indefinite" life [*Jacoby and Davis*, 1941, p. 81]. A similar phenomenon can be observed where old pilings are exposed in rivers and estuaries, such as the wharf pilings of the ghost town of Dyea, Alaska, constructed in 1898. The pilings below ground level remain in good condition after more than a hundred years, sufficient time for trees planted on the river's floodplain to obtain substantial size (Plates 6b and 6c). A simple model of wood decay can provide a basic guideline for estimating longevity. The model assumes cylindrical log geometry with homogeneous decay and is very sensitive to an assumed decay exponent (Figure 3), which varies substantially between tree species and the depositional setting. The mass of a log at time t can be predicted using the following:

$$M(t) = M(0)e^{k(t-t_0)}, \tag{16}$$

where

$M(t)$ mass at future time t;
$M(0)$ mass at time of placement;
k decay coefficient;
t future time;
t_0 starting time.

On the basis of the assumed decay rate, log mass and diameter can be predicted for a given time frame, thereby allowing an assessment of the structure's integrity for specific design lives. Forest floor decay rates, k, of common Pacific Northwest species range from 0.001 for red cedar (*Thuja plicata*) to 0.006 for Douglas-fir (*P. menziesii*) to 0.031 for black cottonwood (*Populus trichocarpa*) [*Harmon et al.*, 1986]. It is likely that decay rates are higher in warmer climates but may be offset in the case of timbers that are more resistant to decay such as gum trees, mahogany, and ironwood. Decay rates are very much dependent on a variety of environmental settings, physical condition of the wood, and agents of decay (e.g., bacteria, fungus, and termites). When exposed to these agents, wood may only last several decades [e.g., *Hyatt and Naiman*, 2001]. In soils where wood is susceptible to wetting and drying, restoration design should carefully consider potential biochemical degradation and whether the wood will achieve the desired design life. As wood decomposes, it rapidly loses strength, which may be important in using posts or piles to provide lateral resistance. The role of wood decay in the failure of natural and engineered wood structures is unknown and, thus, an important area for additional research. The current engineering practice in restoration assumes structurally sound timber, an assumption that while valid today, may not be valid in 25 years. As wood decays, strength is lost more rapidly than mass [*Abbe*, 2000], so it is wise to err on the

Plate 7. In small headwater streams of the Puget Sound Lowlands, wood can account for much of the creeks' head loss and sediment storage. In this 12% gradient segment of Schmitz Creek in west Seattle, Washington, historic "relic" wood buried in the alluvium accounts for over 90% of the head loss and helps stabilize banks despite heavy foot traffic (July 2009 photo).

side of larger timber whenever possible. In critical sites, it may be worth considering environmentally sensitive wood treatments for structural elements such as piling. The key to rehabilitating wood in rivers is ensuring riparian forest conditions will ultimately negate the need for in-stream wood placements. Logjams can play an important role creating riparian forest refugia within active channel migration zones [*Abbe and Montgomery*, 1996; *O'Connor et al.*, 2003]. The design life of wood structures built in rivers and floodplains should allow sufficient time to reestablish functional wood recruitment on and adjacent to LWD structures.

The other critical aspect of designing longevity for restoration projects involves replacement; once an individual structure reaches its design life, will its function be adequately replaced by the restored riparian forest? Replacement should be the long-term goal of all restoration projects. That is, we are restoring the process role of wood, not simply building engineered structures. If riparian conditions cannot be restored to conditions that will sustain the function of the original wood structures, then it should be made clear that future work, from maintenance to new construction will be required. In situations where it is impossible to fully restore riparian forest conditions with associated wood recruitment, and longevity of individual structures is critical, the focus should preferentially be on function rather than materials. In difficult environments, such as urban creeks, where a high factor of safety and longevity are paramount, materials such as concrete logs or steel piles can be used, as long as the completed structure emulates the desired function of natural wood. Real wood debris (particularly racking material) can be integrated with these other materials to provide the desired biological attributes and visual aesthetic. In some urban environments "relic" wood, comprised of large old logs, is all that prevents some creeks from undergoing severe incision and bank erosion, even despite dramatic increases in the magnitude and frequency of peak flows (Plate 7). These relic logs

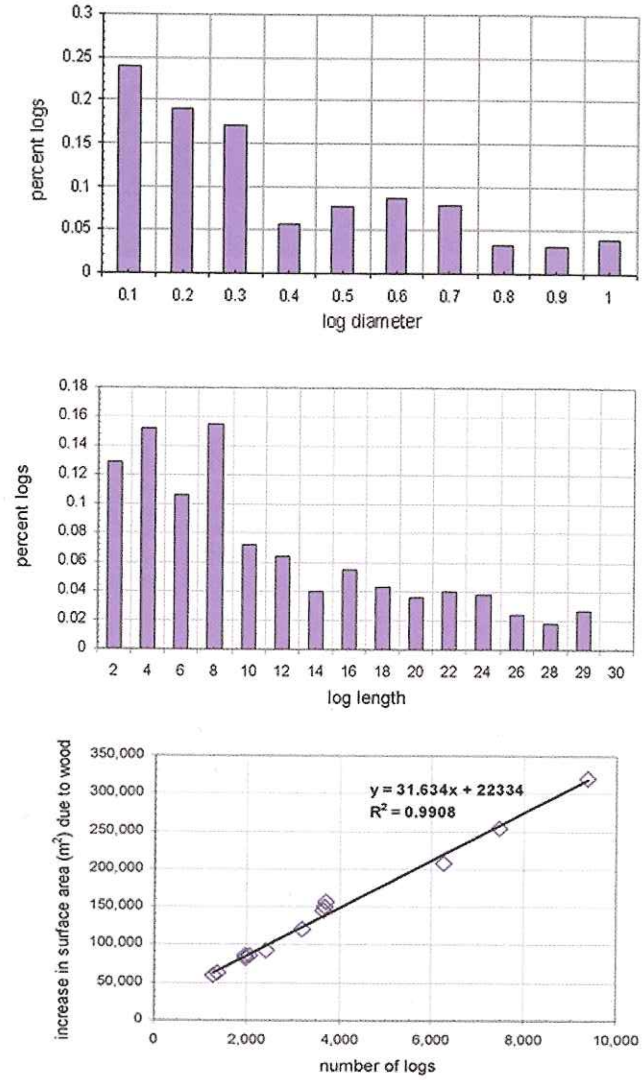

Plate 8. (top and middle) Example distribution of racking logs in a logjam by diameter and length and (bottom) the resulting increase in surface area based on number of racked logs. The last chart shows how this distribution of log sizes creates surface area within the river as the number of logs increase in the jam. This example is conservative since it does not include fine organic debris (diameters <0.1 m), which would increase the surface area significantly.

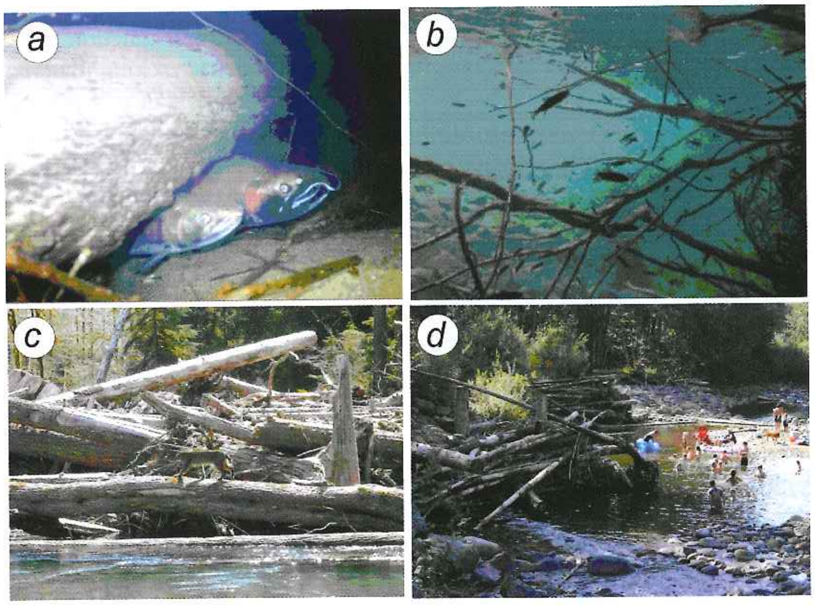

Plate 9. Logjams form the most complex habitat found in rivers, forming pools, bars, and cover for all sorts of species. The interstitial spaces within the structures offer (a and b) cover for fish and (c) river access for predators and (d) create pools that humans enjoy during hot summers (Mashel River engineered logjams (ELJs) in Smallwood Park, Eatonville, Washington). Plate 9a courtesy of G. Pess, Plate 9b courtesy of Wild Fish Conservancy, and Plate 9c courtesy of P. Caton.

are typically large and composed of wood that is more resistant to decay (e.g., cedar or tight grain old growth). If these logs are not ultimately replaced, the creek may be at serious risk of incision. This same principle is needed in restoration projects where engineered structures are placed.

4. WOOD COMPLEXITY AND HABITAT

By adding wood roughness to a channel, shear stress is partitioned among the channel form, sediment, and wood, thereby reducing the effective shear stress available for

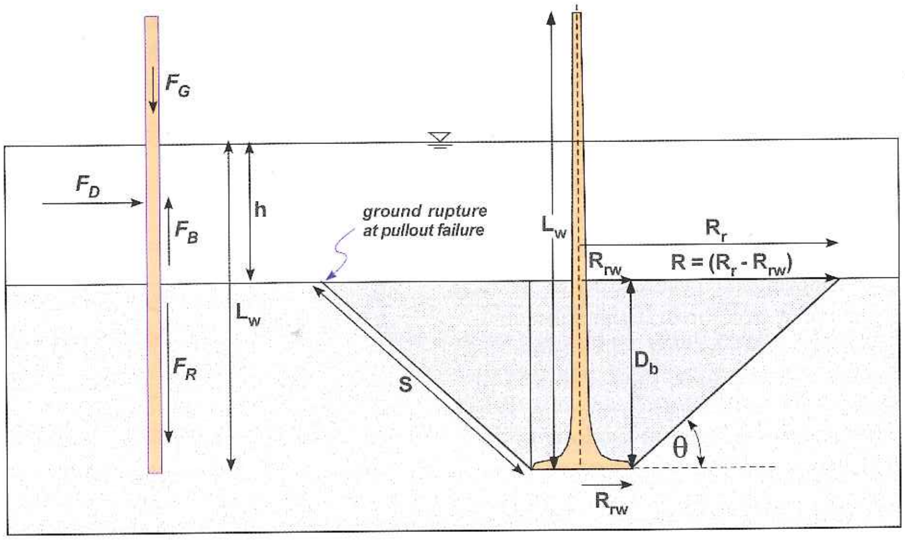

Plate 10. Timber piles and posts. A traditional driven pile (left) consisting of a vertical cylinder that relies only on skin friction for resisting buoyancy when fully submerged. A buried root wad post benefits from additional surcharge of overlying alluvium. Forces acting on an embedded root wad pile or post (right) are the same as a simple pile (left), with the addition of the geostatic load of the alluvium.

sediment transport, which consequently reduces the overall bed grain size [*Manga and Kirchner*, 2000]. Even small amounts of wood debris can have a significant effect on bed textures, thereby modifying aquatic habitat [*Buffington and Montgomery*, 1999a, 1999b]. On a larger scale, logjams form bluff bodies that alter flow patterns within a channel [*Abbe and Montgomery*, 1996]. A logjam structure introduces a unique substrate to the stream ecosystem (wood) in concentrated and complex assemblages that have been found to be heavily used by invertebrates [*Coe et al.*, 2006] and fish [*Peters et al.*, 1998].

