American Fisheries Society Symposium xx:xxx–xxx, 2003

Wood in River Rehabilitation and Management

Timothy B. Abbe

Herrera Environmental Consultants, Inc.
2200 Sixth Avenue, Suite 1100, Seattle, Washington 98121, USA

Andrew P. Brooks

Centre for Catchment and in-Stream Research
Griffith University, Nathan, Queensland, Australia 4111

David R. Montgomery

Department of Earth and Space Sciences
University of Washington, Seattle, Washington 98195, USA

Abstract.—Wood induces hydraulic, morphologic, and textural complexity into fluvial systems in forested regions around the world. Snags and logjams can create complex networks of channels and wetlands across entire river valleys and historically posed a significant obstacle to navigation. The clearing of wood from rivers and riparian forest land along streams and rivers reduced or eliminated the supply of wood into rivers in many regions of the world. Ecological restoration of fluvial environments increasingly includes the placement of wood. But few guidelines exist on appropriate methods for emulating natural wood accumulations, where and how to place wood, its longevity, the hydraulic and geomorphic consequences of wood, and how to manage systems where wood is reintroduced. Important issues to understand when placing wood in rivers include the watershed and reach-scale context of a project, the hydraulic and geomorphic effects of wood placements, possible changes in wood structures over time, and how it may impact human infrastructure and safety. Engineered logjams constructed in Washington, USA and New South Wales, Australia offer examples of how wood reintroduction can be engineered without the use of artificial anchoring to form stable in-stream structures as part of efforts to rehabilitate fluvial ecosystems and provide ecologically sensitive means to treat traditional problems such as bank stabilization and grade control.

Introduction

The geomorphic effects of wood on fluvial systems range in scale from controlling bed forms and influencing channel patterns to floodplain development (e.g., Wolff 1916; Davis 1901; Guardia 1933; Keller and Swanson 1979; Lienkaemper and Swanson 1987; Harwood and Brown 1993; Abbe and Montgomery 1996, 2003; Buffington and Montgomery 1999; Brooks 1999; Brooks and Brierley 2002). Snags and logjams can be the principal mechanism creating habitat complexity not only within an active channel, but also by inducing localized flooding and creating and sustaining secondary channels and wetlands (Triska 1984; Sedell and Froggatt 1984; Abbe 2000; Collins and Montgomery 2002). Examples of these complex fluvial systems with numerous side channels that extend across much of a river valley are increasingly rare (Figure 1). Habitat complexity directly or indirectly related to wood clearly benefits many aquatic ecosystems (e.g., Pearsons et al. 1992; Quinn and Peterson 1996; Lehtinen et al. 1997; Inoue and Nakano 1998), and reduced fish populations can reflect the extensive loss of physical complexity in fluvial systems resulting from wood removal, channelization, and floodplain development (e.g., Shields and Smith 1992; Beechie et al. 2001; Collins et al. 2003; Pess et al. 2003). Rehabilitation of fluvial ecosystems depends on re-es-

FIGURE 1. Snags and logjams contribute to the development of a complex mosaic of anastomosing channels, wetlands, and floodplain forest in river valleys such as Taiya River in southeast Alaska.

tablishing natural processes and conditions that create and sustain physical complexity, such as restoring instream structure and cover, mature riparian forests, floodplain connectivity, and channel migration zones (CMZs). Reintroduction of wood is an important part of river rehabilitation but must be balanced with the potential for physical changes that are ecologically beneficial to have negative consequences to existing human development. The use of wood to restore streams and rivers should be based on sound science, engineering, and an understanding of the magnitude to which the system may change.

Although the role of wood in many parts of the world remains to be investigated, it has been found to play a significant role in the ecology and morphology of streams and rivers in a wide range of climates and physiographic regions, including Asia (e.g., Inoue and Nakano 1998; Rikhari and Singh 1998), Australia and New Zealand (e.g., Mosley 1981; Nanson et al. 1995; Gippel et al. 1996a; Weigelhofer and Waringer 1999; Brooks and Brierley 2002; Webb and Erskine 2003), Europe (e.g., Gregory et al. 1993; Piegay 1993; Maridet et al. 1996; Piegay and Gurnell 1997; Gurnell and Sweet 1998; Hering et al. 2000a, 2000 b; Diez et al. 2001; Kail 2003), northeastern North America (e.g., Zimmerman et al. 1967; Thompson 1995; Beebe 1997), southeastern North America (e.g., Veatch 1906; Guardia 1933; Diehl 1997; Wallerstein et al. 1997), southwestern North America (e.g., Haden et al. 1999), and northwestern North America (e.g., Keller and Swanson 1979; Harmon et al. 1986; Lienkaemper and Swanson 1987; Andrus et al. 1988; Robison and Beschta 1990; Nakamura and Swanson 1993; Maser and Sedell 1994). Historical management of wood in rivers has focused on the removal of snags and logjams, which were considered threats to navigation, flooding, and even fish passage (e.g., Ruffner 1886; McCall 1984; Maser and Sedell 1994; Collins et al. 2002). Additional river management practices that have reduced the supply of wood include dams, bank stabilization, and removal of riparian forests. In many regions, retention of wood was further diminished by the loss of large trees capable of forming stable snags, as well as effects associated with channel straightening, levees, and navigation improvements. But it is worth noting that, through much of history, wood has been considered a viable material for instream structures and extensively utilized for infrastructure in rivers, such as bulkheads, spur dikes, bridge abutments and piers, weirs, and dams.

Large scale efforts to reintroduce wood to streams and rivers have been limited to the Pacific Northwest of North America. An increase in the passive reintroduction of wood associated with the reforestation of riparian areas, such as occurring in parts of the United States and Europe, will have physical consequences, such as increased channel width and complexity (e.g., Davies 1997; Trimble 1997; Collins and Montgomery 2002), increasing flood inundation, and redirecting channels (Figure 2). Such physical effects can improve ecological conditions, but they may not be compatible with existing or future development and can pose a significant challenge to efforts to restore streams and rivers. Channel clearing (removal of snags and logjams) continues to be a common practice in river management around the world despite international recognition of the ecological benefits of wood and studies demonstrating that significant quantities of wood can be left in some channels without adverse impacts on flow conveyance (e.g., Shields and Gippel 1995; Gippel et al. 1996b). Because wood is not simply a “cosmetic” feature in streams and rivers, greater accountability for potential effects may be demanded for projects incorporating direct or passive wood reintroduction. Successful rehabilitation of fluvial ecosystems will depend on understanding the dynamics and effects of wood and identifying and resolving potential problems (e.g., Maridet et al. 1996; Abbe et al. 2003). While the scientific understanding of the physical dynamics and effects of wood is still developing, substantial progress has been made regarding the patterns in which wood accumulates, its hydraulic and geomorphic effects, mechanics and longevity, and the performance of wood placements (e.g., House and Boehne 1985, 1986; Murphy and Koski 1989; Gregory et al. 1993; Shields and Gippel 1995; Abbe and Montgomery 1996, 2003; Gippel et al. 1996a, 1996b; Abbe et al. 1997, 2003; Wallerstein et al. 1997, 2001, 2002; Gurnell and Sweet 1998; Syndi et al. 1998; Braudrick and Grant 2000).

Wood influences fluvial geomorphology by altering both the hydraulics and distribution of flow within a fluvial corridor and, thereby, the deposition and transport of sediment. Instream wood can provide stable flow obstructions that not only store sediment, but can also sustain and even enlarge pools in aggrading channels that have been subjected to increases in sediment supply (Lisle 1995; Lisle and Napolitano 1998). Natural wood accumulations can dam headwater channels (e.g., Keller and Swanson 1979; Marston 1982) and redirect the course of large rivers (Wolff 1916; Guardia 1933; Sedell and Froggatt 1984; Triska 1984; Abbe and Montgomery 1996; Collins and Montgomery 2002). Numerous studies have described significant geomorphic effects of wood on relatively small channels (e.g., Zimmerman et al. 1967; Keller and Swanson 1979). For example, instream wood can account for 8% to more than 80% of the elevation loss of montane forest channels (Tally 1980; Marston 1982; Thompson 1995; Abbe 2000). Montgomery and Buffington (1997) show that reach-scale channel morphologies associated with lower gradients can be imposed upon much steeper channels by the presence of wood. In the coast ranges of western Washington and Oregon, USA, stable log steps transform stream segments from bedrock to alluvial channels (Montgomery et al. 1996, 2003). When wood is removed from these streams, the sediment transport capacity exceeds supply and the channel segments revert to bedrock. Stable instream wood accumulations can also increase pool frequency (Andrus et al. 1988; Robison and Beschta 1990; Montgomery et al. 1995; Abbe and Montgomery 1996; Beechie and Sibley 1997), and individual snags or log jams can have both local effects on channel bed texture (Buffington and Montgomery 1999) and broader effects on stream morphology (e.g., Keller and Tally 1979; Nakamura and Swanson 1993; Montgomery and Buffington 1997). In some sand-bed channels, virtually all pools can be attributed to either the direct or indirect control of wood (Brooks and Brierley 2002; Webb and Erskine 2003).

Wood can also have reach-scale effects on channel form in large rivers (e.g., Davis 1901; Russell 1909; Wolff 1916; Triska 1984; Abbe and Montgomery 1996; Collins and Montgomery

