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Managing for Large Wood and Beaver Dams in Stream Corridors

Ellen Wohl, Daniel N. Scott and Steven E. Yochum

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Abstract

Large wood and beaver dams are fundamental components of forested stream ecosystems but can also create hazards. We present guidelines for identifying stream segments that maximize environmental benefits while minimizing hazards. We focus on lesser gradient stream segments, although wood can be ecologically beneficial anywhere in a river network. Stream segments can be targeted for field-based evaluation using checklists for scenarios of either retention or reintroduction for logjams or beaver dams. We also present the Wood Jam Dynamics Database and Assessment Model, which incorporates a machine-learning-based statistical analysis to predict wood jam dynamics and provides a standardized survey protocol for wood jams.

Keywords: stream restoration; stream ecosystem; large wood; beaver dam; stream corridor; resilience

Cover: Top-Left: Beaver dam on Hague Creek in Rocky Mountain National Park, Colorado; Top-Right: Aerial picture of constructed large wood jams on the North Fork Teanaway River, WA. Flow from right to left. Bottom: A panorama from the right valley wall looking towards the left bank showing a large channel-spanning wood jam on Shale Creek, WA. Flow from left to right. This jam formed due to a landslide on the right valley wall.

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Executive Summary

Streams are dynamic ecosystems. Large wood, defined as pieces > 10 cm in diameter and 1 m in length, and beaver dams are fundamental components of forested stream ecosystems. More than a century of wood and beaver removal from streams has created a widespread perception that these features are relatively rare or even undesirable features in streams, but extensive scientific research firmly supports the critical ecosystem services provided by large wood and beaver dams. Because large wood and beaver dams can also create hazards in streams, this document presents guidelines for evaluating the potential environmental benefits versus potential hazards associated with individual logjams and beaver dams.

Stream management in diverse regions of the United States and the world increasingly emphasizes retaining or actively reintroducing large wood and beavers to streams. Developing trends with respect to large wood include:

- increasing use of soft placement techniques that allow some wood movement rather than completely anchoring wood in place;
- passive recruitment of wood from natural source areas;
- placing wood in locations where channel geometry and hydraulics favor stability and where additional wood is likely to accumulate;
- consideration of changes in channel morphology resulting from wood placement and potential hazards to humans, infrastructure, and property associated with the presence of wood;
- using a watershed-scale perspective that recognizes temporal and spatial variability associated with natural disturbances when estimating desirable wood loads; and
- monitoring wood and employing monitoring results in adaptive management.

Developing trends with respect to beaver dams include:

- modeling habitat suitability and carrying capacity to evaluate the ability of a stream segment to support beaver populations;
- active reintroduction of beavers;
- use of beaver dam analogs, either in lieu of actual beavers in situations where the animals cannot survive, or as a precursor to return of beavers to a site;
- use of techniques that can reduce hazards and nuisances created by beaver dams, such as pipes to maintain backwater ponds below a threshold water level or fencing around culverts; and
- monitoring and adaptive management.

Here, we present guidelines for identifying stream segments that maximize the potential environmental benefits associated with logjams and beaver dams, while minimizing the potential hazards associated with these features. We suggest focusing on lesser gradient stream segments within a watershed because these segments are likely to have wider valley bottoms and floodplains that facilitate greater spatial extent of backwaters, organic matter retention, and habitat associated with jams and dams. Such segments typically exhibit slopes ≤ 0.05 m/m, although this varies widely between watersheds. A floodplain can reduce the hazards associated with jams and dams by accommodating flood flows that may be enhanced by the presence of wood. However, wood reintroduction and the preservation of natural wood structures can be ecologically beneficial in most parts of a river network. Stream segments can be targeted for field-based evaluation using checklists and a jam stability model. These segments can be identified based on prior knowledge of a drainage network. Alternatively, GIS tools can be used to combine DEM analysis (including channel gradient, confinement, and geomorphic unit mapping) with other data such as infrastructure (roads, road crossings, flow diversions, and private property), recreational use, and vegetation characteristics to identify stream segments where jams and dams have a high potential for enhancing ecological function while posing acceptably little hazard, and could be managed cost effectively.

