Management of Large Wood in Streams of Colorado's Front Range:

A Risk Analysis Based on Physical, Biological, and Social Factors

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COMPLETION REPORT

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Abstract

Instream and floodplain wood can provide many benefits to river ecosystems, but can also create risks to inhabitants, infrastructure, property, and recreational users in the river corridor. In this report we outline a decision process for managing large wood, and particularly for assessing the relative benefits and risks 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 of whether 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 might require removal in a highly urbanized setting, for example, but provide sufficient benefits to justify retention in a natural area. Our intent is that the decision process outlined here can be used by individuals with diverse technical backgrounds and in a range of urban to natural river reaches.

Keywords: large wood, Front Range rivers, hazards, environmental benefits, recreational users

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I. 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 very 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 currently have little wood compared to their condition prior to European settlement of the United States. Historical descriptions of the entire spectrum of rivers across the country, 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 downed wood was present within channels and across floodplains (Triska, 1984; Harmon et al., 1986; Collins et al., 2002; Wohl, 2014). One of the first activities of European settlers in forested regions was to remove 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. Congress made appropriations to remove wood from rivers as early as 1776 (Harmon et al., 1986) and individuals or small groups of people began wood removal even earlier. In 1824, Congress assigned the 'improvement' of inland rivers to the U.S. Army Corps of Engineers (Reuss, 2004). Much of this improvement focused on removing wood.

Direct removal 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 wood to channels, but also via: channelization (dredging, straightening, bank stabilization) that removed existing wood and reduced the ability of a river to retain subsequently recruited wood; log floating in association with timber harvest, which included removing naturally occurring instream wood, as well as cut logs; and flow regulation, which limited downstream transport of wood. The net effect of these activities was to remove almost all instream and floodplain wood, typically prior to the 20th century (Wohl, 2001). Consequently, most people do not expect downed wood to be abundant in the riverine environment (Chin et al., 2008), and so are not accustomed to seeing the elements that make up a naturally functioning river flowing through a forested region.

Extensive September 2013 rain and post-storm flooding in northern Colorado resulted in abundant wood in river channels and floodplains of streams originating in the Front Range. This event motivated us to seek a dialogue with municipalities and managers of these streams to consider leaving some wood in streams and floodplains, because wood is a natural landscape feature with high ecological benefit. However, large wood in rivers also poses risks to human infrastructure and safety. Current practices involve automatically removing all large wood from Front Range rivers. Under this approach, there is no systematic evaluation of benefits and risks and managers do not differentiate between wood that creates hazards and wood that creates little or no risk. Wood that creates little or no risk is removed at the expense of ecological benefits that might result from this wood. Wood deposited during the September 2013 flood, for example, was almost universally perceived as a risk to infrastructure and safety, irrespective of the actual location and condition of the wood. This underscored the need for a risk assessment framework that managers can use to systematically and transparently weigh multiple considerations, including safety, infrastructure, recreation, and ecological aspects of wood.

In this paper, we describe a process that managers can use to evaluate the risks and benefits of instream wood. We first discuss the benefits and risks associated with large wood in channels and on floodplains regarding the physical and biological processes occurring within river environments, as well as public safety. For example, potential risk to humans and infrastructure created by wood is a primary motivation for managers to remove wood. We then present a check-list based decision-making and risk-assessment process for managers to evaluate the merits of keeping or removing individual pieces of wood or jams. This section describes wood treatment options that may reduce risk and tools to measure stability and habitat created by wood left in the channel or floodplain. Decision bands allow managers to further evaluate merits and risks of retaining or adding wood to a stream reach.

Our aim is to offer a straightforward management procedure that incorporates realistic analysis of human and infrastructure risk, but also integrates the ecological benefit of 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 river systems in settings with high human use.

II. Benefits and Risks Associated with Large Wood

This section provides a discussion of the benefits and risks that result from the presence of large wood in channels and on floodplains. We first discuss the beneficial effects of wood on the movement of water and sediment at the surface and within the hyporheic zone (shallow subsurface) that is present beneath the bed of river systems. This is followed by discussion of the biological benefits of wood for fish, stream invertebrates, and other aquatic and terrestrial invertebrates and vertebrates. The final portion discusses public safety considerations associated with wood, in the context of hazard to inhabitants and infrastructure within the river system and to recreational users of the river environment.

1. Physical Benefits of Large Wood

The physical benefits of large wood result from the interaction of wood with water and sediment moving down the channel. The magnitude of the effects that result from these interactions largely depends on the orientation and stability of the wood and on the volume of wood within the channel relative to the cross-sectional area of the channel (Klaar et al., 2011). A single piece of wood within a large channel will have only very local effects, whereas a large jam that spans a channel can influence process and form along an entire channel reach. 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). This reduces average flow velocity (Daniels and Rhoads, 2004; Davidson and Eaton, 2013), which can in turn lead to slower passage of flood waves and 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).

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). Larger wood obstructions, such as jams, typically 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). Wood on floodplains provides substrate and cover for a range of organisms, including aquatic types that prefer 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, amphibians and reptiles that use the wood for feeding or nesting sites (Harmon et al., 1986).

The influence of wood on the geomorphic form of stream and river channels commonly results in increased roughness, which 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). The presence of wood that is not contributing to major morphological features influences hyporheic exchange by increasing flow velocities between the wood and bed (Sawyer et al., 2011, 2012), which may have significant implications for stream water temperature dynamics (Sawyer and Cardenas, 2012). Hyporheic zones of streams have been described as analogous to livers for their ability to remove pollutants from stream water (Fischer et al., 2005), thus providing a self-cleansing process to improve water quality. Hyporheic exchange also moderates stream water temperature as a result of interaction with groundwater (Arrigoni et al., 2008).

There is a direct influence of hyporheic exchange on stream aquatic ecosystem condition, habitat, and processes. Hyporheic exchange has been shown to influence selection by spawning fish of nest sites, for example, and 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 of their several life stages (Stanley and Boulton, 1993; Williams, 1993). Hence, instream wood has the potential to significantly impact stream ecosystems through its direct influence on hyporheic exchange.

Finally, instream wood is particularly important because of the variable flow velocities created around wood. Reduction in flow velocity around wood can increase the retention of particulate organic matter that is a fundamental energy source in many stream ecosystems. If finer 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). In addition, large wood commonly traps leaves, sticks, and other plant parts that fall into streams, thereby providing a site for larger macroinvertebrate shredders to begin breaking down this coarse particulate organic matter into finer size fractions that can be used by other organisms (Flores et al., 2011, 2013). Slow as well as fast water velocities created by wood provide a variety of habitat for stream fishes and macroinvertebrates 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.

In contrast to the beneficial physical effects of instream and floodplain wood, removal of wood can create physical risks. Because wood enhances sediment storage, removal of wood and consequent reduced flow resistance and obstruction can result in erosion of stream beds. 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; Erskine and Webb, 2003).

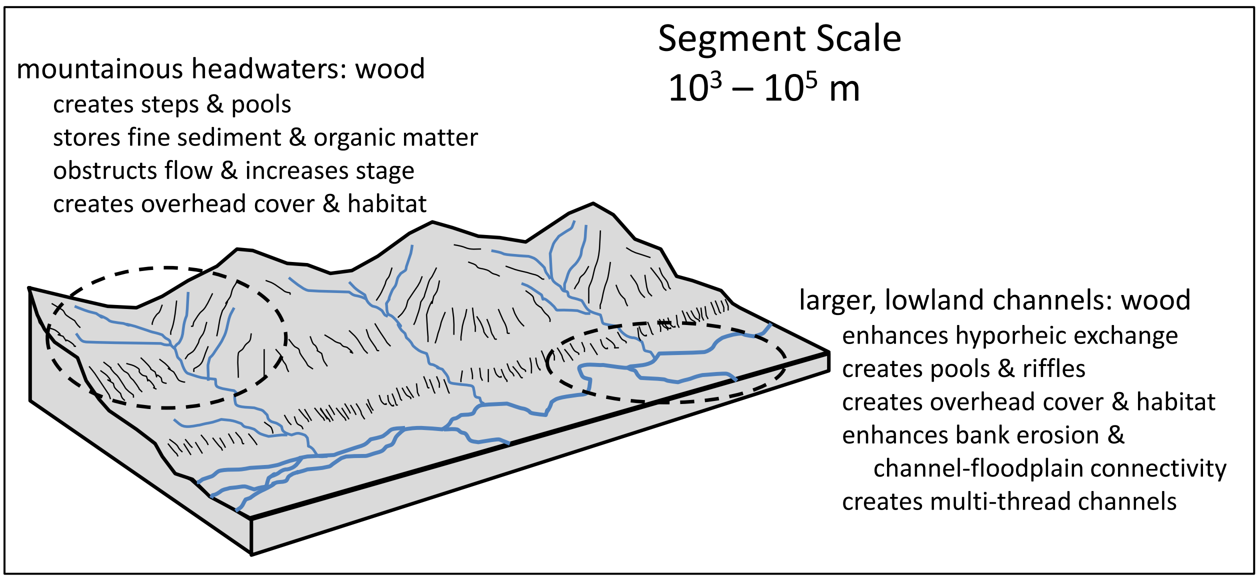

Figure 1A. Schematic illustration of the physical benefits of wood at progressively smaller spatial scales. At stream lengths of 1 to 100 km (10^3 to 10^5 m), known as the segment scale (Fausch et al., 2002), the effects of wood strongly depend on valley geometry and location within a drainage basin. In confined, steep headwater valleys, wood primarily affects channel process and form. In lowland channels with floodplains, wood within the channel also affects the floodplain process and form.