The surface area of individual pieces of wood and accumulations has important implications with regard to biological productivity that can affect wood decay and the amount of habitat availability [*Wondzell and Bisson*, 2003; *Coe et al.*, 2006]. Two simple principles apply with regard to surface area available to invertebrates and other crucial organisms: (1) the smaller the tree, the greater the surface area relative to the tree's volume (Plate 5), and (2) the more trees in a logjam, the greater the surface area. Large tree stems with attached root wads are key to structure stability and longevity, but small debris is key to creating the complexity, substrate, and cover to enhance the food web [*Coe et al.*, 2006]. Smaller wood has a higher ratio of surface area to volume and, thus, is prone to higher decay rates since decay is proportional to both variables (increases with surface area and decreases with volume). When accumulations of small debris form against larger key pieces, they not only greatly enhance the ecologic functions of the structure but they can also improve stability by reducing scouring flow through the key members. The largest logjams form on larger rivers where massive accumulations of smaller, more mobile debris accumulate (Figure 4). The accumulations of wood debris not only split up the river flow, but they also create entire ecosystems within the river.

Logjams can introduce a tremendous amount of physical complexity and organic substrate within a river. Modeling debris as simple cylinders, and assuming a random distribution of sizes representative of the material entering the river, a logjam of 1000 logs can have a surface area of over 60,000 m^2, while an accumulation of 10,000 logs will have a surface area of over 300,000 m^2 (Plate 8).

Because the wood in a logjam is composed of a broad distribution of sizes and shapes, it creates a complex matrix with a wide range of interstitial spaces that can accommodate a commensurate range of organisms of various sizes. In addition to the range of interstitial area is a range of hydraulic conditions and lighting. A logjam is similar to a densely populated urban area of many different tenements. *Peters et al.* [1998] observed that both juvenile and adult fish seek refuge within logjams during the day (Plate 9). *Coe et al.* [2006] found that invertebrate densities are much greater within logjams when compared to alluvial banks. Moreover, because logjams extend above the water, they form excellent habitat for birds and mammals (Plate 9). *Harvey et al.* [1999] found that fish holding at large woody debris accumulations were less likely to move away from the wood over varying flows as opposed to fish using portions of a stream without obstructions. In the Williams River wood reintroduction experiment in southeastern Australia, the numbers of Australian bass (*Macquaria novemaculeata*) found within the confines of a single logjam on one sampling occasion exceeded those found within the entire 1.1 km study reach, over seven sampling occasions, across several years [*Brooks et al.*, 2006].

5. DESIGNING WOOD DEBRIS STRUCTURES

Engineered logjams (ELJs) have been widely used in the Pacific Northwest of North America over the past decade, as

Figure 4. Wood accumulation on a constructed logjam in the Hoh River in 2008, 4 years after construction. Person in foreground gives scale of logjam. The ELJ has accumulated several thousand of pieces of debris ranging in length from 1 to over 20 m and diameters from 0.1 to 1 m. The logjam increases the surface of cover and organic substrate by over 100,000-fold.

well as in Australia, as an alternative, more sustainable approach to river management [*Brooks et al.*, 2004, 2006; *Brooks*, 2006]. In particular, they have been used for bank protection and habitat enhancement in high-energy gravel bed rivers supporting migratory species of Pacific salmon. Two general types of wood structures exist: (1) grade control and (2) flow deflection. The focus of this chapter is the latter. Grade control structures are predominantly found in small to moderate-sized channels where log lengths equal or exceed channel widths. In these systems, wood can be a very important structural component in dissipating energy and capturing sediment. Flow deflection structures are typically used in large alluvial systems where channel widths exceed log lengths.

Distinct types of logjams, or in-stream woody debris accumulations, are found in different parts of a channel network [*Abbe et al.*, 1993; *Wallerstein et al.*, 1997; *Abbe and Montgomery*, 2003; *Comiti et al.*, 2006; *Andreoli et al.*, 2007; *Baille et al.*, 2008]. Using observations from the Queets River basin on the Olympic Peninsula in Washington, distinct types of logjams have been classified according to the presence or absence of key members, source and recruitment mechanism of the key members, logjam architecture (i.e., log arrangement), geomorphic effects of the logjam, and patterns of vegetation on or adjacent to the logjam [*Abbe et al.*, 1993; *Abbe*, 2000; *Abbe and Montgomery*, 2003]. Six of these logjam types provide naturally occurring templates for ELJs intended for grade control and flow manipulation. Logjam types primarily applicable for grade control include log steps and valley jams; types more applicable for flow manipulation include flow deflection, bankfull bench, bar apex, and meander jams [*Abbe et al.*, 1993; *Abbe and Montgomery*, 2003; *Abbe et al.*, 2003b, 2003c].

The number of different architectures for these structures is infinite, but all will be subjected to similar processes, and their structural integrity is based on the same set of principles. We have compiled a planning framework for wood projects including objectives, opportunities, constraints, and project elements. We then briefly describe some of the key factors influencing wood stability and wood function to consider in designing each type of structure and present examples.

5.1. Project Planning

Before delving into the specifics of designing an individual wood structure, it is critical to assess the site and understand the geomorphic, hydrologic, hydraulic, ecological, and human context of the project. This assessment will all go into clearly defining the project goals and constraints, which in turn will influence structure design. Wood and wood structures are just one part of river restoration and management; hence, a much more comprehensive view of the system, from the physical processes to the politics, will be crucial to implement successful projects. All projects should be designed to accommodate the physical and biological processes to which the project will be subjected and emulate natural self-sustaining structures. ELJ technology [*Abbe et al.*, 1997, 2003c] was developed out of recognition of the natural role of logjams, particularly in their ability to form "hard points" in large alluvial rivers and was applied to river management. The philosophic elements of this approach are mirrored in the emerging field of "biomimicry" [*Benyus*, 2002]. A better understanding of natural processes and structures, exemplified by wood in rivers, offers plenty of opportunity in civil engineering and landscape architecture to develop much more sustainable long-term approaches to land management.

5.2. Project Design

The design process used for ELJ structures follows a formal geotechnical and civil engineering design approach similar to that used in traditional infrastructure development. The design process includes a formal quality assurance and quality control program, a reach analysis, data collection and verification, the establishment of a design basis, modeling, iterative design development with risk assessment, constructability and cost, public relations efforts and education, regulatory approval, and contract package development.

A reach analysis provides the necessary background information on historic and current conditions including channel geometry, substrate, hydrology, hydraulics, wood loading, and disturbance processes. Risk assessments can be relatively brief for projects with no risks to property, infrastructure, or life and can be extensive for projects with potential risks. In either case, a risk assessment should include all aspects of the project (Plate 10). Initially, the results of the reach analysis (including a geomorphic analysis and a review of field data) serve as the platform for determining the risk associated with the preliminary conceptual plan. The description of historical channel dynamics and flooding formulated during the reach analysis is essential for documenting preexisting conditions and risks at the project site if no ELJs were constructed. A reach analysis must be performed at spatial and temporal scales that are adequate for describing these relationships. Conceptual design alternatives are prepared, and a feasibility analysis is performed to compare the habitat benefits, cost, and initial risk associated with achieving the performance objectives of the project with each of the design alternatives.

If the results of the risk assessment indicate that the preliminary conceptual plan falls within an acceptable range of risk and meets the goals of the project, the preliminary conceptual plan then undergoes a hydraulic and scour analysis. Hydraulic modeling is done to evaluate flow regimes under current conditions and under potential build-out scenarios. In a geomorphic reach analysis, areas of physical constraints are identified and demarcated. These areas are then incorporated into the design alternatives; for example, differentiating areas within the channel migration zone where the main stem channel can freely move, areas in the channel migration zone where only secondary channels are acceptable, areas that can tolerate inundation but no channels, and areas in which no erosion or inundation is acceptable. Hydraulic modeling and scour analysis are an iterative process that allow for changes in the number and location of proposed structures. Hydraulic modeling should include a one-dimensional (1-D) model of the project reach to determine potential backwater effects of the project [e.g., *Brummer et al.*, 2006] and 2-D modeling as needed to evaluate the effects of structures on flow deflection and localized water elevations. Scour estimates should include all aspects of relative scour, including general, contraction, pier, and abutment scour [e.g., *Liu et al.*, 1961; *Johnson and Torrico*, 1994; *Hoffmans and Verheij*, 1997; *Fischenich and Landers*, 2000; *Melville and Coleman*, 2000; *Federal Highway Administration (FHWA)*, 2001; *Chase and Holnbeck*, 2004; *Fael et al.*, 2006]. The designs are modified to achieve the goals of the project and to minimize the risk associated with the designs. With this understanding, ELJs can be designed and placed in such a way that they achieve the desired goals, accommodate natural processes, and even diminish risks to infrastructure and property.

After a thorough understanding of the project reach and watershed, a clear definition of project opportunities and constraints, and the selection of appropriate natural analogs, the engineering design can proceed. Design development begins by refining the conceptual plan on the basis of the performance goals of the project. The results of the initial geomorphic analysis, risk assessment, hydraulic modeling, and scour analysis are incorporated into the preliminary design plans to refine the number of structures, structure archetypes, orientation, and predicted channel response.

5.3. Structure Stability Assessment

For wood debris that is held in place by burial or ballasting, it is critical to estimate the buoyant force acting on individual logs and the total structure. Stability is commonly quantified using a factor of safety (FS) estimate taking the ratio of resisting forces to driving forces. So for hydrostatic conditions, the ratio will be the gravitational force acting downward over the buoyant force acting upward. If FS is greater than 1, the wood should be stable under the set of assumptions built into the calculation. For engineered structures, a minimum FS of 1.5 or greater is used. One of the key assumptions in estimating a FS for embedded wood is that the surcharge material, typically native alluvium or imported rock, remains in place. Thus, if bank erosion or scour removes the surcharge, it could impact the long-term stability of the wood structure. So it is important to determine whether or not the surcharge material will be a risk in the future. For example, burying a log into the bank and then placing boulders on top of the log assumes that the boulders will not roll off the log, which may not be a safe assumption if the log is otherwise set within native alluvium that can be eroded by the stream. Placement of ballast should be designed to ensure it functions as desired, which will require an understanding of channel dynamics and structure performance. Structures such as embedded bendway weir logs could be put at risk if localized bank erosion exposes the buried portion of the logs. More complex structures, such as timber cribs, can be designed to retain their ballast even when completely exposed to the stream since the material is situated within the interior of the crib. Here again it is important to understand the architecture of the structure with regard to ballast retention. If the crib has an open bottom and scour gets beneath the structure, ballast can "bleed" out and compromise stability. Bleeding can also occur along the flanks of the structure if gaps between log layers of the crib are larger than the surcharge material, which is commonly the case when native alluvium is used. Both of these conditions (bleeding through base or sides of a wood structure) can be solved in multiple ways, which will be discussed further under structure design.

The final design plans should include plans for temporary erosion and sedimentation control, construction sequencing, surveyor control, traffic access, ELJ locations, grading for the ELJ structures, and planting, as well as detailed cross sections of the ELJ structures.

As outlined above, many types of ELJ structures exist, and the selection of a specific set of materials and architecture depends on the particular site, project goals, acceptable levels of risk, costs, and constraints. Experiences with ELJs to date suggest that, in certain circumstances, they can provide an economical method of bank protection and help in managing debris (especially mobile wood) that may be hazardous to bridges and culverts. At the same time, installation of an ELJ can reestablish important habitat elements of forest streams that have been degraded by conventional river engineering and management. While the situations in which ELJ technology can provide a sound engineering solution that delivers measurable environmental and esthetic benefits are numerous, in some situations, an ELJ structure would be inappropriate.

Natural accumulations of wood debris exhibit distinct size, shape, and orientation, which combine to create various hydraulic and geomorphic effects in different portions of mountain channel networks. Therefore, the design of an ELJ project should include careful scoping of the types of logjams that are likely to prove stable and meet the design objectives in the local geomorphic context.

Assessment of whether ELJs represent an appropriate approach and, ultimately, the final design specifications for a site, depend on both the geomorphic and hydraulic characteristics of the stream reach and floodplain, as well as human objectives and constraints. Consequently, investigations and analyses associated with ELJ design need to address (1) potential local and watershed disturbances that might influence the project, (2) historical planform characteristics and changes in channel, floodplain, and forest patterns in the valley bottom, both upstream and downstream of the project site, (3) results of topographic, geomorphic, geotechnical, and hydraulic analyses of the project reach and the subreach-scale area where the ELJ structures will be built, and (4) size, position, spacing, and architecture of the ELJs and constituent logs. ELJ stability is based upon the composite framework of large key members and stacked logs that provide a foundation for smaller stacked and racked pieces.