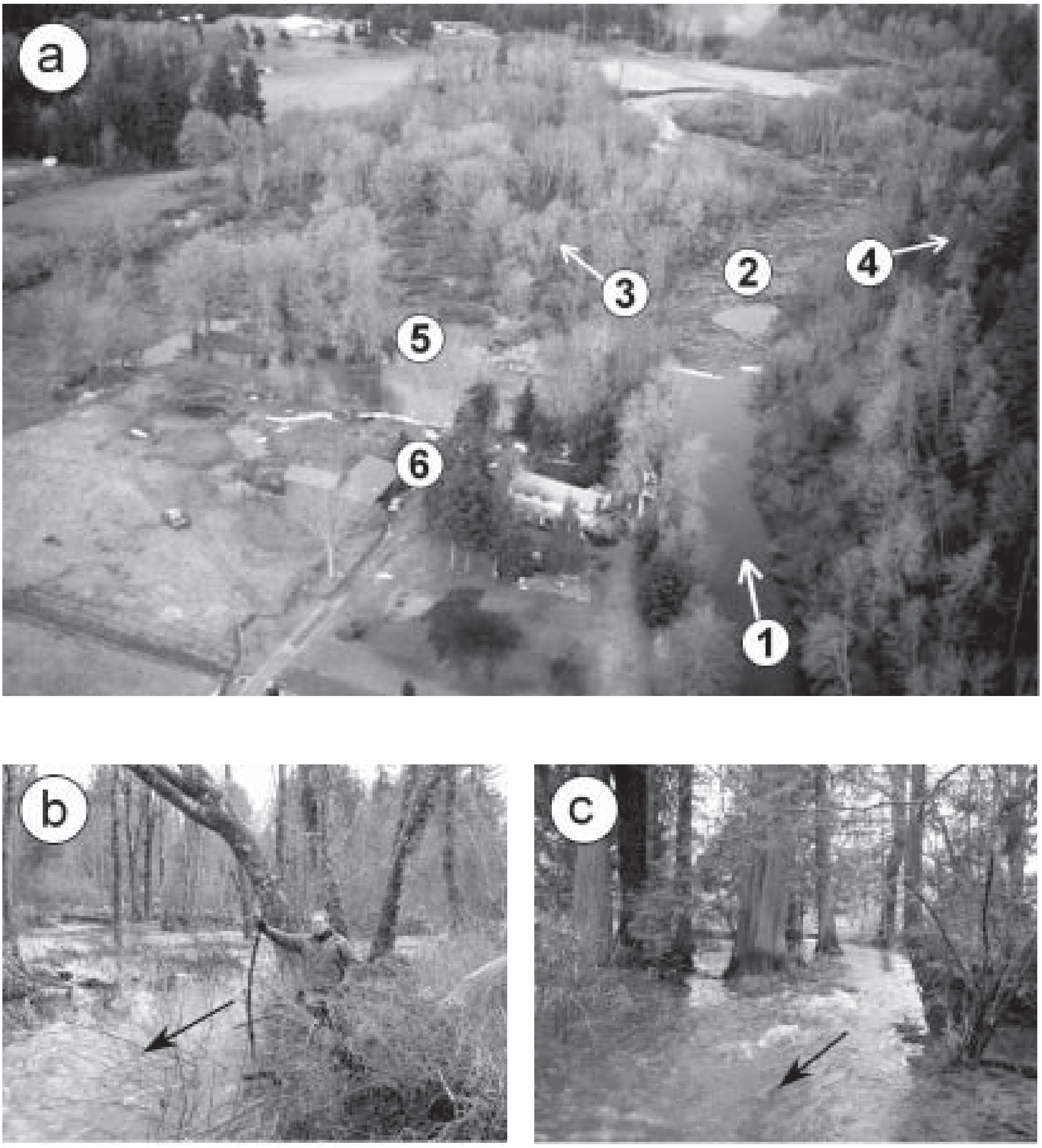

FIGURE 2. (a) The Deschutes River approximately 20 km south of Olympia, Washington on 4 February 2002. Flow is to the north (location 1). The large logjam (2) began forming in the 1990s and grew substantially in the winter of 2001–2002. As a result, river stage upstream of the logjam increased about 1.3 m during low flow conditions (~7 m^3/s versus a mean daily discharge of 14 m^3/s). Higher water elevations inundated adjacent floodplain areas (locations 3–5) and threatened low-lying homes (location 6). (b) Newly developed channel through relatively young floodplain on left side of logjam (location 3 on photo a). (c) Newly developed channel through mature cedar floodplain on right side of logjam (location 4 on photo a). All photographs were taken during low flow conditions, and arrows depict direction of flow. Despite the significant increase in the extent and complexity of aquatic habitat resulting from the logjam, it was cleared by private landowners in the fall of

2002). The anastomosing channel pattern (i.e., multiple channels separated by vegetated islands) of some large alluvial rivers has been attributed to an abundance of snags and logjams (Sedell and Froggatt 1984; Harwood and Brown 1993; Abbe 2000; Collins and Montgomery 2002; Abbe and Montgomery 2003). Effects of wood accumulations can extend beyond the confines of the bankfull channel to the development of floodplains and even terraces (Abbe 2000; Abbe and Montgomery 2003). In some circumstances, it is clear that wood accumulations were instrumental in vastly expanding the area of land subjected to inundation and fluvial processes (Ruffner 1886; Veatch 1906; Guardia 1933; Triska 1984; Collins and Montgomery 2001; Brooks et al. 2003).

Observations of geomorphic change that occurred after removal or addition of wood illustrate the magnitude to which wood can control river gradient and store immense quantities of sediment. A particularly striking example is given by clearing of wood from the Red River in Louisiana, USA, which caused portions of the river to incise more than 4 m (Veatch 1906; Guardia 1933; Harvey et al. 1988a, 1988b), increased the river gradient by an order of magnitude, and resulted in a sixfold increase in sediment transport capacity (Harvey et al. 1988a). Conversely, large wood accumulations can result in substantial aggradation of channels and floodplains. After a single year of unexceptional flows, the channel bed upstream of a logjam on Alta Creek, a tributary of the Queets River in Washington State, aggraded over 4 m (Abbe and Montgomery 2003). Channel aggradation upstream of wood accumulations results in distinctive landforms that resemble terraces but have surface gradients less than those of the valley in which they occur.

Brooks (1999) presents a dramatic example of the effect of instream wood debris and floodplain forests on the geomorphology of rivers in southeast Australia by comparing two adjacent sand-bed rivers: the relatively undisturbed Thurra River and the extensively disturbed Cann River. By early in the 20th century, the Cann River floodplain forest had been extensively cleared. The channel was then progressively cleared of wood through the 20th century. Prior to channel incision, the Cann River had not experienced any other significant types of disturbance (e.g., dams, grade control), and, outside the valley bottom, the catchment remains under forest cover. Hence, channel and floodplain clearing represent the only feasible explanations for the river's present condition.

Relict channels and sedimentology of the Cann River's floodplain indicate that the river originally resembled the nearby Thurra River, which has remained undisturbed. The sand-bed Thurra River has a narrow sinuous channel with very high wood loading (0.032–0.044 m^3/m^2 within the wetted perimeter) that flows through a heavily forested floodplain (Brooks and Brierley 2002). Over the last 100 years, however, and particularly the last 30 years, the channel capacity of the Cann River increased 700%, its morphological bankfull discharge has increased 45-fold, mean annual sediment transport has increased 850-fold, and peak instantaneous sediment transport capacity has increased up to 40,000-fold. Bank stability parameters have also fundamentally changed, as have roughness characteristics of the channel and wood (Brooks 1999; Brooks et al. 2003). The Thurra River has exhibited no such changes, demonstrating not only the profound effect wood and riparian vegetation have on channel morphology and processes, but also on the evolution of the floodplain. A key finding from the undisturbed Thurra River was that, in addition to the wood contained within the channel wetted perimeter, wood comprised around 7% by volume of the channel bed to a depth of 1.8 m (Brooks and Brierley 2002). The hydraulic roughness and stability imparted by this wood, coupled with macrophytes growing on the bed, prevented incision into what might otherwise be a highly unstable channel, thereby allowing the long-term aggradation of the channel and the entire floodplain (Brooks and Brierley 2002).

In gravel-bed rivers, natural logjams can form stable "hard points" within the channel migration zone, and that can limit bank erosion (Abbe and Montgomery 1996; O'Connor et al. 2003). Channel migration at these hard points is retarded, and the radius of curvature of river bends is reduced, forming tighter meanders over time (Abbe and Montgomery 2003). For example, throughout the Queets River valley in northwest Washington, USA, the radius of curvature of channel meanders associated with logjams is considerably less than for alluvial meanders with no logjams (Figure 3). This effect on channel geometry can have important consequences to hydraulic processes within the river, which, in turn, can result in additional geomorphic effects. Using a simple model for super-elevation of a water surface around a bend (Chow 1959), a reduction in the channel's radius of curvature, R_c, will increase water elevations at the outside of the bend:

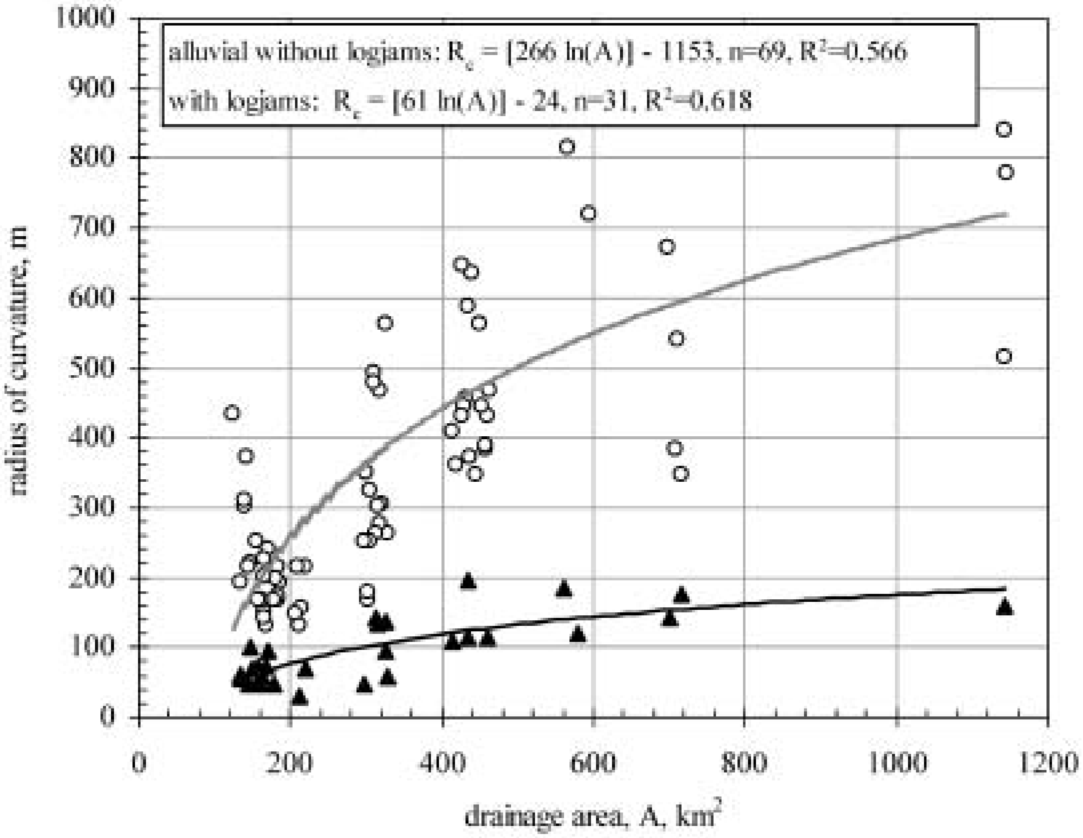

FIGURE 3. Radius of curvature of alluvial channel meanders in the Queets River, Washington. Meanders with logjams (solid triangles) have a significantly lower radius of curvature than meanders with no logjams (open circles) for the same reaches of the river system. Stable logjams form "hard points," which limit channel migration and result in the radius of curvature diminishing over time until formation of an avulsion or cutoff moves channel away from the logjam (modified from Abbe and Montgomery 2003).

$$\Delta h = \frac{W}{R_c} \times \frac{U^2}{g} ,$$

where Δh is the increase in water elevation around the bend (super-elevation), W is channel width, g is the acceleration of gravity, and U is the mean flow velocity around the bend. Manning's equation provides simple means of estimating velocity:

$$U = \frac{s^{1/2}\ h^{2/3}}{n} ,$$

where S is the hydraulic gradient, h is the mean water depth, and n is Manning's roughness coefficient. Differences in super-elevation between meanders with and without logjams, estimated using a simple model in which all channel variables except for radius of curvature, are dependent on drainage area. The results indicate that super-elevation around bends associated with logjams is as much as 0.5 m more than meanders without logjams (Figure 4). These increased water elevations will increase the frequency of overbank flows and be more prone to initial development of avulsions and side channels.