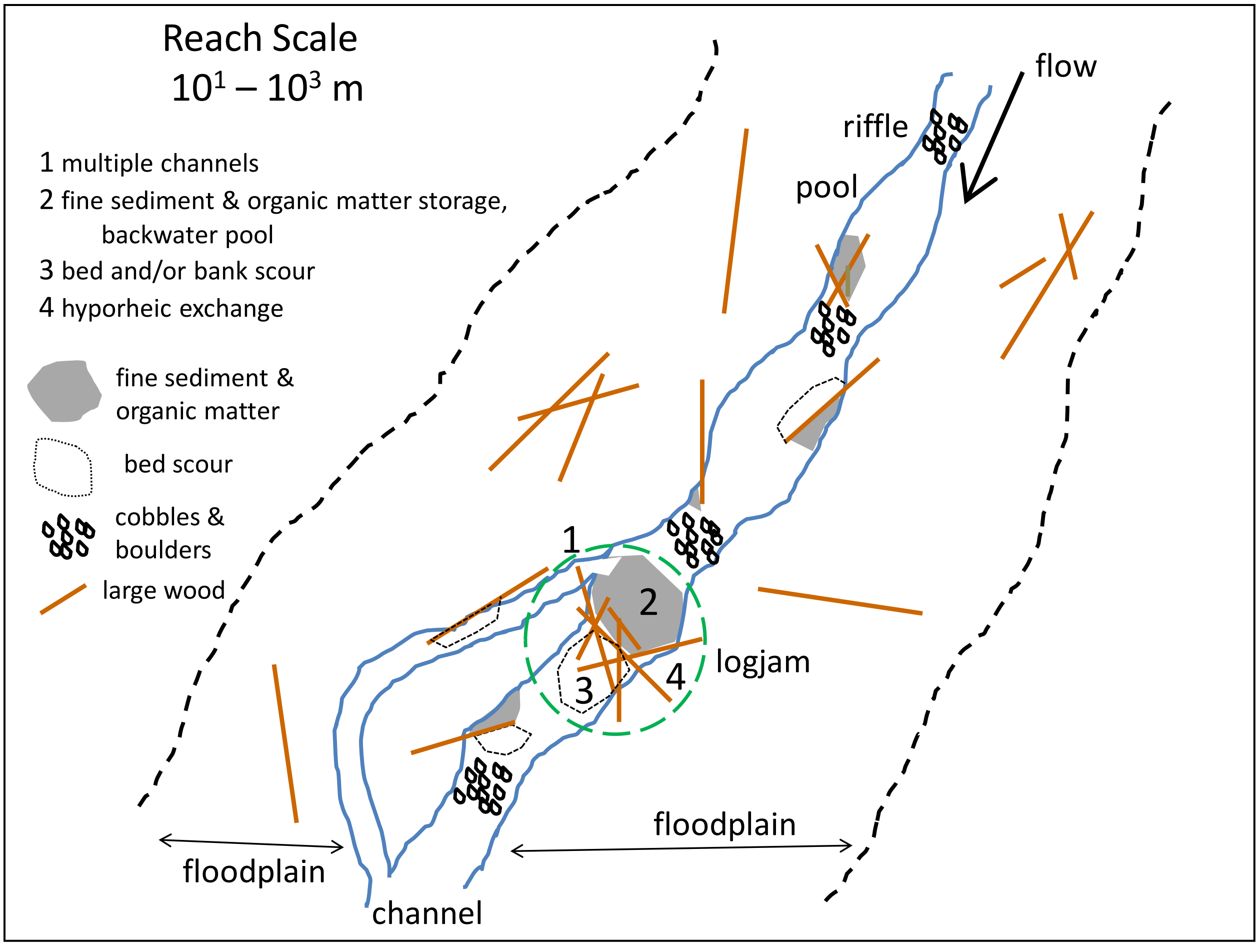

Figure1B. At stream lengths of tens to thousands of meters, known as the reach scale, wood can strongly influence channel planform and morphology. By forming obstructions to flow, logjams can create backwater pools upstream from the jam and plunge pools downstream from the jam, and enhance overbank flows. 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). Wood can also create pressure differentials that drive hyporheic exchange (4), with downwelling into the stream bed upstream from the wood and upwelling from the stream bed downstream from the wood.

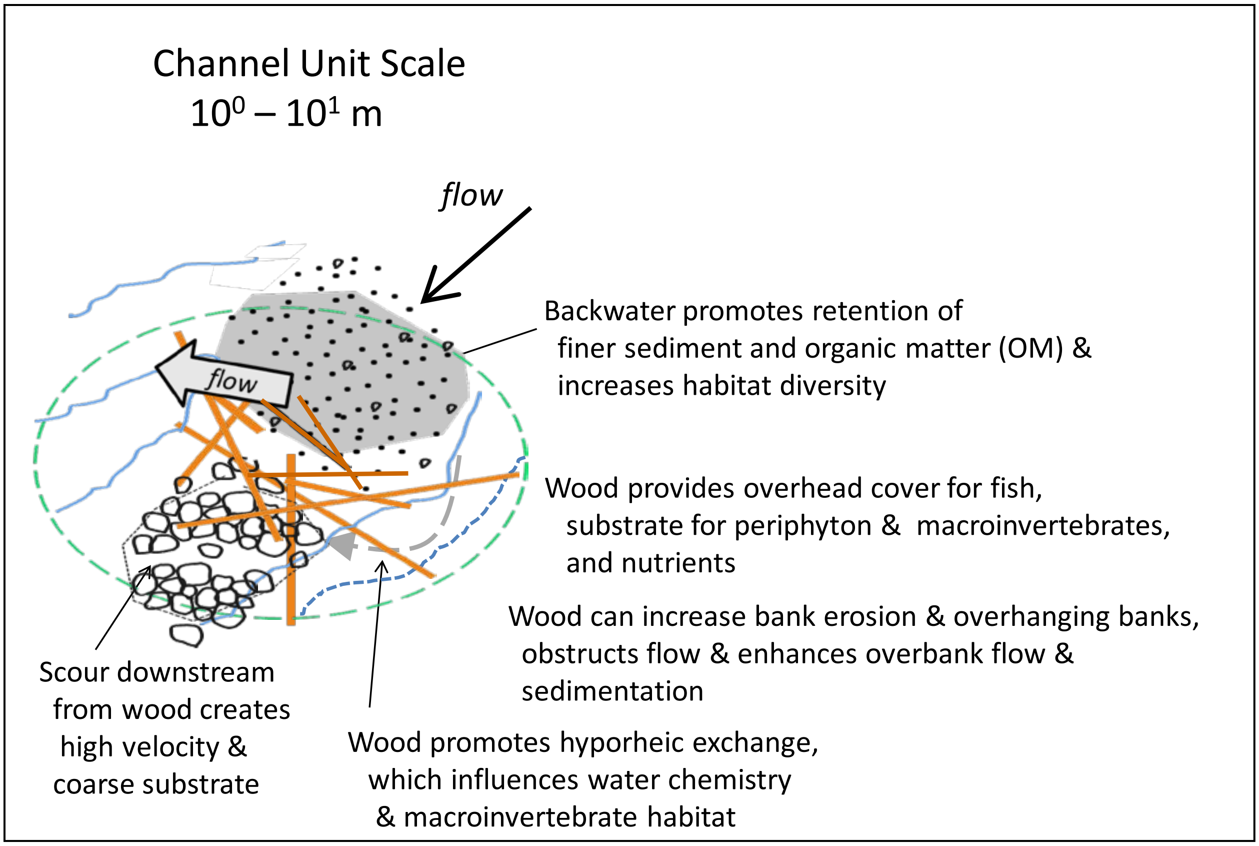

Figure 1C. At stream lengths of a meter to tens of meters, known as the channel unit scale, individual pieces of wood or logjams create the effects described for the reach scale. Among these effects are overhead cover, velocity refuges, and visual isolation, all of which are important to fish (Fausch, 1993) and invertebrates.

2. Biological Benefits of Large Wood

The benefits of large wood to river organisms such as fish and aquatic invertebrates are likely to be of three main types. First, the geomorphic effects of wood on channel structure create pools, runs, and riffles (termed 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 are colonized by aquatic invertebrates that fish eat and hard surfaces that grow algae that these invertebrates eat (Benke and Wallace, 2003). These hard surfaces are particularly scarce in lowland streams that are dominated by silt substrate.

2.1. 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 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, especially in Australia (Crook and Robertson, 1999; Howell et al., 2012) and the southeastern U.S. (Benke and Wallace, 2003). The key points of this research will be emphasized here and placed in the context set by other research on coldwater streams. 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. The transition zone of rivers along Colorado's Front Range, after they exit the mouths of canyons, traverse a transition between coldwater segments that support primarily trout throughout the year to cool- and warmwater segments that support more fish species (often 15-20 species total; Fausch and Bestgen, 1997). Therefore, research on the benefits of wood in both coldwater and warmwater lowland streams are of relevance here.

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 (both percichthyids, related to striped bass *Morone saxitalis*, in North America) were more often associated with patches of large wood than other habitat types, and this was consistent across four segments of different geomorphic character that spanned about 400 km of the Barwon-Darling River (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 relationships are important because 97% of the river length in Australia is in lowland rivers, 83% of which are dryland rivers like those in the lowlands of Colorado.

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. For example, Nagayama et al. (2012) found that an assemblage of coldwater salmon, charr, large minnows, sticklebacks, and lamprey was more abundant and diverse in habitat patches formed by large wood than in patches without wood in a lowland river in Hokkaido, northern Japan. Of interest was that the four dominant species selected patches with wood for different habitat features. The salmon and charr selected locations with high current variability, where they can find low-velocity foraging locations close to swift currents (see Fausch, 1984), whereas the sticklebacks and lamprey require low velocities with fine substrate. Given that fish in streams and rivers worldwide evolved with much higher loads of 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.

Several investigators have used artificial structures to separate the preference of fish for the velocity refuges, visual isolation from other fish, and overhead cover from predators that large wood provides. For example, Fausch (1993) installed artificial structures in a lowland British Columbia stream that isolated these variables, by using clear Plexiglas structures to provide only velocity refuges and then painting parts of them black to create lateral visual isolation or overhead cover. Results of this research and other studies on charr, salmon, and smallmouth bass (6 species total) showed that all responded most strongly to the overhead cover features, but in many cases also selected structures that offered velocity refuges and visual isolation (see Table 1 in Crook and Robertson, 1999). Many lowland rivers are naturally turbid, so the overhead cover and visual isolation features of large wood may be less important there.

2.2. Stream Invertebrates

As for fish, large wood can create habitat conditions favorable to certain groups of aquatic invertebrates, such as pools or backwaters, but can also provide hard substrate for growth of stream algae and subsequent colonization by invertebrates (Benke and Wallace, 2003). Some of these invertebrates scrape algae as a food source, others use the wood as attachment sites from which to filter particles from the water flowing by, and still other taxa gouge and burrow in the wood itself.

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 in low-gradient rivers of the Coastal Plain in the southeastern U.S. showed that large wood in several rivers in Georgia supported a unique assemblage of invertebrates, some of which use it for egg-laying sites (above or below the water), to find refuge from predation, or forage across it themselves for other invertebrate prey. Because animals that colonize stable wood substrates are larger than those on sand and silt, biomass of invertebrates on wood in one southeastern Georgia river was 10-60 times greater per square meter than other bottom substrates and production ($g/m^2/yr$) was more than 4 times higher. Although the surface area of wood pieces made up only 4% of habitat area, wood contained 60% of the invertebrate biomass per lineal meter of river, and produced 70-80% of the numbers and biomass of drifting invertebrate prey. In turn, the biomass in diets of 5 of 6 fish species examined in detail that ate primarily invertebrates (insectivores) consisted of about 45-75% invertebrates that originated from large wood substrates. Other smaller species of fishes (e.g., minnows and darters) not analyzed ate more prey from the bottom substrates, and the abundance of these fish can increase when wood is removed (Angermeier and Karr, 1984).