Consistent with the objective of imitating natural processes, ELJs are typically built of native wood debris and alluvial soils. However, imported and engineered materials such as piles, rock, or concrete logs have been used in the core structure, so long as the complete structure still looks and acts like a natural structure, thus understanding the range of natural structures is directly applicable to restoration design. All ELJ designs should be based on local conditions.

5.4. Structural Design

ELJ structures are designed to be stable against lateral velocity (drag) and vertical lift and buoyancy forces. The parameters used as input to the calculations of these forces include coefficients of drag and lift, cross-sectional area of the part of the structure projection that is perpendicular to flow, volume of wood material in the structures, density of water, specific weight of alluvium and wood, active and passive earth pressures, flow velocities as noted above, and water surface elevations. ELJ structures are used in a variety of situations and can be subjected to a wide range of loading. The structures are engineered to allow changing load paths by the strategic orientation and interlacing of individual structure members. One way to increase the structural stability and the FS is to incorporate inclined or vertical timber or steel piles.

For example, piling is designed for bending loads rather than axial loading. Drag loads are treated as a point load acting at the midpoint of the pile, and the piles (or column) are treated as cantilevered beams fixed at selected scoured bed elevation. The pile loading consists of static head, velocity head, and drag load. The angle at which forces from the river would act on the logjam is based on historical channel planforms and the channel migration zone. The worst-case flow, perpendicular flow, is used in the load calculations. The calculations are based on two separate conditions: (1) maximum probable scour with the pile exposed and (2) predicted scour with one third of the pile exposed.

5.4.1. Static head. Static head is used in the calculations, assuming water is backed up behind the entire height of the structure, which would cause the largest load (height of the ELJ compared to water elevations during the design flood event, e.g., 100 year flood).

5.4.2. Velocity head. Velocity head is based on hydraulic modeling, typically using flows from the 25 and 100 year flood events.

5.4.3. Drag load. Drag load is induced by flowing water that impinges upon the upstream face of the ELJ. The ELJ must resist overturning and sliding.

5.4.4. Lift. Lift consists of upward forces to consider for individual logs that will experience overtopping flow, particularly relevant in grade control structures using log weirs.

ELJ design can include quantitative assessment of failure modes for each structural element (log) and the entire structure. Looking at how each element contributes to the stability of the completed structure and what kind of forces or changes it may be subjected to is critical. For example, one of most common failure mechanisms for wood structures is scour. Important questions include, but are not limited to, the following: (1) How will the structure fare if a deep scour pool forms? (2) What type of scour will the structure experience? (3) What is the incident flow direction, and if that changes, how will the stability and performance of the structure be impacted? (4) Is structure stability based on pilings or ballast? (5) If the structure is dependent on ballast, will the ballast stay intact if the structure is undercut by scour?

Stable ELJs can be built without the use of cable, earth anchors, chain, imported rock, or steel piling, but all these structural elements have been used in construction of some ELJs. These types of anchoring should not be depended upon without thorough consideration of their purpose, the forces to which they will be subjected, and how they will perform as the channel deforms. For example, one of the most misapplied anchoring techniques is cable earth anchors. If a log starts to move, so will the cable. Once a cable starts oscillating, it is similar to a cable saw and is prone to do more damage than good. Therefore, if cable anchors are used, they should be arranged to prevent any log displacement, which typically means at least three points of attachment at each end of a log. If scour undercuts the log and it settles, the cables will slack and be subject to motion. Given this tendency, it is always best to embed wood into the channel bed as much as possible, which can preclude any need for cable anchors. Cable or chain can still be used in attaching logs to one another, but slack or loose cable should always be avoided. The following section discusses the structural advantages of embedded wood.

5.5. Piles, Posts, and Embedment

Embedment, or burial, is the single most important factor for wood stability in an alluvial channel. A pile can remain stable even when totally submerged with only minimal burial depth and despite having no surcharge. Under hydrostatic conditions, a pile is held in place by its skin friction, which is a function of the earth materials, pile composition, and burial depth. Piles illustrate a means of introducing stable wood into rivers that have been around for thousands of years. Several ways exist to get embedment in a timber structure: (1) driven vertical or inclined ("batter") piles, (2) excavated posts with or without root wads, (3) excavating the entire structure to the maximum scour depth, (4) creating a self-settling gravity structure, or (5) a combinations of these. Piles and buried posts are a cost-effective element for stabilizing ELJ structures. To keep descriptions clear, we define piles as driven straight timbers and posts as excavated timbers with or without attached root wads (Plate 11). The mechanics of pile and post stability are linked to how they interact with the substrate, skin friction, geostatic loads, and passive earth pressures. Estimates of log buoyancy are critical in designing buried timber structures. Also important is estimation of the lift forces acting on a log weir. Logs protruding from the streambed will be subjected to significant drag forces and should also be assessed for likelihood of breakage.

5.6. Skin Friction

The unit skin friction or shaft resistance of a buried pile (q_s) is equal to the product of the angle of wall friction (δ), the earth pressure coefficient (K_s), and the average vertical effective stress (σ'_v) [*Broms and Hellman*, 1970]:

$$q_s = (K_s \sigma'_v \tan\delta). \tag{17}$$

The angle of wall friction is dependent on the pile material and the angle of internal friction of the substrate (ϕ'). The total skin friction resistance is given by the sum of layer resistances, with A_w is vertical area of embedded wood in each soil layer:

$$\Phi_s = \sum(K_s \sigma'_v \tan\delta A_w). \tag{18}$$

The average vertical effective stress acting on the pile is the difference of the normal stress of the soil, σ_s, and the pore pressure within the soil, u:

$$\sigma'_v = \sigma_S - u. \tag{19}$$

The average pore pressure is proportional to the depth of water, h, and water density, ρ_f:

$$u = 0.5h\rho_f. \tag{20}$$

Normal stress of soil is proportional to the depth of soil, d_s, and soil density, ρ_s.

$$\sigma_S = 0.5d_S\rho_S. \tag{21}$$

Unit skin friction resistance is a function of the earth pressure coefficient, K_s, the vertical effective stress, σ_v', and the wall friction angle, δ. The wall friction angle is dependent on the pile material and the friction angle of the soil, ϕ', for timber $\delta = 2/3\ \phi'$ (for concrete it is $J\ \phi'$ and 20° for steel). The ultimate unit skin friction is expressed as

$$q_S = K_s \sigma'_v \tan(\delta). \tag{22}$$

The coefficient K_s depends on the pile material and soil density. K_s values for timber range from 1.5 to 4.0, for low- to high-density soils, respectively. From equation (22), we can simplify equation (18) to the sum of the product of q_s and A_w for each soil layer:

$$\Phi_s = \sum(q_s A_w). \tag{23}$$

The FS for a simple pile coming out of the riverbed under hydrostatic loading is

$$\mathrm{FS} = \frac{\Phi_s + W_W}{F_B}, \tag{24}$$

where W_w is dry weight of pile and F_B is buoyant force.

A pile 9.1 m in length, 0.3 m in diameter, and situated in 3 m of water would have to be buried at least 1.5 m to stay in place (Figure 5). If the burial depth is doubled to 3 m, the FS increases eightfold. Based on empirical studies, skin friction resistance can reach a maximum at depths of between 10 and 20 pile diameters [*Broms and Hellman*, 1970]. With regard to

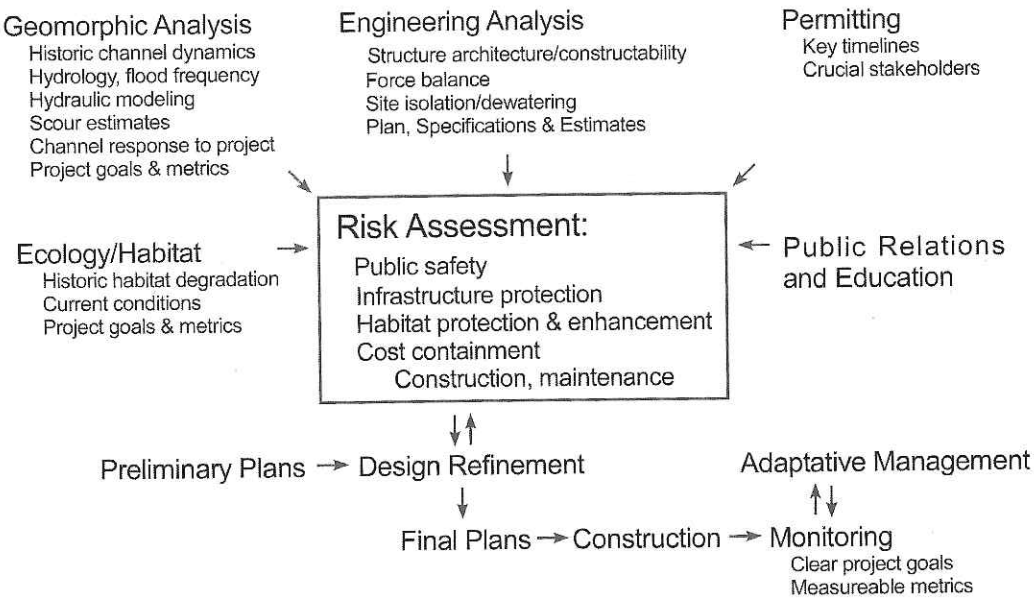

Figure 5. General risk assessment process for designing, constructing, and managing wood in rivers.

lateral loading on a pile, passive earth pressures continue to increase proportional to depth [*Abbe et al.*, 2003b].

For a vertical timber post with its root wad buried, the pull-out resistance will be proportional to the volume of overlying soil (as defined by internal friction angle), which can be expressed as the difference between the frustum defining the soil volume from the root wad to the ground surface and the buried volume of the timber (Figure 6):

$$V = \left[\frac{\pi D_b(R^2 + Rr + r^2)}{3} + \pi R_{\mathrm{rw}}^2 D_h\right] - \left[\frac{\pi R_{\mathrm{rw}}^2}{2t+1}(X_i^{2t+1} - 1)\right]. \tag{25}$$

The effectiveness of burying a post with attached root wad as compared to burial of simple cylindrical post can be illustrated by burying scale models similar to those depicted on Figure 6. The results for dry soil show the significant increase

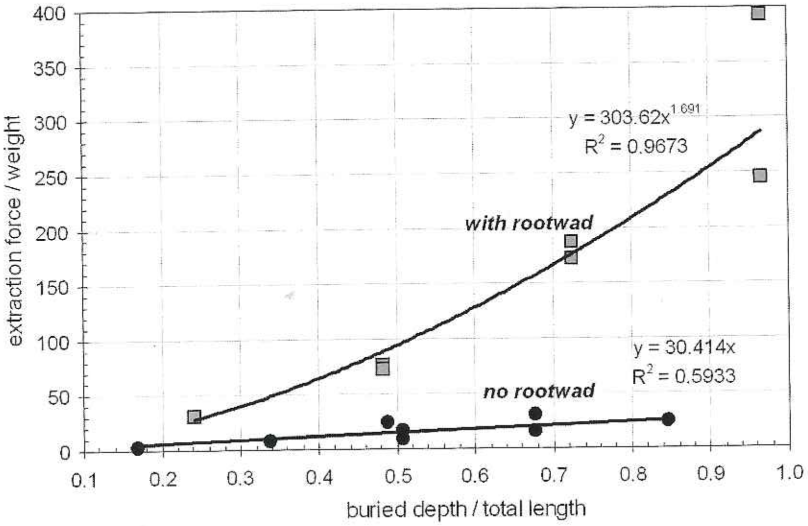

Figure 6. Experimental results of buried piles with and without root wads relative to snag dry weight and length. Simple piles without root wads increase resistance with burial length by a factor of 30 of the log weight. Root wad piles exhibit a nonlinear increase in the extraction force relative to log weight as burial depth is increased.