Introducing a flow obstruction to a stream causes several indirect consequences related to the drag imposed on the flow. An increase in flow depth upstream of an obstruction can result from backwater effects. Because a flow obstruction results in a stagnation point where the velocity is essentially zero (Abbe and Montgomery 1996), the flow depth at that point is equivalent to the specific energy of the flow or $U^2/(2g)$. For a channel with a mean velocity of 3 m/s, the velocity head

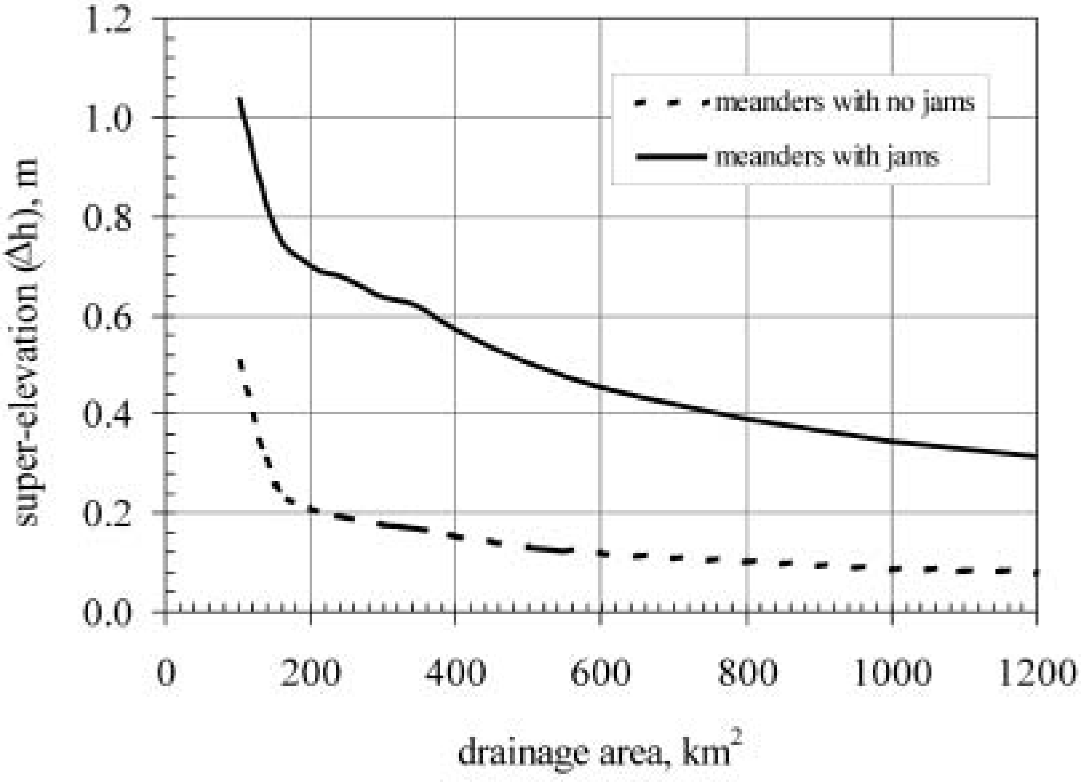

FIGURE 4. Significant reductions in a channel's radius of curvature can result in elevated water elevations around the outer bank of the meander due to super-elevation. Results of a simple model for estimating super-elevation along the Queets River, assuming only a change in radius curvature between meanders with and without logjams are plotted.

upstream of a snag or logjam would be about 46 cm, or 82 cm for a flow of 4 m/s. If the snag or logjam was located along the bank, these local increases in water elevation can deliver flow to secondary channels and the floodplain at lower discharges than it would otherwise take if the obstruction were not there. Localized increases in water elevations along riverbanks due to super-elevation and velocity head provide a mechanism to explain how logjams can contribute to the development of channel avulsions.

Gippel et al. (1996b) found that channel backwater effects are insignificant when wood occupies less than 5% of the bank-full cross-sectional area (a blockage coefficient of 0.05) but rapidly become more pronounced when more than 10% of the cross-sectional area is blocked. Increases in water elevation upstream of wood can be predicted given the water depth and Froude number of flow downstream of the obstructed area and the blockage and drag coefficients of the wood (Gippel et al. 1996b).

The stability of an individual piece of wood depends on whether the sum of resisting forces is greater than the sum of driving forces. The principal driving forces are buoyancy (function of displaced volume of water) and drag (function of flow velocity and cross-sectional area of wood within flow). The principal resisting forces are normal forces (function of the weight of wood and any surcharge due to overlying wood or sediment), bed friction (function of the wood's bed footprint and the bed material), skin friction (function of the burial depth of wood into substrate), and passive earth pressures (function of the depth of sediment leeward of wood and bed material). The strength of wood can also influence its stability in small, steep channels where the wood is subjected to significant bending movements that could break a piece into smaller, more mobile pieces. Wood stability in large channels is primarily dependent on how the wood interacts with the channel bed, which is a function of the shape and size of the wood and the type of substrate

(Abbe 2000). Resisting forces increase exponentially with burial of the wood due to skin friction, passive earth pressures, and surcharge.

Wood tends to be most efficiently transported through the deepest portion of a channel (thalweg), where it is subjected to the greatest buoyant and drag forces and least resistance. Just like a boat, floating wood has draft and will experience the least resistance where the water is deepest. Because only the largest snags are stable in the thalweg, stable wood accumulations paradoxically can initiate in the thalweg where large snags become deeply embedded in the river (Figure 5). Once stable, a snag begins to redirect flow and trap other wood moving through the system (Abbe and Mongtomery 1996). As the channel continues to migrate, snags that formed in the thalweg become incorporated into bars and floodplains (Abbe and Montgomery 1996, 2003). It is important to differentiate the wood that is stable in the thalweg from the material that deposits on bars or other depositional features. There will always be smaller pieces of wood that deposit in areas of diminished depth and velocity, such as bars. But it is those pieces of sufficient size and shape to create stable flow obstructions that are crucial for altering channel morphology and retaining mobile wood or drift within the system (Keller and Swanson 1979; Nakamura and Swanson 1993; Abbe 2000; Abbe and Montgomery 1996; Abbe et al. 2003).

The draft of a tree bole increases substantially if it retains some of its root mat. The centroid of a symmetrical tree bole will tend to be along the center line running through the middle of the bole. The centroid of a simple cylindrical log with no root mat is mid-way along the log's length. Situated on a smooth bed, a simple cylindrical log will distribute its mass along its entire length, resulting in relatively low normal stress and low resistance (Abbe 2000). Logs with specific gravity less than unity will be buoyant at some water depth less than the log diameter. In contrast, the centroid of a bole with an attached root mat is located much closer to the basal end of the log, and mass tends to be concentrated on a small area of the bed resulting in relatively high normal stress. The root mat also raises the centroid elevation, and the buoyant depth becomes more a function of the root mat diameter than of the bole diameter. This means that significantly greater flow depths are typically required to mobilize a log with a root mat than without. If a snag's resisting forces are still greater than the driving forces at the time bedload transport is initiated, bed deformation occurs around the snag. Once partially em-

FIGURE 5. Snags embedded in thalweg of Mendenhall River, Alaska. Large trees eroded from outer bank of meander fall into river and become deeply imbedded in channel. Note crown of buried snag exposed in toe of point bar to left as river migrates to the right.

bedded, a snag can prove extremely difficult to move.

Factors that tend to increase wood stability—such as larger size, denser wood, and deposition in deep portions of the river where the wood is more likely to remain saturated—tend to also increase the wood's resistance to decay and its longevity in a system. Larger or key members also have high lignin contents and lower surface area to volume that tend to further reduce decay rates (Bisson et al. 1987; Melillo et al. 1983). Carbon dating of buried wood demonstrates that large logs can last hundreds to thousands of years in both high gradient gravel-bed and low-gradient sand-bed rivers (Murphy and Koski 1989; Nanson et al. 1995; Brooks 1999; Abbe 2000; Hyatt and Naiman 2001). Wood can remain in near pristine conditions indefinitely if it is kept either completely dry or saturated in anaerobic conditions. For example, timber piles used in the foundation of St. Mark's in Venice were found to be so well preserved they were left to support the reconstructed tower after already serving for more than 1,000 years (Jacoby and Davis 1941). Even the rapid decay rates associated with species such as black cottonwood *Populus trichocarpa* can be significantly reduced in near anaerobic conditions (Van Der Kamp and Gokhale 1979). Successful reintroduction of wood to rivers should focus on key pieces, the snags that have the most substantial geomorphic influence and longest longevity. Likewise, wood structures that incorporate key pieces will more likely to persist in the system.

Integration of Wood into River Restoration

Large-scale efforts to reintroduce wood to streams in the Pacific Northwest of North America, particularly in rural forest land, were well underway in 1980s (e.g., House and Boehne 1985, 1986). While most wood reintroduction projects are well intended, the majority have been based simply on subjective decisions and have lacked rigorous scientific and engineering basis. Unfortunately, guidelines for stream restoration have little or no discussion of the mechanics and geomorphic effects of wood, nor do they provide natural analogs for the wood placements described (Rosgen and Fittante 1986; Rosgen 1996; Fischenich and Morrow 1999). The poor performance of many restoration projects is in part due to an insufficient understanding of the fluvial processes a project will be subjected to, how the project will influence these processes, and the consequences to habitat (Frissell and Nawa 1992). Preconceived perceptions that wood is inherently unstable and inadequate physical explanations of why wood was naturally stable in many streams and rivers have led to the widespread use of steel cables and artificial anchors or ballast for wood placements (e.g., D'Aoust and Millar 2000; Fischenich and Morrow 1999; Shields et al. 2000; Nichols and Sprague 2003). However, the stability of natural wood obviously never depended on such methods. For situations in which channel degradation has created conditions that are more inhospitable for wood stability than had naturally existed, such as incised channels or where large trees are no longer available, artificial means of stabilization may be necessary. A quantitative assessment of site conditions and a force balance analysis can provide the means to evaluate the stability of a proposed wood placement and help determine where artificial ballast is appropriate (Abbe et al. 1997; D'Aoust and Millar 1999, 2000; Castro and Sampson 2001; Shields et al. 2000). When cable is used in wood structures, it should only be used to secure logs tightly to one another or directly to rock ballast so that all the components act as one unified structure (D'Aoust and Millar 2000). Cable anchoring (e.g., dead-man or duck-billed anchors) is commonly used in wood placements (Fischenich and Morrow 1999) but poses significant risks that should be considered. A flexible medium, such as a cable, will not prevent wood from moving up and down or side to side with fluctuating stage or turbulence. Movement of the wood will move the cable, and an oscillating or vibrating cable will tend to cut away the material within which it is set. The cable can become exposed to create an entanglement hazard or simply fail and liberate the log that it was intended to secure. On the contrary, stable wood structures can be designed without the use of any cable (Abbe et al. 1997, 2003; Brooks et al. 2001).

The observation that logjams act as a natural type of bank protection over long periods of time led to the idea that similar structures could be "engineered" to provide bank protection that better reflects the natural character of rivers than traditional engineering measures, such as rock revetments, bulkheads, and spur dikes. The term engineered logjams (ELJs) was proposed to refer to a general group of structures based on the premise of emulating natural fluvial systems using scientific observations and engineering design principles (Abbe et al. 1997). “Restoring” the natural quantities of wood loading in rivers associated with natural logjams may be unrealistic because the geomorphic consequences might be incompatible with social needs and require time scales beyond the realm of planning. But there are many situations where instream wood can be reintroduced with no adverse impacts and even enhance habitat while solving traditional engineering problems. Unlike conventional river engineering solutions for flood risk reduction (e.g., bank and bridge protection, grade control, snag management), ELJ technology is founded on engineering designs that emulate boundary conditions and processes of the natural fluvial system. This approach can offer the distinct advantage of contributing to the restoration or rehabilitation of the riverine ecosystem, while still complying with constraints imposed by human development.

Design Considerations for Engineered Logjams

ELJ design begins with a clear statement of the project objectives. The type of ELJ selected depends on site conditions and project objectives. The type of structure appropriate for a site is dependent on local climate, hydrology, channel and bank characteristics, bed material, objectives, and constraints. Analysis of flow conditions at the site, assessment of the conditions required for bed mobility, and a force balance of individual logs and the complete ELJ are fundamental parts of the design process. Both theoretical models and empirical relationships are utilized to evaluate factors such as buoyancy, drag, resistance, decay, and bed scour. Other design considerations include ELJ size and spacing, wood budget, sediment transport, channel migration and avulsions, potential flood effects, and safety issues. Such analyses contrast with more traditional river restoration efforts that use generalized conceptual guidelines (House and Boehne 1985, 1986; Rosgen and Fittante 1986; Fischenich and Morrow 1999).