Across studies, large wood is a hotspot for invertebrate biomass, production, and diversity. Mean annual biomass was higher on wood habitats than in streambed sediments in 6 of 8 studies in lowland streams of the southeastern U.S. and Australia (Benke and Wallace, 2003). Likewise, annual invertebrate (secondary) production was higher on wood in 5 of 6 studies in these same locations. When averaged across surface area of substrates, wood commonly contributed 20% or more of the total numbers of invertebrates and 30-60% of the total biomass of invertebrates in these lowland rivers. Likewise, wood habitat commonly supports more than half the invertebrate species (i.e., diversity) found in rivers like these where it makes up much of the stable substrate, such as in southeastern U.S. rivers with sandy habitats and those in New Zealand with pumice substrates (Benke and Wallace, 2003). As for fish, various experiments adding wood have been conducted and their effects on invertebrates measured. In several cases, abundance and biomass were significantly higher (often by 2-8 times or more) on the added wood, or in habitats created by it, than on other surrounding substrates of sand, gravel, or cobble (e.g., Wallace et al., 1995; Coe et al., 2009).

2.3. Effects of Wood on Other Aquatic and Terrestrial Invertebrates, Vertebrates, and Floodplain Vegetation

Although not considered in detail, large wood in streams and in riparian floodplains may have important effects on other vertebrates and invertebrates, from stream and pond-dwelling amphibians to riparian spiders, reptiles, birds, and small mammals. These groups have received far less study than fish or macroinvertebrates. Roni (2003) reported no detectable effects of large wood placement on giant salamanders (*Dicamptodon* spp.) in paired treatment-control reaches of 29 coastal streams of Washington and Oregon, based on a careful extensive post-treatment study, although lamprey and sculpins (a bottom-dwelling fish) did increase in various ways (e.g., density and growth). Fish owls (*Bubo blakistoni*) in far-eastern Russia 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, their primary prey (Slaght et al., 2013). Small mammals, such as Preble's jumping mouse (*Zapus hudsonius preblei*; listed as Threatened under the Endangered Species Act), also use riparian habitat. Trainor et al. (2007, 2012) reported that this species used habitats close to streams, and detected some evidence that it was associated with large wood, probably because the wood supported both invertebrates and fungi that are food sources. Benjamin et al. (2011, and unpublished data) found that tetragnathid spiders, which live only near and above streams, were especially dense on downed wood that provided web supports directly over the stream, 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 diversity for various species of plants and animals (Harmon et al., 1986).

3. Public Safety Considerations Associated with Large Wood

3.1. Potential Hazards for Inhabitants and Infrastructure

Physical risks 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 risks to people and infrastructure are increased flow stage, altered movement of sediment and patterns of erosion and deposition, and mobile wood.

By increasing resistance and obstructions to flow, wood can create higher water levels for any discharge. This can create overbank flooding hazards along segments of a stream where overbank flow is not desirable. Wood can accumulate at bridges, for example, causing increased scour of piers and abutments or exacerbating upstream flooding. Wood can also block culverts, increasing flooding and eroding roadbeds. Large amounts of wood can potentially raise water elevations above existing regulatory mandates, such as the 100-year flood used for Federal Emergency Management Agency (FEMA) compliance. An indirect effect of wood may be to encourage beavers to build dams that contribute to flooding of adjacent areas.

Because wood alters velocity and sediment transport capacity in its immediate vicinity, the presence of wood can alter localized sediment dynamics. A concentration of wood along one bank can deflect flow toward the opposite bank, for example, accelerating erosion of that bank. Altered sediment dynamics can also result in lateral channel movement across the floodplain or local aggradation or scour, each of which can cause flooding or endanger infrastructure.

Finally, wood within the channel or floodplain can be transported during higher discharges, potentially damaging downstream infrastructure such as bridges or pipelines. Guidelines and methods, including modeling, for assessing the risk of wood to inhabitants and infrastructure are more fully discussed in sections III and IV.

3.2. Potential Hazards for Recreational Users

Concerns regarding instream wood and public safety can also apply to river reaches that are frequently visited for such activities as wildlife viewing, fishing, picnicking, swimming, tubing, boating, hiking, walking and jogging, among others. Some instream wood is a risk to recreational users in the channel as strainers or foot entrapment hazards (see glossary for definition of these terms). However, instream wood can also make a reach safer for recreational users by providing zones of lower velocity and opportunities to rest, regroup or escape. It is important to realize that the same piece of wood can be more or less of a risk to recreational users depending on individual skill and prior knowledge about the wood. What follows is a discussion of potential factors which increase or decrease the level of risk that instream wood has on the safety of recreational users. Eight categories are discussed: access, reach characteristics, ability to avoid, prior knowledge, placement, snagging potential, strainers, and anchoring. The first four categories emphasize user and reach characteristics that impact risk, whereas the second four categories emphasize intrinsic wood characteristics that impact risk to any user, no regardless of skill or background.

Access. The first considerations are whether the reach is accessible to the general public and what type of recreational user is likely to visit. The risk that instream wood has on public safety increases with the frequency of recreation use because there are more chances for wood-human interaction. However, risk decreases quickly for recreational users experienced in navigating through and around rivers. For example, wood placement is safer along reaches visited only by experienced kayakers and anglers than along favorite family swimming locales or popular tubing destinations.

Reach Characteristics. Risk increases with water velocity because faster flow decreases the reaction time and capabilities that a swimmer, tuber, or boater has to avoid a hazard. Placing or keeping wood in lower velocity reaches is less risky than placing wood in reaches with swift current. In natural streams, most large log jams and most wood are located along slower rather than higher velocity sections. In straight sections of rivers with uniformly swift velocity from bank to bank, flush drownings can occur when a swimmer has no chance to reach shore for long distances. In this scenario, instream wood jams with low porosity that pool water behind the jam can be used to increase the safety of a reach by creating areas of lower velocities near shorelines. However, the jam or pieces from the jam can be mobilized and re-deposited in a more hazardous spot. Generally, river sections that are constricted with steeper gradients and faster currents are higher risk than low gradient meandering, open sections.

Ability to avoid. Upstream visibility and an onshore escape route strongly reduce hazards caused by instream wood. Structures just around corners 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 wood and react by either navigating around it or moving to the shore and getting out above it. A signed route to walk around the wood structure 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 paddle or swim around it. Ability to avoid wood also depends on the skill level of the users. The same piece of wood that is a hazard to a low-skilled recreational user may be easy to avoid for a high-skilled user. Thus, the skill level of the type of recreational users for a reach should be considered when thinking about risk related to this category.

Prior knowledge. Most importantly, prior knowledge of new wood along commonly navigated sections is vitally important to reduce risk. Regardless of location placement, new pieces of wood in previously clear channels typically create the greatest hazards. River users commonly become complacent with sections of river that they run frequently and thus are not as attentive to their surroundings as they navigate downriver. In addition, river users typically become habitualized to navigating through a section of river the same way. Unknown, new wood along the normal route can be dangerous because it is not expected. One of the best risk-reducing measures that can be taken is to make sure that new instream wood is not a surprise to river enthusiasts. Several ways to do this are to: contact American Whitewater (a national river advocacy group), inform local groups through clubs and online river forums, and add signage at river access points.

Placement. The placement of jams and single pieces has important effects on the risk associated with instream wood. For example, wood that is placed close to the water surface creates higher risk than wood far enough above the channel for recreational users to float under, or far enough below the water surface to float over. Because vertical position changes with water level, fluctuations in water level should be taken into account. Wood in contact with the bed so that no water is flowing underneath it has very low risk. Any wood near the bed with some water flowing under creates a foot entrapment hazard. Drownings from foot entrapment can occur in very shallow rivers at low flows because once the foot is entrapped, the person can fall face-first into the stream and not be able move from that position. This is a concern for anglers or for anyone wading in streams. For wood above the water column, American Whitewater (Colburn, n.d.) suggests a generous 1 m (3 ft) of clearance for kayaks and 1.8 m (6 ft) for rafts. Skilled kayakers are adept at safely passing beneath smooth logs as close as 0.3 m (1 ft) above the water. With respect to the horizontal dimension, wood that spans the entire length of the channel is fairly dangerous unless it is in contact with the bed all the way across. Wood or jams that partially span the channel are much safer because a route around the wood remains open. Vertical orientation of logs (like fence posts) should be avoided because floating items such as rafts can be wrapped around the wood.

Snagging potential. Although snagging was used previously to refer to the historic practice of removing pieces of wood from the channel, snagging to the water enthusiast refers to the potential of a river hazard, such as wood, to snag a piece of clothing or gear as a swimmer or boat passes. Wood with many larger limbs creates more risk for swimmers and boaters, especially if the wood is within high velocity zones in the channel. Wood can be stripped of large branches and branch stubs to reduce snagging potential, although this may reduce the ecological benefits of the wood. If more complex wood with more branches is highly desired for ecological reasons, it should be placed in low risk locations on the margins of the channel, in low velocity reaches, or on reaches that are rarely visited by recreationalists or only visited by highly experienced recreationalists.

Strainers. Although a single piece of wood with few to no branches creates relatively low risk, a porous jam can be hazardous. Jams with high porosity are those in which water runs swiftly through the jam rather than pooling upstream. These are known in the boating community as “strainers.” A person can be easily pushed up against the jam by water currents and not be able to swim through. However, a jam with enough wood and litter such as twigs and leaves will create an upstream backwater that is an advantageous and safe feature because it creates a safe place away from the swift main current for boaters and swimmers to rest, get out or regroup.

Anchoring. Although securing wood in place with cables, ropes, rebar, or other artificial material may help to ensure that wood does not threaten downstream infrastructure, these anchoring devices can be extremely hazardous to public safety if they are exposed within the channel. This can occur if the channel scours around secured wood or if the wood becomes detached. For the river enthusiast, cable-anchored wood is more dangerous than unanchored wood. If wood needs to be anchored, we recommend that wood be secured naturally through burial or weighting with natural materials.

The perception by the general public is that wood is not natural in a stream and detracts from the esthetics (Piégay et al., 2005), in part because much of the wood historically in streams has been removed and people are not accustomed to seeing it (Chin et al., 2008). It is important that the public becomes knowledgeable and informed about wood structures through signs and public outreach to avoid an outcry against leaving wood in streams, to prevent citizens and boaters from removing carefully placed or retained wood features, and to decrease the risk to public safety associated with new wood installments.