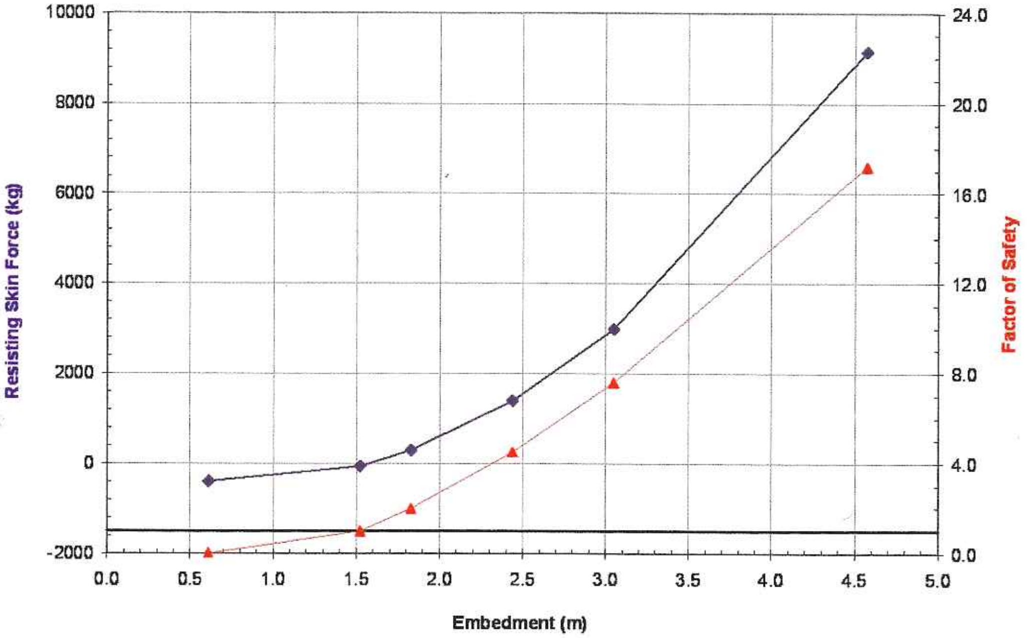

Plate 11. Resistance and factor of safety attributed to skin friction under hydrostatic conditions as a function of embedment depth (9.1 m pile, 0.3048 m in diameter, submerged in 3 m of water).

in vertical force necessary to pull out a buried root wad as opposed to a simple pile (Figure 6). At burial depths of 20%, the post length addition of a root wad doubles the resistance, and at depths of half the post length, resistance increases sixfold. Basic analysis elements for evaluating loads on piles and posts are presented below in summary of force balance calculations.

5.7. Example of an Engineered Flow Deflection Logjam

Engineered wood placements designed to redirect flow such as bar apex and meander jams [*Abbe and Montgomery*, 2003] include a core structure with a facing of racked logs. The number of architectures for the structure core is infinite, but the purpose is always to ensure the structure's stability

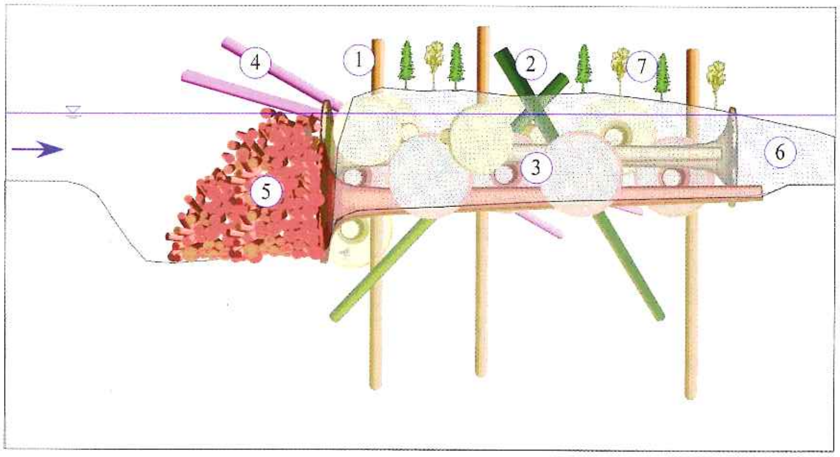

Plate 12. Some of the basic components that can be used in a flow deflection engineered wood placement: (1) driven vertical piles, (2) inclined or "batter" piles, (3) core structure of ELJ, (4) racking retention logs embedded into core, (5) racking debris, (6) compacted backfill in core, and (7) reforestation on top of core. The architecture and types of materials used to create the core can vary substantially.

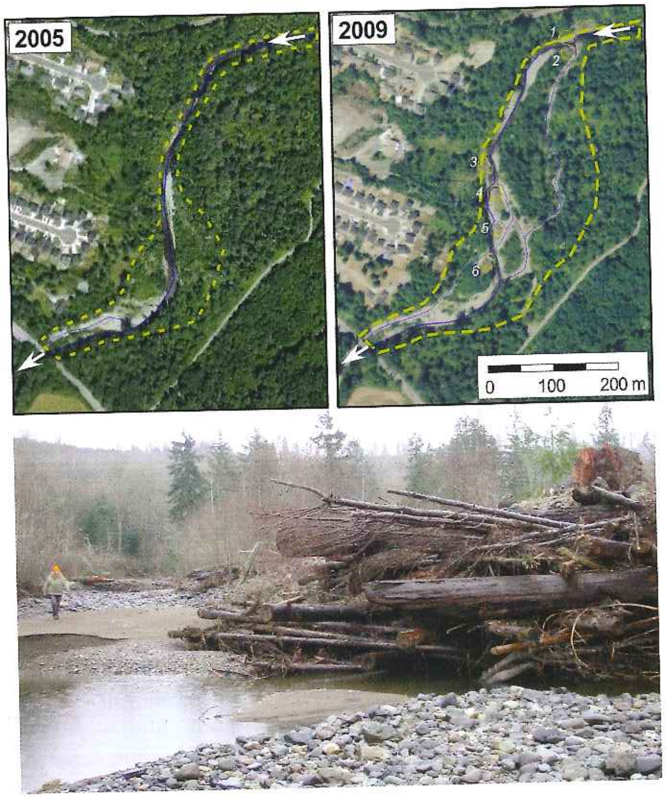

Plate 13. Project example of introducing ELJs to increase channel complexity by creating channel anabranching in the Upper Mashel River near Eatonville, Washington. Air photos of preproject (2005) and postproject (2009) conditions at restoration project constructed in 2006 and 2007 (consisting of six ELJs delineated on 2009 photo). With addition of side channels activated by ELJS, total bankfull channel length increased approximately 180% from about 890 to 1610 m. Floodplain connectivity almost doubled from about 3.6 to 6.9 ha (yellow dashed lines). The project successfully experienced a peak flow greater than 50 year recurrence flood in January 2009 with estimated velocities of over 4 m s^{-1} and maximum shear stress of 166 Pa. Bottom photo is ELJ 2 in 2008 with side channel to left.

over its design life. The most effective means of creating a stable core that can resist lateral and vertical loads is to use piles or buried posts. While timber piles are typically used, other materials could be used if warranted. Piles can be driven or excavated. When pile depth is limited, burying root wads can significantly add to the structure's integrity as explained earlier. Designing the size and spacing of ELJ structures placed along riverbanks can draw from the literature on spur dikes [e.g., *Copeland*, 1983].

Typical elements of an engineered flow deflection logjam (Plate 12) include the following: (1) vertical piles or posts, either with root wads (excavated) or without (driven), (2) batter or inclined piles/posts, (3) key and stacked logs comprising crib box at core of structure, (4) inclined "retention" logs protruding from internal crib to hold racking logs in place, (5) racked logs, (6) internal lining of small wood debris (small logs and slash applied to plug gaps in crib and prevent "bleeding" of backfill, live stake bundles can be used higher in the structure, as long as the stake tips reach the water table), (7) backfill surcharge filling crib box, and (8) revegetation on surface of structure.

5.8. *Basic ELJ Force Balance Analysis*

A force balance analysis is an important part of design that should be done for any engineered wood placement in streams and rivers. Owing to the many types of engineered wood structures (including the wide variety of ELJ types), the force balance should be structure specific. In the force balance analysis, it is important to clearly describe assumptions and data sources regarding water depths, flow velocities, substrate material, incident angle of flow, and scour depths. Free-body diagrams help with understanding the forces acting on individual pieces and entire structures. A comprehensive treatment of force balance is beyond the scope of this chapter, but we provide basic outline of formulae to consider in evaluating buoyancy and horizontal forces acting on an ELJ structure.

5.8.1. Buoyancy analysis. The following steps should be undertaken for buoyancy analysis.

1. Calculate volumes of logs.

$$V_i = \pi\left(\frac{D_i}{2}\right)^2 L_i n_i, \tag{26}$$

where

V_i volume of log type i (m^3);
D_i diameter of log type i (m);
L_i length of log type i (m);
n_i number of logs of type i.

$$V_{\mathrm{tot}} = \sum_{i=1}^{k} \pi\left(\frac{D_i}{2}\right)^2 L_i n_i, \tag{27}$$

where

V_{tot} total volume of logs (m^3);
i log type (identifier) (number);
k total number of log types;
n_i number of logs of type i.

With root wad,

$$V_i = \left(\pi\left(\frac{D_i}{2}\right)^2 L_i + \pi\left(\frac{D_{\mathrm{rw},i}}{2}\right)^2 L_{\mathrm{rw},i}(1-e_{\mathrm{rw}})\right) \times n_i, \tag{28}$$

where

D_i	diameter of log stem (m);
$D_{\mathrm{rw},i}$	diameter of root wad (m);
L_i	length of log stem (m);
$L_{\mathrm{rw},i}$	length of root wad (m);
e_{rw}	ratio of voids in root wad.

2. Calculate buoyant forces on submerged logs. If all logs are of uniform density and submerged, then

$$F_B = (\gamma_{\mathrm{lwd}} - \gamma) V_{\mathrm{lwd}}, \tag{29}$$

where

F_B	buoyant force (N);
γ_{lwd}	unit weight of wood piece (N m^{-3});
γ	unit weight of water (9810 N m^{-3});
V_{lwd}	submerged wood volume.

For different densities per log type,

$$\sum F_B = \sum_{i=1}^{n} (\gamma_{\mathrm{lwd}(i)} - \gamma) V_i, \tag{30}$$

where $\sum F_B$ is total buoyant force of all LWD (N), $\gamma_{\mathrm{lwd}(i)}$ is unit weight of log type i (N m^{-3}), and n is total number of submerged pieces of LWD.

3. Calculate downward forces of submerged fill (sediment).

Determination of volume of interior to be filled by soil

$$V_J = l_J w_J h_J, \tag{31}$$

where

V_J	interior volume of ELJ (m^3);
l_J	interior length of ELJ (m);
w_J	interior width of ELJ (m);
h_J	interior height of ELJ filled with alluvium (m).

Determination of volume of submerged soil inside the interior

$$V_{\mathrm{ss}} = \{(1-k)V_J\} - \sum V_{\mathrm{LWD}}, \tag{32}$$

where V_{ss} is volume of submerged soil in the ELJ (m^3), k is void ratio of the soil, and $\sum V_{\mathrm{LWD}}$ is volume of LWD in the interior (m^3)

Determination of weight of submerged soil

$$W_{\mathrm{ss}} = V_{\mathrm{ss}}(\gamma_{\mathrm{ss}} - \gamma), \tag{33}$$

where W_{ss} is weight of submerged soil (N) and γ_{ss} is saturated unit weight of soil (N m^{-3}).

Determination of weight of submerged boulder ballast (if used)

$$W_{\mathrm{sb}} = \pi \frac{D_b^3}{6} (\gamma_b - \gamma) n, \tag{34}$$

where

W_{sb}	submerged weight of boulder (N);
D_b	diameter of boulder (m);
γ_b	unit weight of boulder (N m^{-3});
n	number of boulders submerged.

4. Calculate downward forces of unsubmerged ELJ components (cover sediment, boulders, and logs).

Determination of volume of alluvium/soil above waterline

$$V_{\mathrm{soil}} = A_{\mathrm{soil}} h_{\mathrm{soil}}, \tag{35}$$

where V_{soil} is volume of soil above waterline (stage of design flow, m^3), h_{soil} is depth of soil above water (m), and A_{soil} is area of soil cover (m^2).