Careful consideration should be given to how and why wood is reintroduced into the fluvial environment, not only in regard to wood stabilization, but also how it is likely to respond to the system (e.g., existing flux of mobile wood, channel migration rates, riparian forest conditions) and the potential effects wood placements may have (e.g., increasing erosion, flood, avulsion risks, or hazards to human safety). Evaluating a project within a watershed and reach-scale context and how individual structures may alter the system or be altered (e.g., changes in size) over time serves as a means of assessing project performance.

Any ELJ project begins with a geomorphic analysis of past, present, and probable future conditions of the fluvial system. Has the river changed during historical times; could these type of changes impact the project? If so, further analysis is needed to identify the factors responsible for those changes. ELJs may be used to reverse river changes previously identified or used to invoke changes to mitigate impacts elsewhere. An assessment of the potential direct and indirect consequences of predictable changes, such as significant increases in ELJ size or channel changes that could affect the ELJs, can weigh the relative importance of project maintenance, which may temper the advisability of an ELJ project. An example of change commonly associated with relatively low-gradient alluvial rivers is lateral channel migration and bank erosion. The rate of channel migration and planform development of a river results from a complex interaction of numerous variables, but significant changes in certain factors, such as sediment supply, hydraulic geometry of the channel, channel planform, or bank vegetation, can accelerate or decelerate the migration rate. Assessment of the local geomorphic context, the characteristics and availability of large wood, and evidence for the type of natural wood jams is necessary to determine the appropriate type of ELJs for a particular site. The flow regime (hydraulics) of the channel and the availability of material for construction and subsequent recruitment will also influence ELJ design. Finally, infrastructure that affects hydraulic and geomorphic boundary conditions, such as bridges and the like, may also influence ELJ design.

Selecting an appropriate design for a project depends on the project objectives and constraints, the type of channel and its characteristics (gradient, size, bed material), and floodplain conditions. Several types of problems common in river engineering can be effectively addressed with different types of ELJs, such as grade control (i.e., halting or retarding channel incision), bank protection, habitat rehabilitation, and creation of side channels. Geomorphic conditions influencing ELJ designs include bed and bank stability, site location in the channel network, disturbance history, and changes in channel conditions or processes.

The first step in ELJ design is to determine the appropriate type of ELJ for the project purpose and location. In some instances, such as controlling channel alignment upstream of a bridge and reducing debris accumulation on bridge piers, the location is set and the ELJ is selected to fit the location and purpose. Another situation might prioritize establishment of pool habitat for fisheries enhancement. In this instance, the purpose and type of ELJ may be set, and the challenge is to determine the most suitable location within the stream reach of interest. The objectives of the project and the specific conditions and context of the project reach will determine how many jams may be necessary for an ELJ project.

Confidence in ELJ stability and longevity increases if the structures are evaluated for the range of discharges and stages expected to occur over the design life of the structure. The expected stage associated with higher frequency flood events is particularly important in the design of ELJs. An ELJ structure is designed to resist floatation utilizing its own mass and frictional resistance rather than employing artificial means, such as cabling. However, several additional factors reduce buoyancy and add resistance to an ELJ, so that, when submerged at some high stage, the ELJ does not become unstable. Both designed surcharge and natural sedimentation, as well as the accumulation of additional wood over time, all serve to further stabilize an ELJ. In effect, postconstruction sedimentation and wood recruitment increase safety factors in the design of ELJ structures.

Because floatation is a key design issue, certain physical sites are well suited for ELJs. Sites with unconstrained alluvial channels and floodplains are ideally suited for wood structures that can be securely buried into the substrate. The larger shear stresses necessary to mobilize gravel make it more difficult for snags to become embedded than if they were situated in a sand-bed channel. But scour depths around a snag or logjam in a sand-bed channel are significantly greater, which can either undermine and destabilize the wood or bury it even deeper, firmly securing it. If buried so deep that only a small portion of the wood interacts with the flow, it may not have the desired effects. Confined channels, particularly those with bedrock beds, are more difficult sites for building stable instream wood structures. Wood structures have been applied with some success to incised channels, though typically with the addition of steel cable anchoring (House and Boehne 1985, 1986; Shields et al. 2000). In locations such as Australia, where timber with high specific gravity is available, stable wood structures without cable or artificial ballast have been built in incised, deep channels (Brooks and Brierley 2002).

Wood Stability and Longevity

Based on historical accounts, describing the difficulties typically encountered in removing natural snags and logjams from rivers (e.g., Ruffner 1886; McCall 1984), and studies of the age of wood in a variety of river systems (e.g., Nanson et al. 1995; Abbe and Montgomery 1996; Gippel 1996b; Brooks 1999; Abbe 2000), it is clear that natural wood can be remarkably stable over long periods of time. Field studies of natural log jams have shown that the stability of wood accumulations is linked to the presence of one or more immobile snags or key members (Keller and Swanson 1979; Murphy and Koski 1989; Abbe and Montgomery 2003; Fox et al. 2003). Key member stability in steep channels is typically provided by interaction with pre-existing boundary conditions, such as bedrock outcroppings, boulders, or channel banks, and the strength properties of the tree, which determine its ability to withstand rupture. If the tree breaks, the smaller pieces become more susceptible to transport downstream. Log diameter, length, and strength are the principal factors influencing wood stability in this environment (Abbe 2000).

Once the root mat becomes partially embedded in the channel bed, it becomes more difficult to move. A sediment buttress downstream of a root mat can form in situ by the accumulation of sediment in the leeward eddy or if the root mat sinks into the bed under its own weight. If an embedded rootwad begins to slide downstream, it will push up a mound of sediment, similar to a bulldozer, making further downstream movement increasingly difficult. Rootwads of natural snags are commonly observed to be at least partially embedded in the channel bed. Assuming a cohesionless substrate, the magnitude of resistance will depend on the depth to which the snag extends into the substrate, the surface area of the embedded portion of the root mat, the submerged weight of the alluvium, the friction angle of the alluvium, and the skin friction between the wood surface and alluvium. The importance of partial burial in the stability of wood is clearly illustrated by timber piles. A properly placed pile remains stable, even at its maximum buoyancy (fully submerged), despite having no ballast or anchoring. The stability of piles is entirely due to skin friction between the pile surface and the substrate. Frictional resistance of timber piles in various types of alluvium range from less than 1,000 N / m^2 to more than 10,000 N / m^2 (Jacoby and Davis 1941). It can take remarkably little burial to provide enough skin friction to compensate for buoyancy; for example, a cylindrical pile 10 m long, 0.6 m in diameter, and a specific gravity of 0.5 would require a burial depth of 2.4 m for a substrate of loose sand (Figure 6). Skin friction tends to increase with increasing grain size and compaction of the substrate. Compact sand provides more than three times the skin friction of loose sand (Jacoby and Davis 1941). Since skin friction increases as a product of $2\pi R$, where R is pile radius and wood volume increases as a function of $\pi^2 R$, the relative importance of skin friction resistance varies inversely with diameter.

Additional resistance to longitudinal forces is provided by the passive earth pressure of sediment downstream of the snag. This is the depth of sediment buttressing the downstream or leeward side of a buried log or root mat. The passive earth pressure per unit width of buried wood, P_P, in N / m, is a function of the depth of burial and physical characteristics of the substrate (Canadian Geotechnical Society 1985):

$$P_P = K_P \frac{\lambda_s z^2}{2} ,$$

where γ_s, = submerged bulk density of substrate in N / m^3, z is the depth of the buried wood segment, K_P = (1 + sinϕ) / (1 – sinϕ) = coefficient of lateral passive earth pressure, and ϕ = internal friction angle of the substrate in degrees. For a bur-

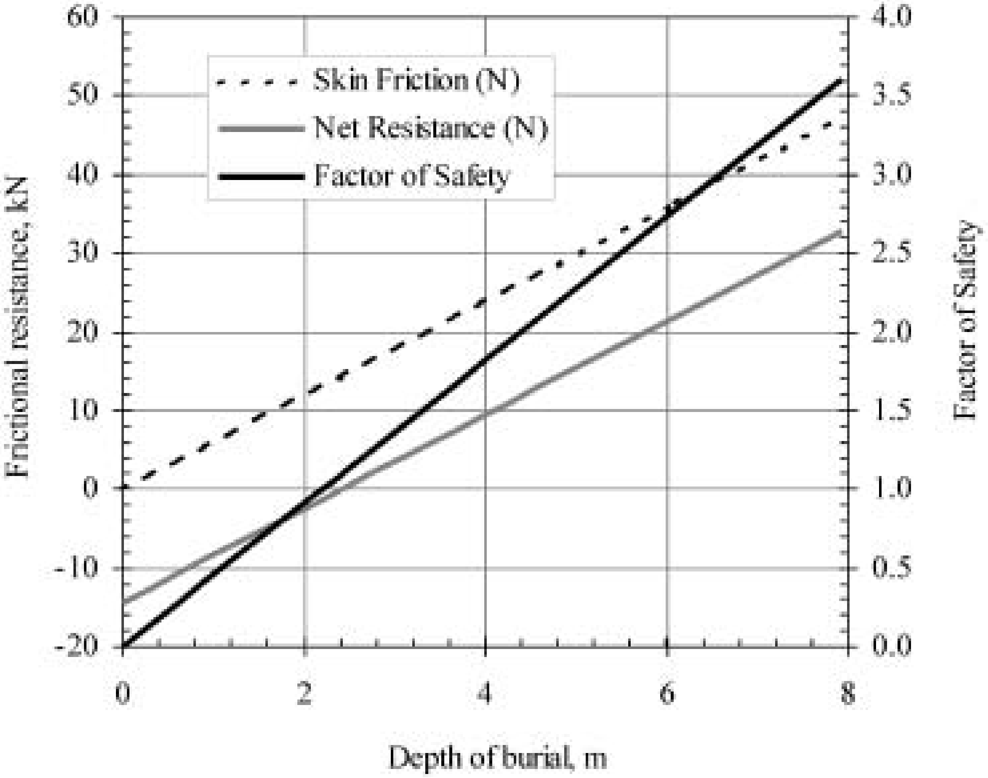

FIGURE 6. Skin friction for a timber pile as a function of burial depth in loose sand with a frictional resistance of 9.8 kN/m^2 (Jacoby and Davis 1941). Pile is 9.1 m (30 ft) in length, 0.6 m (2 ft) in diameter, and has an effective density of 500 kg/m^3. The pile is assumed to be completely submerged and thus have a constant upward buoyant force of 13.0 kN. Net resistance is equal to the skin friction—buoyant force (a negative value equals an upward force or unstable configuration). Factor of safety is net resistance divided by the buoyant force.

ied segment of a circle, such as a partially buried root mat (Figure 7):

$$\mathrm{dP}_P = P_P \mathrm{dx} ,$$

where dP_p, = incremental passive earth pressure of buried segment of width dx = $(x_{i+1} - x_i)$ and the average depth of increment, z, between x_i and x_{i+1}. Summing each increment of the buried segment provides an estimate of the total resisting force imposed by passive earth pressure, F_P:

$$F_P = \Sigma \mathrm{dP}_P \mathrm{dx} .$$

The following example offers an illustration of how bed deformation (scour and lowering of wood into bed and sediment deposition downstream of wood) can contribute sufficient resistance to stabilize a snag. Assuming an alluvial substrate composed of moderately rounded coarse gravel with a median grain size of 36 mm, $\phi = 35^o$, then $K_p = 3.7$. The following assumptions also apply:

- substrate has a submerged bulk density of 1,200 N / m^3,
- snag has a homogeneous specific gravity = 0.5.
- snag is symmetrical about the axis of its bole
- snag bole axis is parallel to bed surface with root mat facing upstream
- snag radius = 2 m
- water depth = 2 m
- incident flow is uniformly distributed with a constant velocity = 3 m / s
- root mat is small relative to channel (no blockage effect on drag)

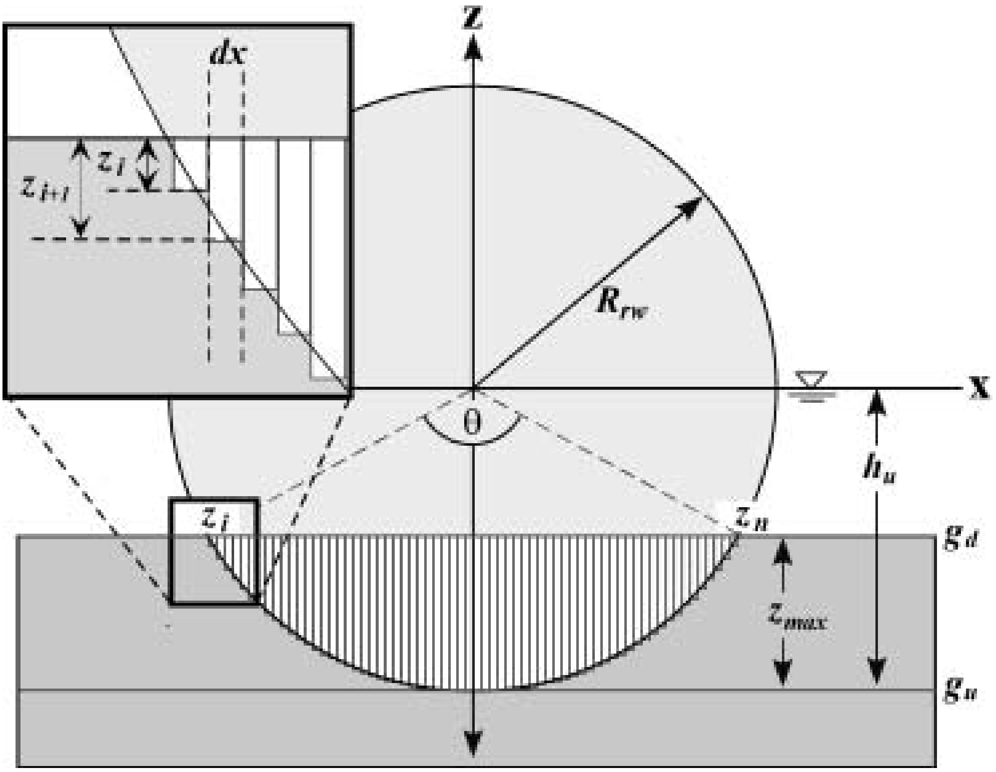

FIGURE 7. Two-dimensional representation of snag root mat with radius R_{rw} oriented normal to flow (in the downstream-facing view shown, the bole extends into the page). Water depth upstream of the root mat h_u is assumed to extend to lowest point of root mat (ground level upstream of root mat g_u), giving a conservative (high) measure of drag. Ground level downstream of root mat g_d represents the depth of sediment to the lee of the root mat for measuring passive earth pressures for each root mat increment of width dx and depth z. Angle Θ defines the arc of the buried segment of the root mat.

- drag coefficient = 1.5 (Gippel et al. 1996b)
- submerged area of root mat subjected to flow remains constant with respect to burial

Based on these assumptions, the snag is buoyant and therefore doesn't exert any normal force on the bed. The driving force exerted on the snag by flow is a function of the snag's submerged area normal to flow, the flow velocity, and the drag coefficient associated with the shape of the snag:

$$F_D = \frac{C_D A_o \rho U^2}{2} ,$$

where F_D is the drag imposed on the snag, C_D is the drag coefficient, U is velocity of flow, A_o is the cross-sectional area of the snag normal to flow, and r is the fluid density. Without any burial of the root mat, the snag has no resisting force and is unstable (Figure 8). Based on the assumptions of a constant uniform flow and that the submerged area, A_o, of the root mat remains constant, the drag force imposed on the snag remains constant (Figure 8). The resisting force rapidly increases with the depth of sediment downstream of the root mat, and a factor of safety of 1 is reached at a depth of about 1.0 m when the resisting and driving forces are equivalent at 42 kN (Figure 8). With an additional burial depth of 0.5 m (total depth of 1.5 m), the factor of safety = 2.8.

Sediment deposition on a tree bole can add substantial surcharge and thus further increase the stability of a snag or logjam. Field observations show that sediment commonly accumulates downstream of the eddy created by the root mat and buries part or all of the tree bole. In some cases, the entire root mat becomes buried deep within the bed. Fluvial sediments composed of coarse sand and gravel have dry bulk densities of 1,400–2,200 kg / m^3, about 3–4 times the densities of most woods, so overburden depths less than the log radius can be sufficient to negate any positive buoyancy of the wood.

If channel bed material is likely to be mobi-

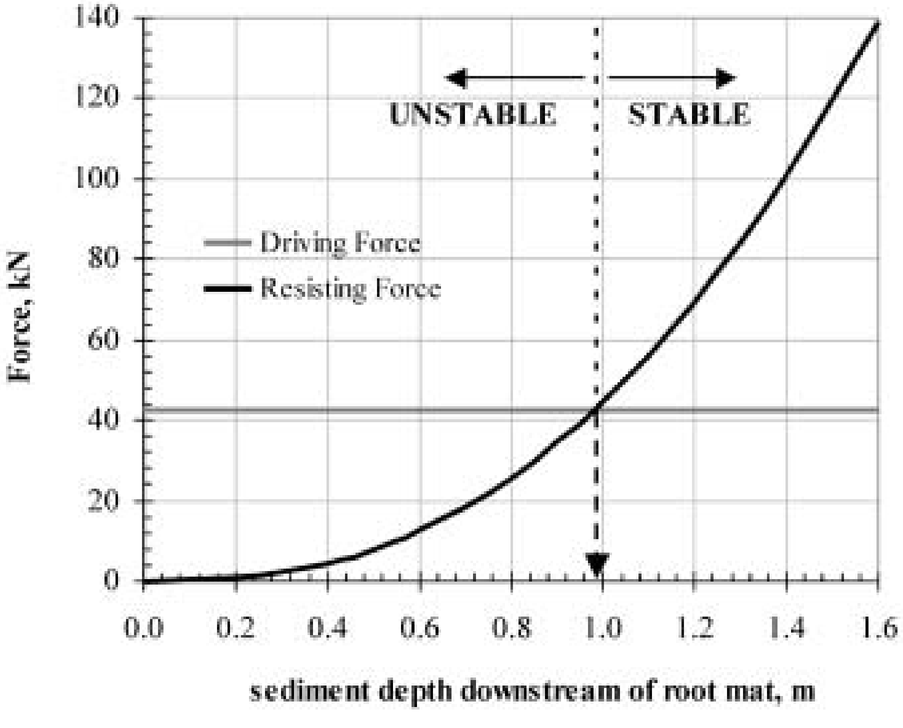

FIGURE 8. Simple example of driving and resisting forces on a snag with its root mat facing upstream and bole parallel to flow. Rootwad radius and flow depth are assumed to be 2 m, and therefore, snag is buoyant (no resisting force with no sediment leeward of root mat). Bed substrate is gravel and root mat subjected to a uniform constant flow velocity of 3 m/s.

lized under flow conditions in which a tree bole remains stable, then the stability of the bole should increase due to accumulation of sediment immediately downstream. As flow moves past an obstruction (such as stable wood debris), a separation envelope in which flow moves upstream will form directly behind the obstruction, separated from the downstream flow of water by a shear zone. Sediment moving in the main flow is aggressively entrained by vortices in the shear zone and transferred into the recirculation zone where rapid deceleration leads to deposition. Such sedimentation influences debris stability in several ways: forming a buttress, which the rootwad must move up and over or plow through; adding surcharge or weight to buried portions of the tree bole; and increasing frictional resistance with burial, similar to the "embeddedness" concept by which most ship anchors work. Partial burial of a tree can increase the tree's resistance several fold and can help to explain why many snags and logjams remain stable even when completely submerged and subjected to extreme flows.

If an ELJ remains stable after bedload transport has been initiated, then accumulation of sediment in the downstream separation envelope should further stabilize the structure. In most gravel-bed channels, bedload transport begins at flows near or below bank-full stage. Hence, key members designed to be stable in flows exceeding bank-full conditions should become more stable after experiencing several bed-mobilizing events.

Another factor that can influence a force balance analysis of wood stability is the effective density of wood based on its moisture content. Most dry woods have densities less than water (1.0 kg / m^3) and cannot exceed a density of 1.5 kg / m^3, the density of the cellulose and ligin within wood (Harmon et al. 1986). As wood gets wet, its effective density can increase substantially, sometimes to values sufficient to cause it to sink, as illustrated in samples taken from wood placed in the North Fork Stillaguamish River, Washington, USA (Figure 9). Stability of wood through time can also be influenced by root cohesion and surcharge provided by vegetation growing above a snag or logjam.

Log and channel dimensions in rivers throughout western Washington provide an empirical model of wood stability using dimensionless variables of log size: the ratio of log diameter to bank-full depth, D/h_{bf}, and the ratio of log length to channel width, L/w_{bf} (Abbe and Montgomery 2003). Stable logs, or key members, form the critical components holding wood accumulations in jams. In surveys of large alluvial channels, stable logs had minimum values of L/w_{bf} equal to 0.1 and values of D/h_{bf} rarely below 0.8. In channels exceeding 40 m in bank-full width, all key members consisted of a bole and a root mat with a diameter greater than the bank-full depth.

The buttressing or taper of a tree's bole concentrates a substantial portion of a tree's mass near its base, which significantly affects the log's mass and buoyant depth. A root mat both raises the center of mass or centroid, up to more than five times the tree's diameter breast height, and the root mat itself acts like a plow, further increasing resistance. The presence of an attached root mat substantially increases the stability of a snag by elevating the centroid and increasing the frictional resistance (Abbe and Montgomery 1996; Abbe 2000; Braudrick and Grant 2000; Castro and Sampson 2001).

The availability of material to form key, stacked, and racked members is important when considering the use of ELJs. In some areas, the availability of large trees for use as key members may be a critical obstacle to the use of ELJ technology. The size of key members increases with both expected discharge and flow depth and can be related to the size of the channel, as discussed in the design section of this document. Costs for installation can vary greatly depending on the proximity of key members to the site location. As the size requirements for key members increase, transporting them becomes increasingly more difficult and expensive. Smaller racked members can account for 70–90% of the logs used in some types of ELJs that project into the flow, whereas some types of ELJ structures used for grade control or to harden a bank may have no racked members at all (Abbe et al. 2003).