When placing or leaving wood in streams, contacting the local boating community and/or American Whitewater is useful. Boaters often safely navigate many sections of streams with large amounts of wood. Thus, they are a good resource to include in the decision-making process because they can help make decisions about the safe placement of new wood. If boaters are included early in the project, they will be informed about the wood and will be less likely to remove it. The boating community is well connected and word will spread quickly. In addition to contacting American Whitewater, there are numerous online boating and angling forums that can be useful to managers if they seek public comments.

This section was written based on personal experience of the last author (a professional kayaker who grew up river rafting and tubing), as well as reports on wood and public safety by an advocacy group for kayakers and rafter (American Whitewater; Colburn, n.d.) and by the Bureau of Reclamation (Svoboda et al., 2013). The American Whitewater report is an excellent general reference for understanding river features and risk from the point of view of a boater. The Bureau of Reclamation report goes beyond public safety and outlines research needs for large wood design and placement, structure stability, risk analysis and liability.

III. Description of Tools that can be Used to Assess Large Wood

As discussed in previous sections, river managers need to understand the stability of individual wood pieces and jams within channels and on floodplains, and the physical and ecological effects created by this wood, in order to effectively manage the wood. This section briefly introduces two categories of tools that can be used to better understand wood stability, benefits, and risks. In the following sections we first introduce a spreadsheet-based program designed specifically to evaluate wood, and then 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.

1. Large Wood Structure Stability Analysis Tool

The Large Wood Structure Stability Analysis Tool developed by Michael Rafferty, P.E. is a spreadsheet-based tool that can be used to efficiently evaluate 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 the internet link below summarizes the design rationale, methodologies, procedure, limitations, and example applications to illustrate how the tool can be used to design stable wood structures. http://www.engr.colostate.edu/~bbledsoe/streamtools/

2. Flow and Habitat Models

Several tools are available to assist with evaluation of the effects of wood on flow and potential benefits of wood for fish in Front Range streams. For example, the HEC-RAS (Hydrologic Engineering Center River Analysis System, http://www.hec.usace.army.mil/software/hec-ras/) software program 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, an implicit component of 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 has value in estimating the lateral extent of flooding when wood has been placed or retained in the active river channel or floodplain. The HEC-RAS software may also be used to estimate flow velocities to help predict scour or erosion resulting from placement or retention of wood in the stream channel.

Modeling tools are also available for estimating the quantity and quality of fish habitat. 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 stream flows (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., fry, 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 placement or retention of wood in streams, especially to predict how 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, as described above. 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 system. 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 fish biomass at a river-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.

Mean depth and velocity characteristics of streams can be estimated in less time with the simpler one-dimensional models. However, two-dimensional models have the advantage of predicting habitat change as flows fluctuate seasonally and as channel shape changes, and also allow incorporating predictions of 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 the following models, which are in the public domain and can be obtained free of cost:

- RIVER2D: a two-dimensional, depth-averaged, finite element hydrodynamic model that has been customized for fish habitat evaluation studies. The model suite consists of four programs, each of which has a graphical user interface that is supported by any 32-bit version of Windows. http://www.river2d.ualberta.ca/
- SRH-2D: a two-dimensional hydraulic, depth-averaged, finite-volume numerical model for sediment, temperature, and vegetation in systems developed by the U.S. Bureau of Reclamation. The model suite consists of modules for hydraulics (in existence), and bed sediment transport, temperature, and vegetation (under development). http://www.usbr.gov/pmts/sediment/model/srh2d/index.html

Other models are also available commercially:

- commercial codes include 2d MIKE 21c (http://www.mikebydhi.com/Products/WaterResources/MIKE21C.aspx), but most users will only go to a commercial code for three-dimensional modeling, and this code would likely be FLOW3d (http://www.flow3d.com/) or FLUENT (http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent)

IV. Decision Process for Managing Large Wood

1. Background on Risk Assessment

Engineers have a long tradition of performing risk assessments focused on structural stability or safety. However, it is only recently, with an upsurge in the practice of river restoration involving intentional placement and retention of large wood, that the need for risk assessments focused on wood has become pressing. Given longstanding concerns about public safety, property, and infrastructure in the river environment, risk assessments are increasingly being incorporated into river management and restoration efforts to ensure that the potential adverse consequences of projects have been adequately considered (e.g., Thorne et al., 2014).

Risk is inherent in river management given the range of complexity in channel responses to changes in delivery of water, sediment, and large wood. The purpose of any risk assessment is not to eliminate risk, but to objectively evaluate the potential risk elements and assess how a particular design or management action can address and alleviate those risks. It is important to note that there is commonly a significant risk of continued geomorphic and ecological degradation if large wood is not retained or re-introduced to a stream or river, and this risk should be included in every risk assessment. Therefore, a primary purpose of risk 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).

Risk is commonly defined as the potential of losing something of value, weighed against the potential to gain something of value. Risk may be mathematically defined as the probability of an event happening multiplied by the resulting consequences (cost or benefit) if it does:

$$Risk = P(E) \times \sum(C)$$

in which $P(E)$ is the probability of a specific event (E) or combination of events occurring and $\sum(C)$ is the summation of the consequences of the event occurring (typically presented as a monetary cost). If there are no negative consequences of a particular event occurring, then there is no risk. If the consequences are grave, then even an event with low probability of occurring may pose more risk than is tolerable.

2. Procedure for Assessing Risks Posed by Large Wood

Risk assessment for large wood in streams is best regarded as an ongoing process because of likely changes in risk through time as a result of natural processes (e.g., high stream flows) and human modifications (e.g., stabilizing or pruning the wood). Consequently, we suggest a process illustrated by the flow chart in Figure 2, which incorporates four tools. If wood is present in a channel, a simple checklist (Tool 1) 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 (Tool 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 (Figure 3; Tool 3) to qualitatively assess the alternative actions listed within the oval in Figure 2. The Decision Bands are used to assign risk to a high, medium or low category with respect to three characteristics: legal/property/infrastructure/inhabitants, recreation, and the ecosystem.

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

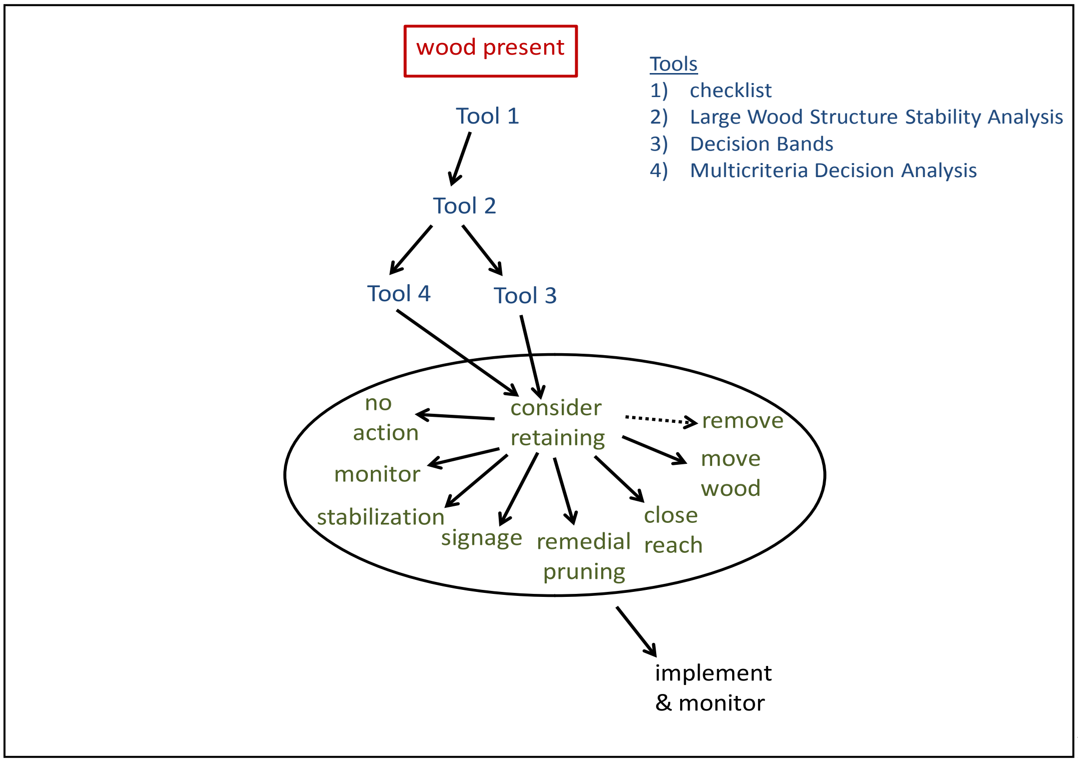

Figure 2. Illustration of the sequence of tasks, and associated tools, which can be used to assess risk created by large wood in streams.

3. Tools

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

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 flood district 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 flood district 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.

Tool 2. Large Wood Structure Stability Analysis (see section III.1)

Tool 3. Decision Bands

The decision bands shown in Figure 3 are designed to assist field-based evaluation of the relative risk created by individual pieces of 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 risk. We emphasize that these decision bands represent a starting point for a complicated assessment process that is very context-specific. Some river reaches will have minimal recreational use or potential, for example, or no floodplain habitat. 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 (section III.2).

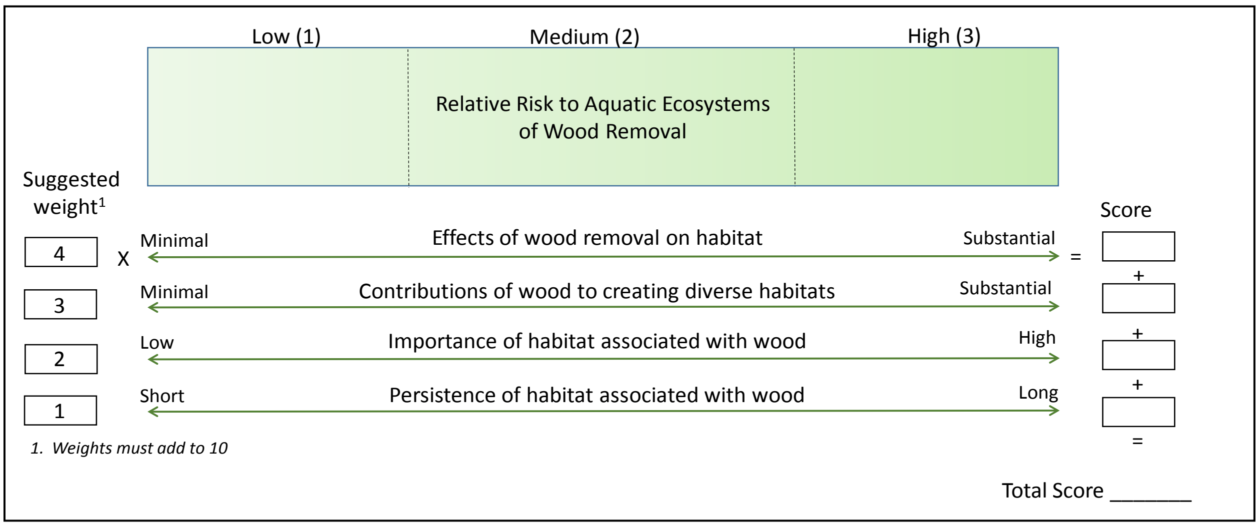

Figure 3A. Decision bands for assessing the relative risk to different components of river systems associated with wood removal. Individual bands relate to (A) aquatic or in-channel ecosystems, (B) riparian or floodplain ecosystems, (C) recreational users, (D) recreational user risk, (E) water surface 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. (A) Decision band for assessing the relative risk to aquatic ecosystems of wood removal.