Determination of weight of cover soil

$$W_{\mathrm{soil}} = V_{\mathrm{soil}} \gamma_{\mathrm{soil}}, \tag{36}$$

where W_{soil} is weight of dry alluvium/soil and γ_{soil} = bulk weight of dry soil.

Determination of weight of boulder ballast (if relevant)

$$W_b = \pi \frac{D_b^2}{6} \gamma_b n, \tag{37}$$

where

W_b	dry weight of boulder (kg);
D_b	diameter of boulder (m);
γ_b	unit weight of boulder (kg m^{-3});
n	number of boulders above waterline.

Determination of weight of logs above water

$$W_{\mathrm{dry\ lwd}} = \sum_{i=1}^{n} V_i \gamma_{\mathrm{lwd}(i)}, \tag{38}$$

where

$W_{\mathrm{dry\ lwd}}$	dry weight of boulder (kg);
V_i	volume of LWD piece i (m^3);
$\gamma_{\mathrm{lwd}(i)}$	unit dry weight of LWD piece i (kg m^{-3});
n	number of LWD pieces above waterline.

5. Find net force.

$$F_n = \sum(F_B) + W_{\mathrm{ss}} + W_{\mathrm{soil}} + W_{\mathrm{sb}} + W_b + W_{\mathrm{dry\ lwd}}. \quad (39)$$

Determination of FS (do layer by layer)

$$\mathrm{FS} = \frac{F_n}{\sum F_B}. \quad (40)$$

5.8.2. Horizontal forces calculations. The following steps should be undertaken for horizontal forces calculation.

1. Calculate the force due to water velocity.

$$F_D = C_D A \rho \left(\frac{U^2}{2}\right), \quad (41)$$

where

F_D	force due to the velocity of the water (N);
C_D	drag coefficient;
A	area projection equals ELJ width times channel depth (m^3);
ρ	density of water (1000 kg m^{-3});
U	design flow in channel (typically associated with 100 year flood event) (m s^{-1}).

2. Calculate difference in hydrostatic force upstream and downstream of ELJ.

Calculation of hydrostatic force upstream of the ELJ

$$F_{H0} = A_0 P_0, \quad (42)$$

where F_{H0} is hydrostatic force upstream of the ELJ face, A_0 is cross-sectional area of upstream face of ELJ, and P_0 is pressure of water on the upstream face of the ELJ (see below).

$$A_0 = (h_0 + d_{S0}) w_{J0}, \quad (43)$$

where h_0 is depth of channel upstream of logjam, d_{S0} is depth of scour on upstream side of logjam, and w_{J0} is upstream width of ELJ.

$$P_0 = \left(\frac{h_0 + d_{S0}}{2}\right)\gamma, \quad (44)$$

where γ is unit weight of water (N m^{-3}).

Calculation of hydrostatic force downstream of the ELJ

$$F_{H1} = A_1 P_1, \quad (45)$$

where F_{H1} is hydrostatic force downstream of the ELJ, A_1 is ELJ area on the downstream side, and P_1 is pressure of water on the downstream side of the ELJ.

$$A_1 = (h_1 + d_{S1}) w_{J1}, \quad (46)$$

where h_1 is depth of channel downstream of logjam, d_{S1} is depth of scour on downstream side of logjam, and w_{J1} is downstream width of ELJ.

$$P_1 = \left(\frac{h_1 + d_{S1}}{2}\right)\gamma. \quad (47)$$

Calculation of difference in hydrostatic force

$$\Delta F_H = F_{H0} - F_{H1}. \quad (48)$$

3. Calculate net horizontal force.

$$F_x = F_V - \Delta F_H + F_D. \quad (49)$$

4. Determine force per pile (assuming equal distribution)

$$F_{x(\mathrm{pile})} = \frac{F_x}{n}, \quad (50)$$

where $F_{x(\mathrm{pile})}$ is net horizontal force per pile (*N*), and *N* is number of piles.

5.9. Scour Analysis

Bed deformation around wood accumulations is an essential means by which the structures create important habitat, whether deep pools with adjacent cover or shallow riffles and bars in depositional areas. Scour is the primary failure mechanism for in-stream structures such as bridge piers, abutments, or bank protection. Predicting the depth and dimensions of scour is critical to designing wood structures. Different types of scour are linked to the hydraulic conditions induced by the structure, including plunging scour (such as flow over a weir), contraction scour (concentrated flow channel constriction), pier scour (flow around either side of an obstruction), and abutment scour (flow around one side of an obstruction). Scour is cumulative, so if two ELJs are placed opposite one another, they can induce both pier and constriction scour. Scour equations are largely dependent on laboratory experimentation and empirical coefficients, so the results of various equations can vary considerably, which requires a great deal of professional judgment and clear assumptions when applying results to a particular situation and design. Included here are some examples of different equations to estimate maximum scour depths for designing in-stream structures. Because these equations are primarily based on empirical data from laboratory flume experiments, they should be used in the context of professional judgment and actual on-site evidence of scour depths. Existing residual pool depths within a project reach provide a minimum estimate of potential scour, so close attention should be given to the maximum pool depths and their causal mechanisms within the project area. Recent advances in scour predictions around wide piers [*Sheppard et al.*, 2011] and around piers with wood accumulations [*Lagasse et al.*, 2010] offer refinements and new insights into predicting scour around structures similar to a large ELJ.

5.9.1. Local Pier Scour. The Colorado State University (CSU) equation was developed for the U.S. Federal Highway Administration for local pier scour under either clear water (no bed load input) or live-bed (active bed load) conditions [*Hoffmans and Verheij*, 1997; *FHWA*, 2001; *Melville and Coleman*, 2000]. The CSU equation includes a correction factor to adjust for bed material for cases where the $D_{50} \geq$ 2 mm and the $D_{90} \geq 20$ mm.

$$\frac{d_{\mathrm{ps}}}{y_1} = 2.0K_1K_2K_3K_4\left(\frac{a}{y_1}\right)^{0.65}Fr^{0.43}, \tag{51}$$

where

d_{ps}	maximum scour depth (m);
y_1	flow depth immediately upstream of pier (m);
a	pier width (m);
K_1	correction factor for pier nose shape (for square $K_1 = 1.1$);
K_2	correction factor for flow angle of attack $[\cos\theta + (L/a)\sin\theta]^{0.65}$
L	pier length;
θ	incident angle of flow on pier (0 = hitting straight on, parallel to channel);
K_3	correction factor for bed condition for clear water/plane bed conditions $K_3 = 1.1$, for dunes $K_3 = 1.1$ to 1.3);
K_4	correction factor for bed armoring (minimum value is 0.4) $0.4\ V_r^{0.15}$ (Meuller K-4 correction [*FHWA*, 2001]);

where

$$V_r = \frac{V - V_{icD_{50}}}{V_{cD_{50}} - V_{icD_{95}}} > 0, \tag{52}$$

$$V_{icD_X} = 0.645V_{cD_X}\left(\frac{D_X}{a}\right)^{0.053}, \tag{53}$$

$$V_{cD_X} = 6.19y_1^{1/6}D_x^{1/3} \tag{54}$$

where

V	velocity of upstream approach flow (m s^{-1});
V_{icDx}	approach velocity necessary to initiate scour of grain size D_x (m s^{-1});
V_{cDx}	critical velocity for incipient motion of D_x (m s^{-1});
Fr	Froude number = $V/(gy_1)^{0.5}$;
g	gravitational acceleration, 9.81 (m s^{-1}).

5.9.2. The Johnson and Torrico Correction Factor for Wide Piers. FHWA [2001] recommends application of the Johnson and Torrico correction factor [*Johnson and Torrico*, 1994] in the CSU equation when the ratio of flow depth to pier width is less than 0.8, the ratio of pier width to D_{50} is greater than 50, and when $Fr < 1$ (subcritical flows). In many ELJ situations, these conditions would apply, but in cases where $Fr > 1$, predictions using the Johnson and Torrico correction factor will underpredict scour.

$$\frac{d_{\mathrm{ps}}}{y_1} = 2.0K_1K_2K_3K_4K_w\left(\frac{a}{y_1}\right)^{0.65}Fr^{0.43}. \tag{55}$$

For cases where $V/V_c < 1$,

$$K_w = 2.58\left(\frac{y}{a}\right)^{0.34}Fr^{0.65}. \tag{56}$$

For cases where $V/V_c \geq 1$,

$$K_w = 1.0\left(\frac{y}{a}\right)^{0.13}Fr^{0.25}. \tag{57}$$

5.10. The Modified Froehlich Equation for Abutments in Sand Bed Rivers

Contraction scour is not directly accounted for in the modified Froehlich equation, so a safety factor of +1 is added [*Fischenich and Landers*, 2000]. The equation was derived for scour at abutments in sand bed channels and has input parameters for abutment shape, incident flow angle, and abutment length perpendicular to flow:

$$y_s = y_1 2\left(\frac{\theta}{90}\right)^{0.13}\left(\frac{W_0}{y_a}\right)^{0.43}Fr^{0.61} + 1.0, \tag{58}$$

where

y_s	scour depth below water surface (m);
y_1	depth of flow at structure (m);
W_0	length of structure projected perpendicular to flow (m);
θ	angle of embankment to flow (degrees);
Fr	Froude number of flow upstream of structure = $V/(gy_1)^{0.5}$.

5.11. Simplified Chinese Equation for Live-Bed Scour in Coarse-Bedded Channels

Chase and Holnbeck [2004] present the simplified Chinese equation for live-bed scour that is applicable to examining the effect of large ELJ flow deflection structures in coarse-bedded rivers. The Chinese equation was developed from laboratory and field data for both live-bed and clear water scour situations. Only the live-bed formulae for situations in which the critical velocity exceeds the approach velocity are presented here.

For live-bed scour (when $V_o > V_c$),

$$y_s = 0.6495 K_s b^{0.6} y_0^{0.15} D_m^{-0.07} \left(\frac{V_0 - V_{ic}}{V_c - V_{ic}} \right)^c . \tag{59}$$

For clear-water scour,

$$y_s = 0.834 K_s b^{0.6} y_0^{0.15} D_m^{-0.07} \left(\frac{V_0 - V_{ic}}{V_c - V_{ic}} \right)^c , \tag{60}$$

where

y_s	depth of pier scour (m);
K_s	pier shape coefficient (dimensionless), equal to 1.0 for cylinders, 0.8 for round-nosed piers, and 0.66 for sharp-nosed piers;
b	width of pier normal to flow (m);
y_0	depth of incident flow upstream of pier (m);
D_m	mean particle diameter of substrate (m);
V_0	approach velocity upstream of pier (m s^{-1});
V_c	critical velocity for incipient motion of bed material (m s^{-1}), assuming density of water is 1000 kg m^{-3} and gravity of bed material is 2.65.

$$V_c = \left(\frac{y_0}{D_m} \right)^{0.014} \left(29.035 D_m + 6.05 E^{-7} \left[\frac{10 + y_0}{(D_m)^{0.72}} \right] \right)^{0.5} . \tag{61}$$

The approach velocity corresponding to the critical velocity at the pier is calculated as

$$V_{ic} = 0.645 \left(\frac{D_m}{b} \right)^{0.053} V_c , \tag{62}$$

where

$$c = \left(\frac{V_c}{V_0} \right)^{8.20 + 2.23 \log D_m} . \tag{63}$$

5.12. Contraction Scour

FHWA [2001] recommends the modified Laursen equation for estimating contraction scour under live-bed conditions. The equation was developed for sand-bedded channels and is, thus, likely to overpredict scour in gravel-bedded channels.

$$d_{cs} = y2 - y0 , \tag{64}$$

where

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1} \right)^{6/7} \left(\frac{W_1}{W_2} \right)^{k_1} , \tag{65}$$

where

d_{cs}	average depth of contraction scour (m);
y_0	existing depth in contracted channel segment prior to scour (m);
y_1	average depth upstream of contracted channel segment (m);
y_2	average depth in contracted channel segment after scour (m);
Q_1	flow upstream of contracted channel segment (m^3 s^{-1});
Q_2	flow in contracted channel segment (m^3 s^{-1});
W_1	channel bottom width upstream of contracted channel segment (m);
W_2	channel bottom width in contracted channel segment (m);
k_1	average depth in contracted channel segment after scour (m), where $u^*/\omega < 0.5$, $k_1 = 0.59$ (most sediment moving as bed load) and $0.5 < u^*/w < 2.0$, $k_1 = 0.64$ (some suspended sediment transport), $u^*/\omega > 2.0$, $k_1 =$ 0.69 (most sediment moving as suspended load);
u^*	shear velocity in upstream channel segment (m s^{-1}), equal to $(g y_1 S)^{0.5}$;
ω	fall velocity of D_{50} of bed material (m s^{-1}) equal to $[(G - 1) g D_{50}]^{0.5}$.
G	specific gravity = (sediment density/water density);
S	energy slope of flow in channel upstream of contracted segment (m m^{-1}).

