JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 52, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2016

MANAGEMENT OF LARGE WOOD IN STREAMS: AN OVERVIEW AND PROPOSED FRAMEWORK FOR HAZARD EVALUATION[1]

Ellen Wohl, Brian P. Bledsoe, Kurt D. Fausch, Natalie Kramer, Kevin R. Bestgen, and Michael N. Gooseff[2]

ABSTRACT: Instream and floodplain wood can provide many benefits to river ecosystems, but can also create hazards for inhabitants, infrastructure, property, and recreational users in the river corridor. We propose a decision process for managing large wood, and particularly for assessing the relative benefits and hazards associated with individual wood pieces and with accumulations of wood. This process can be applied at varying levels of effort, from a relatively cursory visual assessment to more detailed numerical modeling. Decisions to retain, remove, or modify wood in a channel or on a floodplain are highly dependent on the specific context: the same piece of wood that might require removal in a highly urbanized setting may provide sufficient benefits to justify retention in a natural area or lower-risk urban setting. The proposed decision process outlined here can be used by individuals with diverse technical backgrounds and in a range of urban to natural river reaches so that opportunities for wood retention or enhancement are increased.

(KEY TERMS: instream wood; large woody debris; hazard; river restoration; recreation; floodplain management; habitat.)

Wohl, Ellen, Brian P. Bledsoe, Kurt D. Fausch, Natalie Kramer, Kevin R. Bestgen, and Michael N. Gooseff, 2016. Management of Large Wood in Streams: An Overview and Proposed Framework for Hazard Evaluation. *Journal of the American Water Resources Association* (JAWRA) 52(2): 315-335. DOI: 10.1111/1752-1688.12388

INTRODUCTION

Large wood has been systematically studied and described in the scientific literature since the 1970s (e.g., Swanson *et al.*, 1976; Harmon *et al.*, 1986; Montgomery *et al.*, 2003). The phrase “large woody debris” (LWD) has been in widespread use for decades, but this phrase is a legacy from timber harvest, when the unused slash was typically left on the ground and in streams as debris. Because debris has negative connotations, we instead refer to downed wood greater than 10 cm in diameter and 1 m in length simply as large wood.

Rivers in forested regions of the temperate zone currently have minimal large wood compared to their condition prior to industrial-scale timber harvest in Europe (Schama, 1995; Francis *et al.*, 2008; Comiti, 2012) or European settlement of North America, Australia, and New Zealand (Erskine and Webb, 2003; Brooks *et al.*, 2004; Wohl, 2014). Historical descriptions of the entire spectrum of rivers across the United States (U.S.), for example, from the smallest headwater creeks in New England to the lower Mississippi and the large rivers of the Pacific Northwest, clearly indicate that much more large wood was present within channels and across floodplains (Triska, 1984; Harmon *et al.*, 1986; Collins *et al.*, 2002; Wohl,

---

[1] Paper No. JAWRA-15-0021-P of the *Journal of the American Water Resources Association* (JAWRA). Received February 16, 2015; accepted November 21, 2015. © 2016 American Water Resources Association. **Discussions are open until six months from issue publication**.

[2] Professor (Wohl) and PhD candidate (Kramer), Department of Geosciences; Professor (Bledsoe, Gooseff), Department of Civil and Environmental Engineering; and Professor (Fausch) and Senior Research Scientist (Bestgen), Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, Colorado 80523-1482 (E-Mail/Wohl: ellen.wohl@colostate.edu).

2014). One of the first activities of European settlers in forested regions was to remove large wood from rivers (Sedell *et al.*, 1991), both directly by pulling wood from channels and indirectly via deforestation that reduced natural inputs of wood (wood recruitment) into channels. Congressional appropriations to remove wood from rivers were available as early as 1776 (Harmon *et al.*, 1986), an action likely sparked by earlier removal efforts of individuals. By 1824, Congress assigned improvement of inland rivers to the Army Corps of Engineers (Reuss, 2004), with much early effort focused on removing large wood.

Direct removal of large wood to facilitate navigation and control floods involved the use of snag boats that broke up logjams and pulled up wood pieces partly buried in the streambed or banks (Paskoff, 2007). Indirect removal occurred not only by timber harvest that reduced subsequent recruitment of large wood to channels, but also via: channelization (dredging, straightening, bank stabilization) that removed existing wood and reduced retention of subsequently recruited wood; log floating in association with timber harvest, which included removing naturally occurring large wood, as well as cut logs; and flow regulation, which limited recruitment and transport of large wood. The net effect of these activities was to remove almost all instream and floodplain wood within the U.S., typically prior to the 20th Century (Wohl, 2001, 2014). Consequently, most people do not expect large wood to be abundant in rivers (Chin *et al.*, 2008) and do not consider it a natural component of river ecosystems and habitat.

Streams along the Front Range in Colorado are no exception to the typical modern wood-impoverished state, as current practices usually involve automatic removal of all large wood. Extensive September 2013 rain and post-storm flooding in northern Colorado recruited abundant large wood to river channels and floodplains of streams originating in the Colorado Front Range and flowing eastward to the South Platte River. This event motivated us to work with municipalities and managers to consider leaving some wood in streams and floodplains, because wood is a natural landscape feature with high ecological benefit (Harmon *et al.*, 1986). However, large wood in rivers also poses hazards for human infrastructure and safety, especially in or near urban settings (Mazzorana *et al.*, 2011; Ruiz-Villanueva *et al.*, 2014a). Under a strict paradigm of large wood removal, there is no systematic evaluation of benefits and hazards and managers do not differentiate between large wood that creates hazards and large wood that creates little or no hazard and has high ecological benefits. Wood deposited during the September 2013 flood was almost universally perceived as creating a hazard to infrastructure and safety, irrespective of the location and condition of the wood. This underscored the need for a hazard assessment framework that managers can use to systematically and transparently weigh multiple considerations, including safety, hazards to infrastructure and recreational users, and ecological benefits of large wood.

In this article, we propose a process that managers can use to evaluate hazards and benefits of large wood. In this context, we define hazard as a negative consequence of the presence of large wood and we define benefit as a positive consequence of the presence of large wood. We first discuss benefits and hazards associated with large wood in channels and on floodplains with respect to the physical and biological processes occurring within river environments, as well as public safety and infrastructure. We then present a check-list based decision-making and hazard-assessment process for managers to evaluate the merits of keeping or removing individual pieces of wood or jams, including wood treatment options that may reduce hazards, and tools to measure stability and habitat created by large wood left in the channel or floodplain. Finally, we propose a series of decision bands that allow managers to further evaluate merits and hazards associated with retaining or adding large wood to a stream reach.

Effectively testing the framework proposed here will require evaluation of individual wood pieces and wood accumulations in diverse river environments over a period of at least a few years with varying flows at each river site. We present this framework in the hope that river managers will adopt and test the procedure, which we expect to be applicable across a range of channel sizes, flow regimes, and land-use characteristics. Our aim is to offer a straightforward management procedure that incorporates realistic analysis of hazards to humans and infrastructure, but also integrates the ecological benefits of large wood in streams and floodplains. Thus, goals of human safety and infrastructure preservation may be achieved while also increasing the geomorphic and ecological functioning and environmental health of rivers in settings with high human use.

BENEFITS AND HAZARDS ASSOCIATED WITH LARGE WOOD

This section reviews the benefits and hazards that result from the presence of large wood in channels and on floodplains. We first discuss the physical effects of large wood on the movement of water and sediment at the surface and within the hyporheic zone (shallow subsurface) present around river beds and banks. This is followed by discussion of the biological benefits of large wood for fish, stream invertebrates, and other aquatic and terrestrial invertebrates and vertebrates. The final portion discusses public safety considerations associated with large wood, in the context of hazards to inhabitants and infrastructure in or near the river and to recreational users.

Physical Benefits of Large Wood

The physical benefits of large wood result from its interactions with water and sediment moving down the channel. The magnitude of the effects that result from these interactions largely depends on orientation and stability of the large wood and the volume of wood in the channel relative to the cross-sectional area of the channel (Klaar *et al.*, 2011; Collins *et al.*, 2012). A single piece of large wood in a large channel, for example, will likely have only local effects, whereas a large jam that spans a channel can influence process and form along an entire stream reach (Wohl, 2011). These and other scale considerations are schematically illustrated in Figure 1.

Individual pieces of wood and wood collected into jams create obstructions that can substantially increase the frictional resistance to flow (Shields and Smith, 1992; Shields and Gippel, 1995; Curran and Wohl, 2003; Mutz, 2003). Obstructions reduce flow velocity (Daniels and Rhoads, 2004; Davidson and Eaton, 2013), which can in turn lead to slower passage of flood waves and increase local storage of sediment and organic matter around the wood (Bilby and Likens, 1980; Nakamura and Swanson, 1993; Faustini and Jones, 2003). If sufficient wood is present within the channel during high flows, the resulting flow obstruction can increase the magnitude, duration, and frequency of overbank flows (Triska, 1984; Brummer *et al.*, 2006). Increased overbank flows enhance the connections of water, sediment, nutrients, and organisms between the channel and floodplain (Collins *et al.*, 2012). This greater connectivity can facilitate storage of sediment and nutrients on floodplains, access to floodplain habitat by aquatic organisms, lateral channel movement across the floodplain (O'Connor *et al.*, 2003), and the formation of secondary channels that provide additional, diverse aquatic habitat (Abbe and Montgomery, 2003; Wohl, 2011; Collins *et al.*, 2012).

Large wood can increase habitat diversity within channels and on floodplains through various processes. Instream wood typically causes flow separation and localized scour of the bed and banks, resulting in pools and undercut banks (Buffington *et al.*, 2002; Collins *et al.*, 2002). Localized deposition associated with the flow separation creates areas of finer substrate on the streambed (e.g., patches of sand along a cobble-bed stream) (Keller and Swanson, 1979; Faustini and Jones, 2003). Larger wood obstructions, such as jams, commonly have upstream backwater areas of lower velocity and greater water depth (Brummer *et al.*, 2006). Wood can alter the type and dimensions of bedforms present along a channel. Diverse studies have documented scenarios where wood traps sufficient sediment to create an alluvial channel instead of a bedrock channel (Massong and Montgomery, 2000) and alters the dimensions of pool-riffle and step-pool bedforms (Robison and Beschta, 1990). Large wood interacts with sediment in flux down a river and with living riparian vegetation to enhance habitat diversity in different types of rivers (Pettit and Naiman, 2006; Collins *et al.*, 2012; Gurnell *et al.*, 2012).

The influence of large wood on flow resistance and the geomorphic form of stream and river channels creates more diverse hydraulic gradients not only in the channel, but also between the channel and aquifer. Increased heterogeneity of channel morphology is commonly associated with enhanced stream-groundwater exchange, and in particular hyporheic exchange (the exchange of stream water through stream-adjacent aquifers in which mixing with groundwater occurs) (Gooseff *et al.*, 2007). Wood-caused steps have been identified as important morphologic features that drive hyporheic exchange in some headwater streams (Kasahara and Wondzell, 2003; Wondzell, 2006). Although wood-driven hyporheic exchange may not be substantial in streams with large proportions of sand in the streambed, the wood can still significantly influence total hydraulic retention by creating low velocity zones within the channel (Stofleth *et al.*, 2008). The presence of large wood that is not contributing to major morphological features can also influence hyporheic exchange by increasing flow velocities between the wood and bed (Sawyer *et al.*, 2011, 2012). This may have significant implications for stream water temperature dynamics because groundwater is typically cooler than surface water (Arrigoni *et al.*, 2008; Sawyer and Cardenas, 2012). Hyporheic zones of streams have been described as analogous to vertebrate livers for their ability to remove pollutants (Fischer *et al.*, 2005), thus providing a self-cleansing process to improve stream water quality.