Rationale:
Effects of wood removal on habitat 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 wood creates multiple types of habitat, such as pool scour and overhead cover for fish, diverse coarse and fine substrates for macroinvertebrates, perching habitat for birds, or backwater pools for fish and macroinvertebrates. If so, then removing wood creates a substantial risk of reducing habitat diversity. Aquatic habitat diversity primarily requires a diversity of flow depth, flow velocity, streambed substrate, and complex physical structure created by wood. Importance of habitat

associated with wood includes considerations such as abundance of wood-related habitat 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 the wood creates the only pool habitat for fish within a particular stream reach, then the importance would be rated as high and the risk of reducing habitat by removing wood is also high. In contrast, if the wood creates no pool or a very small pool, then the importance and the risk could be rated as low. Likewise, 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 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 wood persists for a long period, then the risk to aquatic habitat posed by removing it is high.

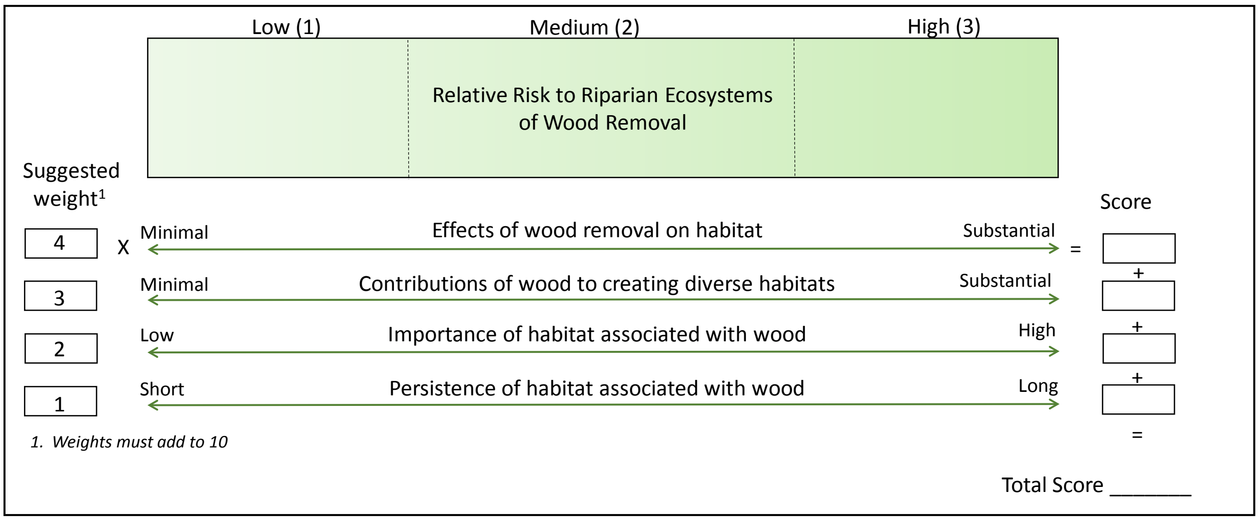

Figure 3B. Decision band for assessing the relative risk to riparian ecosystems of wood removal.

Rationale: The basic characteristics of the features (effects of wood removal, contributions of wood, importance of habitat, and persistence of habitat) are the same as described above for aquatic ecosystems, except that they are applied to riparian organisms. As reviewed in section I.2, floodplain wood can create germination sites for riparian vegetation and provide habitat for invertebrates, amphibians, reptiles, small mammals, and birds. Where a long piece of wood spans both the channel and the floodplain, decision bands (A) and (B) should be used together to assess the wood.

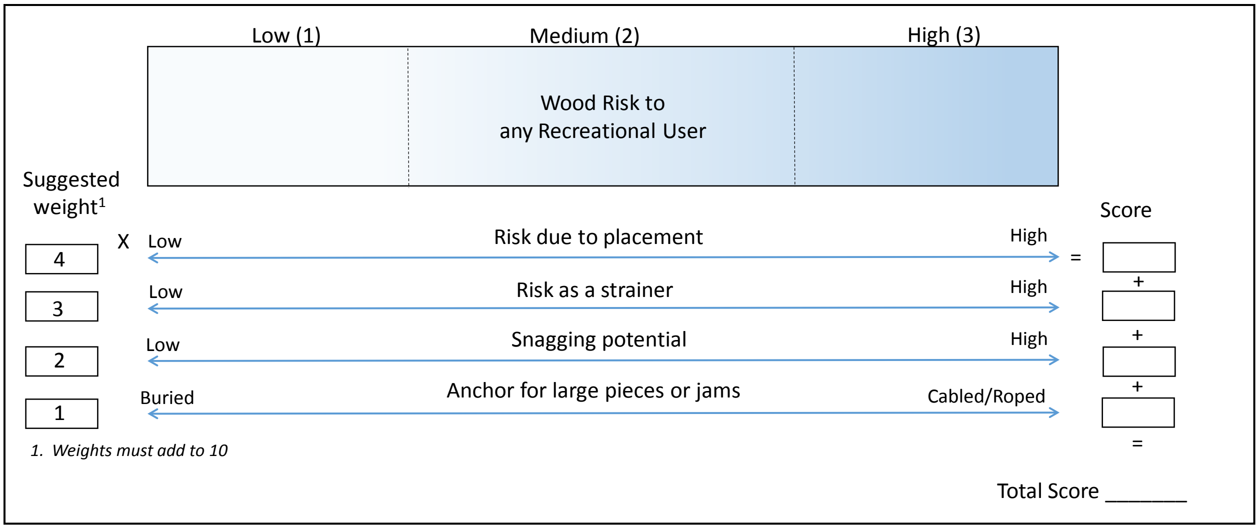

Figure 3C. Decision band for assessing the relative risk of wood to any recreational user.

Rationale:
This decision band emphasizes recreational users' risks from wood presence over the intrinsic risk of wood. Each band is described in more detail in section II.3. In general, it is much more risky to have wood in reaches heavily accessed by less skilled users than in lightly accessed reaches with primarily skilled users, no matter what the wood configuration is. Wood presence on reaches that are steeper and swifter with confined walls is riskier than on low gradient reaches with low velocities. The ability and skill to see and avoid wood greatly reduce risk. The ability to avoid wood depends both on how visible the wood is and the ease with which recreational users navigating the river or stream can avoid the wood. For example, the same piece of wood may be very hard for a tuber to avoid, but very easy for a kayaker. Prior knowledge of wood greatly reduces the risk for any recreational user. If a piece of wood is new and a surprise, then it is much more dangerous than if its location is well known.

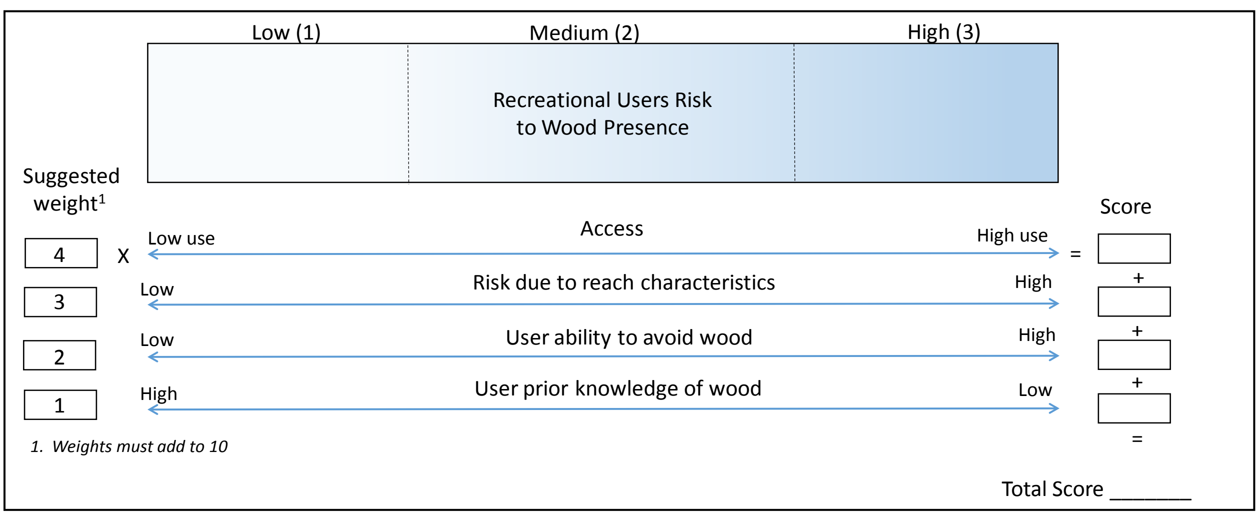

Figure 3D. Decision band for assessing recreational users' risk to wood presence.

Rationale:
This decision band emphasizes the risk of wood to recreational users, regardless of user skill or other general reach characteristics. Each band is described in more detail in section II.3. In general, wood that is placed in swift current is much more risky than wood placed in zones of low velocity or on the floodplain. Wood that is on the outside of bends is more hazardous than wood on the inside of bends because it is much more likely for objects or people to be swept into the wood. Strainers are wood accumulations or single pieces of wood that have enough space between pieces to allow water to flow through them, but not people or objects. Wood with multiple branches or wood pointing upstream are likely to snag floating objects, whereas wood that doesn't have branches or is pointing downstream is much less likely to do this. Anchoring with cables or ropes creates very high risk for recreational users if the cables or ropes are ever exposed through bank or bed erosion. These cables can be hidden hazards that are very hard to see or avoid. The hazard of unanchored or mobile wood depends on its size, placement and likelihood that it will move to a hazardous position.