5.13. Abutment Scour

ELJs placed along a bank and intended to act like flow deflection groins are similar to bridge abutments. *Melville and Coleman* [2000] and *FHWA* [2001] recommend the modified *Froehlich* [1989] equation for live-bed scour around a local abutment. The equation was based on regression results of laboratory flume experiments.

$$\frac{d_{as}}{y} = 2.27 K_1 K_2 \left(\frac{L'}{y} \right)^{0.43} Fr^{0.61} + 1.0 , \tag{66}$$

where

d_{as}	depth of scour (m);
K_1	coefficient for abutment shape;
K_2	coefficient for angle of abutment relative to flow, equal to $(\theta/90)^{0.13}$, $\theta < 90°$ if abutment points downstream, $\theta > 90°$ if abutment points upstream;

L' length of abutment projected perpendicular to flow (m), $L \cos \theta'$ if $\theta > 90°$ then $\theta' = \theta - 90$, if $\theta < 90°$ then $\theta' = \theta$;
y flow depth (m).

For sand-bedded channels, *Hoffmans and Verheij* [1997] recommend the Liu equation for abutment scour [*Liu et al.*, 1961], which was developed based on dimensional analysis,

$$d_{\text{as}} = K_L y \left(\frac{L}{y}\right)^{0.4} Fr^{0.33}, \qquad (67)$$

where

d_{as} depth of scour (m);
K_L coefficient for abutment shape, streamlined, $K_L = 1.1$, blunt, $K_L = 2.15$;y flow depth (m);
L abutment length perpendicular to flow (m).

6. PERFORMANCE OF ELJS AND LESSONS LEARNED

While ELJ projects have been constructed in western Washington state since 1995 and have performed well through many large floods, ELJs remain an experimental technology. The projects constructed to date confirm that postconstruction inspections and maintenance are needed as an essential component of ELJ projects that are designed to control bank erosion. Whereas these ELJ demonstration projects show the technology to be an environmentally and economically viable alternative to traditional river engineering in certain applications, inappropriate design and application of ELJs can result in locally accelerated bank erosion, unstable debris, or channel avulsion. Care should be taken to understand local hydraulic, geologic and geomorphic, and sociopolitical conditions for every site, particularly the effect of spatial and temporal variability. Continued research and experimental applications of ELJs in a variety of topographic and climatic settings are needed to help refine the design guidelines for their use in rehabilitating and managing river systems. Integrating the elements discussed above and drawing from various guidelines and publications [e.g., *Abbe et al.*, 1997, 2003b, 2008; *Brooks*, 2006; T. B. Abbe et al., Bank protection and habitat enhancement using engineered log jams: An experimental approach developed in the Pacific Northwest, unpublished report, Natural Resources Conservation Service, 2005, hereinafter referred to as Abbe et al. unpublished report, 2005], we have put together a general checklist for reintroducing wood to rivers and restoration projects (Figure 7).

Hundreds of engineered wood structures have been built for river restoration throughout North America and elsewhere. The beneficial effects of ELJ projects on channel morphology and habitat has been widely recognized, from creating pools and cover, to increasing floodplain connectivity and creating more complex channel planform [e.g., *Abbe and Montgomery*, 1996, 2003; *Brooks and Brierly*, 2004; *Brooks*, 2006; Abbe et al., unpublished report, 2005]. The Upper Mashel River restoration project offers an example of how ELJs were used to increase natural wood debris retention, channel length, pool frequency, cover, and floodplain connectivity (Plate 13). The Mashel project transformed an incised single thread plane bed channel reach into a multichannel pool-riffle complex.

Thus far, ELJs have performed remarkably well in a variety of streams and rivers, though no impartial scientific investigation that takes into account the many different site locations, flow conditions, or distinct design conditions has been performed to date. Table 1 is a compilation of a small sample of ELJ projects that illustrate how different types of ELJs have fared through a range of project sites and flow events. Structural complexity of these projects varied from minimal engineering to high levels of engineering (e.g., steel H piles, scour aprons, and rock ballast), which has definitely influenced structure performance. Damages to ELJ structures appear primarily to be associated with scour and turbulence along the flanks of the structures, though overtopping flows have also resulted in loss of some backfill and revegetation of one structure. Failures have resulted from structures being "plucked" apart piece by piece, as opposed to the downstream transport of an intact ELJ, which has not been observed.

7. SUMMARY OF RECOMMENDED ELJ DESIGN PROTOCOL

7.1. Reach Analysis

Research analysis attempts to answer questions such as (1) Why is the road or infrastructure at risk? (2) What are the processes causing the damage? (3) Are things getting worse or better?

The analysis should document historical channel changes, sediment transport and deposition, bank materials and stability, hydrology and hydraulics, ecologic and biological conditions and opportunities, riparian conditions, and infrastructure constraints. The reach analysis should provide sufficient information to make predictions about the river's future under various scenarios so that sustainable logjam designs can be developed that emulate natural conditions and processes.

7.2. Feasibility Study

A feasibility study evaluates actions that should be considered and assesses solutions that are realistic from a cost

Guideline Checklist for Re-introduction of Wood in Rivers, version 2.0

Project Information	**Project:**		**Project Team:**	**Initials**
	Owner:			
	Location:			
	River System:			
	Date:			
			Reviewed:	
			Approved:	

	Topic	**Considered Yes/No/NA**	**Date**	**Initials**	**Notes**	**Review Date**	**Initials**
Project Definition	1. **Identification of Project Goals**						
	a. Clear description of goal(s), e.g.:						
	i. Increase in pool frequency						
	ii. increase/sustain side channels						
	iii. control incision of bank erosion						
	iv. Promote specific bed substrate						
	v. increase productivity						
	introduce and trap organic matter						
	fish cover, invertebrate substrate						
	vi. attenuate downstream flooding						
	b. Quantification of project goals						
	i. Identify success factors						
	ii. Identify project requirements and constraints						
	funding						
	landowner						
	technical						
	regulatory (solicit agency input)						
	c. Assess project sustainability (concept screening)						
	i. Environmental						
	(geomorphic/aquatic/riparian habitat, natural processes)						
	ii. Social (human community)						
	iii. Financial						
	(cost/benefit relative to environmental and social factors)						
	2. **Existing/Historical site conditions**						
	a. Channel gradient						
	b. Channel type(s)						
	c. Hydrology, flow regime						
	d. Is wood part of system? Was it once? What changed?						
	e. Historical channel mapping (HCMZ)						
	f. Geologic controls						
	g. Floodplain &riparian conditions						
	h. Hydrology and flow regime (base flow, water table, peak flows)						
	i. Hazard identification						
	3. **Watershed Disturbance**						
	a. Natural (e.g., fire, dam breaks, debris flows)						
	b. Development (e.g., timber harvest, urbanization, incision, trends)						
	c. Climate Change						
	d. Historical channel response (aggradation, incision, brands)						
	4. **Identification of Opportunities and Constraints (O&C)**						
	a. Consistent with existing and future system changes						
	b. Hazard Identification						
	i. Flood inundation, real and jurisdictional						
	ii. Channel Migration Zone / erosion hazard areas						
	iii. Wood debris loading (include future riparian projections)						
	iv. Projected channel response to watershed disturbances						
	c. Upstream or downstream impacts						
	i. flooding						
	ii. erosion						
	d. Critical infrastructure						
	e. Public Safety						
	f. Environmental						
	g. Social (human community)						
	h. Financial						
	i. Technical						
	j. Construction (feasibility, O&C)						

Figure 7. General guidelines for reintroduction of wood to rivers.

	k. Political (public and stakeholder)						
	l. Regulatory						
	m. Legal						
	5. Concept Development						
	a. Hazard Identification						
	b. Opportunity and constrain review						
	c. Develop concept alternatives						
	6. Stakeholders and the community						
	a. Identify (landowners, interest groups, regulatory)						
	b. Identify interest groups						
	c. Outreach and coordination						
	Reach Analysis Report						
Design Development	**7. Design flows**						
	a. Hydrology and flow regime (base flow, water table, peak flows)						
	b. Hydraulics (roughness, depths and velocities)						
	i. Measured						
	ii. Modeled						
	c. Flow scenarios (anticipated response)						
	d. Fish passage considerations						
	8. Substrate						
	a. Substrate composition (clay/silt/sand/gravel/cobble/bedrock)						
	b. Critical shear stress to initiate motion & associated discharge						
	c. Geotechnical properties (internal angle of friction)						
	d. Depth and stratigraphy of alluvium and subsurface geology						
	e. Scour depths (general and local)						
	f. Sediment transport and budget						
	9. Wood debris transport and budget						
	a. Wood inventory (length, DBH, rootwad diameter, species)						
	b. Piece mobility (force-balance)						
	c. Wood recruitment potential (riparian conditions)						
	d. Future conditions associated with riparian management						
	10. Hazard delineations						
	a. Flood inundation, real and jurisdictional						
	b. Channel Migration Zone / erosion hazard areas						
	c. Wood debris loading (include future riparian projections)						
	d. Projected channel response to watershed disturbances (5)						
	11. Alternatives Assessment						
	a. Establish comparison criteria consistent with project goals						
	b. Identify concept alternatives						
	c. Identify risks						
	d. Identify costs						
	e. Identify benefits						
	f. Compare concepts and select preferred alternative						
	12. Hazard and Risk Assessment						
	a. Define hazards and probabilities						
	e.g., floods, debris flows, dam breaks, channel migration						
	b. Define risks (consequences)						
	e.g., impacts to habitat, public safety, property, infrastructure						
	c. Estimate risk, evaluate with owner						
	Preliminary Design Report (Preferred alternative)						
	13. Structure design						
	a. Location						
	b. Architecture						
	c. Scour (general, local – e.g., pier, abutment)						
	d. Force Balance						
	i. Buoyancy						
	ii. Drag/lift						
	iii. Ice loading (impact, lift, shear, jacking)						
	IV. Impact						
	v. Embeddment / skin friction						
	VI. Passive Earth Pressure						
	VII. Surcharge						
	v. Member strength and size						
	e. Material alternatives (timber, steel, rock, etc.)						
	f. Structure performance to:						
	II. channel change						
	ii. predicted wood loading scenarios						
	ii. hydraulic conditions						
	g. Factors of Safety (consistent with Hazard and Risk Assessment)						

Figure 7. (continued)

	ii. sensitivity analysis						
	ii. redundancy						
	h. Structure design life						
	i. Required design life						
	ii. Decay analysis						
	i. Revegetation (root cohesion, surcharge, erosion protection)						
	j. Prediction of future channel conditions (5, 10, 50 yrs)						
	k. Concept 30% Plans						
	l. Stakeholder presentation of plan						
	14. Construction Planning						
	a. Contracting (format, specifications, contract type)						
	b. Sequencing						
	c. Timing: staging/construction/planting						
	d. Site access, traffic control						
	e. Fish protection/exclusion						
	f. Construction period peak flow analysis and contingency plan						
	g. Material specifications						
	h. Excavation and shoring						
	i. Piling (excavated, impact, vibratory)						
	j. Diversions, dewatering, crossings						
	k. Turbidity and erosion control						
	l. Construction risk assessment and plan for flood response						
	m. Revegetation and treatment of disturbed areas						
	n. Permitting, Permit Level Plans (60-70%)						
	15. Public Safety and Signage						
	a. Recreational Safety Checklist						
	b. Public education and notification						
	c. Signage						
	16. Basis of Design or Design Documentation						
	a. Design Criteria						
	b. Modeling						
	c. Scour						
	d. Design Calculations						
	e. Alternatives Assessment						
	f. Hazard and Risk Assessment						
	g. Signage, Public Education, and Recreational Safety Checklist						
	h. Risk Management measures and responsibilities						
	Basis of Design Report						
	Contract Documents: 100% Plans, Specifications and Estimates (PS&E)						
Implementation	**17. Construction**						
	a. Contract type						
	b. Final PS&E, Final Permits						
	c. Contract prep and bidding support						
	d. Pre-construction meeting						
	e. OVERSIGHT; daily reports w/ photo documentation,						
	f. Stakeholder meetings (weekly)						
	g. Pay estimation based on work complete (monthly)						
	h. Site winterization / project close-out						
	i. BMP & turbidity monitoring						
	j. As-built & construction report						
	k. Design team & stakeholder debrief						
	18. Project performance monitoring						
	a. Stability, scour, wood accumulation						
	b. Habitat diversity and area habitat utilization (fish and wildlife)						
	c. Fish and wildlife						
	d. Wood longevity						
	19. Adaptive management						
	a. Identify management criteria						
	b. Adaptive management plan						
	c. Maintenance						
	d. Documentation						

DISCLAIMER: This is a general checklist for stream and river wood projects. Specific sites may involve different elements not provided here, nor does this list provide the details of each element. Please send comments to Tim Abbe at tim.abbe@gmail.com.