We present checklists to evaluate two scenarios each for logjams and beaver dams: retention of an existing jam or dam, and reintroduction of large wood or beaver. To supplement these checklists, we also present the Wood Jam Dynamics Database and Assessment Model (WooDDAM), an open tool for understanding and predicting wood jam change through time (jam dynamics). The checklists and WooDDAM are designed to be simple in application and reproducible among operators. WooDDAM incorporates a machine-learning-based statistical analysis to predict wood jam dynamics (including mobility) that uses a public database of wood jam characteristics and dynamics. The purpose of the model is to provide interpretable predictions of wood jam dynamics, based on region-specific environmental characteristics (e.g., hydrologic regime), channel characteristics, and the characteristics of specific wood jams. The model is evolving because it is based on continuing data inputs from users, and the predictions the model generates are informed by the database it is paired to; the model will evolve as users submit data to it. The database and model are designed to be used within specific environmental contexts (e.g., users working in the southern Appalachians could seek predictions of wood jam dynamics and review data relevant to that region). WooDDAM also provides a standardized survey protocol to survey wood jam characteristics and resurvey wood jams to measure wood jam dynamics. This survey protocol is designed to facilitate the contribution of data to the database. WooDDAM is available through the USDA Forest Service's National Stream and Aquatic Ecology Center website (https://www.fs.fed.us/biology/nsaec/index.html). We encourage those who study and/or manage large wood in rivers to utilize WooDDAM and contribute to the database to enhance its usefulness. We conclude this document with a series of brief case studies from a variety of regions in the continental United States.

In this document, stream refers to the stream corridor, which includes the bankfull channel (or channels, if secondary channels are present), the floodplain, the channel migration zone, and the underlying hyporheic zone. Much of the material presented in this document with regard to evaluating wood piece stability and benefits versus hazards has been published in Wohl et al. (2016) and much of the background discussion on large wood is derived from Wohl (2017). WooDDAM is new (see section II.C.3). Our primary intent here is to compile within a single document a thorough literature review of the potential benefits and hazards associated with the presence of large wood and beaver dams, and to present methods for evaluating these benefits and hazards at a site.

Part I. Context for Large Wood (LW) and Beaver in Stream Corridors

A. Review of Environmental Benefits and Potential Hazards of Large Wood and Beaver in Stream Corridors

1. Introduction

1.1. Conceptualizing Streams and Definition of Terms

Streams can be conceptualized in various ways. At the simplest level, a stream is a channel that conveys water downstream. The channel is defined by a bed and banks that are commonly lower in elevation than adjacent parts of the landscape, and the upper elevation of each bank defines the active or bankfull channel (fig. 1). The channel can be bounded by upland environments in a very steep canyon or by a floodplain or riparian zone that creates a transition between aquatic and terrestrial environments.