Finally, instream wood is particularly important because of the mosaic of flow velocities created around wood. Reduction in flow velocity around wood can increase the retention of particulate organic matter (Beckman and Wohl, 2014a) that is a fundamental energy source in many stream ecosystems. If finer

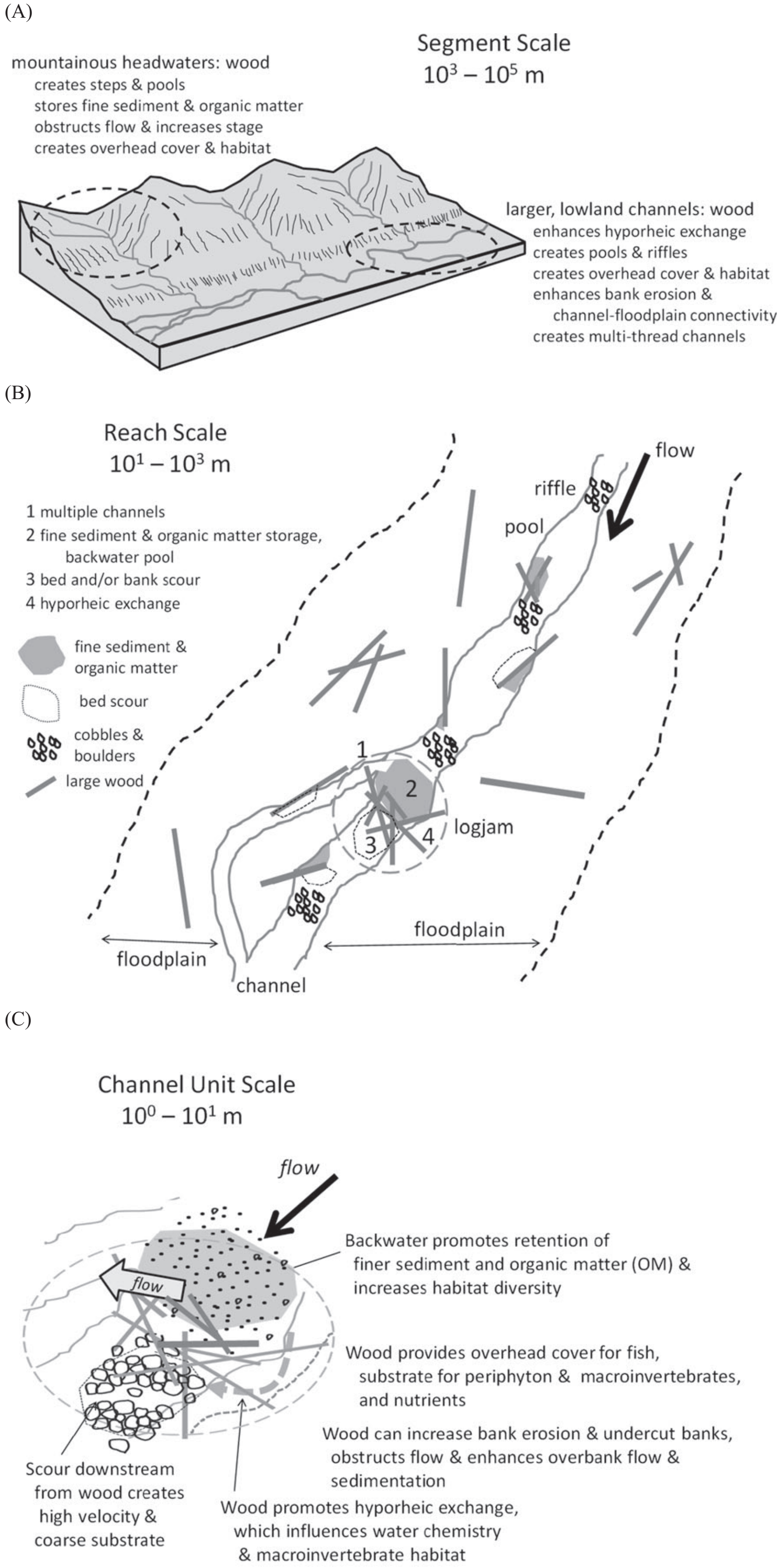

(A)
Segment Scale
$10^3 - 10^5$ m
mountainous headwaters: wood
creates steps & pools
stores fine sediment & organic matter
obstructs flow & increases stage
creates overhead cover & habitat
larger, lowland channels: wood
enhances hyporheic exchange
creates pools & riffles
creates overhead cover & habitat
enhances bank erosion & channel-floodplain connectivity
creates multi-thread channels
(B)
Reach Scale
$10^1 - 10^3$ m
1 multiple channels
2 fine sediment & organic matter storage, backwater pool
3 bed and/or bank scour
4 hyporheic exchange
fine sediment & organic matter
bed scour
cobbles & boulders
large wood
flow
riffle
pool
1
2
3
4
logjam
floodplain
floodplain
channel
(C)
Channel Unit Scale
$10^0 - 10^1$ m
flow
flow
Backwater promotes retention of finer sediment and organic matter (OM) & increases habitat diversity
Wood provides overhead cover for fish, substrate for periphyton & macroinvertebrates, and nutrients
Wood can increase bank erosion & undercut banks, obstructs flow & enhances overbank flow & sedimentation
Scour downstream from wood creates high velocity & coarse substrate
Wood promotes hyporheic exchange, which influences water chemistry & macroinvertebrate habitat

FIGURE 1. Schematic Illustration of the Physical Benefits of Large Wood at Progressively Smaller Spatial Scales. (A) At stream lengths of 1-100 km (10^3-10^5 m), known as the segment scale (Fausch *et al.*, 2002), the effects of wood strongly depend on valley geometry and location within a drainage basin. In confined, steep headwater valleys, large wood primarily affects channel process and form. In lowland channels with floodplains, large wood within the channel also affects floodplain process and form. (B) At stream lengths of tens to thousands of meters, known as the reach scale, large wood can strongly influence channel planform and morphology. By forming obstructions to flow, logjams can create backwater pools upstream from the jam and plunge pools downstream from the jam, and enhance overbank flows. Greater overbank flows increase channel-floodplain connectivity, bank erosion, channel avulsion, and the formation of secondary channels (location 1 in figure). Backwater pools enhance storage of finer sediment and organic matter within the stream (2), increasing habitat diversity for stream organisms. Flow separation around individual pieces of wood or jams can create localized bed and bank scour (3). Large wood can also create pressure differentials that drive hyporheic exchange (4), with downwelling into the streambed upstream from the wood and upwelling from the streambed downstream from the wood. (C) At stream lengths of a meter to tens of meters, known as the channel unit scale, individual pieces of wood or logjams create the effects described for the reach scale and illustrated here. Among these effects are overhead cover, velocity refuges, and visual isolation, all of which are important to fish (Fausch, 1993) and invertebrates.

---

particulate organic matter is stored for even a few hours, rather than remaining in transit, it can be accessed by microbial and macroinvertebrate communities that extract nutrients from it (Bilby, 1981; Raikow *et al.*, 1995; Battin *et al.*, 2008).

In contrast to the beneficial physical effects of instream and floodplain wood, removal of large wood can create physical hazards. Because wood enhances sediment storage, removal of wood and consequent reduced flow resistance and obstruction (Shields and Gippel, 1995) can result in erosion of streambeds (Faustini and Jones, 2003). Wood removal on diverse streams has resulted in significantly increased bed erosion and channel widening, with individual river reaches changing from sediment storage areas when wood is present to sediment source areas when wood is removed (Brooks *et al.*, 2003, 2006; Erskine and Webb, 2003).

Biological Benefits of Large Wood

The benefits of large wood to river organisms such as fish and aquatic invertebrates are likely to be of four main types. First, the geomorphic effects of wood on channel structure create pool, run, and riffle mesohabitats required by these biota to complete their life cycles, across a range of scales from reaches to riverscapes (Fausch *et al.*, 2002). Second, the habitat complexity created by wood provides critical microhabitats that fish and other organisms need for feeding, resting, and isolation and protection from competitors and predators (e.g., Sechnick *et al.*, 1986; Fausch, 1993; Nagayama *et al.*, 2012). Third, stable wood pieces provide hard surfaces that support an algal food base and associated aquatic invertebrates that feed on this algae and are themselves eaten by fish (Benke and Wallace, 2003). These hard surfaces are particularly scarce in lowland streams dominated by silt or sand substrate. Fourth, the effects of instream wood on hyporheic exchange have a direct influence on stream aquatic ecosystem processes, habitat, and condition. Hyporheic exchange influences nest-site selection by spawning salmon and trout, for example, and increases subsequent embryo survival (Baxter and Hauer, 2000; Malcolm *et al.*, 2004). Hyporheic zones also provide habitat for a variety of macroinvertebrates in one or more life stages (Stanley and Boulton, 1993; Williams, 1993).

Fish. Most of what we know about the role and functions of wood that benefit fish is from comparative studies and experiments conducted on salmon and trout in small- and medium-sized coldwater streams (e.g., Gowan and Fausch, 1996; Lehane *et al.*, 2002; see Whiteway *et al.*, 2010 for a review). Moreover, given the widespread decline in large wood in streams owing to clearing and snagging, and deforestation of riparian zones, much of the research has been done to understand what kinds of habitat restoration are most useful to increase numbers of trout and salmon. Nevertheless, there are recent research reports and reviews of the importance of wood in lowland warmwater streams for other fish species, especially in Australia (Crook and Robertson, 1999; Howell *et al.*, 2012) and the southeastern U.S. (Benke and Wallace, 2003). One main difference is that coldwater streams and rivers are typically inhabited by fewer fish species, so the responses measured are simpler than those of the many-species assemblages occupying warmwater lowland streams and rivers.

Fish typically need different habitats that are dispersed throughout reaches to riverscapes during different stages of their life cycle and at different times of year (Schlosser, 1991), and move among these to fulfill their needs (Fausch *et al.*, 2002; Falke and Fausch, 2010). For example, large wood can create pools with overhead cover that are critical for fish to survive during winter and also provides physical refuges from swift currents that can displace fish during high flows and floods, especially during spring snowmelt runoff (Shuler and Nehring, 1993; Crook and Robertson, 1999). Adding stable wood structures that create pools in Colorado mountain streams can increase trout biomass by about 50% (Gowan and

Fausch, 1996) and this increase can be sustained for more than two decades (White *et al.*, 2011). Likewise, in a large lowland river of Australia, two large native predatory fish were more often associated with patches of large wood than other habitat types (Boys and Thoms, 2006). Boys and Thoms (2006) hypothesized that large wood provides important foraging sites for these predators, which ambush their prey, as well as hard substrates for invertebrates to colonize in these lowland rivers (see Crook and Robertson, 1999 for a review). These sites are a critical component of physical habitat in arid and coastal regions dominated by rivers with fine-grained substrate.

Both comparative data and experiments also provide strong evidence that fish select locations near large wood and other structures that provide refuges from high current velocities and visual isolation and overhead cover from competitors and predators (Fausch, 1993; Nagayama *et al.*, 2012). Slow as well as fast water velocities created by large wood provide a variety of habitat for stream fishes because habitat selection is commonly dictated by body size- and velocity-dependent processes (e.g., Fausch, 1984, 2014). Consequently, a variety of flow velocities may provide habitat for several species or life stages. Given that fish in streams and rivers worldwide evolved with much higher loads of large wood than are now present, it stands to reason that many different species would be adapted to use the habitat structure created by these natural materials.

Stream Invertebrates. As for fish, aquatic invertebrates benefit from habitat such as pools or backwaters created by large wood and wood provides attachment surfaces for algae and invertebrates (Benke and Wallace, 2003). Some of these invertebrates scrape algae as a food source, others use the wood as attachment sites to filter particles from flowing water, and still other taxa gouge and burrow in the wood itself. In addition, large wood commonly traps leaves, sticks, and other organic matter that falls into streams, thereby providing a site for larger macroinvertebrate shredders to break down coarse particulate organic matter into smaller particles that are then used by other organisms (Flores *et al.*, 2011, 2013).

Large wood can have profound effects on the diversity, abundance, biomass, and production of stream invertebrates, especially in lowland rivers where most other substrates are shifting sand or silt. Extensive research showed that large wood in several low-gradient rivers in Georgia supported a unique assemblage of invertebrates, some of which use it for egg-laying sites, to find refuge from predation, or forage across it themselves for other invertebrate prey (Angermeier and Karr, 1984). Across studies, large wood is a hotspot for invertebrate biomass, production, and diversity (Wallace *et al.*, 1995; Benke and Wallace, 2003; Coe *et al.*, 2009).

Effects of Large Wood on Other Aquatic and Terrestrial Invertebrates, Vertebrates, and Floodplain Vegetation. Wood on floodplains provides substrate and cover for a range of organisms, including aquatic animals that prefer large wood as a substrate during overbank floods (Benke and Wallace, 1990), plants that use the nutrient-rich decaying logs as germination sites (Schowalter *et al.*, 1998), and small mammals, birds, reptiles, amphibians, and spiders that use wood for feeding or nesting sites (Harmon *et al.*, 1986; Roni, 2003). These groups have received far less study than fish or macroinvertebrates. Fish owls (*Bubo blakistoni*), for example, used nesting and foraging locations associated with large old trees and riparian old-growth forests, which the authors inferred were also important in creating suitable river habitat for salmon and charr, the owl's primary prey (Slaght *et al.*, 2013). Small mammals, such as Preble's jumping mouse (*Zapus hudsonius preblei*; listed as Threatened under the U.S. Endangered Species Act), also use riparian habitat associated with large wood, probably because the wood supports both invertebrates and fungi food sources (Trainor *et al.*, 2007, 2012). Benjamin *et al.* (2011) found that tetragnathid spiders, which live only near and above streams, were especially dense on downed wood that provided web supports directly over the water, because these spiders eat only insects emerging from streams.