Figure 7. (continued)

Table 1. Performance of Selected Engineered Logjams as of 2009

Project (River)	Type[a]	Year Built	Number of ELJs	Intact in 2009	Stabilization[b]	Gradient (MM^{-1})	1 Year Q (cm)	100 Year Q (cm)	Maximum Q as of 2007 (cm)	Recurrence Interval of Maximum Peak Flow to Date (years)	Estimated Basal Shear Stress Experienced to Date (Pa)	Estimated Basal Shear Stress for 100 Year Q (Pa)
Upper Cowlitz	P[c]	1995	3	1	none	0.0044	127	1186	932	28	50	130
NF Stillaguamish RM 21	R/P/B	1998	5	4	E,[d] A	0.0028	108	643	679	>100	90	90
NF Stillaguamish RM 22	R	1999	3	3	E, A	0.0028	108	643	679	>100	90	90
Lower Elwha[e]	R	1999	21	21	E, A, Pt, C	0.0048	116	1176	920	27	70	110
Cispus RM 19	P/R	1999	7	7	E, A	0.007	37	528	419	25	120	180
Methow Tennis Family	P	2003	3	3	E, A	0.013	40	291	223	8	150	270
Hoh RM 14	P	2004	12	12	E, A, Ps, C, Sa	0.002	319	1902	1671	25	50	120
SF Nooksack Hutchinson	R	2006	6	6	E, A, Pt	0.0125	97	682	222	10	100	260
Mashel	R/P	2006	6	6	E, A, Pt	0.0057	34	159	~127	50	166	170
Williams (Australia)	R/G/P	2000	20	17	E, A., Pt	0.002	170	~800	270	8	100	120
Stockyard Ck (Australia)	R/P/G	2002	19	18	E, A, Pt, C	0.0025	7	190	116	50	65	76
Hunter River (Australia)	R/P/G	2004	33	33	E, A, Pt, C	0.001	170	3760	350	2	50	120

[a] Types are defined as follows: R restoration; P, bank protection; B, bridge protection; and G, grade control.

[b] Stabilization abbreviations are as follows: E, embedment; A, alluvial backfill; Pt, timber piles; Ps, steel H piles; C, chain used to attach logs to one another or piles (no earth anchors); Sa, scour apron; and R, rock ballast.

[c] Upper Cowlitz was emergency response constructed in December 1995.

[d] Excavation for NF Stillaguamish did not get to estimated scour depths.

[e] Lower Elwha structures constructed from 1999 to 2004.

and constructability perspective. The feasibility study should help answer important questions such as (1) Can the threatened infrastructure be relocated? (2) How much of the channel migration zone can be preserved or regained? (3) Can habitat be enhanced as part of solving traditional problems, such as bank protection and flood control? (4) Are local construction materials available? (5) Will partnerships with other stakeholders benefit the project?

7.3. Risk Assessment

Risk assessment evaluates and predicts how the project will perform under both normal and adverse conditions and evaluates the accuracy of the scientific data to be used in the project design. The risk assessment should also determine the potential effects on changes in the river channel (including flood levels, scour, sedimentation, and bank erosion) and evaluate potential short- and long-term impacts on humans, infrastructure, and natural habitat. The assessment should include appropriate public outreach and involvement, during which project stakeholders and affected groups and individuals are educated about the project and provide project managers and experts with feedback, insights, and ideas. Liability of building structures in rivers is becoming a major issue in some areas where the recreational community and flood protection districts have a long history of channelized rivers. Restoration advocates must take time to educate stakeholders and ensure their projects are compatible with local communities.

7.4. Design

The design of a project builds in factors of safety that are equivalent to those applied to any other civil engineering project. In doing so, geomorphologists and engineers should determine the type, size, location, and strength of the structures needed to withstand maximum forces and achieve the highest level of public and environmental protection.

7.5. Construction

Construction entails preparation of the site and delineation of the specific construction sequence, including site access, flow diversions and dewatering, major excavation and grading, careful placement of structural elements, fish removal and protection, water quality and erosion control, and revegetation. Construction of ELJs can range from relatively simple placement of large woody debris directly into a stream or river to more complex structures. The construction can be accomplished in many different ways, which can greatly affect the cost, regulatory compliance, and final outcome. Based on the complexity of these structures, it is essential that the designer be integrated into construction inspection.

7.6. Monitoring and Maintenance

Monitoring and maintenance provide periodic monitoring and maintenance of the structures. Monitoring should include an evaluation of structural integrity, scour, drift accumulation, and their ecological effects, such as surveys of fish and invertebrate use [e.g., *Abbe et al.*, 2003b, also unpublished report, 2005; *Brooks et al.*, 2004; *Brooks*, 2006]. Maintenance can include culling, repairing any structural damage, and revegetating, as needed. Too often, this phase is underemphasized or ignored.

Many things need considering in restoring and managing rivers, particularly when considering the reintroduction and management of wood debris. Figure 7 presents a checklist for the design of wood in river restoration [*Abbe et al.*, 2008], which is offered as a set of guidelines and reminders of the many factors for restoration design and river management.

8. CONCLUSION

Wood debris has been a natural part of the sediment load in rivers since woody vegetation appeared on Earth 360 million years ago. Both alive and dead trees have a significant influence on the morphology and habitat complexity of streams and rivers. Wood accumulations attenuate flood peaks, dissipate energy, trap sediment, deflect flows, and create anabranching channels, pools, and cover. Reintroducing wood to rivers is a critical component of habitat restoration in a wide range of environments throughout the world. We have presented some of the many issues to consider when designing wood structures in fluvial systems. Properly designed, wood debris structures, such as ELJs, have been very successful components of river restoration, whether used for grade control, flow deflection, pool formation, or increasing channel complexity and floodplain connectivity. Many issues need considering when doing any river restoration project, particularly with regard to wood debris. This consideration is even more important regarding the potential liability of placing flow obstructions in a river or structures that may be washed downstream if not properly designed and constructed. A great deal needs to be learned about ELJs including the hydraulics, longevity, influence on wood budgets, and effects of natural wood accumulation. For many river systems, wood is an essential element of any restoration and management planning. The key consideration should always be process when incorporating wood into river restoration planning. Wood structures should not simply be seen as yet another structural measure for controlling rivers.

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REFERENCES

Abbe, T. B. (2000), Patterns, mechanics, and geomorphic effects of wood debris accumulations in a forest river system, Ph.D. dissertation, Univ. of Wash., Seattle.

Abbe, T. B., and D. R. Montgomery (1996), Large woody debris jams, channel hydraulics, and habitat formation in large rivers, *Reg. Rivers Res. Manage.*, *12*, 201–221.

Abbe, T. B., and D. R. Montgomery (2003), Patterns and processes of wood 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, WA, *Eos Trans. AGU*, *74*(43), Fall Meet. Suppl., 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, in *Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision*, edited by S. S. Y. Wang, E. J. Langendoen, and F. D. Shields Jr., pp. 809–816, Univ. of Miss., Oxford.

Abbe, T. B., A. Brooks, and D. R. Montgomery (2003a), Wood in river restoration and management, in *The Ecology and Management of Wood in World Rivers*, edited by S. Gregory, K. L. Boyer, and A. M. Gurnell, pp. 367–389, Am. Fish. Soc., Bethesda, Md.

Abbe, T. B., J. Bountry, L. Piety, G. Ward, M. McBride, and P. Kennard (2003b), Forest influence on floodplain development and channel migration zones, *Geol. Soc. Am. Abstr. Programs*, *35*, 352.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston (2003c), Integrating engineered logjam technology in river rehabilitation, in *Restoration of Puget Sound Rivers*, edited by D. R. Montgomery et al., pp. 443–490, Univ. of Wash. Press, Seattle.

Abbe, T. B., C. Miller, M. Rudd, and B. Belby (2008), Guidelines for re-introducing and managing wood, paper presented at 7th Annual Northwest Stream Restoration Design Symposium, River Restor. Northwest, Stevenson, Wash.

Andreoli, A., F. Comiti, and M. A. Lenzi (2007), Characteristic, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes, *Earth Surf. Processes Landforms*, *32*, 1675–1692.

Baille, B. R., L. G. Garrett, and A. W. Evanson (2008), Spatial distribution and influences of large woody debris in an old-growth forest river system, New Zealand, *For. Ecol. Manage.*, *256*, 20–27.

Benda, L., D. Miller, D. Martin, R. Bilby, C. Velduisen, and T. Dunne (2002), Wood budgeting quantitative theory, field practice and modeling, in *The Ecology and Management of Wood in World Rivers*, edited by S. Gregory, K. L. Boyer, and A. M. Gurnell, chap. 10, pp. 49–73, Am. Fish. Soc., Bethesda, Md.

Benyus, J. M. (2002), *Biomimicry: Innovation Inspired by Nature*, Perennial, New York.

Bernhardt, E. S., et al. (2005), Synthesizing U.S. river restoration efforts, *Science*, *308*(5722), 636–637.

Boulton, A. J. (2007), Hyporheic rehabilitation in rivers: Restoring vertical connectivity, *Freshwater Biol.*, *52*, 632–650.

Brakenridge, G. R. (1984), Alluvial stratigraphy and radiocarbon dating along the Duck River, Tennessee: Implications regarding flood-plain origin, *Geol. Soc. Am. Bull.*, *95*, 9–25.

Braudrick, C. A., and G. E. Grant (2000), When do logs move in rivers?, *Water Resour. Res.*, *36*, 571–583.

Broms, B. B., and L. Hellman (1970), Closure on end bearing and skin friction resistance of piles, *J. Soil Mech. Found. Div. Am. Soc. Civ. Eng.*, *95*, 1538–1539.

Brooks, A. P. (2006), *Guideline for the Reintroduction of Wood Into Rivers*, 85 pp., Land and Water Aust., Canberra.

Brooks, A. P., and G. J. Brierly (1997), Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926, *Geomorphology*, *18*, 291–304.

Brooks, A. P., and G. J. Brierly (2002), Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river, *Earth Surf. Processes Landforms*, *27*, 343–367.

Brooks, A. P., 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 floodplain evolution: Insights from a paired catchment study in south-eastern 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 Res. Appl.*, *20*, 513–536.

Brooks, A. P., T. Howell, T. B. Abbe, and A. Arthington (2006), Confronting hysteresis: Wood based river rehabilitation in highly altered riverine landscapes of south-eastern Australia, *Geomorphology*, *79*, 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, USA, *Geomorphology*, *80*, 295–309.