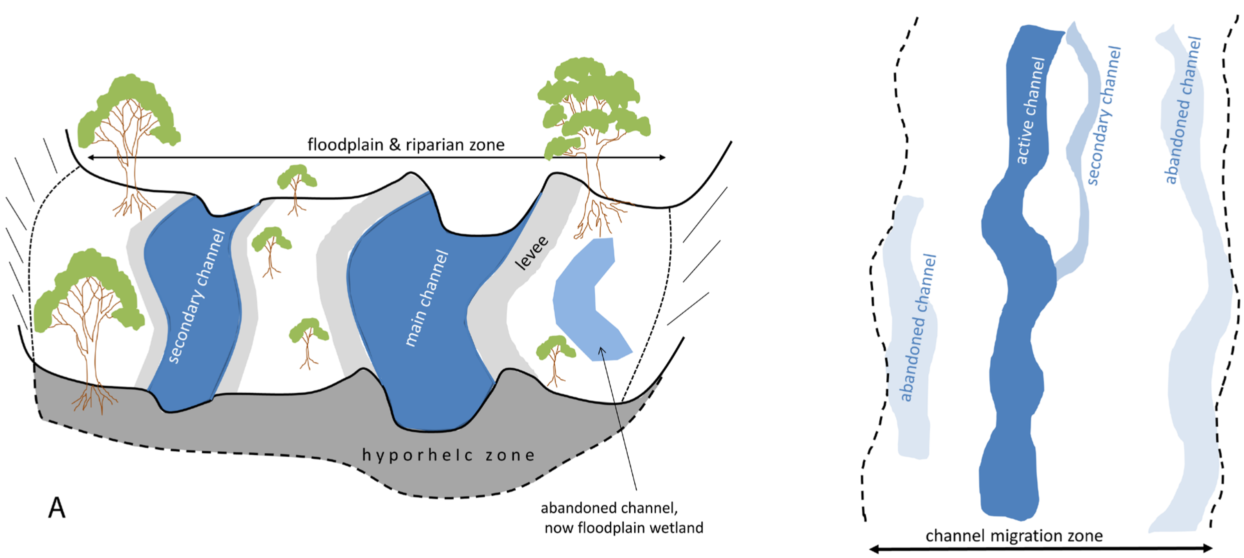

Figure 1a-b. Idealized illustrations of the components of a stream corridor. A) The active channel(s), bankfull channel, floodplain, riparian zone, and hyporheic zone. In the scenario of multiple channels, bankfull channel width is commonly designated as the average width of the main channel. B) Plan view of the channel migration zone.

This conceptualization of a stream is overly simplistic for at least two reasons. First, a stream channel is a conduit for more than water (fig. 2a-b). Mineral sediment, particulate organic matter, and dissolved materials move downstream, and diverse aquatic organisms move up- and downstream within stream channels. The movements of these materials and organisms can strongly influence processes and form in the channel. Mineral sediment, for example, spends more time in storage along a channel than in transport (Meade 2007). The channel features (bars, bedforms) created by stored sediment strongly affect hydraulic resistance to flow, as well as aquatic habitat and hyporheic exchange.