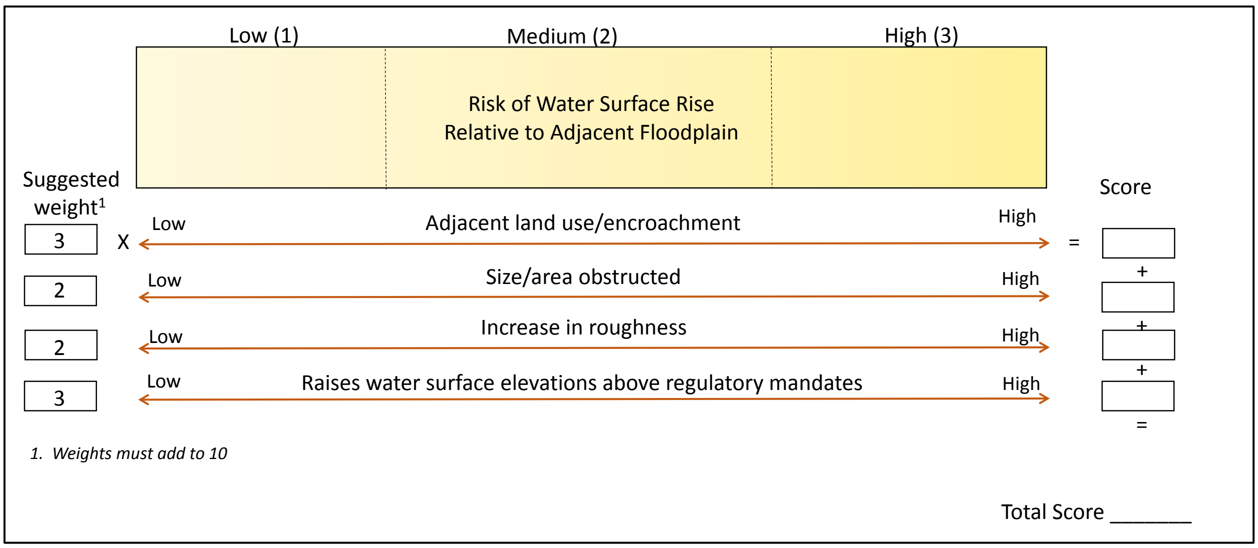

Figure 3E. Decision band for assessing the risk of water surface rise relative to the adjacent floodplain if wood is present.

Rationale:
Potential costs and the risk of negative consequences associated with large wood retention and placement depend on site-specific channel and floodplain characteristics. 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 risk 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 (a.k.a. roughness) 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 instream wood will alter water surface elevations to an extent that requires regulatory action such as generating a letter of map revision. The impact of such regulatory implications must be evaluated on a case-by-case basis by floodplain managers.

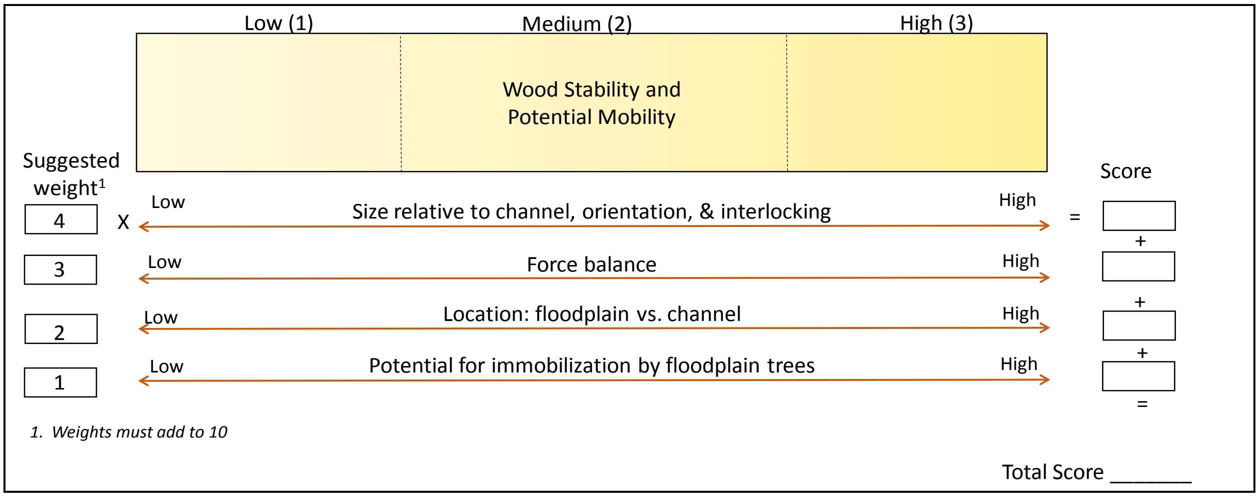

Figure 3F. Decision band for assessing the relative risk of wood stability and mobility.

Rationale:
Large wood that presents little risk in its current location may nevertheless produce much greater risks if transported downstream to a location where it could exacerbate flooding and/or threaten property and infrastructure. 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 decision band F). 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. 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. Physically-based models that explicitly account for the various forces acting on instream wood can be very useful and informative in assessing stability and the potential for downstream transport. To our knowledge, the spreadsheet-based force balance tool of Rafferty (2013) is the most rigorous and complete model of this type that is currently available. Wood mobility depends on the balance of stream power available to transport the wood versus the resistance of the wood to motion based on its weight, situation, 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 wood.

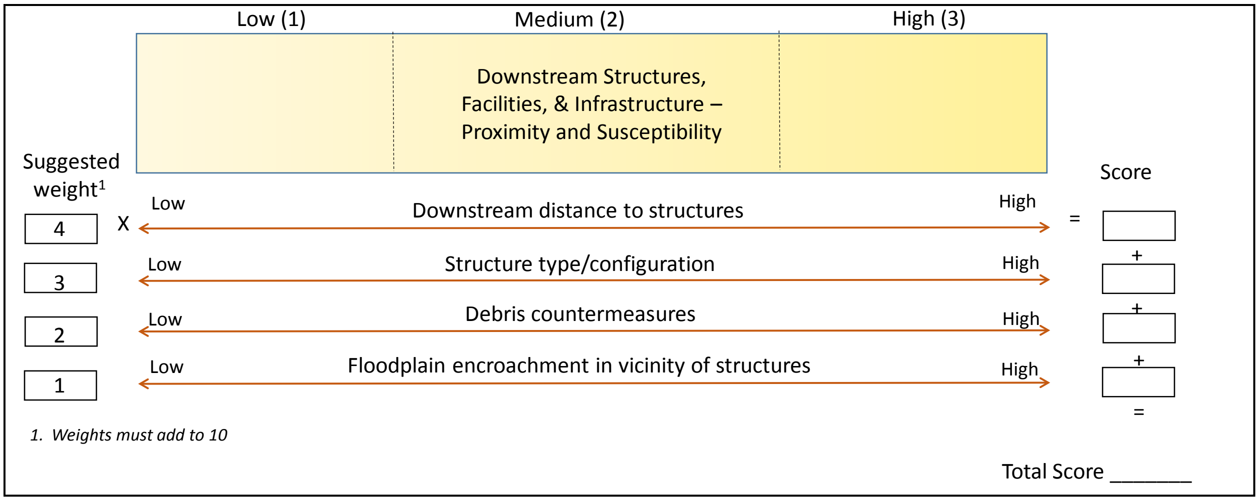

Figure 3G. Decision band for assessing the relative risk to downstream structures, facilities, and infrastructure resulting from the presence of instream wood.

Rationale:
Once 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 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 to loss of conveyance, damage, and failure is highly variable (FHWA, 2005). Factors that affect a structure's capacity to safely convey 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. There are many types of structural and non-structural debris countermeasures for bridges and culverts (FWHA, 2005). Assessing structure vulnerability and the potential effectiveness of 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. Decision band D focuses on floodplain land use and encroachment in the immediate vicinity of instream wood without consideration of potential downstream effects. Accordingly, this decision band requires an evaluation of the potential consequences of reduced flood conveyance and damage to structures if wood is transported to vulnerable downstream locations.

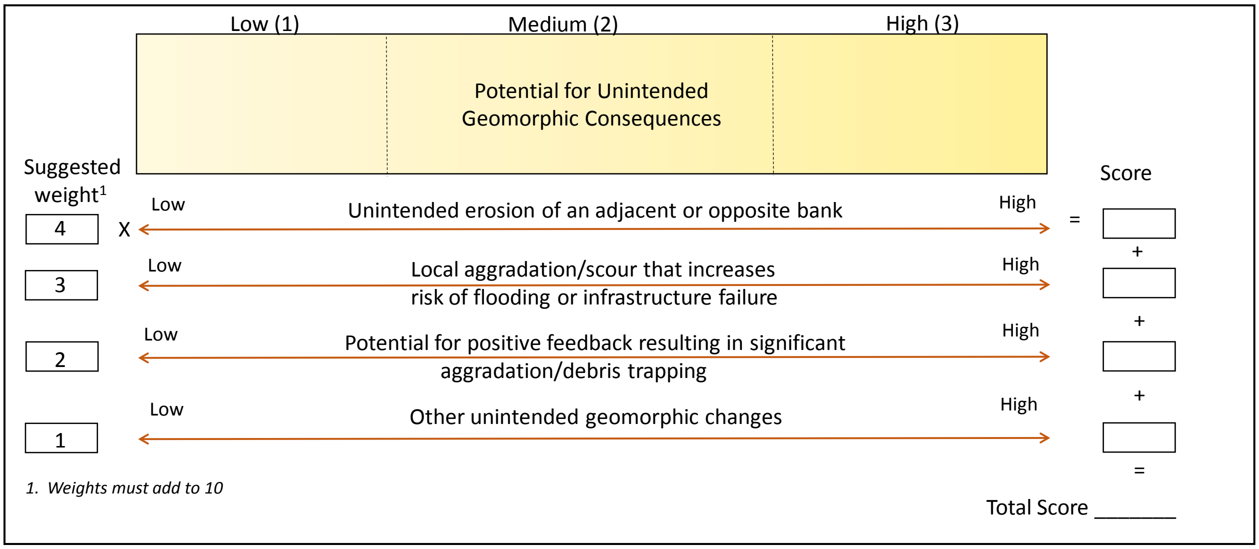

Figure 3H. Decision band for assessing the potential for unintended geomorphic consequences as a result of the presence of wood.

Rationale:

Instream 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 instream wood to produce channel adjustments that conflict with adjacent property values and floodplain management objectives. 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 instream 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 direct experience in managing instream wood.