Buffington, J. M., and D. R. Montgomery (1999a), Effects of hydraulic roughness on surface textures of gravel-bed rivers, *Water Resour. Res.*, *35*, 3507–3521.

Buffington, J. M., and D. R. Montgomery (1999b), Effects of sediment supply on surface textures of gravel-bed rivers, *Water Resour. Res.*, *35*, 3523–3530.

Catlin, G. (1832), *View on the Missouri, Alluvial Banks Falling in, 600 Miles Above St. Louis*, Natl. Mus. of Am. Art, Smithsonian Inst., Washington, D. C.

Chase, K. J., and S. R. Holnbeck (2004), Evaluation of pier-scour equations for coarse-bed streams, *U.S. Geol. Surv. Sci. Invest. Rep., 2004-5111*.

Chin, A., et al. (2008), Perceptions of wood in rivers and challenges for stream restoration in the United States, *Environ. Manage.*, *41*(6), 893–903.

Coe, H. J., P. M. Kiffney, and G. R. Pess (2006), A comparison of methods to evaluate the response of periphyton and invertebrates to wood placement in large Pacific coastal rivers, *Northwest Sci.*, *80*, 298–307.

Collins, B., and D. R. Montgomery (2002), Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington, *Restor. Ecol.*, *10*, 237–247.

Collins, B., and A. Sheikh (2004), Historic channel locations of the Nooksack River, report submitted to Whatcom County Public Works Department, Dep. of Earth and Space Sci., Univ. of Wash., Bellingham.

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.

Copeland, R. R. (1983), Bank protection techniques using spur dikes, *Pap. HL-83-1*, Hydraul. Lab., U.S. Army Waterw. Exp. Stn., Vicksburg, Miss.

Cordova, J. M., E. J. Rosi-Marshall, A. M. Yamamuro, and G. A. Lamberti (2006), Quantity, controls and functions of large woody debris in Midwestern USA streams, *River Res. Appl.*, *23*, 21–33.

Dacy, G. H. (1921), Pulling the Mississippi's teeth, *Sci. Am.*, *75*(4), 60, 70.

Dolloff, C. A., Jr. (1994), Large woody debris: The common denominator for integrated environmental management of forest streams, in *Implementing Integrated Environmental Management*, edited by J. Cairns Jr., T. V. Crawford, and H. Salwasser, Univ. Cent. for Environ. and Hazard. Mater. Stud., Va. Polytech. Inst. and State Univ., Blacksburg.

Erskine, W. D., and A. A. Webb (2003), Desnagging to resnagging: New directions in river rehabilitation in southeastern Australia, *River Res. Appl.*, *19*, 233–249.

Fael, C. M. S., G. Simarro-Grande, J.-P. Martín-Vide, and A. H. Cardoso (2006), Local scour at vertical-wall abutments under clear-water flow conditions, *Water Resour. Res.*, *42*, W10408, doi:10.1029/2005WR004443.

Federal Highway Administration (FHWA) (2001), Evaluating scour at bridges, in *Hydraulic Engineering Circular 18*, 4th ed., *Publ. FHWA NHI 01-001*, Washington, D. C.

Fischenich, C., and M. Landers (2000), Computing scour, in *EMRRP Technical Notes Collection, Rep. ERDC TN-EMRRP-SR-5*, U.S. Army Eng. Res. and Dev. Cent., Vicksburg, Miss.

Fox, M., and S. Bolton (2007), A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State, *North Am. J. Fish. Manage.*, *27*, 342–359.

Froehlich, D. C. (1989), Local scour at bridge abutments, paper presented at 1989 National Conference on Hydraulic Engineering, Am. Soc. of Civ. Eng., New Orleans, La.

Gastaldo, R. A., and C. W. Degges (2007), Sedimentology and paleontology of a Carboniferous log jam, *Int. J. Coal Geol.*, *69*, 103–118.

Gerhard, M., and M. Reich (2000), Restoration of streams with large wood: Effects of accumulated and built-in wood on channel morphology, habitat diversity and aquatic fauna, *Int. Rev. Hydrobiol.*, *85*(1), 123–137.

Guardia, J. E. (1933), Some results of the log jams in the Red River, *Bull. Geogr. Soc. Philadelphia*, *31*(3), 103–114.

Guyette, R. P., D. C. Dey, and M. C. Stambuagh (2008), The temporal distribution and carbon storage of large Oak wood in streams and floodplain deposits, *Ecosystems*, *11*, 643–653.

Harmon, M. F., et al. (1986), Ecology of coarse woody debris in temperate ecosystems, *Adv. Ecol. Res.*, *15*, 133–302.

Hartopo, (1991), The effect of raft removal and dam construction on the Lower Colorado River, Texas, M.S. thesis, Tex. A&M Univ., College Station.

Harvey, B. C., R. J. Nakamoto, and J. L. White (1999), Influence of large woody debris and a bankfull flood on movement of adult resident coastal cutthroat trout (*Oncorhynchus clarki*) during fall and winter, *Can. J. Fish. Aquat. Sci.*, *56*, 2161–2166.

Hoffmans, G. J. C. M., and H. J. Verheij (1997), *Scour Manual*, A. A. Balkema, Rotterdam, Netherlands.

Hyatt, T. L., and R. J. Naiman (2001), The residence time of large woody debris in the Queets River, Washington, USA, *Ecol. Appl.*, *11*, 191–202.

Jacoby, H. S., and R. P. Davis (1941), *Foundations of Bridges and Buildings*, 535 pp., McGraw-Hill, New York.

Johnson, P. A., and E. F. Torrico (1994), Scour around wide piers in shallow flow, *Recent Research on Hydraulics and Hydrology, Transp. Res. Rec. 1471*, pp. 66–70, Transp. Res. Board, Natl. Res. Counc., Washington, D. C.

Keller, E. A., and T. Tally (1979), Effects of large organic debris on channel form and fluvial processes in the coastal Redwood environment, in *Adjustments of the Fluvial System: Proceedings of the 10th Annual Binghamton Geomorphology Symposium*, edited by D. D. Rhodes and G. P. Williams, pp. 169–197, Kendal-Hunt, Dubuque, Iowa.

Lagasse, P. F., P. E. Clopper, L. W. Zevenbergen, W. J. Apitz, and L. G. Girard (2010), Effects of debris on bridge pier scour, *NCHRP Rep. 653*, Natl. Coop. Highway Res. Program, Transp. Res. Board, Washington, D. C.

Lane, E. W. (1955), The importance of fluvial morphology in hydraulic engineering, *Pap. 745*, Am. Soc. of Civ. Eng., Reston, Va.

Lisle, T. E. (1995), Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington, *Water Resour. Res.*, *31*, 1797–1808.

Liu, H. K., F. M. Chang, and M. M. Skinner (1961), Effect of bridge constriction on scour and backwater, *CER 60 KHL 22*, Eng. Res. Cent., Colo. State Univ., Fort Collins.

Lyell, C. (1830), *Principles of Geology*, vol. I, John Murray, London, U. K [Published in 1990, Univ. of Chicago Press, Chicago, Ill.]

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.

Manga, M., and J. W. Kirchner (2000), Stress partitioning in streams by large woody debris, *Water Resour. Res.*, *36*, 2373–2379.

Manners, R. B., M. W. Doyle, and M. J. Small (2007), Structure and hydraulics of natural woody debris jams, *Water Resour. Res.*, *43*, W06432, doi:10.1029/2006WR004910.

Maser, C., and J. R. Sedell (1994), *From the Forest to the Sea: The Ecology of Wood in Streams, Rivers, Estuaries and Oceans*, St. Lucie Press, Delray Beach, Fla.

Mehan, G. T., R. J. Naiman, and J. J. Latterell (2006), River restoration, *Issues Sci. Technol.*, *22*(3), 17–19.

Melville, B. W., and S. E. Coleman (2000), *Bridge Scour*, Water Resour. Publ., Highlands Ranch, Calif.

Montgomery, D. R., and T. 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, *Quat. Res.*, *65*, 147–155.

Montgomery, D. R., and J. M. Buffington (1997), Channel reach morphology in Mountain drainage basins, *Geol. Soc. Am. Bull.*, *109*, 596–611.

Montgomery, D. R., J. M. Buffington, R. D. Smith, K. M. Schmidt, and G. Pess (1995), Pool spacing in forest channels, *Water Resour. Res.*, *31*, 1097–1105.

Montgomery, D. R., T. Abbe, N. P. Peterson, J. M. Buffington, K. M. Schmidt, and J. D. Stock (1996), Distribution of bedrock and alluvial channels in forested mountain drainage basins, *Nature*, *381*, 587–589.

Muir, J. (1878), The new sequoia forests of California, *Harpers New Monthly Mag.*, *57*, 813–827.

Nanson, G. C., M. Barbetti, and G. Taylor (1995), River stabilisation due to changing climatic and vegetation during the late Quaternary in western Tasmania, Australia, *Geomorphology*, *13*, 145–158.

O'Connor, J. E., M. A. Jones, and T. L. Haluska (2003), Flood plain and channel dynamics of the Quinault and Queets rivers, Washington, USA, *Geomorphology*, *51*, 31–59.

Peters, R., B. Missildine, and D. Low (1998), Seasonal fish densities near river banks stabilized with various stabilization methods, report, 34 pp., U.S. Fish and Wildl. Serv., West. Washington Off., Lacey, Wash.

Raven, J., and P. Crane (2007), Trees, *Curr. Biol.*, *17*, R303–R304.

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*, John Wiley, New York.

Russell, I. C. (1909), *Rivers of North America*, G. P. Putnam's Sons, New York.

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, *Verh. Int. Ver. Theor. Angew. Limnol.*, *22*, 1828–1834.

Sheppard, D. M., H. Demir, and B. Melville (2011), Scour at wide piers and long skewed piers, *NCHRP Rep. 682*, Natl. Coop. Highway Res. Program, Transp. Res. Board, Washington, D. C.

Simpson, W. T. (1993), Specific gravity, moisture content and density relationship for wood, *Gen. Tech. Rep. FPL-GTR-76*, 13 pp., For. Products Lab., For. Serv., U.S. Dep. of Agric., Madison, Wis.

Skaar, C. (1988), *Wood-Water Relations*, 283 pp., Springer, New York.

Spanhoff, B., C. Alecke, and E. Irmgard Meyer (2001), Simple method for rating the decay stages of submerged woody debris, *J. North Am. Benthol. Soc.*, *20*, 385–394.

Stofleth, J. M., F. D. Shields Jr., and G. A. Fox (2008), Hyporheic and total transient storage in small, sand-bed streams, *Hydrol. Processes*, *22*, 1885–1894.

Veatch, A. C. (1906), Geology and underground water resources of northern Louisiana and southern Arkansas, *U.S. Geol. Surv. Prof. Pap.*, *46*.

Wallerstein, N., C. R. Thorne, and M. W. Doyle (1997), Spatial distribution and impact of large woody debris in northern Mississippi, in *Management of Landscapes Disturbed by Channel Incision*, edited by S. S. Y. Wang, E. J. Langendoen, and F. D. Shields Jr., pp. 145–150, Univ. of Miss., Oxford.

Williams, M. (2003), *Deforesting the Earth: From Prehistory to Global Crisis*, Univ. of Chicago Press, Chicago, Ill.

Wohl, E., P. L. Angermeier, B. Bledsoe, G. M. Kondolf, L. MacDonnell, D. M. Merritt, M. A. Palmer, N. L. Poff, and D. Tarboton (2005), River restoration, *Water Resour. Res.*, *41*, W10301, doi:10.1029/2005WR003985.

Wolff, H. H. (1916), The design of a drift barrier across the White River, near Auburn, Washington, *Trans. Am. Soc. Civ. Eng.*, *16*, 2061–2085.

Wondzell, S. M., and P. A. Bisson (2003), Influence of wood and aquatic biodiversity, in *The Ecology and Management of Wood in World Rivers*, edited by S. Gregory, K. Boyer, and A. Gurnell, pp. 249–264, Am. Fish. Soc., Bethesda, Md.

Wondzell, S. M., J. LaNier, and R. Haggerty (2009), Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream, *J. Hydrol.*, *364*, 142–151.

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