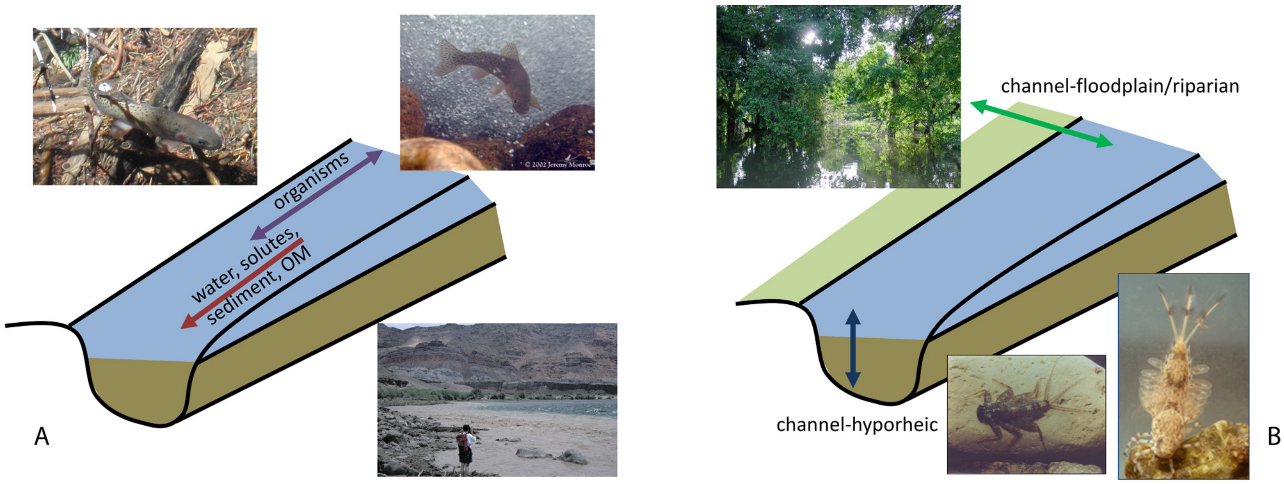

Figure 2a-b. Schematic illustration of fluxes within a stream corridor. A) Longitudinal fluxes of water, solutes, particulate material, and organisms. Inset photographs illustrate salmonids and mixing of turbid flow from a tributary with flow from the main channel. B) Lateral and vertical fluxes between the active channel and the floodplain and the hyporheic zone and ground water. Inset photographs illustrate a floodplain forest partly submerged during overbank flow and macroinvertebrates. Photographs at top center and lower right courtesy of Freshwaters Illustrated.

Second, a stream channel is neither static nor passive in the sense of a clearly defined, unchanging feature that does not interact with other parts of the landscape (fig. 2a-b). On the contrary, channels typically interact with adjacent surface and subsurface environments, including the hyporheic zone, floodplain, and riparian zone, and channels commonly move either abruptly or gradually over varying timescales. Interactions with the hyporheic zone underlying a channel occur in the form of downwelling of water and solutes from the channel into the hyporheic zone and upwelling of water and solutes into the channel. These exchanges of material strongly influence water quality and stream biota, as examined in more detail in section A.2.1.

Interactions between the channel and the floodplain and riparian zone can take the form of either overbank flow during periods of high discharge, when water, particulate material, and organisms spread from the channel across the floodplain, or lateral channel migration, when the active channel migrates laterally through progressive bank erosion or through the abrupt shift in location known as avulsion. The floodplain and riparian zone also contribute material to the channel, including sediment eroded from the floodplain along the channel margins; nutrients and organisms carried back into the channel during the waning stage of a flood; and particulate organic matter dropping into the channel from adjacent riparian vegetation.

Because of the vital connections between a channel and adjacent portions of the landscape, from here onward, stream refers to the stream corridor, which includes the bankfull channel (or channels, if secondary channels are present), the floodplain, the channel migration zone, and the hyporheic zone. The bankfull channel is defined by bankfull discharge, which is the flow stage coincident with the uppermost level of the stream banks (Wolman and Leopold, 1957; Osterkamp, 2008). This definition of a bankfull channel is based solely on channel morphology and does not necessarily imply anything about the recurrence interval of the flow that reaches bankfull stage. In many streams, a flow that recurs on average every 1 to 2 years equates to bankfull stage (Leopold et al. 1964; Castro and Jackson 2001; Simon et al. 2004), but this is not necessarily the case (Williams 1978; Petit and Pauquet 1997). Similarly, the morphological definition of a bankfull channel does not necessarily imply anything about flow duration. A bankfull channel can be delineated for an ephemeral stream that flows only during and soon after precipitation inputs and for an intermittent stream that flows continuously only during certain times of the year, as well as for a perennial stream that has longitudinally continuous surface flow throughout the average year.

Floodplains can be defined based on geomorphic characteristics or based on recurrence interval of inundation. We use the geomorphic definition of a floodplain as a relatively flat sedimentary surface adjacent to the active channel that is built by stream processes and inundated frequently, typically at least once every few years (Dunne and Aalto 2013). Floodplains are sometimes defined in a regulatory context as the area that is inundated by a flood with a specified recurrence interval (e.g., 100-year floodplain). Here, however, floodplain refers to a more frequently flooded surface. Surfaces created by stream processes but largely abandoned because of channel downcutting and therefore inundated less frequently, are here referred to as terraces.

The channel migration zone is the width of the valley bottom across which main and secondary channels can migrate and have migrated under the contemporary flow regime. In stream corridors that are laterally confined by steep valley walls, the channel migration zone can be minimal or non-existent. In lowland channels, the channel migration zone can be several times the average bankfull channel width.