Several studies have demonstrated the importance of large wood to floodplain ecosystems. Floodplain wood creates germination sites for riparian vegetation (Schowalter *et al.*, 1998; Pettit and Naiman, 2006). Water-transport of propagules is important to many riparian species and water-borne seeds are preferentially deposited against floodplain logs (Schneider and Sharitz, 1988). Floodplain wood also enhances nutrient cycling and soil formation (Zalamea *et al.*, 2007), provides invertebrate habitat (Benke, 2001; Braccia and Batzer, 2001), and enhances habitat for plants and animals (Harmon *et al.*, 1986).

Public Safety Considerations Associated with Large Wood

Potential Hazards for Inhabitants and Infrastructure. Physical hazards associated with large wood, like benefits from wood, strongly depend on the volume of wood within a channel and on whether the wood remains stationary or becomes mobile during high discharges. The three primary hazards to people and infrastructure when wood is present are increased flow stage, altered movement of sediment and patterns of erosion and deposition, and mobile wood.

By increasing resistance and obstructions to flow, large wood can create higher water levels at any discharge (Chow, 1959). This may result in overbank flooding hazards along stream segments where it is not desirable. Large wood can accumulate at bridges, for example, and cause increased scour of piers and abutments or exacerbate upstream flooding (Lagasse *et al.*, 2009; Schmocker and Hager, 2011). Large wood can also block culverts and increase flooding and roadbed erosion (Lagasse *et al.*, 2012). Large amounts of wood may also raise water elevations (Schmocker and Weitbrecht, 2013) above existing regulatory mandates, such as the 100-year flood used for Federal Emergency Management Agency (FEMA) compliance in the U.S.

Because large wood alters velocity and sediment transport capacity in its immediate vicinity, the presence of wood can alter localized sediment dynamics. A concentration of large wood along one bank can deflect flow toward the opposite bank, for example, accelerating erosion (Montgomery, 1997). Altered sediment dynamics can also result in lateral channel movement across the floodplain or local aggradation or scour (Brummer *et al.*, 2006; Wohl, 2011; Collins *et al.*, 2012), each of which can cause flooding or endanger infrastructure.

Finally, large wood within the channel or floodplain can be transported during higher discharges, potentially damaging downstream infrastructure such as bridges or pipelines or causing watercraft collisions. The mobility of individual wood pieces is strongly influenced by piece size relative to channel dimensions. Pieces shorter than average channel width and narrower than average flow depth are most likely to be mobile (Lienkaemper and Swanson, 1987; Braudrick and Grant, 2000), but channel-margin irregularities such as constrictions, expansions, and bends and the presence of natural obstructions within the channel (e.g., large boulders, stable pieces of wood) can also strongly influence piece mobility (Braudrick and Grant, 2001; Bocchiola *et al.*, 2006; Beckman and Wohl, 2014b). Rapid recruitment of large volumes of wood into a channel, such as via bank erosion during a flood, can result in congested transport in which multiple logs move as a single mass (Braudrick *et al.*, 1997), allowing channel-margin irregularities to be particularly effective in trapping wood. Less is known about the conditions under which logjams are likely to move or remain stable, but even large, channel-spanning logjams can become mobile (e.g., Wohl and Goode, 2008). Guidelines and methods, including modeling, for assessing the hazards created by wood for inhabitants and infrastructure are more fully discussed in subsequent sections.

Potential Hazards for Recreational Users. Concerns regarding large wood and public safety can also apply to river reaches that are frequently visited for instream (e.g., kayaking) and floodplain (e.g., hiking) activities. Some large wood creates strainers or foot entrapment hazards for recreational users. Strainers are wood accumulations or single pieces of wood that have enough space between pieces to allow water to flow through, but not people or objects. Foot entrapment hazards are submerged wood on the streambed, which may trap an ankle or foot, causing a person to fall and be held underwater by currents. However, large wood can also increase recreational user safety by providing zones of lower velocity and opportunities to rest, regroup, or escape hazards. Eight factors increase or decrease the level of hazard that large wood creates for the safety of recreational users: access, reach characteristics, ability to avoid hazards, prior knowledge, location, snagging potential, strainers, and anchoring. The first four factors emphasize user and reach characteristics that influence hazard, whereas the second four emphasize intrinsic wood characteristics that influence hazard to any user, regardless of skill or background.

Access. An important hazard consideration is whether the reach is accessible to the general public and what type of recreational user is likely to visit. Large wood is safer along reaches visited only by experienced kayakers and anglers, for example, than along favorite family swimming locales or popular tubing destinations.

Reach Characteristics. Hazards from large wood increase in reaches with higher water velocity because faster flow decreases reaction time and ability of a swimmer, tuber, or boater to avoid the wood. Thus, keeping wood in lower velocity reaches is less hazardous than in reaches with swift current. In natural streams, most wood and logjams are located along lower velocity depositional areas. In straight river sections with uniformly swift velocity, drowning can occur when a swimmer has no chance to reach shore for long distances, but large wood jams with low porosity that pool water upstream from the jam may increase the safety of a reach by creating areas of lower velocities near shorelines. Generally, river sections that are constricted, with steeper gradients and faster currents, are more hazardous than low gradient, meandering, open sections.

Ability to Avoid. User visibility from upstream and an onshore escape route reduce hazards caused by large wood. In contrast, wood not visible around sharp bends or just downstream of large drops can be difficult for boaters or swimmers to see and avoid. A boater or swimmer should have ample time to see large wood and react by either navigating around it or moving to the shore and getting out above the large wood. A signed route to walk around the wood is particularly helpful. If private property or steep banks prevent avoiding the wood via the shore, the wood should be readily visible from far upstream, with ample room to navigate around it. The skill level and type of recreational users typical for a reach should be considered.

Prior Knowledge. Most importantly, prior knowledge of new large wood along commonly navigated sections is vitally important to reduce hazards because users will not be surprised by unaccustomed features. An effective hazard-reducing measure for new large wood is communication with local or national recreational groups and online river forums, and adding signs at river access points.

Location. Large wood close to the water surface creates greater hazards than wood high enough to float under, recognizing that vertical position will change with flow level. Wood in contact with the bed so that no water is flowing underneath it creates minimal hazards. Conversely, wood near the bed with water flowing under creates a hazard for wading persons. For wood above the water column, American Whitewater suggests 1 m of clearance for kayaks and 1.8 m for rafts (http://www.americanwhitewater.org). Channel-spanning wood may be dangerous unless it continuously contacts the bed. Vertically oriented wood (e.g., fence posts) should be avoided because water craft can wrap around it.

Snagging Potential. Snagging here refers to the potential of large wood to catch clothing or gear and hold a swimmer or flip a water craft as it passes. Wood with many larger limbs creates more risk for swimmers and boaters, especially if the wood is in areas with high water velocity. Wood can be stripped of large branches and stubs to reduce snagging potential, although this may reduce the ecological benefits of the wood. If complex large wood is desired for ecological reasons, it should be placed in less hazardous locations, in low velocity reaches, or on remote reaches visited infrequently and only by experienced recreationists.

Strainers. Although a single piece of large wood with few to no branches creates relatively low hazard, a porous jam can be hazardous because people or objects can become pinned.

Anchoring. Large wood that is intentionally placed or retained with appropriate anchoring can be an ecological or aesthetically valuable structure. However, wood anchored with cables, ropes, rebar, or other artificial material may be hazardous if anchors are exposed within the channel or become exposed when the channel scours around secured wood or the wood becomes detached. If large wood needs to be anchored in reaches with high recreational use, we recommend it be secured through burial or weighting with natural materials.

Recreationists may view large wood in channels as a hazard and not aesthetically pleasing, in part because of unfamiliarity with the historical significance and positive attributes of large wood in stream channels (Piégay *et al.*, 2005; Chin *et al.*, 2008). It is important that the public be informed about wood structures to avoid citizens removing carefully retained or expensively placed wood features. Boaters are an especially good resource to include in the decision-making process regarding large wood in streams because they can identify low *vs.* high hazard wood and, if included in planning, will be less likely to remove wood.

DESCRIPTION OF TOOLS TO ASSESS LARGE WOOD

As discussed above, river managers need to understand stability of individual large wood pieces and jams within channels and on floodplains, and physical and ecological effects created by this wood, to effectively manage large wood. This section briefly introduces two assessment tools that can be used to better understand large wood stability, benefits, and hazards. We first introduce a spreadsheet-based program designed specifically to evaluate large wood, and second, review a group of numerical models designed to assess hydraulics and aquatic habitat, which can be applied to the understanding of instream and floodplain wood.

Large Wood Structure Stability Analysis Tool

The Large Wood Structure Stability Analysis Tool is a spreadsheet-based approach that can be used to efficiently evaluate large wood stability and options for the design and placement of wood, based on factors including the size and species of wood, configurations, and anchor requirements (Rafferty, 2013). Users are required to input basic information on channel dimensions, discharge, streambed substrate, and wood characteristics. A companion report at http://www.fs.fed.us/biology/nsaec/products-tools.html summarizes the design rationale, methodologies, procedure, limitations, and example applications to illustrate how the tool can be used to design stable large wood structures (Figure 2).

Flow and Habitat Models

Several tools are available to assist with evaluation of the effects of large wood on flow and potential benefits of wood for fish in streams. Numerical models include one-dimensional and two-dimensional simulations of hydraulics. One-dimensional models are typically easier to use because of lesser requirements for input data, user expertise in hydraulics, and computational power, but these models may not simulate relevant processes with sufficient accuracy for evaluating local effects of individual wood pieces or accumulations. An example of a widely used one-dimensional model is the HEC-RAS software program (Hydrologic Engineering Center River Analysis System, http://www.hec.usace.army.mil/software/hec-ras/), which can be used to model hydraulic characteristics in a variety of channel types.

Developed in part to model floodplain management and insurance studies for potential flood damage, HEC-RAS allows modeling one-dimensional changes in water surface elevation (stage) as it varies with flow (discharge). Large wood can impede flow velocity in a stream channel or on an inundated floodplain and thereby increase the stage and alter channel or floodplain flow dynamics. Thus, when properly applied, HEC-RAS can estimate lateral extent of flooding (or lack thereof) when large wood has been placed or retained in the active river channel or floodplain. Shields and Gippel (1995) describe a procedure that can be used to estimate effects on reach-scale one-dimensional flow of adding or removing individual wood although, as they caution, wood removal can trigger complicated responses that are difficult to predict and the effect on resistance of adding or removing wood may not be linear (Wilcox *et al.*, 2006). The HEC-RAS software may also be used to estimate flow velocities to help predict scour or erosion resulting from placement or retention of large wood in the stream channel. Based on a recent beta release of HEC-RAS 5.0, we anticipate that future versions will provide two-dimensional modeling capabilities with the potential to improve assessments of the influence of large wood on flood stages and sedimentation processes.