Appropriate sizes, locations, and spacing for wood structures depends upon the project goals, the channel and its migration zone, human constraints, and acceptable risk. Bank protection projects, for example, could consist of continuous natural log revetments (e.g., bank-full bench jams, flow deflection jams, chatoic cribs) and interspersed structures (e.g., meander jams, flow deflection jams, crib groynes). The specific spacing of ELJ structures can be based on experimental studies of flow deflection by rock groynes and pile dikes (Klingeman et al. 1984). Our experience to date suggests that a spacing of about four times the protrusion into the main flow provides a conservative value for ELJ spacing; however, a spac-

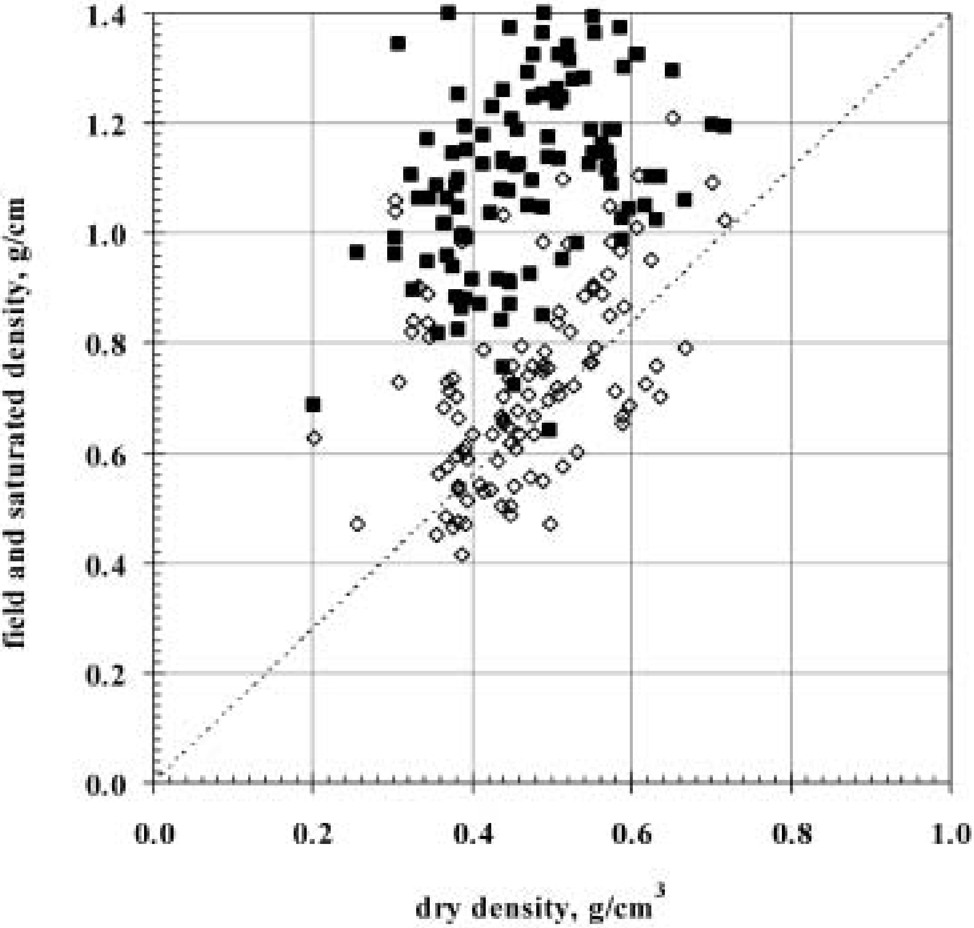

FIGURE 9. Densities of 109 core samples from trees used in engineered logjams constructed in North Fork Stillaguamish River, Snohomish County, Washington, 1998. Green (open circles) and saturated (solid squares) of same data set are plotted as a function of their oven dry densities. Tree species in data set include *Tsuga heterophylla, Thuja plicata, Picea sitchensis, Pseudotsuga menziesii*, and *Populus trichocarpa*.

ing of up to seven times may prove acceptable in many situations, depending on the bend radius of curvature. A tighter bend will require closer spacing of the structures than a straight reach. Long-term project success will be better ensured by evaluating project designs under different scenarios representing the range of channel conditions, such as changes in the direction of incident flow on a structure (or set of structures), channel location, radius of curvature, bed elevations, or water surface profiles.

Wood Structure Dynamics Over Time

A key concern among many designers in regard to using wood structures is the longevity of wood as a material. How long wood lasts depends on factors such as the type of wood, the environment in which it is located, its size, and the age of tree at death. If wood remains saturated in freshwater, it can last almost indefinitely; it is not uncommon to recover premium grade timber that has been submerged in lakes for over a century. Boles of large deciduous trees found in river gravels of the ancient Rhine River in Germany have been dated at more than 18,000 years old and yet were still in excellent condition (Becker and Schirmer 1977; Becker 1980). Eucalyptus and pine logs found in floodplain sediments and across streams in southeast Australia and northwest Tasmania have yielded ^{14}C ages as old as 13,000–17,000 years b.p. (Gippel et al. 1996a; Nanson et al. 1995; Brooks and Brierley 2002). Several studies have shown that large boles comprising wood jams in relatively small streams found in coniferous forests can last for hundreds of years based on the age of trees growing on top (Keller and Tally 1979; Tally 1980; Hogan 1987; Murphy and Koski 1989). Wood from 30 buried logjams exposed in alluvial banks of the Queets River, Washington dated from modern to 1,324 ± 20 years b.p., averaging about 400 years b.p. (Abbe 2000). In contrast, log jams composed of relatively small pieces debris, such as slash commonly left behind after timber harvest, last only several years (Lisle 1986b).

Few data exist for absolute decay rates of different types of wood in fluvial environments, but there is an extensive literature on decay rates of wood on forest floors (see Mackensen and Bauhus 1999 for a recent review). Such studies of the decay rates of timber under moist aerobic conditions on a forest floor can provide a conservative estimate for timber decay used in the construction of wood structures in rivers. Accelerated laboratory tests to determine decay rates of some typical Australian eucalyptus species came up with turnover times (i.e., the time taken for a block of wood 5 cm × 1.25 cm × 1.25 cm to decay to 95% of its initial mass) ranging from around 30–375 years. The authors of these experiments acknowledge that these rates are conservative for the species being tested, given that the experimental blocks have much higher ratios of surface area to volume than large logs. Species that might typically be used in river rehabilitation projects in Australia, such as river red gum *Eucalyptus camaldulensis*, forest red gum *E. tereticornis*, or iron bark *E. paniculata*, have values at the upper end of this range.

Models for wood longevity can be applied to estimate the design life of individual logs based on tree species, log diameter, and environmental setting (Abbe 2000). Decay rates can vary substantially for the same species and settings, but, in general, the longer and more continuously the wood remains submerged, the longer it will last. Assuming a constant decay rate, k, and knowing the initial mass of a log, M(o), the log's mass at some time, $M(t)$, can be predicted using the simple decay model:

$$M(t) = M(o)e^{k(\Delta t)} ,$$

where Dt is the number of years from when first placed in the stream, assuming its mass was M(o) when first placed. The effective diameter of a log after some time can also be predicted using the same model and assuming that decay proceeds uniformly into a cylindrical log from its perimeter (Figure 10). This type of procedure can be used to specify the size of logs that will most likely meet minimum specifications over the design life of a structure. Wood decay is a complex and highly variable process dependent on the species and physical condition of the wood, microclimate and organisms breaking down the wood, so information regarding local decay processes and rates will improve design predictions.

A substantial increase in ELJ size can occur over time if it collects debris moving through the channel. Changes in the ELJ size can subsequently obstruct a larger portion of the channel cross-sectional area and result in significantly higher water surface elevations than anticipated in the original project design. The risk will depend on changes in channel position relative to the ELJs and the flux of wood moving through the system at particular flow levels. An examination of the watershed and stream system above the site is important to get some understanding of the flux of drifting wood through the project reach and whether its accumulation at the ELJs is likely to create management problems.

Wood reintroduction projects will benefit from adaptative management plans that provide protocols for determining when additional wood accumulation may become a problem and providing guidelines for what, where, and when to remove selected pieces. These plans can also include inspection criteria for assessing the structural integrity of ELJs and what to do if maintenance becomes necessary. Failure to establish a reasonable inspection and maintenance program is likely to elevate risk of project failure or development of adverse effects due to evolution of an ELJ to conditions outside the scope of project design.

Examples of Engineered Logjam Projects

Although ELJs remain a relatively new technology, they have been successfully used in a growing number of contexts. Demonstration projects include three ELJs constructed in the upper Cowlitz River in 1995 (Abbe et al. 1997), five ELJs in the North Fork Stillaguamish River in 1998, and seven ELJs in the Cispus River in 1999 (Abbe et al. 2003). Each of these projects have experienced multiple overtopping flows, and all remain intact in 2003.

Nineteen ELJ structures built on the Williams River, New South Wales, Australia in September–

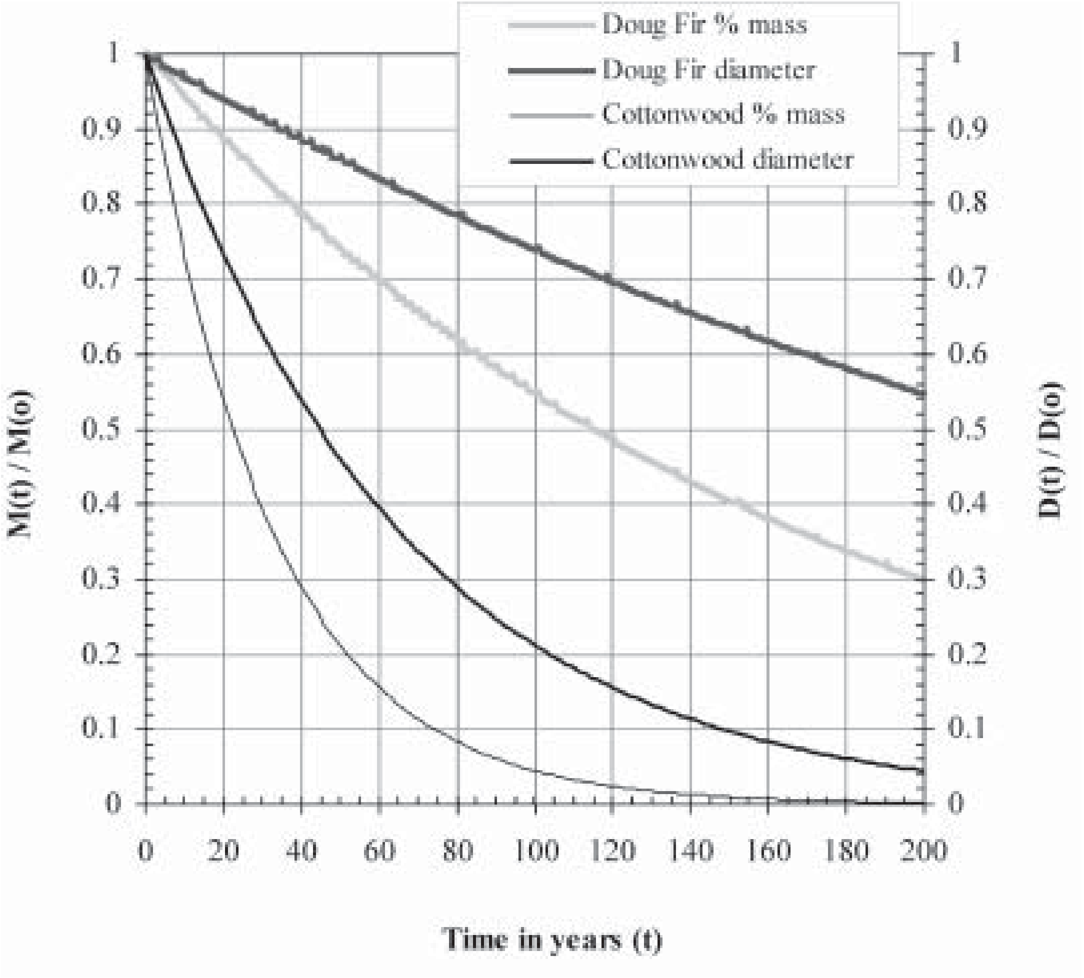

FIGURE 10. Simple decay model to estimate mass and effective diameter of a log after some time. Dimensionless mass and diameter are plotted as a function of time. $M(t)$ is its mass after time t, and $M(o)$ is the log's initial mass when placed. Diameter is derived assuming uniform decay from the perimeter of a cylindrical log to its central axis. Two different species, *Pseudotsuga menziesii* (Douglas fir) and *Populus trichocarpa* (cottonwood), are presented using decay rates for logs lying on the ground in areas west of the Cascade Range of Oregon and Washington (Harmon et al. 1986).