The hyporheic zone consists of unconfined, near-stream aquifers where stream water is present because flow paths originate and terminate at the channel. This zone can extend several meters below large alluvial streams and as far as 2 km laterally from the active channel in stream corridors with broad, gravel floodplains (Stanford and Ward 1988). The length and travel time of flow paths within the hyporheic zone vary from minutes to many hours across the stream corridor and downstream, as well as through time in response to fluctuations in discharge (Gooseff 2010). Hyporheic exchange flows strongly influence water temperature, dissolved oxygen, and nutrient levels, and the hyporheic zone is inhabited by microbial and macroinvertebrate communities (Nihlgard et al. 1994; Harvey and Fuller 1998; Tonina and Buffington 2009).

A stream is most appropriately conceptualized as an ecosystem that includes the active channel(s), the floodplain, the channel migration zone, and the underlying hyporheic zone.

1.2. Perceptions of Stream Health and Large Wood

Stream health is a controversial phrase because of the difficulty of reaching a consensus as to what constitutes stream health and therefore how to assess it. The phrase is intuitively appealing, however, and continues to be used by stream scientists and by the public. We use the phrase here to refer to physical process and form and biotic communities. A healthy stream could be thought of as having geomorphic and ecological integrity. Geomorphic integrity for streams refers to a set of active stream processes and landforms such that the stream corridor adjusts to changes in water and sediment inputs within limits of change defined by societal values (Graf 2001). Ecological integrity describes the ability of the stream corridor to support and maintain a community of organisms with species composition, diversity, and functional organization similar to those within natural habitats in the same region (Parrish et al. 2003).

People who are not stream scientists, engineers, or natural resources managers may have very simplistic expectations of what a “healthy” stream looks like. The idea of stream health is controversial even among stream scientists, partly because there is no simple or consistent definition of what constitutes stream health or how it should be measured (Fairweather 1999; Norris and Thoms 1999). Stream health can be judged based on attributes of physical habitat (Maddock 1999), indices of biotic integrity (Harris and SIlveira 1999), characteristics of connectivity (Boulton 1999), and trophic characteristics of the aquatic ecosystem (Bunn et al. 1999), as well as other factors. Part of the difficulty in characterizing stream health lies in the importance of having: realistic models of interactions among streams, watersheds, and human communities; appropriate classification systems; and some idea of natural range of variability or reference conditions, all of which can be challenging to develop (Karr 1999). Where most of the streams in a region have been highly altered and reference conditions do not really exist (e.g., Comiti 2012), management must focus on desired outcomes rather than re-creation of natural conditions. In this context, environmental flow prescriptions (Tharme 2003; Richter et al. 2012) or development of a balanced sediment regime that maintains desired channel characteristics (Wohl et al. 2015a) are more appropriate than emphasis on a natural flow (Poff et al. 1997) or sediment regime.

Analogous to flow and sediment regimes, the wood regime within a stream can be defined as inputs, outputs, and storage of large wood from a length of stream over a specified time interval (Wohl et al. 2019). The concept equates to a wood budget, as described in section B.1.2. Like water and sediment, large wood supplied to, stored within, and transported by forested streams is a fundamental driver of stream condition, affecting water quality, thermal regime, habitat, aquatic and riparian communities, stream stability, and natural hazards (Kramer and Wohl 2017).

Despite the lack of consensus among stream scientists regarding stream health, the phrase is increasingly used. As discussed by Kondolf (2006), many people expect a healthy stream to have clear, clean water, a meandering form, and an open, park-like riparian woodland. Streams that do not meet these expectations–braided or anastomosing streams, streams with turbid flow, marshy swales, ephemeral or intermittent streams, or streams with abundant large wood–may be perceived as unattractive, unhealthy, and in need of restoration, *even if these streams are perfectly natural and healthy*.