Investigators working in mountainous regions of Europe have recently developed two-dimensional, integrated modeling approaches that use GIS software to evaluate the recruitment of large wood to river corridors, as well as entrainment and transport of the large wood based on the balance of hydrodynamic and resistance forces acting on individual wood pieces (e.g., Mazzorana *et al.*, 2011, 2013; Ruiz-Villanueva *et al.*, 2014a, b). These modeling approaches

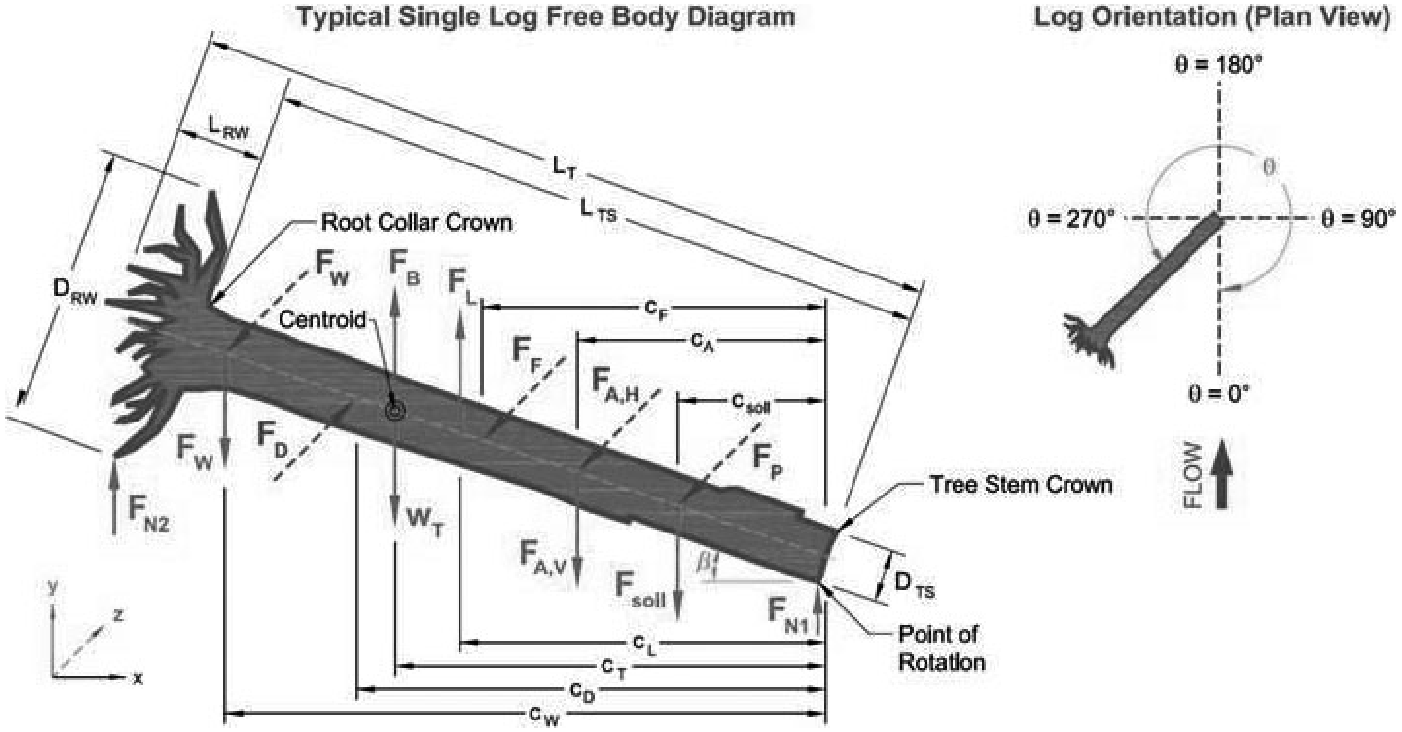


FIGURE 2. Screen Capture of the Website for the Large Wood Structure Stability Analysis Tool of Rafferty (2013): http://www.fs.fed.us/biology/nsaec/products-tools.html.

incorporate infrastructure scenarios such as locations of bridge piers or abutments and can be used to assess hazards during floods that transport large wood (Mazzorana *et al.*, 2009).

The choice of one- *vs.* two-dimensional models will partly depend on the scale at which large wood is being assessed. Examination of a single piece of wood or a limited number of wood pieces within a short length of channel may be most effectively done using the Large Wood Structure Stability Analysis Tool (Rafferty, 2013) or a two-dimensional model. Examination of multiple pieces throughout a longer section of channel and floodplain may be more efficiently approached using a less detailed model such as HEC-RAS. When applying any model, the user must balance considerations of spatial and temporal resolution of available input data and of desired model output.

Modeling tools are also available for estimating the quantity and quality of fish habitat related to retention or loss of large wood. One such tool is the instream flow incremental methodology (IFIM) and the associated physical habitat simulation tool (PHABSIM), which allows estimating usable fish habitat at different streamflows (Stalnaker *et al.*, 1995; Bovee *et al.*, 1998). This technique incorporates curves describing fish use (and assumed preference) of depth, velocity, and substrate microhabitat characteristics, which differ by fish species and life stage (e.g., larvae, juveniles, adults, spawning adults). These characteristics are then predicted using hydraulic assessments of the stream cross-section, and the results combined into an index of "weighted usable area" for a given fish species and life stage. Such techniques may be useful in assessing improvements to habitat by placement of certain quantities of large wood or retention of wood in streams, and especially to predict how large wood affects the diversity of habitat at particular transects. For example, flow and depth variability may be greater in a habitat transect that contains large wood than one without, and these characteristics may be important to certain fish species or life stages. Two key caveats are that (1) hydraulic habitats are characterized by complex three-dimensional flow patterns that are typically poorly represented by one-dimensional simulation models and (2) habitats that are critical for fish reproduction, growth, and survival may be important at spatial scales larger than the microhabitat scale (Fausch *et al.*, 2002). Thus, such models should be used judiciously.

Flow and habitat assessments based on one-dimensional models can incorporate variable discharge levels but are not useful to assess spatial changes in habitat. Spatially explicit flow models that can be mapped in either two- and three-dimensions are necessary to describe more fully the spatial and temporal heterogeneity in a river. Such models are useful to predict physical features of the habitat as well as understand relationships between fish, flows, and habitat quality and diversity (Bovee, 1996; Ghanem *et al.*, 1996). For example, Stewart *et al.* (2005) used two-dimensional modeling to correlate meso-habitat variables to native fish biomass at a reach scale. They also validated the model, predicting fish biomass in different channel types over a range of flows, and attendant depth and velocity conditions.

Estimation of mean depth and velocity characteristics of streams using the simpler one-dimensional models requires less hydraulic expertise, lower resolution input data, and less computational time and power. However, two-dimensional models have the advantage of more accurately predicting habitat change as flows fluctuate seasonally and as channel shape changes, thus predicting changes in biomass as flows and spatial habitat change. This is an important consideration when evaluating potential effects of large wood addition or retention in a stream reach, because wood effects can be modeled as a spatially explicit variable.

The additional effort and resources involved in using two-dimensional flow models can be justified when detailed information on habitat associated with wood is required. Consequently, users may want to consider models that are in the public domain and can be obtained free of cost. These include RIVER2D (http://www.river2d.ualberta.ca/), a two-dimensional, depth-averaged, finite element hydrodynamic model that has been customized for fish habitat evaluation studies, and SRH-2D (http://www.usbr.gov/pmts/sediment/model/srh2d/index.html), a two-dimensional hydraulic, depth-averaged, finite-volume numerical model developed by the U.S. Bureau of Reclamation for sediment, temperature, and vegetation in rivers. Other models are also available commercially.

DECISION PROCESS FOR MANAGING LARGE WOOD

Background on Hazard Assessment

Hazards are inherent in river management given the range of complexity in channel responses to changes in delivery of water, sediment, and large wood. A primary purpose of hazard assessment is to assure designers, managers, stakeholders, and the general public that the potential short- and long-term effects of the proposed action have been considered, and that the expected benefits of the project outweigh the potential negative consequences (Abbe *et al.*, 2014; Thorne *et al.*, 2015). Engineers have a long tradition of performing hazard and risk assessments focused on structural stability or safety. However, the recent upsurge in river restoration activities involving intentional placement and retention of large wood has increased the need for hazard assessments focused on wood. The purpose of any hazard assessment is not to eliminate hazard, but to objectively evaluate the potential hazardous elements and assess how a particular design or management action can address and alleviate those hazards. It is important to note that there is a significant, but commonly underappreciated, hazard of continued geomorphic and ecological degradation if large wood is not retained or re-introduced to a stream or river, and this hazard should be included in every assessment.

In formal hazard evaluation, hazard is defined as the probability that an event of a specified intensity will occur during a specified exposure time, whereas risk is defined as the probability that a loss affecting a specified element will occur as a consequence of that event. In common usage, risk refers to the potential of losing something of value, weighed against the potential to gain something of value. As noted above, we are using hazard informally, to describe a negative consequence of the presence of large wood.

Procedure for Assessing Hazards Posed by Large Wood

Hazard assessment for wood in streams is best regarded as an ongoing process because of likely changes in hazard through time as a result of natural processes (e.g., high streamflows) and human modifications (e.g., stabilizing or pruning the wood). Consequently, we suggest a process illustrated by the flowchart in Figure 3, which incorporates four tools. If large wood is present in a channel, a simple checklist (Tool 1; Figure 4) can be used for an initial assessment of whether to remove the wood or consider other options. If options other than immediate removal are considered, the Large Wood Structure Stability Analysis tool (Rafferty, 2013) (Tool 2; Figure 2) can be used to assess the likely stability of the wood during differing discharges. The outcome of Tool 2 can then be used with the decision bands (Tool 3; Figure 5) to qualitatively assess the alternative actions listed within the oval in Figure 3. The decision bands are used to assign hazard to a high, medium, or low category with respect to three characteristics: the ecosystem, recreation, and legal/property/infrastructure/inhabitants.

The outcome of Tool 2 can also be used in a more quantitative approach based on a multi-criterion

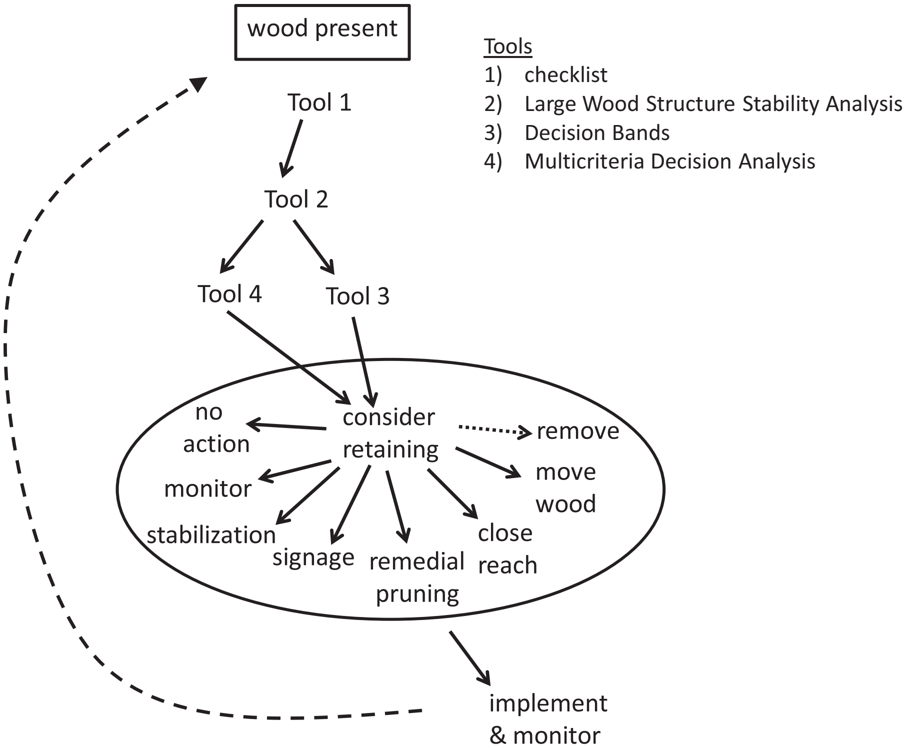


FIGURE 3. Illustration of the Sequence of Tasks, and Associated Tools, Which Can Be Used to Assess Hazards Created by Large Wood in Streams. The arrow from the lower portion of the figure back to the top rectangle indicates that, after implementation and monitoring, the whole process may be repeated, starting with use of tools, and retained wood reassessed.

1. *Imminent Threat to Public Safety*

a) Has a river recreation accident involving the wood been reported?
If yes, remove.
If no, proceed to consider retaining.

b) Does the wood accumulation have crevices that can trap recreational users (i.e., is it porous) **and** completely span the active river channel in a location and season known for high recreational use?
If yes, remove.
If no, proceed to consider retaining.

2. *Imminent Threat to Property and Infrastructure*

a) Has the wood already damaged a facility or public or private structure?
If yes, remove.
If no, proceed to consider retaining.

b) Could the wood potentially create, or increase the extent of, damage to a facility or public or private structure that may cause loss of function to the facility or structure?
If yes, remove.
If no, proceed to consider retaining.

3. *Legalities*

For any reason, are you legally bound to extract the wood?
If yes, remove
If no, proceed to consider retaining

4. *Overall*

If the answer to all of the preceding questions was a clear ‘no,’ retain wood.
If the answers involved some qualifications, proceed to Tools 2-4 and consider retaining.

FIGURE 4. Tool 1: Checklist for Initial Assessment of Individual Wood Pieces or Wood Accumulations.

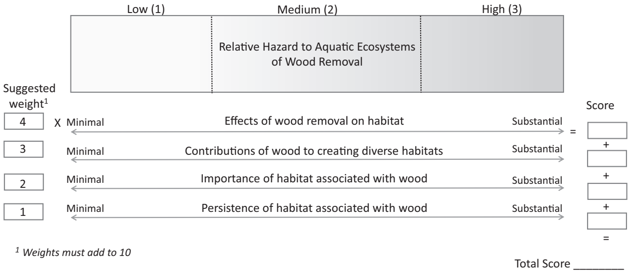
decision analysis (MCDA) approach (e.g., Pomerol and Romero, 2000; Kiker *et al.*, 2005; Suedel *et al.*, 2011). MCDA provides a flexible, rational, and transparent means to establish decision-making criteria and prioritize options and typically involves five steps (Chee, 2004): (1) define the goals and objectives; (2) identify decision options; (3) select the criteria that measure performance relative to the objectives; (4) determine the weights for the various criteria; and (5) apply the procedures and perform the mathematical calculations to rank options.