October 2000 (Brooks et al. 2001) show that ELJs may be applied beyond the Pacific Northwest. In September 2000, 19 ELJs incorporating 430 logs were constructed in a 1.1-km-long reach of the Williams River as part of an experimental reintroduction of wood into Australian Rivers. The ELJ structures included both flow deflection structures along the river's banks and channel-spanning grade control structures intended to prevent channel incision and trap additional sediment within the project reach. All of the structures were built without any artificial anchoring (i.e., no cabling or imported ballast). The study site experienced six flows that overtopped most of the structures in the first 6 months after construction (Figure 11). Three of these peak flows exceeded the mean annual flood, inundating 18 of the ELJs by 2–3 m and 1 by 0.5 m. All the structures remain intact and, thus far, they are performing as intended, with a net increase of 40–60 m^3 of sediment storage per 1,000 m^2 of bed surface within the test reach and a substantial increase in channel complexity. A control reach 5 km upstream experienced a net export of 15 $m^3/1{,}000$ m over the same period.

As of 20 March 2002, the five ELJs in the North Fork Stillaguamish have been completely inun-

FIGURE 11. View from upstream of 2 of 15 engineered logjams constructed in the Williams River, northwest New South Wales, Australia. (a) As-built structures in September 2000, (b) March 2001 flood during which peak flow overtopped structures by approximately 2 m with velocities exceeding 3 m/s, and (c) same structures in 2002 after six overtopping flows.

dated by at least 30 flows and have successfully met objectives for increasing pool frequency and cover, bifurcating the river into two perennial channels, protecting 200 m of eroding bank, and improving a chronic problem of drift accumulation on a bridge directly downstream of the project (Abbe et al. 2003). The ELJs were designed to collect mobile wood (i.e., drift or flotsam) upstream of the bridge while increasing the conveyance capacity of water and flotsam beneath the bridge by improving channel alignment. Flotsam has yet to rack up on the bridge's center piling, even though hundreds of logs have been deposited on four of five ELJs. Of the logs that moved and were subsequently found in 1999, those that were initially located upstream of at least one ELJ traveled from 200 to 600 m. Logs that moved downstream of the bridge, where there are significant flow obstructions in the river, traveled much further, from 2 to 11 km. This data suggests that the position and frequency of logjams reduces the travel distance of wood and increases wood residence time within the fluvial system.

The successful performance of ELJ projects to date is largely attributed to the comprehensive geomorphic, engineering, and ecological analysis leading to design and implementation. Many questions remain regarding the science, engineering, risk assessment, and long-term performance of ELJs. For this reason, implementation of additional projects still should be viewed as applied research that contributes to advancing the existing body of knowledge. In situations where natural recovery of river corridors is unlikely or unduly constrained by human development, however, ELJs offer exciting possibilities for reintroducing wood to rehabilitate fluvial environments.

Conclusions

The use of wood in river restoration should be founded on emulating natural processes through a comprehensive approach to understanding current and historical conditions within a river reach and its watershed, identification of opportunities and constraints within the project reach, and application of sound engineering practice. Projects constructed to date in the United States and Australia offer examples of engineered logjams that have experienced overtopping flows and have successfully met objectives to rehabilitate habitat, protect banks, reverse channel incision, and reduce risks to bridges. Specifically, several projects have demonstrated that ELJs (1) can remain stable in 20+ year recurrence interval floods; (2) can be effective at redirecting even large channels to control local bank erosion; (3) can dramatically enhance physical habitat, such as pool frequency and depth, and cover; and (4) need not exacerbate local flooding or erosion. The application of ELJ technology in these projects demonstrates the potential to address both river engineering and habitat concerns. As with any relatively new technology, further experimental applications are warranted before formalization of design standards. However, site-specific geomorphic and stability analyses based on general principles of ELJ design appear to provide a reasonable framework for the assessment, design, and implementation of successful projects.

The last several decades have seen an unprecedented growth of grassroots community efforts to rehabilitate urban and rural streams in both the United States and Australia. Widespread recognition by the scientific community and the public regarding the environmental and economic costs associated with human alteration of fluvial systems has probably never been greater. In many regions, dramatic changes are occurring in government policies regarding fluvial systems through increased regulation of land use within floodplains and channel migration zones. But the long-term success of efforts to rehabilitate or restore the physical and biological attributes of fluvial systems will depend on development of management and engineering strategies that better emulate natural processes. Experience to date demonstrates that, in the overall context of these changing approaches to river management, wood can be an integral part of strategies aimed at rehabilitating and maintaining natural conditions while still attaining reliable engineered solutions to local problems.

Acknowledgments

Initial development of engineered logjam technology was made possible through a grant from the Watershed Science Institute of the Natural Resources Conservation Service, U.S. Department of Agriculture, with special thanks to Carolyn Adams. Australian research is funded by Land and Water Australia grants MQU9 and GRU29, in collaboration with the Department of Land and Water Conservation, Hunter Region, and the Hunter Catchment Management Trust. Selene Fisher was a tremendous help in editing our initial draft, and three anonymous reviewers helped to significantly improve the final manuscript. Mary Lou White and Washington Trout coordinated monitoring efforts in the North Fork Stillaguamish River. The Cispus project was made possible by Donna Ortiz de Anaya and Brenda White. And thanks to Jill Silver and Jim Turner for their steadfast commitment to protecting rivers.

References

Abbe, T. B. 2000. Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system. Doctoral dissertation. University of Washington, Seattle.

Abbe, T. B., and D. R. Montgomery. 1996. Interaction of large woody debris, channel hydraulics and habitat formation in large rivers. Regulated Rivers Research & Management 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, and C. Petroff. 1997. Design of stable in-stream wood debris structures for bank protection and habitat restoration: an example from the Cowlitz River, WA. Pages 809–816 *in* S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, Jr., editors. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. University of Mississippi, University.

Abbe, T. B., G. Pess, D. R. Montgomery, and K. L. Fetherston. 2003. Integrating engineered logjam technology in river rehabilitation. Pages 443–490 *in* D. R. Mongtomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

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

Becker, B. 1980. Progress in dating the Holocene valley development by subfossil trees. Bulletin de l'Association Francaise pour l'Etude du Quaternaire 1–2:85–86.

Becker, B., and W. Schirmer. 1977. Palaeoecological study on the Holocene valley development of the River Main, southern Germany. Boreas 4:303–321.

Beebe, J. T. 1997. Fluid patterns, sediment pathways and woody obstructions in the Pine River, Angus, Ontario. Doctoral dissertation. Wilfrid Laurier University, Waterloo, Ontario.

Beechie, T. J., and T. H. Sibley. 1997. Relationship between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126:217–229.

Beechie, T. J., B. D. Collins, and G. R. Pess. 2001. Holocene and recent geomorphic processes, land use, and salmonid habitat in two north Puget Sound river basins. Pages 37–54 *in* J. B. Dorava, D. R. Montgomery, B. Palcsak, and F. Fitzpatrick, editors. Geomorphic processes and riverine habitat. American Geophysical Union, Water Science and Application 4, Washington, D.C.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143 to 190 *in* E. O. Salo and T. W. Cundy, editors. Streamside management: forestry and fishery interactions. University of Washington, Institute of Forest Resources Contribution No. 57, Seattle.

Braudrick, C. A., and G. E. Grant. 2000. When do logs move in rivers? Water Resources Research 36:571–583.

Brooks, A. P. 1999. Pre- and post-European disturbance river morphodynamics in East Gippsland, Australia. Doctoral dissertation. Macquarie University, Sydney, Australia.

Brooks, A. P., T. B. Abbe, J. D. Jansen, M. Taylor, C. J. Gippel. 2001. Putting the wood back into our rivers: an experiment in river rehabilitation. Pages 73–80 *in* I. Rutherfurd, F. Sheldon, G. Brierley, and C. Kenyon, editors. Proceedings of the 3rd Australian Stream Management Conference. Brisbane, Australia.

Brooks, A. P., and G. J. Brierley. 2002. Mediated equilibrium: the influence of riparian vegetation and wood on the long term character and behaviour of a near pristine river. Earth Surface Processes and Landforms 27:343–367.

Brooks, A. P., G. J. Brierley, 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 southeastern Australia. Geomorphology 51:7–29.

Buffington, J. M., and D. R. Montgomery. 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35:3507–3522.

Canadian Geotechnical Society. 1985. Canadian Foundation Engineering Manual, 2nd Edition. Bitech Publishers, Vancouver.

Castro, J., and R. Sampson. 2001. Incorporation of large wood into engineering structures. U.S. Department of Agriculture, Natural Resource Conservation Service Engineering Technical Note No. 15, Boise, Idaho.

Chow, V. T. 1959. Open-channel hydraulics. McGraw-Hill Book Company, Inc., New York.

Collins, B. D., and D. R. Montgomery. 2001. Importance of archival and process studies to characterizing pre-settlement riverine geomorphic processes and habitat in the Puget Lowland. Pages 227–243 *in* J. B. Dorava, D. R. Montgomery, B. Palcsak, and F. Fitzpatrick, editors. Geomorphic processes and riverine habitat. American Geophysical Union, Water Science and Application 4, Washington, D.C.

Collins, B. D., and D. R. Montgomery. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland. Restoration Ecology 10:237–247.

Collins, B. D., D. R. Montgomery, D. R., and A. Haas. 2002. Historic changes in the Distribution and functions of large woody debris in Puget Lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences 59:66–76.

Collins, B. D., D. R. Montgomery, and A. J. Sheikh. 2003. Reconstructing the historical riverine landscape of the Puget lowland. Pages 79–128 *in* D. R. Mongtomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

D'Aoust, S. G., and R. G. Millar. 2000. Stability of ballasted woody debris habitat structures. Journal of Hydraulic Engineering 126:810–817.

D'Aoust, S. G. D. and R. G. Millar. 1999. Large woody debris fish habitat structure performance and ballasting requirements. BC Ministry of Environment, Lands and Parks and BC Ministry of Forests, British Columbia Watershed Restoration Program, British Columbia.

Davies, R. J. 1997. Stream channels are narrower in pasture than in forest. New Zealand Journal of Marine and Freshwater Research 31:599–608.

Davis, W. M. 1901. Physical geography. Ginn & Company, Boston.

Diehl, T. 1997. Drift in channelized streams. Pages 139–143 *in* S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, Jr., editors. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. University of Mississippi, University.

Diez, J. R., A. Elosegi, and J. Pozo. 2001. Woody debris in North Iberian streams: influence of geomorphology, vegetation, and management. Environmental Management 28(5):687–698.

Fischenich, C., and J. Morrow, Jr. 1999. Streambank habitat enhancement with large woody debris. U.S. Army Engineer Research and Development Center, EMRRP Technical Notes Collection, ERDC TN-EMRRP-SR-13, Vicksburg, Mississippi.

Fox, M., S. Bolton, and L. Conquest. 2003. Reference conditions for instream wood in western Washington. Pages 361–393 *in* D. R. Mongtomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12:182–197.