Overall Decision Band Score Sheet

Ecosystems Risk Scores from Decision Bands		Suggested Weights		Score
________Relative Risk to Aquatic Ecosystems of Wood Removal				
________Relative Risk to Riparian Ecosystems of Wood Removal				
Average[1] ______	x	2	=	______
Recreational User Risk Scores from Decision Bands				+
________Recreation Users risk to Wood Presence				
________Wood Risk to any Recreational User				
Average[1] ______	x	3	=	______
Property, Infrastructure, and Public Safety Risk Scores from Decision Bands				+
________Risk 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	________

FigureE 3I. Overall Decision Band score sheet for assessing relative risks to ecosystems of removing wood and risks to recreational users, property, infrastructure, and public safety of retaining wood.

Rationale:

Decision band I integrates the results of decision bands A through H into an overall assessment score for relative risk of removing or removing wood.

Applying Decision Band scores

Decision band scores consistently in the medium-high range of decision bands A and B (risk to aquatic and riparian ecosystems of wood removal) and in the low range of decision bands C to H suggest options of no action, monitoring, stabilization, or signage (Figure 2). 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 or moving the wood (Figure 2). Table 1 provides further information on the implications of choosing one of the options within the oval in Figure 2. The overall decision band score sheet can be used to compare relative risks between ecosystems, recreational use, and public infrastructure and safety. Overall scores can be used to compare wood risks between different reaches or specific wood locations in order to assist in the prioritization and cost-benefit evaluations of restoration or management efforts.

Table1. Implications of individual options in Figure 2

No action	• can help to ensure continued beneficial habitat effects of wood • low risk to recreational users
Monitor	• can help to ensure continued beneficial habitat effects of wood • facilitates evaluating how interactions among discharge, sediment and wood influence habitat through time • low risk for recreational users in a high use reach or moderate to high risk wood in a low used reach
Stabilization	• can help to ensure continued beneficial habitat effects of wood • can reduce risks to infrastructure • to reduce recreational risk of unstable pieces moving to high-risk locations after assessment • reduce recreational risk by using natural stabilization techniques such as burial rather than cables and ropes
Signage/Outreach	• can reduce risks to recreational users; inform recreational users of new wood & educate recreational users to avoid public protest
Remedial pruning	• can reduce risks to recreational users by reducing snagging potential & making avoidance easier • may reduce beneficial effects to habitat
Close reach	• can help to ensure continued beneficial habitat effects of wood • can reduce risks to recreational users but may not be well recieved
Move wood	• may reduce beneficial habitat effects of wood • can reduce risks to infrastructure & recreational users for moderate-high risk wood in moderate-high use areas

V. Concluding Remarks

Figure 2 provides an overview of the sequence of steps that we suggest for assessing the benefits and risks posed by wood in stream channels and on floodplains. This sequence starts with the relatively short Checklist for Initial Assessment of Wood (Tool 1), followed by the Large Wood Structure Stability Analysis (Tool 2), the Decision Bands (Tool 3), and/or the Multi-Criterion Decision Analysis (Tool 4). We suggest that any decision to retain wood should be coupled with ongoing monitoring. Monitoring can be used to re-evaluate wood benefits and risks if conditions at a site, such as bed elevation or channel cross-sectional change as part of the natural dynamics of a river. Monitoring can also be a key component of ongoing refinement of risk assessment. The procedures outlined in this report should be implemented by experienced, interdisciplinary teams. The weights that we tentatively suggest in the decision bands can also be adjusted based on stakeholder input.

The procedures outlined in this report represent a more nuanced approach to managing wood in river systems than automatically removing all wood. However, managers in some regions of the country are being more proactive than simply considering retaining naturally recruited instream wood. Managers in the U.S. Pacific Northwest, in particular, are now actively adding individual wood pieces and engineered logjams to channels because of the recognized physical and ecological benefits of wood. Jones et al. (2014) review some of these restoration projects and the success of the projects in achieving desired restoration of fish habitat.

Figure 4. An example of a large engineered logjam built by the Washington State Department of Transportation on the bank of the Hoh River along U.S. Highway 101.

Photo from Herrera Environmental Consultants, Inc (http://www.fhwa.dot.gov/ publications/publicroads/ 06jan/05.cfm)

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VII. Reference List

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets River basin, Washington. *Geomorphology* 51: 81-107.

Abbe T., Embertson L, Bruzgul J, Maher K. 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.

Angermeier PL, Karr JR. 1984. Relationships between woody debris and fish habitat in a small warmwater stream. *Transactions of the American Fisheries Society* 113:716-726.

Anton A, Elosegi A, Garcia-Arberas L, Diez J, Rallo A. 2011. Restoration of dead wood in Basque stream channels: effects on brown trout population. *Ecology of Freshwater Fish* 20: 461-471.

Arrigoni AS, Poole GC, Mertes LAK, O'Daniel SJ, Woessner WW, Thomas SA. 2008. Buffered, lagged, or cooled? Disentangling hyporheic influences on temperature cycles in stream channels, *Water Resources Research* 44: W09418, doi:10.1029/2007WR006480.

Baxter CV, Hauer FR. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (Salvelinus confluentus). *Canadian Journal of Fisheries and Aquatic Sciences* 57: 1470-1781.

Benjamin JR, Fausch KD, Baxter CV. 2011. Species replacement by a nonnative salmonid alters ecosystem function by reducing prey subsidies that support riparian spiders. *Oecologia* 167:503-512.

Benke AC. 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 AC, Henry RL III, Gillespie DM, Hunter RJ. 1985. Importance of snag habitat for animal production in southeastern streams. *Fisheries* 10(5):8-13.

Benke AC, Wallace JB. 1990. Wood dynamics in coastal plain backwater streams. *Canadian Journal of Fisheries and Aquatic Sciences* 47: 92-99.

Benke AC, Wallace JB. 2003. Influence of wood on invertebrate communities in streams and rivers. *Ecology and Management of Wood in World Rivers*. American Fisheries Society Symposium. 37:149-177.

Bilby RE. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology* 62: 1234-1243.

Bilby RE, Likens GE. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 61: 1107-1113.

Bovee KD. 1996. Managing instream flows for biodiversity: a conceptual model and hypotheses. In, *Proceedings of the Northern River Basins Study*. NRBS Project Report No. 66: 83–100.

Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Heriksen J. 1998. *Stream Habitat Analysis Using the Instream Flow Incremental Methodology*. Information and Technology Report. US Geological Survey, Biological Resources Division.

Boys CA, Thoms MC. 2006. A large-scale, hierarchical approach for assessing habitat associations of fish assemblages in large dryland rivers. Hydrobiologia 572: 11-31.

Braccia A, Batzer DP. 2001. Invertebrates associated with woody debris in a southeastern U.S. forested floodplain wetland. *Wetlands* 21: 18–31.

Brooks AP, Brierley GJ, Millar RG. 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 AP, Howell T, Abbe TB, Arthington AH. 2006. Confronting hysteresis: wood based river rehabilitation in highly altered riverine landscapes in south-eastern Australia. *Geomorphology* 79:395-422.

Brummer CJ, Abbe TB, Sampson JR, Montgomery DR. 2006. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology* 80: 295-309.

Buffington JM, Lisle TE, Woodsmith RD, Hilton S. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18: 507-531.

Chee YE. 2004. An ecological perspective on the valuation of ecosystem services. *Biological Conservation* 120: 549-565.

Chin A, Daniels MD, Urban MA, Piegay H, Gregory KJ, Bigler W, Butt AZ, Grable JL, Gregory SV, Lafrenz M, Laurencio LR, Wohl E. 2008. Perceptions of wood in rivers and challenges for stream restoration in the United States. *Environmental Management* 41: 893-903.

Coe HJ, Kiffney PM, Pess GR, Kloehn KK, McHenry ML. 2009. Periphyton and invertebrate response to wood placement in large Pacific coastal rivers. *River Research and Applications* 25:1025-1035.

Colburn, K. (n.d.). *Integrating Recreational Boating Consideration into Stream Channel Modification and Design Projects*. American Whitewater. Retrieved Feb 2013 from: http://www.americanwhitewater.org/content/Document/fetch/documentid/1006/.raw

Collins BD, Montgomery DR, and Haas AD. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 66-76.

Collins BD, Montgomery DR, Fetherston KL, Abbe TB. 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 BD, Montgomery DR, Haas AD. 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.

Crook DA, Robertson AI. 1999. Relationships between riverine fish and woody debris: implications for lowland rivers. *Marine and Freshwater Research* 50:9441-953.

Curran JH, Wohl EE. 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* 51: 141-157.

Daniels MD, Rhoads BL. 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 SL, Eaton BC. 2013. Modeling channel morphodynamic response to variations in large wood: implications for stream rehabilitation in degraded watersheds. *Geomorphology* 202: 59-73.

Entrekin SA, Tank JL, Rosi-Marshall EJ, Hoellein TJ, Lamberti GA. 2009. Response of secondary production by macroinvertebrates to large wood addition in three Michigan streams. *Freshwater Biology* 54:1741-1758.

Erskine WD, Webb AA. 2003. Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia. *River Research and Applications* 19: 233-249.

Falke JA, Fausch KD. 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, KD. 1984. Profitable stream positions for salmonids: relating specific growth rate to net energy gain. *Canadian Journal of Zoology* 62: 441-451.

Fausch KD. 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, KD. 2014. A historical perspective on drift foraging models for stream salmonids. *Environmental Biology of Fishes* 97: 453-464.

Fausch KD, Bestgen KR. 1997. Ecology of fishes indigenous to the central and southwestern Great Plains. Pages 131-166 *in* F. L. Knopf and F. B. Samson, eds. *Ecology and Conservation of Great Plains Vertebrates*. Ecological Studies 125. Springer-Verlag, New York.

Fausch KD, Torgersen CE, Baxter CV, Li HW. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *BioScience* 52:483-498.

Faustini JM, Jones JA. 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. Available: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/.

Fischer H, Kloep F, Wilzcek S, Pusch MT. 2005. A river's liver: microbial processes within the hyporheic zone of a large lowland river. *Biogeochemistry* 76: 349-371.

Flores L, Larrañaga A, Díez JR, Elosegi A. 2011. Experimental wood addition in streams: effects on organic matter storage and breakdown. *Freshwater Biology* 56:2156-2167.

Flores L, Díez JR, Larrañaga A, Pascoal C, Elosegi A. 2013. Effects of retention site on breakdown of organic matter in a mountain stream. Freshwater Biology 58:1267-1278.

Ghanem A, Steffler P, Hicks F. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. *Regulated Rivers: Resource and Management* 12: 185–200.

Gooseff MN, Hall RO, Tank JL. 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, Fausch KD. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. *Ecological Applications* 6:931-946.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack JR, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* 15: 133-302.

Howell TJ, Pusey B, Arthington A, Brooks AP, Creese R, Chaseling J. 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.