In MCDA, criteria are scored on interval or ratio scales and then transformed to ensure commensurability before ranking options. Criteria scores are aggregated using weights that reflect values, preferences, and expert judgment to transparently compare and rank options. MCDA is essentially a method for combining multiple criteria and value judgments into a concise set for decision making. The MCDA approach is more structured and defensible than best professional judgment, yet more interpretable and less complex and data intensive than sophisticated optimization schemes. Users can also adapt the system to different decision-making situations by adjusting the criteria and weights as knowledge and preferences evolve. Thus, the great strengths of MCDA are its transparency and flexibility.

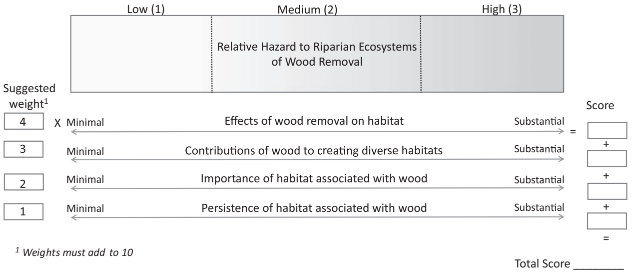
Use of the Tools

Our intent is that the checklist of Tool 1 (Figure 4) can be used for relatively rapid field assessment of hazard associated with large wood. Tool 2 is the Large Wood Structure Stability Analysis (Rafferty, 2013) described earlier. Tool 3 is the series of decision bands in Figure 5. These bands were developed based on consensus of the diverse effects of large wood, and the relative importance of these effects, among our group (civil engineers, ecologists, geomorphologists, and recreational boaters) and staff from the City of Fort Collins and Boulder County stormwater utilities and natural areas programs. The bands are designed to assist field-based evaluation of the relative hazard created by individual pieces of large wood or logjams in a channel or on a floodplain. Individual bands focus on aquatic and riparian ecosystems, recreational users, and inhabitants and infrastructure. The suggested weights assigned to each row below the band, which can be altered by the user, can be used to create a weighted score for comparing different sources of hazards. We emphasize that these decision bands represent a starting point for a complicated assessment process that is context-specific. Some river reaches will have minimal recreational use or potential, for example, or no floodplain habitat.

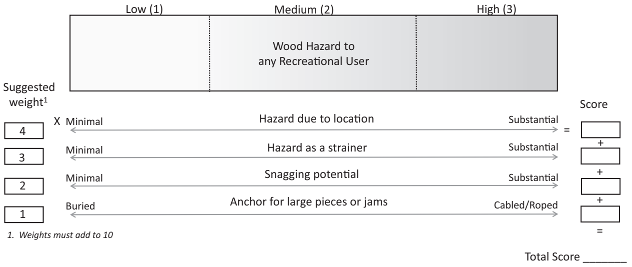
(A) Decision band for assessing the relative hazards to aquatic ecosystems of wood removal



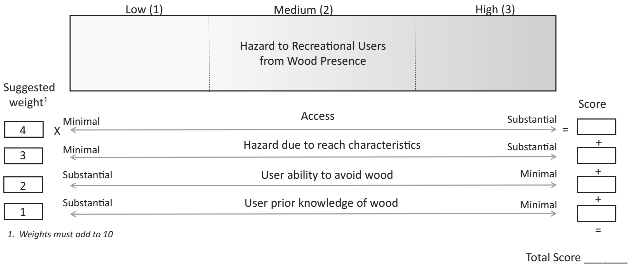
(B) Decision band for assessing the relative hazards to riparian ecosystems of wood removal



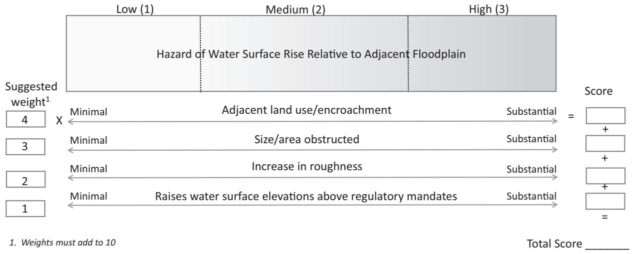
(C) Decision band for assessing the relative hazards from wood presence to any recreational users



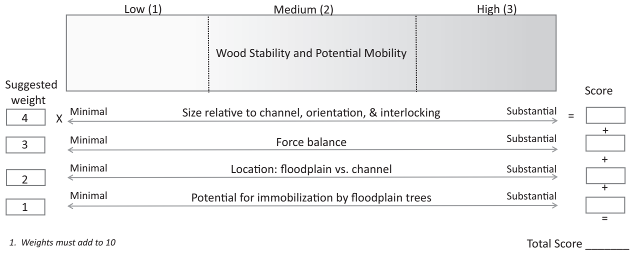
(D) Decision band for assessing hazards to recreational users from wood presence



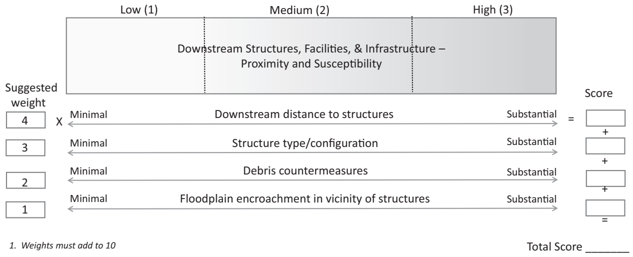
(E) Decision band for assessing the hazards from water surface rise relative to the adjacent floodplain if wood is present



(F) Decision band for assessing the relative hazards from wood stability and mobility



(G) Decision band for assessing the relative hazards to downstream structures, facilities, and infrastructure resulting from the presence of instream wood



(H) Decision band for assessing the potential for unintended geomorphic consequences as a result of the presence of wood

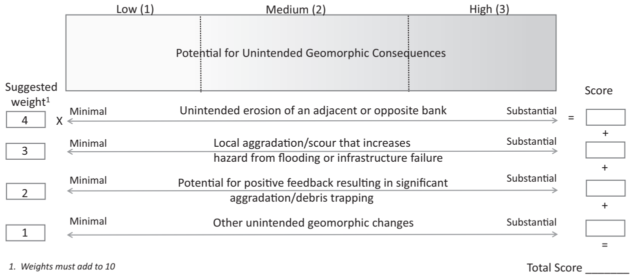
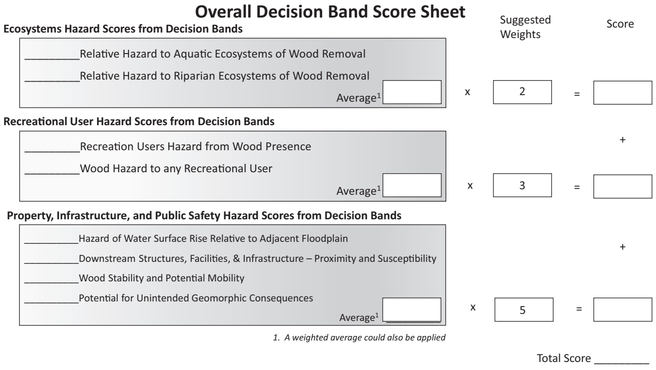


FIGURE 5. Tool 3: Decision Bands for Assessing the Relative Hazards to Different Components of River Systems Associated with Wood Removal. Individual bands relate to (A) aquatic or in-channel ecosystems, (B) riparian or floodplain ecosystems, (C, D) recreational users, (E) water surface rise relative to adjacent floodplain, (F) wood stability and potential mobility, (G) downstream structures, facilities, and infrastructure, (H) potential for unintended geomorphic consequences, and (I) a cumulative assessment for property, infrastructure, and public safety. For each band, the suggested weight in the box at the left in each row is multiplied by one of the numbers at the top of the band (1, 2, or 3) to create a score for that row, and these scores are then summed to create a total score for that decision band. Other weightings are also possible, depending on specific objectives and stakeholder input.

(I) Overall decision band score sheet for assessing relative hazards to ecosystems of removing wood and hazards to recreational users, property, infrastructure, and public safety of retaining wood. Other weightings of the scores are possible, depending on specific objectives and stakeholder input.



Overall Decision Band Score Sheet

	Suggested Weights		Score
Ecosystems Hazard Scores from Decision Bands			
_________Relative Hazard to Aquatic Ecosystems of Wood Removal			
_________Relative Hazard to Riparian Ecosystems of Wood Removal			
Average[1] ☐	x 2	=	☐
			+
Recreational User Hazard Scores from Decision Bands			
_________Recreation Users Hazard from Wood Presence			
_________Wood Hazard to any Recreational User			
Average[1] ☐	x 3	=	☐
			+
Property, Infrastructure, and Public Safety Hazard Scores from Decision Bands			
_________Hazard of Water Surface Rise Relative to Adjacent Floodplain			
_________Downstream Structures, Facilities, & Infrastructure – Proximity and Susceptibility			
_________Wood Stability and Potential Mobility			
_________Potential for Unintended Geomorphic Consequences			
Average[1] ☐	x 5	=	☐

1. A weighted average could also be applied

Total Score _________

FIGURE 5. Continued.

Although we briefly explain the characteristics that can be used to assign a score to each decision band, users who want to evaluate these characteristics in more depth are encouraged to consult the relevant technical literature or disciplinary experts, and to use specific tools such as flow and habitat models.

Hazards to Aquatic Ecosystems. The band for effects of large wood removal on aquatic ecosystems (Figure 5A) assesses whether habitat important to sustain fish or aquatic invertebrates, such as deep pools, is likely to decline as a result of wood removal (which would result in a high score), or is unlikely to be reduced by wood removal (a low score). Contributions of wood to creating diverse habitats assesses whether the large wood creates multiple types of habitat, such as pool scour and overhead cover for fish, diverse coarse and fine substrates for macroinvertebrates or backwater pools for fish and macroinvertebrates. If so, then removing large wood results in a high likelihood of reduced habitat diversity. Diverse aquatic habitat is made up primarily of a diversity of flow depth, flow velocity, streambed substrate, and complex physical structure created by large wood. Importance of wood-associated habitat includes considerations such as abundance of large wood at the reach scale and the need for this habitat by key species. For example, pools are commonly critical habitats for many fish species, so if large wood creates the only pool habitat for fish within a particular stream reach, then the importance is high and the likelihood of reducing habitat by removing large wood is also high. In contrast, if large wood creates no pools or only very small pools, then the importance and the hazard could be rated as low. Likewise, large wood structures that create critical habitat for an at-risk or desired species equate to a higher score for the importance of habitat. Persistence of habitat associated with large wood assesses whether the wood-related habitat is likely to persist for a short period (<5 years) or to persist for longer time periods (5-100 years or more). If large wood persists for a long period, then the hazards for aquatic habitat posed by removing it are high.

In Figure 5B, the basic characteristics of the features (effects of large wood removal, contributions of large wood to creating diverse habitats, importance of habitat, and persistence of habitat) are the same as described above for aquatic ecosystems, except that they are applied to riparian organisms. Where a long piece of wood spans the channel and the floodplain, decision bands (A) and (B) should be used together to assess the wood.

Hazards to Recreational Users. The decision bands in Figures 5C and 5D address the potential recreation hazard from large wood. Recreation hazard is separated into two bands to reflect (1) the hazard that a piece of wood poses to a user based on wood characteristics (placement, size, type, etc.), regardless of user or reach characteristics (5C) and (2) the large wood hazard to users based on user or reach characteristics and regardless of wood characteristics (5D). Recognizing and separating recreation hazards in this way is useful because it allows flexibility to leave wood that scores as potentially hazardous in locations where reach and user characteristics reduce the hazard to manageable levels (high hazard in 5C but low hazard in 5D). In contrast, wood may be removed even though it is scored as low hazard because user skill and reach characteristics nevertheless make the wood hazardous to retain (low hazard in 5C but high hazard in 5D).

With regard to wood characteristics (Figure 5C), large wood in swift current or on the outside of bends creates more substantial hazards than wood in zones of low velocity or on the floodplain. The orientation and shape of wood, as these influence ability of the wood to act as a strainer or to snag floating objects, substantially influence hazard. Anchoring with cables or ropes creates high hazards for recreational users if the cables or ropes are ever exposed.