The disparity that can exist between stream scientists, engineers, and resource managers on the one hand, and the general public on the other hand, is strikingly illustrated in the context of instream wood by a pair of surveys. In these surveys, respondents were asked to rate the same set of 20 photographs of diverse streams. Ten of the streams contained instream wood and 10 did not. Each respondent was asked to rate each photograph with respect to four characteristics: how esthetically pleasing the stream appears; how natural the scene looks; how dangerous the stream appears to be; and the extent to which there is a need for improvement within the stream. The first survey focused on undergraduate students in natural resources fields (geography, geology, environmental science, biology, fisheries, and wildlife) at universities in nine U.S. States. With the exception of students in Oregon, students consistently viewed streams without wood much more positively (Chin et al. 2008). The second survey focused on stream managers across seven U.S. States. In contrast to the students, the managers consistently viewed wood in streams more positively and the degree of positive assessment increased with time in the profession (Chin et al. 2014). These results suggest that education and outreach have the potential to change what are currently largely negative public perceptions of wood in streams. This education and outreach is likely to be an important component of successfully reintroducing wood to streams.

Analogously, public perceptions of natural disasters, such as floods, may also limit acceptance of the changes in channel morphology and the abundance and distribution of wood associated with floods. Even the most altered watersheds and stream corridors can episodically experience substantial large wood (LW) recruitment and transport as a result of a significant disturbance, which can be either natural (e.g., extreme rainfall and flooding, landslides, or debris flows; Aumen et al. 1990; Johnson et al. 2000; May and Gresswell 2003) or human-induced (e.g., dam removal). Given the numerous beneficial effects of LW, what are commonly referred to as natural disasters can beneficially affect a stream ecosystem. Large floods, for example, can:

- cause substantial erosion and deposition and formation of new habitat (e.g., germination sites for riparian plants; new secondary or cutoff channels) (Gurnell et al. 2005);
- rejuvenate existing habitat (e.g., flushing interstitial fine sediment from the streambed) (Schmidt et al. 2001);
- facilitate exchange of organic matter and nutrients between the channel and floodplain (e.g., Junk et al. 1989);
- facilitate dispersal of organisms and plant propagules (e.g., Jansson et al. 2005); and
- recruit and redistribute LW in the stream corridor (Pettit and Naiman 2006).

Because of this, natural events such as floods and managed events such as dam removal can be regarded as an opportunity to introduce LW that can then be managed to sustain beneficial environmental effects. The potential ecological benefits of large floods can be eradicated by post-flood mechanical disturbance for sediment and large clast removal, and clearing and snagging activities.

Large wood and beaver are fundamentally important to maintaining stream health in forested streams of the northern hemisphere.

1.3. Large Wood and Beavers in Stream Corridors

This document focuses on large wood in stream corridors. Large wood (LW) is not consistently defined in existing studies, but the most common criteria are downed, dead wood pieces greater than or equal to 10 cm in diameter and 1 m in length (Keller and Tally 1979; Lienkaemper and Swanson 1987; Fetherston et al. 1995; Hassan et al. 2005; Wohl et al. 2010). These characteristics distinguish LW from what is sometimes referred to as livewood (Opperman et al. 2008), or portions of living woody vegetation within a river, and from fine wood (Triska and Cromack 1980; Culp et al. 1996) or small wood (Lester et al. 2006), which is typically defined as downed, dead wood pieces of smaller size than the dimensions noted above. Although smaller wood pieces are not commonly measured in studies conducted by physical scientists (ecologists are more likely to quantify small wood), the ability of LW jams to trap small wood (e.g., Millington and Sear 2007) exerts an important control on jam porosity and creation of a backwater that retains fine sediment and organic matter. Small wood may also provide more readily available nutrients to biota because of the greater surface area/volume ratio and differences in wood tissue relative to the trunks of large trees.

LW can also be distinguished as instream wood that is present within the bankfull channel or as floodplain wood. To some extent these distinctions are arbitrary, because