Howson TJ, Robson BJ, Mitchell BD. 2009. Fish assemblage response to rehabilitation of a sand-slugged lowland river. *River Research and Applications* 25: 1251-1267.

Jones KK, Anlauf-Dunn K, Jacobsen PS, Strickland M, Tennant L, Tippery SE. 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.

Jowett IG. 2003. Hydraulic constraints on habitat suitability for benthic invertebrates in gravel-bed rivers. *River Research and Applications* 19:495-507.

Kasahara T, Wondzell SM. 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. Water Resources Research 39: doi:10.1029/2002WR001386.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* 4: 361-380.

Kiker GA, Bridges TS, Linkov I, Varghese A, Seager T. 2005. Application of multi-criteria decision analysis in environmental decision-making. *Integrated Environmental Assessment and Management* 1(2): 1-14.

Klaar MJ, Hill DF, Maddock I, Milner AM. 2011. Interactions between instream wood and hydrogeomorphic development within recently degraded streams in Glacier Bay National Park, Alaska. *Geomorphology* 130: 208-220.

Langford TEL, Langford J, Hawkins SJ. 2012. Conflicting effects of woody debris on stream fish populations: implications for management. *Freshwater Biology* 57:1096-1111.

Lehane BM, Giller PS, O'halloran J, Smith C, Murphy J. 2002. Experimental provision of large woody debris in streams as a trout management technique. *Aquatic Conservation-Marine and Freshwater Ecosystems* 12:289-311.

Malcolm IA, Soulsby C, Youngson AF, Hannah DM, McLaren IS, Thorne A. 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival. *Hydrological Processes* 18: 1543-1560.

Massong TM, Montgomery DR. 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.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. In, Gregory SV et al. (eds.), *The ecology and management of wood in world rivers. American Fisheries Society*, Bethesda, MD, 21-47.

Mutz M. 2003. Hydraulic effects of wood in streams and rivers. In, Gregory SV et al. (eds.), *The ecology and management of wood in world rivers*. American Fisheries Society, Bethesda, MD, 93-107.

Nagayama S, Nakamura F, Kawaguchi Y, Nakano D. 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, Swanson FJ. 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 JE, Jones MA, Haluska TL. 2003. Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology* 51: 31-59.

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

Pasternack GB, Bounrisavong MK, and Parikh KK. 2008. Backwater control on riffle–pool hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. *Journal of Hydrology* 357:125-139.

Pettit NE, Naiman RJ. 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, J. Zawiejska. 2005. Public perception as a barrier to introducing wood in rivers for restoration purposes. *Environmental Management* 36(5):665–674.

Pomerol JC, Romero SB. 2000. *Multicriterion Decision in Management: Principles and Practice*. Kluwer Academic Publishers, 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, CO. http://www.engr.colostate.edu/~bbledsoe/streamtools

Raikow DF, Grubbs SA, Cummins KW. 1995. Debris dam dynamics and coarse particulate organic matter retention in an Appalachian Mountain stream. *Journal North American Benthological Society* 14: 535-546.

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

Robison EG, Beschta RL. 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.

Roni P, Hanson K, Beechie T. 2008. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management* 28: 856-890.

Sawyer AH, Cardenas MB. 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 AH, Cardenas MB, Buttles J. 2011. Hyporheic exchange due to channel-spanning logs. *Water Resources Research* 47:W08502, doi:10.1029/2011WR010484.

Sawyer AH, Cardenas MB, Buttles J. 2012. Hyporheic temperature dynamics and heat exchange near channel-spanning logs. *Water Resources Research* 48: W01529, doi:10.1029/2011WR011200.

Schlosser IJ. 1991. Stream fish ecology: A landscape perspective. *BioScience* 41:704-712.

Schneider RL, Sharitz RR. 1988. Hydrochory and regeneration in a bald cypress/water tupelo swamp forest. *Ecology* 69: 1055-1063.

Schowalter TD, Zhang YL, Sabin TE. 1998. Decomposition and nutrient dynamics of oak (*Quercus* spp.) logs after five years of decomposition. *Ecography* 21: 3-10.

Sechnick CW, Carline RF, Stein RA, Rankin ET. 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 JR, Leone FN, Duval WS. 1991. Water transportation and storage of logs. In: Meehan WR (ed) *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats*. Bethesda, MD: American Fisheries Society Symposium 19, pp. 325-368.

Shields FD, Gippel CJ. 1995. Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering* 121: 341-354.

Shields FD, Smith RH. 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 SW, Nehring RB. 1993. Using the physical habitat simulation model to evaluate a stream habitat enhancement project. *Rivers* 4:175-193.

Slaght JC; Surmach SG, Gutierrez RJ. 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 CB, Lamb BL, Henriksen J, Bovee K, Bartholow J. 1995. *The Instream Flow Incremental Methodology: A Primer for IFIM*. Biological Report 29. National Biological Service.

Stanley EH, Boulton AJ. 1993. Hydrology and the distribution of hyporheos: perspectives from mesic rivers and desert streams. *Journal North American Benthological Society* 12: 79-83.

Stewart G, Anderson R, and Wohl E. 2005. Two-dimensional modelling of habitat suitability as a function of discharge on two Colorado rivers. *River Research and Applications* 21:1061-1074.

Stewart GB, Bayliss HR, Showler DA, Sutherland WJ, Pullin AS. 2009. Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: a systematic review. *Ecological Applications* 19: 931-941.

Suedel BC, Burks-Copes K, Kim J, McKay K. 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, MS.

Svoboda CD, Cuhaciyan C, Kimbrel S. 2013. *Improving Public Safety of Large Wood Installations: Scoping Proposal Report of Findings*. Bureau of Reclamation. Retrieved Feb 2013 from: http://www.usbr.gov/research/publications/download_product.cfm?id=802

Swanson FJ, Lienkaemper GW, Sedell JR. 1976. *History, physical effects, and management implications of large organic debris in western Oregon streams*. USDA Forest Service General Technical Report PNW-56.

Thompson DM. 2006. Did the pre-1980 use of in-stream structures improve streams? A reanalysis of historical data. *Ecological Applications* 16: 784-796.

Thorne CR, Castro J, Cluer B, Skidmore P, Shea C. 2014. Project risk screening matrix for river management and restoration. *River Research and Applications*.

Trainor AM, Shenk TS, Wilson KR. 2007. Characteristics of Preble's meadow jumping mouse micro-habitat use in Colorado. *Journal of Wildlife Management* 71:469-477.

Trainor AM, Shenk TS, Wilson KR. 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 FJ. 1984. Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study. *Verh. Internat. Verein. Limnol*. 22: 1876-1892.

Vehanen T, Huusko A, Mäki-Petäys A, Louhi P, Mykrä H, Muotka T. 2010. Effects of habitat rehabilitation on brown trout (*Salmo trutta*) in boreal forest streams. *Freshwater Biology* 55: 2200-2214.

Wallace JB, Webster JR, Meyer JL. 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 SL, Gowan C, Fausch KD, Harris JG, Saunders WC. 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 SL, Biron PM, Zimmerman A, Venter O, Grant JWA. 2010. Do in-stream restoration structures enhance salmonid abundance? a meta-analysis. *Canadian Journal of Fisheries and Aquatic Sciences* 67: 831-841.

Williams DD. 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, CT.

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.

Wondzell SM. 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, Gonzalez G, Ping CL, Michaelson G. 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.

Appendix: Definitions

Bankfull Channel: bankfull can be defined as the portion of the channel that contains relatively frequent floods occurring every 1-2 years, or as the portion of the channel below the inflection point at the top of the bank – above bankfull, flow moves beyond the channel and into the floodplain

Biomass: the mass of living organisms within an area

Channel Morphology: the cross-sectional shape, downstream slope, bedforms (e.g., pools, riffles, steps, dunes), and planform (e.g., straight, meandering, braided) of a channel

Debris: word sometimes used to refer to instream wood

Floodplain: floodplain can be defined based on flood recurrence interval (e.g., 100-year floodplain), or as the portion of the valley bottom that would be inundated relatively frequently (every 1-2 years) under a natural flow regime

Floodplain wood: large wood outside of the channel but within the floodplain

Foot Entrapment: when someone's foot becomes entrapped on the bottom of a shallow stream and the current pushes the person over, such that the individual can no longer stand or extract themselves without help; this usually occurs when someone is trying to stand or wade in shallow, swift moving water.

Habitat Heterogeneity: variation in physical environmental features (e.g., water depth, flow velocity, substrate) within an area

Hyporheic: the portion of unconfined, near-stream aquifers where stream water is present; can also be defined as a flow-through subsurface region containing flowpaths that originate and terminate at the stream

Instream Wood: large wood that is at least partially within the bankfull channel

Large Wood: typically defined as wood pieces greater than 10 cm in diameter and 1 m in length

Lateral Migration: lateral movement of a channel, either via gradual erosion of one bank, or via abrupt shifting (avulsion) across the valley bottom during a flood

LWD: large woody debris, sometimes used to refer to instream wood

Longitudinal: the downstream direction

Macroinvertebrates: an invertebrate large enough to be seen without a microscopic; in streams, these are typically the juvenile stage of insects such as mayflies or caddisflies, and are typically bottom-dwellers (benthic)

Multi-thread Channels: a channel planform that includes multiple flow paths; these can shift laterally relatively rapidly between unvegetated bars (braided channel) or individual sub-channels can be more persistent features with forested islands between them (anastomosing channel)

Natural Flow Regime: the hydrograph that would occur in the absence of human alteration of flow via dams, diversions, groundwater withdrawal, construction of levees, etc

Organic Matter: composed of organic compounds that have come from once-living organisms and their waste products in the environment (e.g., leaves, twigs, pine needles, frass)

Periphyton: a community of algae, bacteria, microbes and fine detritus that is attached to cobbles and wood in the streambed

Reach: any length of stream of interest for a particular study or concern; a reach is often defined as some multiple of the width of the channel at bankfull

Riparian: the valley bottom outside of the channel, typically similar to the floodplain, but characterized by hydrophilic (water-loving) plants tolerant of inundation and mechanical damage during floods

Risk: the probability of something happening multiplied by the resulting cost or benefit if it does

Species Richness: the number of different species represented in an ecological community

Stability: the presence or absence of changes in channel morphology, flow regime, biomass, habitat heterogeneity, and other characteristics of rivers is highly dependent on the timespan being considered – what might appear to be a substantial change and evidence of instability when considered over relatively short time intervals, may appear as part of regular fluctuations within a generally stable state when considered over longer time periods

Strainer: an obstacle in the river that is porous, such that items or people pushed up against it by the current cannot pass or swim through

Uncertainty: limited knowledge makes it impossible to exactly describe the existing state, a future outcome, or more than one possible outcome