With regard to user or reach characteristics (Figure 5D), hazard increases in stream reaches heavily accessed by less skilled users relative to reaches lightly accessed by skilled users. Large wood creates greater hazards in reaches that are steeper and swifter, with confined banks or valley walls, than in low gradient reaches with low velocity. Ability and skill to see and avoid large wood greatly reduces hazards, so the upstream visibility of wood is an important factor. For example, if a snag is cut from a rootwad but the rootwad is left in place just at or under the water surface, the hazard from the wood is greatly increased because it is less visible, even though the snagging hazard is reduced. Ability to avoid large wood also depends on the ease with which recreational users can avoid it. The same piece of large wood may be difficult for a tuber to avoid, but easy for a kayaker. For any recreational user, regardless of skill, prior knowledge of large wood greatly reduces the hazard, while the sudden appearance of new wood increases hazard.

Hazards to Property and Infrastructure. The potential costs and the risk of negative consequences to property and infrastructure associated with large wood retention and placement also depend on site-specific channel and floodplain characteristics (Figure 5E). Encroachment by human development, infrastructure, and other valuable assets tend to increase potential costs associated with floodplain inundation and river channel changes. Thus, local encroachment in the vicinity of large wood is a fundamental consideration. Assessing hazard also requires an understanding of the physical factors that control flood conveyance. The local extent of channel blockage, flow obstruction, and reduced cross-sectional area that may result from large wood retention are fundamentally important. Flow conveyance is also proportional to flow resistance, as expressed by the widely used Manning n. Obstructions directly influence n values, but roughness is included as a separate factor to emphasize the importance of considering relative changes in flow resistance when assessing potential reductions in flood conveyance capacity. A final consideration is whether retention or emplacement of large wood will alter water surface elevations to an extent that requires regulatory action such as generating a letter of map revision (FHWA, 2014). The impact of such regulatory implications must be evaluated on a case-by-case basis by floodplain managers.

Large wood that presents little hazard in its current location may nevertheless produce much greater hazards if transported downstream to a location where it could exacerbate flooding and/or threaten property and infrastructure (Figure 5F). This decision band is intended to address the likelihood of large wood being mobilized and transported downstream without reference to specific downstream conditions (addressed in the decision band in Figure 5G). Individual pieces of wood that are large relative to channel width (e.g., spanning from top of bank to top of bank) may be inherently less mobile for a given amount of flow energy (Lienkaemper and Swanson, 1987; Braudrick and Grant, 2000). Wood that is oriented lengthwise along a streambank in the flow direction is likely to be inherently more stable compared to a piece of wood oriented perpendicular to high velocity flow in the center of the channel (Braudrick and Grant, 2000). Physically-based models that explicitly account for the various forces acting on large wood can be very useful and informative in assessing stability and the potential for downstream transport (e.g., Rafferty, 2013; Ruiz-Villanueva *et al.*, 2014b). Large wood mobility depends on the balance of stream power available to transport the wood *vs.* the resistance of the wood to motion based on its weight, location, orientation, anchoring, and other factors. Floodplain flows, especially in unconfined valleys, typically have less erosive power than in-channel flows and thus less capacity to transport wood. In addition, forested floodplains may have a high capacity for trapping and immobilizing large wood (Wohl *et al.*, 2011).

Once large wood is mobilized downstream from the location where it enters a river or stream, its potential for creating hazards depends on the types of hydraulic structures and infrastructure it encounters. The greater the distance large wood must be transported before encountering vulnerable structures, the more likely the wood is to be immobilized and thus provide opportunities for re-stabilization or removal. The inherent susceptibility of hydraulic structures such as bridges or culverts to loss of conveyance, damage, and failure is highly variable (FHWA, 2005). Factors that affect a structure's capacity to safely convey large wood include opening width(s) and height(s) relative to wood size, pier spacing, shape, and orientation, backwater effects, and the presence of debris countermeasures (Schmocker and Hager, 2011). There are many types of structural and nonstructural debris countermeasures for bridges and culverts (FHWA, 2005; Schmocker and Weitbrecht, 2013). Assessing structure vulnerability and the potential effectiveness of large wood and debris countermeasures requires extensive knowledge of both structures and hydraulic engineering and should be performed by a Professional Engineer. As described above, encroachment by human development, infrastructure, and other valuable assets tends to increase potential costs associated with floodplain inundation and river channel changes. The decision band in Figure 5E focuses on floodplain land use and encroachment in the immediate vicinity of large wood without consideration of potential downstream effects. Accordingly, the decision band in Figure 5F requires an evaluation of the potential consequences of reduced flood conveyance and damage to structures if large wood is transported to vulnerable downstream locations.

Large wood is widely recognized by river scientists for its capacity to create habitat diversity and channel changes that benefit aquatic ecosystems. However, dynamic channel adjustments are commonly socially unacceptable in river corridors that are highly constrained by human encroachment. In such situations, it is important to evaluate the potential for large wood to produce channel adjustments that conflict with adjacent property values and floodplain management objectives (Figure 5H). Potential responses to inputs of large wood include accelerated bank erosion as a result of increased velocities and/or flow redirection, ongoing accumulation of wood and loss of conveyance, backwater effects, and altered sediment transport capacity and downstream supply that affect patterns of sediment scour and deposition. Such channel responses to large wood can be difficult to predict, even for experienced fluvial geomorphologists and river engineers. Therefore, evaluations of potential geomorphic consequences are best performed by interdisciplinary teams of experts with experience managing large wood.

The decision band in Figure 5I integrates the results of decision bands (A) through (H) into an overall assessment score for relative hazard of retaining or removing large wood. Decision band scores consistently in the medium-high range of decision bands (A) and (B) (hazards to aquatic and riparian ecosystems from large wood removal) and in the low range of decision bands (C) to (H) (hazards to recreational users, property, and infrastructure from wood presence) suggest options of no action, monitoring, stabilization, or signs (Figure 3). In contrast, scores in the low range of decision bands (A) and (B) and the medium-high range of the other decision bands suggest options of remedial pruning, closing the reach to use, or moving large wood. Table 1 provides further information on the implications of choosing each of the options within the oval in Figure 3. The overall decision band score sheet can be used to compare relative hazards among ecosystems, recreational use, and public infrastructure and safety. Other weightings are possible depending on the priority placed on each, such as in national parks where effects on ecosystems may have high priority *vs.* urban areas where effects on infrastructure and property are paramount. The score sheet can also be used to compare hazards from large wood among different reaches or specific wood locations, to assist in the prioritization and cost-benefit evaluations of restoration or management efforts.

TABLE 1. Potential Implications and Attributes of Individual Options in Figure 3.

Action	Potential Implications
No action	Ensure continued beneficial habitat effects of wood
Monitor	Ensure continued beneficial habitat effects of wood Facilitates longer term evaluation of how interactions among discharge, sediment, and wood influence habitat Especially appropriate for wood that creates low hazard for recreational users in a high use reach or that creates moderate to high hazard in a low-use reach
Stabilization	Ensure continued beneficial habitat effects of wood Reduce hazards to infrastructure Reduce hazard of unstable pieces moving to high-hazard locations after assessment Natural stabilization techniques such as burial reduce recreational hazard
Signage/outreach	Ensure continued beneficial habitat effects of wood Reduce hazard to recreational users Educates recreational users of wood presence and benefits
Remedial pruning	Reduce snagging potential Reduce beneficial effects to habitat Reduce flow resistance, sedimentation and erosion, and potential for trapping additional wood
Close reach	Ensure continued beneficial effects of wood Reduce hazards to recreational users
Move wood	Reduce beneficial wood habitat Reduce hazards to infrastructure and recreational users

SAMPLE APPLICATION

A natural area along the Poudre River within the City of Fort Collins, Colorado provides a hypothetical example of how the framework described in this article might be used. The Salyer Natural Area (Figure 6) includes a large gravel bar and riparian forest. Individual large wood pieces deposited on the floodplain within the riparian forest are unlikely to be mobile

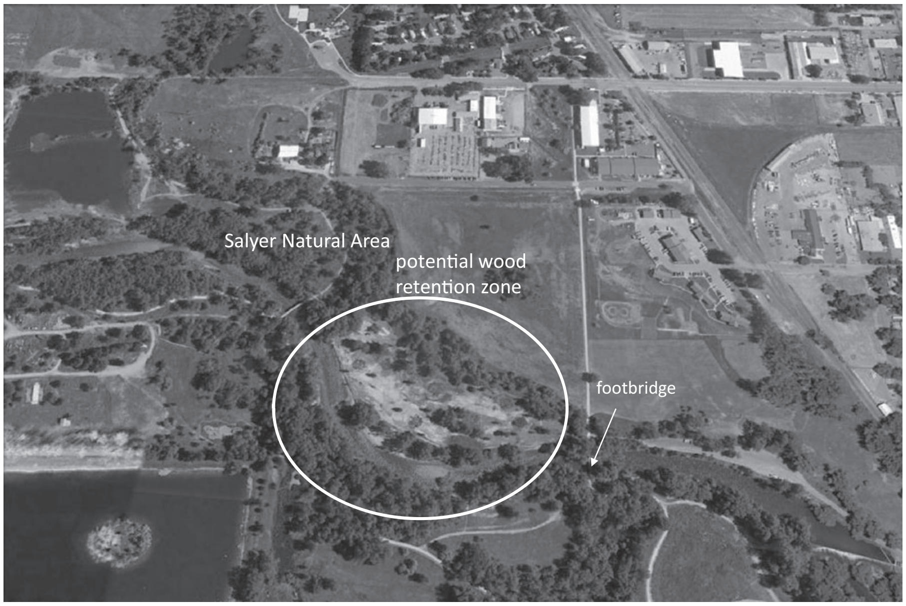


FIGURE 6. Aerial View of the Poudre River within the City of Fort Collins, Colorado. The Salyer Natural Area includes the large gravel bar and riparian woodlands shown in this view. This portion of the river corridor is a zone in which some large wood can likely be retained to provide environmental benefits without adversely affecting downstream structures such as the footbridge identified in this view (image courtesy of Google Earth).

because of the ability of standing floodplain trees to trap the downed wood. Once a year, or after a large flood, staff from the City's stormwater utilities and natural areas programs can visit the site and use the checklist (Tool 1) to assess each piece of wood present. Any wood pieces not identified for immediate removal can then be assessed using Tools 2, 3, and 4. Tool 3, the decision bands, can be readily used while in the field, whereas Tools 2 (Large Wood Structure Stability Analysis) and 4 (Multicriteria Decision Analysis) require access to a computer. The choice of tools to use after Tool 1 will reflect the users' perception of the likelihood that a wood piece will move. A wood piece firmly attached to the soil via an embedded rootwad and trapped between standing trees, for example, likely does not require the time and effort involved in using Tools 2 and 4, but may be readily assessed using Tool 3. Subsequent site visits to monitor wood pieces that are retained can involve simply using Tool 1 to assess whether retained pieces have changed their position, or using Tools 2, 3, and/or 4 to further assess piece stability if the retained wood has moved.

CONCLUDING REMARKS

The assessment procedure that we outline in this article was developed based on meetings in the field with staff from the City of Fort Collins and Boulder County, both in Colorado. We used these meetings to understand the needs of river managers and to refine the tools proposed here. The tools were revised and streamlined based on feedback from these meetings, but lack of subsequent wood recruitment in the area has limited our ability to directly test the proposed assessment procedure. Testing is likely to require a period of a few years, with retained or modified wood pieces subjected to varying flows through time.

We suggest that any decision to retain large wood should be coupled with ongoing monitoring. Monitoring can be used to reevaluate large wood benefits and hazards if conditions at a site, such as bed elevation or channel cross-sectional area change as part of the natural dynamics of a river. Monitoring can also be a key component of ongoing refinement of hazard assessment. As with any form of river restoration or management, detailed monitoring of individual wood pieces or logjams within a limited length of channel should be undertaken with recognition of the watershed context. Potential influences from tributaries and upstream and downstream portions of the river should be considered when assessing benefits and hazards associated with wood, and the abundance of wood within the channel and floodplain can influence the benefits and hazards associated with any individual piece. A single piece of wood in a wood-impoverished channel is unlikely to create substantial hazards, for example, but may produce notable biological benefits.

The procedures outlined here should be implemented by experienced, interdisciplinary teams. We recommend that annual field assessments are performed by the same team each year and that one of the team members is a Professional Engineer. The weights that we tentatively suggest in the decision bands can also be adjusted based on stakeholder input, environmental conditions, or other specific user needs.

There is also the potential to adapt this framework into a cellphone or tablet application that would allow merging data real time during a field inspection. Such an application could integrate the decision tools, such as the checklist in Figure 4, with automatic linking to field notes and other items such as maps, GPS coordinates for large wood, channel features, photos, and video.