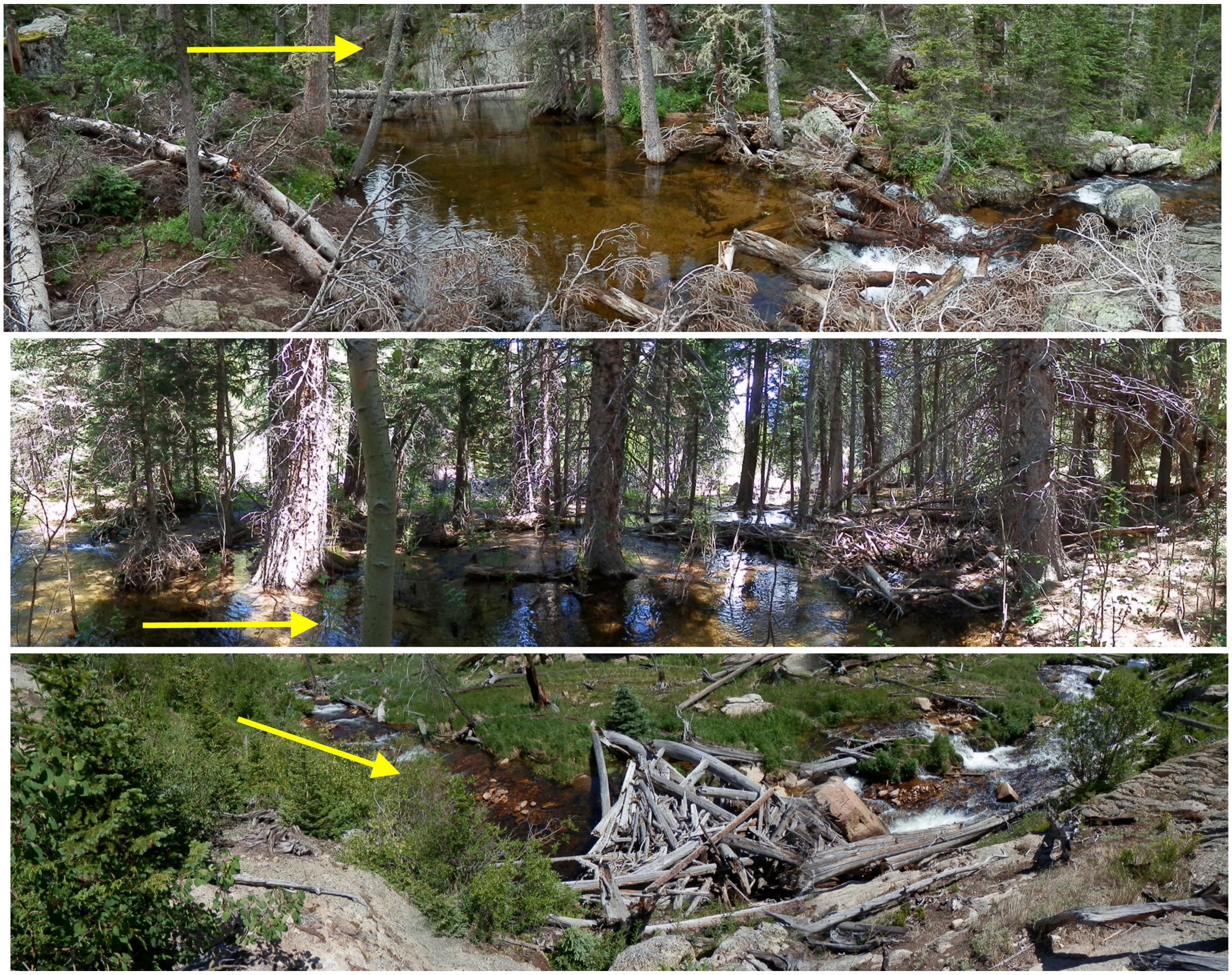

Figure 3. Examples of instream logjams that force flow onto the floodplain. All creeks are in Rocky Mountain National Park in Colorado. Yellow arrow indicates flow direction.

individual, stationary LW pieces commonly occupy portions of both the bankfull channel and the floodplain (fig. 3) and LW pieces in transport during overbank flows commonly move both from the channel to the floodplain and from the floodplain into the channel.