Gippel, C. J., B. L. Finlayson, and I. C. O'Neill. 1996a. Distribution and hydraulic significance of large woody debris in a lowland Australian river. Hydrobiologia 318:179–194.

Gippel, C. J., I. C. O'Neill, B. L. Finlayson, and I. Schnatz. 1996b. Hydraulic guidelines for the reintroduction and management of large woody debris in lowland rivers. Regulated Rivers Research & Management 12:223–236.

Gregory, K. J., Davis, R. J., and S. Tooth. 1993. Spatial distribution of coarse woody debris dams in the Lymington Basin, Hampshire, UK. Geomorphology 6:207–224.

Guardia, J. E. 1933. Some results of log jams in the Red River. The Bulletin of the Geographical Society of Philadelphia 31(3):103–114.

Gurnell, A. M., and Sweet, R. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms 23:1101–1121.

Haden, G. A., D. W. Blinn, J. P. Shannon, and K. P. Wilson. 1999. Driftwood: an alternative habitat for macroinvertebrates in a large desert river. Hydrobiologia 397:179–186.

Harmon, M. F., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cine, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302.

Harvey, M. D., D. S. Biedenharn, and P. Combs. 1988a. Adjustments of Red River following removal of the Great Raft in 1873. EOS, Transactions of the American Geophysical Union 69(18):567.

Harvey, M. D., H. S. Pranger, II, D. S. Biedenharn, and P. Combs. 1988b. Morphologic and hydraulic adjustments of Red River from Shreveport, LA to Fulton, AK, between 1886 and 1980. Pages 764–769 in S. R. Abt and J. Gessler, editors. ASCE National Conference on Hydraulic Engineering. Colorado Springs, Colorado.

Harwood, K., and A. G. Brown. 1993. Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. Earth Surface Processes and Landforms 18:741–748.

Hering, D., M. Mutz, and M. Reich. 2000a. Woody debris research in Germany – an introduction. International Review of Hydrobiology 85:1–3.

Hering, D., J. Kail, S. Eckert, M. Gerhard, E. I. Meyer, M. Mutz, M. Reich, and I. Weiss. 2000b. Coarse woody debris quantity and distribution in central European streams. International Review of Hydrobiology 85:5–23.

Hogan, D. L. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. Pages 343–353 *in* R. L. Beschta, T. Blinn, G. E. Grant, F. J. Swanson, and G. G. Ice, editors. Erosion and sedimentation in the Pacific Rim. International association of Hydrological Sciences, Publication No. 165, Wallingford, UK.

House, R. A., and P. L. Boehne. 1985. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. North American Journal of Fisheries Management 5:283–295.

House, R. A., and P. L. Boehne. 1986. Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon. North American Journal of Fisheries Management 6:38–46.

Hyatt, T. L., and R. J. Naiman. 2001. The residence time of large woody debris in the Queets River, Washington. Ecological Applications 11:191–202.

Inoue, M., and S. Nakano. 1998. Effects of woody debris on the habitat of juvenile masu salmon (*Oncorhynchus masou*) in northern Japanese streams. Freshwater Biology 40:1–16.

Jacoby, H. S. and R. P. Davis. 1941. Foundations of bridges and buildings. McGraw-Hill Book Co., New York.

Kail, J. 2003. Influence of large woody debris on morphology of six central European streams. Geomorphology 51:207–223.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361–380.

Keller, E. A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. Pages 169–197 *in* D. D. Rhodes and G. P. Williams, editors. Adjustments of the fluvial system. Kendal-Hunt, Dubuque, Iowa.

Klingeman, P. C., S. M. Kehe, and Y. A. Owusu. 1984. Streambank erosion protection and channel scour manipulation using rockfill dikes and gabions. Oregon State University, Water Resources Research Institute Technical Report WRRI-98, Corvallis.

Lehtinen, R. M., N. D. Mundahl, and J. C. Madejczyk. 1997. Autumn use of woody snags by fishes in backwater and channel border habitats of a large river. Environmental Biology of Fishes 49:7–19.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas fir forests. Canadian Journal of Forest Research 17:150–156.

Lisle, T. E. and M. B. Napolitano. 1998. Effects of recent logging on the main channel of North Fork Caspar Creek. USDA Forest Service General Technical Report PSW-GTR-168, pp.81–85, Berkeley, California.

Lisle, T. E. 1986b. Stabilization of a gravel channel by large streamside obstructions and bedrock bend, Jacoby Creek, northwestern California. Geological Society of America Bulletin 97:999–1011.

Lisle, T. E. 1995. Effects of woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helen’s, Washington. Water Resources Research 31:1797–1808.

Mackensen, J. and J. Bauhus. 1999. The decay of coarse woody debris. National Carbon Accounting System, Technical Report No. 6. Australian Greenhouse Office, Canberra.

Maridet, L., H. Piegay, O. Gilard, and A. Thevenet. 1996. River wood jams: an ecological benefit? A factor of natural risks? La Houille Blanche 51:32–38.

Marston, R. A. 1982. The geomorphic significance of log steps in forested streams. Annals of the Association of American Geographers 72:99–108.

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, Florida.

McCall, E. 1984. Conquering the rivers: Henry Mill Shreve and the navigation of America’s inland waterways. Louisiana State University Press, Baton Rouge.

Melillo, J. M., R. J. Naiman, J. D. Aber, and K. N. Eshleman. 1983. The influence of substrate quality and stream size on wood decomposition dynamics. Oecologia (Berlin) 58:281–285.

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

Montgomery, D. R., and J. M. Buffington. 1997. Channel reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596–611.

Montgomery, D. R., J. M. Buffington, R. Smith, K. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research 31:1097–1105.

Montgomery, D. R., T. M. Massong, and S. C. S. Hawley. 2003. Debris flows, log jams and the formation of pools and alluvial channel reaches in the Oregon coast range. Geological Society of America Bulletin 115:78–88.

Mosley, M. P. 1981. The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream. Earth Surface Processes and Landforms 6:571–579.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427–436.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surface Processes and Landforms 18:43–61.

Nanson, G. C., Barbetti, M., and G. Taylor. 1995. River stabilization due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. Geomorphology 13:145–158.

Nichols, R. A. and S. G. Sprague. 2003. Use of long-line cabled logs for stream bank rehabilitation. Pages 422 to 442 *in* D. R. Mongtomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

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.

Pearsons, T. N., H. W. Li, and G. A. Lamberti. 1992. Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. Transactions of the American Fisheries Society 121:427–436.

Pess, G., D. R. Montgomery, T. J. Beechie, and L. Holsinger. 2003. Anthropogenic alternations to the biogeography of Puget Sound salmon. Pages 129–154 *in* D. R. Mongtomery, S. Bolton, D. B. Booth, and L. Wall, editors. Restoration of Puget Sound rivers. University of Washington Press, Seattle.

Piegay, H. 1993. Nature, mass and preferential sites of coarse woody debris deposits in the lower Ain Valley (Mollon reach), France. Regulated Rivers: Research and Management 8:359–372.

Piegay, H., and A. M. Gurnell. 1997. Large woody debris and river geomorphological pattern: examples from southeast France and southern England. Geomorphology 19:99–116.

Quinn, T. P., and N. P. Peterson. 1996. The influence of habitat complexity and fish size on over-winter survival and growth of individually marked juvenile coho salmon (*Oncorhynchus kisutch*) in Big Beef Creek, Washington. Canadian Journal of Fisheries and Aquatic Sciences 53:1555–1564.

Rikhari, H. C., and S. P. Singh. 1998. Coarse woody debris in oak forested stream channels in the central Himalaya. Ecoscience 5(1):128–131.

Robison, E. G., and R. L. Beschta. 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA. Earth Surface Processes and Landforms 15:149–156.

Rosgen, D. L. 1996. Applied river morphology. Wildland Hydrology Books, Pagosa Springs, Colorado.

Rosgen, D. L. and B. L. Fittante. 1986. Fish habitat structures - a selection guide using stream classification. Pages 163–179 *in* J. G. Miller, J. A. Arway, and R. F. Carline, editors. 5th Trout Stream Habitat Improvement Workshop. Lock Haven, Pennsylvania. Pennsylvania Fisheries Commission, Hamsburg, Pennsylvania.

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. Wiley, New York.

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

Sedell, J. R., and J. L. Froggatt. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verhandlungen-Internationale Vereinigung für Theoretifche und Angewandte Limnologie 22:1828–1834.

Shields, F. D., and C. J. Gippel. 1995. Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering 121(4):341–354.

Shields, F. D., and R. H. Smith. 1992. Effects of large woody debris removal on physical characteristics of a sand-bed river. Aquatic Conservation: Marine and Freshwater Ecosystems 2:145–163.

Shields, F. D., S. S. Knight, Jr., C. M. Cooper, and S. Testa, III. 2000. Large woody debris structures for incised channel rehabilitation. In R. H. Hotchkiss and M. Glade, editors. Building partnerships: proceedings of the Joint Conference on Water Resources Engineering and Water Resources Planning and Management. Environmental and Water Resources Institute of the American Society of Civil Engineers, Reston, Virginia.

Syndi, J. D., J. C. Fischenich, and S. R. Abt. 1998. Effect of woody debris entrapment on flow resistance. Journal of the American Water Resources Association 34(5):1189–1197.

Tally, T. 1980. The effects of geology and large organic debris on stream channel morphology and process for streams flowing through old-growth Redwood forests in Northwestern California. Doctoral dissertation. University of California, Santa Barbara.

Thompson, D. 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. Geomorphology 11:235–244.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25:467–469.

Triska, F. J. 1984. Role of wood debris in modifying channel morphology and riparian areas of a large lowland river under pristine conditions: a historical case study. Verhandlungen-Internationale Vereinigung für Theorelifche und Angewandte Limnologie 22:1876–1892.

Van Der Kamp, B. J., and A. A. Gokhale. 1979. Decay resistance owing to near-anaerobic conditions in black cottonwood wetwood. Canadian Journal of Forest Research 9:39–44.

Veatch, A. C. 1906. Geology and underground water resources of northern Louisiana and southern Arkansas. U.S. Geological Survey, Professional Paper 46, Washington D.C.

Wallerstein, N., C. R. Thorne, and M. W. Doyle. 1997. Spatial distribution and impact of large woody debris in northern Mississippi. Pages 145–150 *in* S. S. Y. Wang, E. J. Langendoen, and F. D. Shields, Jr., editors. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. University of Mississippi, University.

Wallerstein, N. P., C. V. Alonso, S. J. Bennett, and C. R. Thorne. 2001. Distorted froude-scaled flume analysis of large woody debris. Earth Surface Processes and Landforms 26:1265–1283.

Wallerstein, N. P., C. V. Alonso, S. J. Bennett, and C. R. Thorne. 2002. Surface wave forces acting on submerged logs. Journal of Hydraulic Engineering 128:349–353.

Webb, A. A., and W. D. Erskine. 2003. Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. Geomorphology 51:109–126.

Weigelhofer, G., and J. A. Waringer. 1999. Woody debris accumulations – important ecological components in a low-order forest stream (Weidlingbach, Lower Australia). International Review of Hydrobiology 84(5):427–437.

Wolff, H. H. 1916. The design of a drift barrier across the White River, near Auburn, Washington. Transactions of the American Society of Civil Engineers 16:2061–2085.

Zimmerman, R. C., J. C. Goodlett, and G. H. Comer. 1967. The influence of vegetation on channel form of small streams. Pages 225–275 *in* Symposium on River Morphology. International Association of Science, Hydrological Publication 75, Gentbrugge, Belgium.