The procedures outlined here represent a more nuanced approach to managing large wood in river systems than automatically removing all wood. However, managers in some regions of the U.S. are being more proactive than simply considering retaining naturally recruited large wood. Managers in the U.S. Pacific Northwest, in particular, are now actively adding individual wood pieces as well as engineered logjams to channels because of the recognized physical and ecological benefits of large wood (Abbe and Brooks, 2011; Gallisdorfer *et al.*, 2014). Lawrence *et al.* (2013) and Jones *et al.* (2014) review some of these restoration projects and the success of the projects in achieving desired restoration of fish habitat and the return of stream channels to a more natural state.

ACKNOWLEDGMENTS

We thank the Colorado State University Water Center and Warner College of Natural Resources, as well as the City of Fort Collins Natural Areas for funding to support the development of this report. Discussions with City of Fort Collins Natural Areas and Stormwater Utilities staff and with Boulder County Parks and Open Space staff provided helpful guidance and feedback. The article benefited by comments from three anonymous reviewers and Associate Editor Faith Fitzpatrick.

LITERATURE CITED

Abbe, T. and A. Brooks, 2011. Geomorphic, Engineering, and Ecological Considerations When Using Wood in River Restoration. *In*: Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools, A. Simon, S.J. Bennett, and J.M. Castro (Editors). American Geophysical Union Press, Washington, D.C., pp. 419-451.

Abbe, T., L. Embertson, J. Bruzgul, and K. Maher, 2014. Risk Considerations. Draft chapter prepared for Large Wood National Manual: Guidelines for Planning, Design, Placement and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function and Structure, US Army Corps of Engineers and Bureau of Reclamation, January 2014 Technical Review Draft.

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

Angermeier, P.L. and J.R. Karr, 1984. Relationships between Woody Debris and Fish Habitat in a Small Warmwater Stream. Transactions of the American Fisheries Society 113:716-726.

Arrigoni, A.S., G.C. Poole, L.A.K. Mertes, S.J. O'Daniel, W.W. Woessner, and S.A. Thomas, 2008. Buffered, Lagged, or Cooled? Disentangling Hyporheic Influences on Temperature Cycles in Stream Channels. Water Resources Research 44:W09418, DOI: 10.1029/2007WR006480.

Battin, T.J., L.A. Kaplan, S. Findlay, C.S. Hopkinson, E. Marti, A.I. Packman, J.D. Newbold, and F. Sabater, 2008. Biophysical Controls on Organic Carbon Fluxes in Fluvial Networks. Nature Geoscience 1:95-100.

Baxter, C.V. and F.R. Hauer, 2000. Geomorphology, Hyporheic Exchange, and Selection of Spawning Habitat by Bull Trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences 57:1470-1781.

Beckman, N.D. and E. Wohl, 2014a. Carbon Storage in Mountainous Headwater Streams: The Role of Old-Growth Forest and Logjams. Water Resources Research 50:2376-2393.

Beckman, N.D. and E. Wohl, 2014b. Effects of Forest Stand Age on the Characteristics of Logjams in Mountainous Forest Streams. Earth Surface Processes and Landforms 39:1421-1431.

Benjamin, J.R., K.D. Fausch, and C.V. Baxter, 2011. Species Replacement by a Nonnative Salmonid Alters Ecosystem Function by Reducing Prey Subsidies That Support Riparian Spiders. Oecologia 167:503-512.

Benke, A.C., 2001. Importance of Flood Regime to Invertebrate Habitat in an Unregulated River-Floodplain Ecosystem. Journal of the North American Benthological Society 20:225-240.

Benke, A.C. and J.B. Wallace, 1990. Wood Dynamics in Coastal Plain Backwater Streams. Canadian Journal of Fisheries and Aquatic Sciences 47:92-99.

Benke, A.C. and J.B. Wallace, 2003. Influence of Wood on Invertebrate Communities in Streams and Rivers. *In*: Ecology and Management of Wood in World Rivers, S.V. Gregory, K.L. Boyer, and A.M. Gurnell (Editors). American Fisheries Society Symposium, Vol. 37, Bethesda, Maryland, pp. 149-177.

Bilby, R.E., 1981. Role of Organic Debris Dams in Regulating the Export of Dissolved and Particulate Matter from a Forested Watershed. Ecology 62:1234-1243.

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

Bocchiola, D., M.C. Rulli, and R. Rosso, 2006. Transport of Large Woody Debris in the Presence of Obstacles. Geomorphology 76:166-178.

Bovee, K.D., 1996. Managing Instream Flows for Biodiversity: A Conceptual Model and Hypotheses. *In*: Proceedings of the Northern River Basins Study. NRBS Project Report No. 66, Quebec, Canada, pp. 83-100.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Heriksen, 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology. Information and Technology Report. U.S. Geological Survey, Biological Resources Division, Fort Collins, Colorado, USGS/BRD/ITR-1998-0004.

Boys, C.A. and M.C. Thoms, 2006. A Large-Scale, Hierarchical Approach for Assessing Habitat Associations of Fish Assemblages in Large Dryland Rivers. Hydrobiologia 572:11-31.

Braccia, A. and D.P. Batzer, 2001. Invertebrates Associated with Woody Debris in a Southeastern U.S. Forested Floodplain Wetland. Wetlands 21:18-31.

Braudrick, C.A. and G.E. Grant, 2000. When Do Logs Move in Rivers? Water Resources Research 36:571-583.

Braudrick, C.A. and G.E. Grant, 2001. Transport and Deposition of Large Woody Debris in Streams: A Flume Experiment. Geomorphology 41:263-283.

Braudrick, C.A., G.E. Grant, Y. Ishikawa, and H. Ikeda, 1997. Dynamics of Wood Transport in Streams: A Flume Experiment. Earth Surface Processes and Landforms 22:669-683.

Brooks, A.P., G.J. Brierley, and R.G. Millar, 2003. The Long-Term Control of Vegetation and Woody Debris on Channel and Flood-Plain Evolution: Insights from a Paired Catchment Study in Southeastern Australia. Geomorphology 51:7-29.

Brooks, A.P., P.C. Gehrke, and J.D. Jansen, 2004. Experimental Reintroduction of Woody Debris on the Williams River, NSW: Geomorphic and Ecological Responses. River Research and Applications 20:513-536.

Brooks, A.P., T. Howell, T.B. Abbe, and A.H. Arthington, 2006. Confronting Hysteresis: Wood Based River Rehabilitation in Highly Altered Riverine Landscapes in South-Eastern Australia. Geomorphology 79:395-422.

Brummer, C.J., 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., T.E. Lisle, R.D. Woodsmith, and S. Hilton, 2002. Controls on the Size and Occurrence of Pools in Coarse-Grained Forest Rivers. River Research and Applications 18:507-531.

Chee, Y.E., 2004. An Ecological Perspective on the Valuation of Ecosystem Services. Biological Conservation 120:549-565.

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

Chow, V.T., 1959. Open Channel Hydraulics, McGraw-Hill, New York City, New York.

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

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

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

Comiti, F., 2012. How Natural Are Alpine Mountain Rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms 37:693-707.

Crook, D.A. and A.I. Robertson, 1999. Relationships between Riverine Fish and Woody Debris: Implications for Lowland Rivers. Marine and Freshwater Research 50:9441-9953.

Curran, J.H. and E.E. Wohl, 2003. Large Woody Debris and Flow Resistance in Step-Pool Channels, Cascade Range, Washington. Geomorphology 51:141-157.

Daniels, M.D. and B.L. Rhoads, 2004. Effect of Large Woody Debris Configuration on Three-Dimensional Flow Structure in Two Low-Energy Meander Bends at Varying Stages. Water Resources Research 40, DOI: 10.1029/2004WR003181.

Davidson, S.L. and B.C. Eaton, 2013. Modeling Channel Morphodynamic Response to Variations in Large Wood: Implications for Stream Rehabilitation in Degraded Watersheds. Geomorphology 202:59-73.

Erskine, W.D. and A.A. Webb, 2003. Desnagging to Resnagging: New Directions in River Rehabilitation in Southeastern Australia. River Research and Applications 19:233-249.

Falke, J.A. and K.D. Fausch, 2010. From Metapopulations to Metacommunities: Linking Theory with Empirical Observations of the Spatial Population Dynamics of Stream Fishes. American Fisheries Society Symposium 73:207-233.

Fausch, K.D., 1984. Profitable Stream Positions for Salmonids: Relating Specific Growth Rate to Net Energy Gain. Canadian Journal of Zoology 62:441-451.

Fausch, K.D., 1993. Experimental Analysis of Microhabitat Selection by Juvenile Steelhead (*Oncorhynchus mykiss*) and Coho Salmon (*O. kisutch*) in a British Columbia Stream. Canadian Journal of Fisheries and Aquatic Sciences 50:1198-1207.

Fausch, K.D., 2014. A Historical Perspective on Drift Foraging Models for Stream Salmonids. Environmental Biology of Fishes 97:453-464.

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li, 2002. Landscapes to Riverscapes: Bridging the Gap between Research and Conservation of Stream Fishes. BioScience 52:483-498.

Faustini, J.M. and J.A. Jones, 2003. Influence of Large Woody Debris on Channel Morphology and Dynamics in Steep, Boulder-Rich Mountain Streams, Western Cascades, Oregon. Geomorphology 51:187-205.

FHWA (Federal Highway Administration), 2005. Debris Control Structures Evaluation and Countermeasures. Hydraulic Engineering Circular No. 9. Publication No. FHWA-IF-04-016. http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/, *accessed* September 2015.

FHWA (Federal Highway Administration), 2014. Letter of Map Revision. https://www.fema.gov/national-flood-insurance-program-2/letter-map-revision, *accessed* September 2015.

Fischer, H., F. Kloep, S. Wilzcek, and M.T. Pusch, 2005. A River's Liver: Microbial Processes within the Hyporheic Zone of a Large Lowland River. Biogeochemistry 76:349-371.

Flores, L., J.R. Díez, A. Larrañaga, C. Pascoal, and A. Elosegi, 2013. Effects of Retention Site on Breakdown of Organic Matter in a Mountain Stream. Freshwater Biology 58:1267-1278.

Flores, L., A. Larrañaga, J.R. Díez, and A. Elosegi, 2011. Experimental Wood Addition in Streams: Effects on Organic Matter Storage and Breakdown. Freshwater Biology 56:2156-2167.

Francis, R.A., G.E. Petts, and A.M. Gurnell, 2008. Wood as a Driver of Past Landscape Change along River Corridors. Earth Surface Processes and Landforms 33:1622-1626.

Gallisdorfer, M.S., S.J. Bennett, J.F. Atkinson, S.M. Ghaneeizad, A.P. Brooks, A. Simon, and E.J. Langendoen, 2014. Physical-Scale Model Designs for Engineered Log Jams in Rivers. Journal of Hydro-Environment Research 8:115-128.

Ghanem, A., P. Steffler, and F. Hicks, 1996. Two-Dimensional Hydraulic Simulation of Physical Habitat Conditions in Flowing Streams. Regulated Rivers: Resource and Management 12:185-200.

Gooseff, M.N., R.O. Hall, and J.L. Tank, 2007. Relating Transient Storage to Channel Complexity in Streams of Varying Land Use in Jackson Hole. Wyoming. Water Resources Research 43: W01417, DOI: 10.1029/2005WR004626.

Gowan, C. and K.D. Fausch, 1996. Long-Term Demographic Responses of Trout Populations to Habitat Manipulation in Six Colorado Streams. Ecological Applications 6:931-946.

Gurnell, A.M., W. Bertoldi, and D. Corenblit, 2012. Changing River Channels: The Roles of Hydrological Processes, Plants and Pioneer Fluvial Landform in Humid Temperate, Mixed Load, Gravel Bed Rivers. Earth-Science Reviews 111:129-141.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, J.R. Cromack, and K.W. Cummins,

1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. Advances in Ecological Research 15:133-302.

Howell, T.J., B. Pusey, A. Arthington, A.P. Brooks, R. Creese, and J. Chaseling, 2012. Responses of Fish to Experimental Introduction of Structural Woody Habitat in Riffles and Pools of the Hunter River, New South Wales, Australia. Restoration Ecology 20:43-55.

Jones, K.K., K. Anlauf-Dunn, P.S. Jacobsen, M. Strickland, L. Tennant, and S.E. Tippery, 2014. Effectiveness of Instream Wood Treatments to Restore Stream Complexity and Winter Rearing Habitat for Juvenile Coho Salmon. Transactions, American Fisheries Society 143:334-345.

Kasahara, T. and S.M. Wondzell, 2003. Geomorphic Controls on Hyporheic Exchange Flow in Mountain Streams. Water Resources Research 39, DOI: 10.1029/2002WR001386.

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.

Kiker, G.A., T.S. Bridges, I. Linkov, A. Varghese, and T. Seager, 2005. Application of Multi-Criteria Decision Analysis in Environmental Decision-Making. Integrated Environmental Assessment and Management 1(2):1-14.

Klaar, M.J., D.F. Hill, I. Maddock, and A.M. Milner, 2011. Interactions between Instream Wood and Hydrogeomorphic Development within Recently Degraded Streams in Glacier Bay National Park, Alaska. Geomorphology 130:208-220.

Lagasse, P.F., P.E. Clopper, J.E. Pagan-Ortiz, L.W. Zeverbergen, L.A. Arneson, J.D. Schall, and L.G. Girard, 2009. Bridge Scour and Stream Stability Countermeasures (Third Edition, Vols. 1 and 2), HEC-23, FHWA-NHI-09-111, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Lagasse, P.F., L.W. Zevenbergen, W.J. Spitz, and L.A. Arneson, 2012. Stream Stability at Highway Structures (Fourth Edition), HEC-20, FHWA-HIF-12-004, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Lawrence, J.E., V.H. Resh, and M.R. Cover, 2013. Large-Wood Loading from Natural and Engineered Processes at the Watershed Scale. River Research and Applications 29:1030-1041.

Lehane, B.M., P.S. Giller, J. O'halloran, C. Smith, and J. Murphy, 2002. Experimental Provision of Large Woody Debris in Streams as a Trout Management Technique. Aquatic Conservation-Marine and Freshwater Ecosystems 12:289-311.

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

Malcolm, I.A., C. Soulsby, A.F. Youngson, D.M. Hannah, I.S. McLaren, and A. Thorne, 2004. Hydrological Influences on Hyporheic Water Quality: Implications for Salmon Egg Survival. Hydrological Processes 18:1543-1560.

Massong, T.M. and D.R. Montgomery, 2000. Influence of Sediment Supply, Lithology, and Wood Debris on the Distribution of Bedrock and Alluvial Channels. Geological Society of America Bulletin 112:591-599.

Mazzorana, B., F. Comiti, and S. Fuchs, 2013. A Structured Approach to Enhance Flood Hazard Assessment in Mountain Streams. Natural Hazards 67:991-1009.

Mazzorana, B., H. Hübl, A. Zischg, and A. Largiader, 2011. Modelling Woody Material Transport and Deposition in Alpine Rivers. Natural Hazards 56:425-449.

Mazzorana, B., A. Zischg, A. Largiader, and J. Hübl, 2009. Hazard Index Maps for Woody Material Recruitment and Transport in Alpine Catchments. Natural Hazards and Earth System Sciences 9:197-209.

Montgomery, D.R., 1997. River Management: What's Best on the Banks? Nature 388:328-329.

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

Mutz, M., 2003. Hydraulic Effects of Wood in Streams and Rivers. *In*: The Ecology and Management of Wood in World Rivers, S.V. Gregory, K.L. Boyer, and A.M. Gurnell (Editors). American Fisheries Society, Bethesda, Maryland, pp. 93-107.

Nagayama, S., F. Nakamura, Y. Kawaguchi, and D. Nakano, 2012. Effects of Configuration of Instream Wood on Autumn and Winter Habitat Use by Fish in a Large Remeandering Reach. Hydrobiologia 680:159-170.

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.

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.

Paskoff, P.F., 2007. Troubled Waters: Steamboat Disasters, River Improvements, and American Public Policy, 1821-1860, Louisiana State University Press, Baton Rouge, Louisiana.

Pettit, N.E. and R.J. Naiman, 2006. Flood-Deposited Wood Creates Regeneration Niches for Riparian Vegetation on a Semi-Arid South African River. Journal of Vegetation Science 17:615-624.

Piégay, H., K.J. Gregory, V. Bondarev, A. Chin, N. Dahlstrom, A. Elosegi, S.V. Gregory, V. Joshi, M. Mutz, M. Rinaldi, B. Wyzga, and J. Zawiejska, 2005. Public Perception as a Barrier to Introducing Wood in Rivers for Restoration Purposes. Environmental Management 36(5):665-674.

Pomerol, J.C. and S.B. Romero, 2000. Multicriterion Decision in Management: Principles and Practice, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Rafferty, M., 2013. Development of a Computational Design Tool for Evaluating the Stability of Large Wood Structures Proposed for Stream Enhancement. M.S. Independent Study, Colorado State University, Fort Collins, Colorado. http://www.engr.colostate.edu/~bbledsoe/streamtools, *accessed* September 2015.

Raikow, D.F., S.A. Grubbs, and K.W. Cummins, 1995. Debris Dam Dynamics and Coarse Particulate Organic Matter Retention in an Appalachian Mountain Stream. Journal of the North American Benthological Society 14:535-546.

Reuss, M., 2004. Designing the Bayous: The Control of Water in the Atchafalaya Basin, 1800-1995, Texas A & M University Press, College Station, Texas.

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.

Roni, P., 2003. Responses of Benthic Fishes and Giant Salamanders to Placement of Large Woody Debris in Small Pacific Northwest Streams. North American Journal of Fisheries Management 23:1087-1097.

Ruiz-Villanueva, V., E. Blade, M. Sanchez-Jury, B. Marti-Cardona, A. Diez-Herrero, and J.M. Bodoque, 2014b. Two-Dimensional Numerical Modeling of Wood Transport. Journal of Hydroinformatics 16:1077-1096.

Ruiz-Villanueva, V., J.M. Bodoque, A. Diez-Herrero, and E. Bladé, 2014a. Large Wood Transport as Significant Influence on Flood Risk in a Mountain Village. Natural Hazards 74:967-987, DOI: 10.1007/s11069-014-122-4.

Sawyer, A.H. and M.B. Cardenas, 2012. Effect of Experimental Wood Addition on Hyporheic Exchange and Thermal Dynamics in a Losing Meadow Stream. Water Resources Research 48: W10537, DOI: 10.1029/2011WR011776.

Sawyer, A.H., M.B. Cardenas, and J. Buttles, 2011. Hyporheic Exchange Due to Channel-Spanning Logs. Water Resources Research 47:W08502, DOI: 10.1029/2011WR010484.

Sawyer, A.H., M.B. Cardenas, and J. Buttles, 2012. Hyporheic Temperature Dynamics and Heat Exchange Near Channel-Spanning Logs. Water Resources Research 48:W01529, DOI: 10.1029/2011WR011200.

Schama, S., 1995. Landscape and Memory, Alfred A. Knopf, New York City, New York.

Schlosser, I.J., 1991. Stream Fish Ecology: A Landscape Perspective. BioScience 41:704-712.

Schmocker, L. and W.H. Hager, 2011. Probability of Drift Blockage at Bridge Decks. ASCE Journal of Hydraulic Engineering 137:470-479.

Schmocker, L. and V. Weitbrecht, 2013. Driftwood: Risk Analysis and Engineering Measures. ASCE Journal of Hydraulic Engineering 139:683-695.

Schneider, R.L. and R.R. Sharitz, 1988. Hydrochory and Regeneration in a Bald Cypress/Water Tupelo Swamp Forest. Ecology 69:1055-1063.

Schowalter, T.D., Y.L. Zhang, and T.E. Sabin, 1998. Decomposition and Nutrient Dynamics of Oak (*Quercus* spp.) Logs After Five Years of Decomposition. Ecography 21:3-10.

Sechnick, C.W., R.F. Carline, R.A. Stein, and E.T. Rankin, 1986. Habitat Selection by Smallmouth Bass in Response to Physical Characteristics of a Simulated Stream. Transactions of the American Fisheries Society 115:314-321.

Sedell, J.R., F.N. Leone, and W.S. Duval, 1991. Water Transportation and Storage of Logs. *In*: Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W.R. Meehan (Editor). American Fisheries Society Symposium, Vol. 19, Bethesda, Maryland, pp. 325-368.

Shields, F.D. and C.J. Gippel, 1995. Prediction of Effects of Woody Debris Removal on Flow Resistance. Journal of Hydraulic Engineering 121:341-354.

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.

Shuler, S.W. and N.B. Nehring, 1993. Using the Physical Habitat Simulation Model to Evaluate a Stream Habitat Enhancement Project. Rivers 4:175-193.

Slaght, J.C., S.G. Surmach, and R.J. Gutierrez, 2013. Riparian Old-Growth Forests Provide Critical Nesting and Foraging Habitat for Blakiston's Fish Owl *Bubo Blakistoni* in Russia. Oryx 47:553-560.

Stalnaker, C.B., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow, 1995. The Instream Flow Incremental Methodology: A Primer for IFIM. Biological Report 29. National Biological Service, Fort Collins, Colorado.

Stanley, E.H. and A.J. Boulton, 1993. Hydrology and the Distribution of Hyporheos: Perspectives from Mesic Rivers and Desert Streams. Journal of the North American Benthological Society 12:79-83.

Stewart, G., R. Anderson, and E. Wohl, 2005. Two-Dimensional Modelling of Habitat Suitability as a Function of Discharge on Two Colorado Rivers. River Research and Applications 21:1061-1074.

Stofleth, J., F.D. Shields, Jr., and G.A. Fox, 2008. Hyporheic and Total Hydraulic Retention in Small Sand-Bed Streams. Hydrologic Processes 22:1885-1894.

Suedel, B.C., K. Burks-Copes, J. Kim, and K. McKay, 2011. Using Multi-Criteria Decision Analysis to Support Ecosystem Restoration Planning. U.S. Army Engineer Research and Development Center, EMRRP Technical Notes Collection, ERDC TN-EMRRP-EBA-7, Vicksburg, Mississippi.

Swanson, F.J., G.W. Lienkaemper, and J.R. Sedell, 1976. History, Physical Effects, and Management Implications of Large Organic Debris in Western Oregon Streams. USDA Forest Service General Technical Report PNW-56, Portland, Oregon.

Thorne, C.R., J. Castro, B. Cluer, P. Skidmore, and C. Shea, 2015. Project Risk Screening Matrix for River Management and Restoration. River Research and Applications 31:611-626.

Trainor, A.M., T.S. Shenk, and K.R. Wilson, 2007. Characteristics of Preble's Meadow Jumping Mouse Micro-Habitat Use in Colorado. Journal of Wildlife Management 71:469-477.

Trainor, A.M., T.S. Shenk, and K.R. Wilson, 2012. Spatial, Temporal, and Biological Factors Associated with Preble's Meadow Jumping Mouse (*Zapus hudsonius preblei*) Home Range. Journal of Mammalogy 93:429-438.

Triska, F.J., 1984. Role of Wood Debris in Modifying Channel Geomorphology and Riparian Areas of a Large Lowland River under Pristine Conditions: A Historical Case Study. Verhandlungen des Internationalen Verein Limnologie 22:1876-1892.

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

White, S.L., C. Gowan, K.D. Fausch, J.G. Harris, and W.C. Saunders, 2011. Response of Trout Populations in Five Colorado Streams Two Decades after Habitat Manipulation. Canadian Journal of Fisheries and Aquatic Sciences 68:2057-2063.

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

Wilcox, A.C., J.M. Nelson, and E.E. Wohl, 2006. Flow Resistance Dynamics in Step-Pool Channels: 2. Partitioning between Grain, Spill, and Woody Debris Resistance. Water Resources Research 42:W05419, DOI: 10.1029/2005WR004278.

Williams, D.D., 1993. Changes in Freshwater Meiofauna Communities along the Groundwater-Hyporheic Water Ecotone. Transactions of the American Microscopical Society 112:181-194.

Wohl, E., 2001. Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range, Yale University Press, New Haven, Connecticut.

Wohl, E., 2011. Threshold-Induced Complex Behavior of Wood in Mountain Streams. Geology 39:587-590.

Wohl, E., 2014. A Legacy of Absence: Wood Removal in U.S. Rivers. Progress in Physical Geography 38:637-663.

Wohl, E. and J.R. Goode, 2008. Wood Dynamics in Headwater Streams of the Colorado Rocky Mountains. Water Resources Research 44:W09429, DOI: 10.1029/2007WR006522.

Wohl, E., L.E. Polvi, and D. Cadol, 2011. Wood Distribution along Streams Draining Old-Growth Floodplain Forests in Congaree National Park, South Carolina, USA. Geomorphology 126:108-120.

Wondzell, S.M., 2006. Effect of Morphology and Discharge on Hyporheic Exchange Flows in Two Small Streams in the Cascade Mountains of Oregon, USA. Hydrological Processes 20:267-287.

Zalamea, M., G. Gonzalez, C.L. Ping, and G. Michaelson, 2007. Soil Organic Matter Dynamics under Decaying Wood in a Subtropical Wet Forest: Effect of Tree Species and Decay Stage. Plant and Soil 296:173-185.