LW can take the form of dispersed individual pieces within the stream corridor or concentrations of pieces in the form of jams. A jam here refers to three or more pieces of LW in contact with one another (Wohl and Cadol 2011) (fig. 4). A channel-spanning jam extends across the entire active channel and creates longitudinal discontinuities in the water surface and stream bed across at least two-thirds of the channel (Wohl and Beckman 2014a). Jams can also be distinguished as *in situ* jams that form around a stationary piece recruited from the adjacent riparian forest; transport jams composed of pieces transported downstream; combination jams that include substantial quantities of *in situ* key pieces and racked and loose pieces that were clearly transported to the site; or valley jams that have widths greater than the bankfull channel and extend across a significant portion of the valley bottom (Abbe and Montgomery 2003).

Abbe and Montgomery (2003) further distinguish jams based on their formative process (e.g., bank input, debris flow), their primary effects (e.g., flow deflection jams), and their geomorphic location (e.g., bench jams along the channel margin, bar-apex jams, and meander jams). Wallerstein and Thorne (2004) distinguish: underflow jams in which key LW pieces span the channel at the top of the bank; dam jams that completely block the flow; deflector jams that are narrower than the channel width and deflect flow against one or both banks; and flow parallel or bar head jams that are much narrower than the channel and aligned parallel to the flow or deposited against incipient bars. None of these classifications of jams is widely or consistently used, so the generic word "jam" is used in this document unless a specific type of jam is being described.

In the context of LW dynamics, stream size has been defined relative to average piece size of LW. A small stream is narrower than the locally typical wood piece length, a medium stream is slightly narrower than the longer wood pieces present, and a large stream is wider than the length of all wood pieces delivered to the stream (Gurnell, 2003).

Numerous papers have been published in scientific journals on both LW and beaver dams. To a large extent, these are separate bodies of literature, with relatively few papers treating both topics (exceptions include Kreutzweiser et al. 2005; Polvi and Wohl 2013; Wohl 2015, 2017). In this paper, beaver dams are treated as a distinctive subset of LW that has some similarities with other forms of LW, but also some unique characteristics. Dams built by North American beaver (*Castor canadensis*) are commonly composed primarily of LW or fine wood, although beaver dams can also include substantial proportions of sediment (fig. 5). However, in building their dams, beaver tend to collect and anchor downed wood within the bankfull channel and across the floodplain and the animals actively maintain their dams. This creates differences in LW recruitment and retention in beaver-influenced stream segments.

LW can be present throughout a stream network, although channel-spanning jams are most likely to form in relatively low-order streams. Beaver dams can also be present throughout a stream network, although beavers typically do not dam channels wider than approximately 20 m. This reflects the substantial discharge and velocity associated with larger channels, rather than any inherent length limitation on beaver dams. Beaver dams 60 m long exist at sites with limited discharge and velocity (Rosell et al. 2005) and an 850-m-long beaver dam has been documented in northern Canada. In higher-order stream corridors, beaver dams are more likely to be present on floodplain or secondary channels or on valley-side seeps or springs, rather than on the mainstem.

We consider it appropriate to discuss both LW and beaver dams in this document because both can create similar environmental benefits by modifying downstream fluxes of water, solutes, sediment, and organic matter and increasing habitat abundance and diversity. Analogously, the presence of LW and beaver dams can result in hazards associated with mobile wood pieces, local erosion and deposition, channel avulsion, formation of backwaters, and outburst floods.

Much of the scientific literature on beaver dams involves studies of a single dam-pond pair. Where sufficient space exists, however, beaver commonly create beaver meadows (Ives 1942). Beaver meadows are defined here as spatially extensive complexes of multiple dams and ponds in varying states of activity or abandonment (fig. 6). First described in Morgan (1868), the existence of these environments has been recognized for more than a thousand years by people who preferentially sought the nutrient-rich soil of beaver meadows for grazing or crop lands (Coles and Orme 1983). Individual beaver meadows can be multiple kilometers in length and width (Wohl 2013b), although the dimensions will be governed by factors such as valley geometry, position in the drainage network, and groundwater springs along the valley walls: beaver can build a series of multiple dams along valley-side walls well above the level of the primary channel and floodplain (fig. 7).


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B
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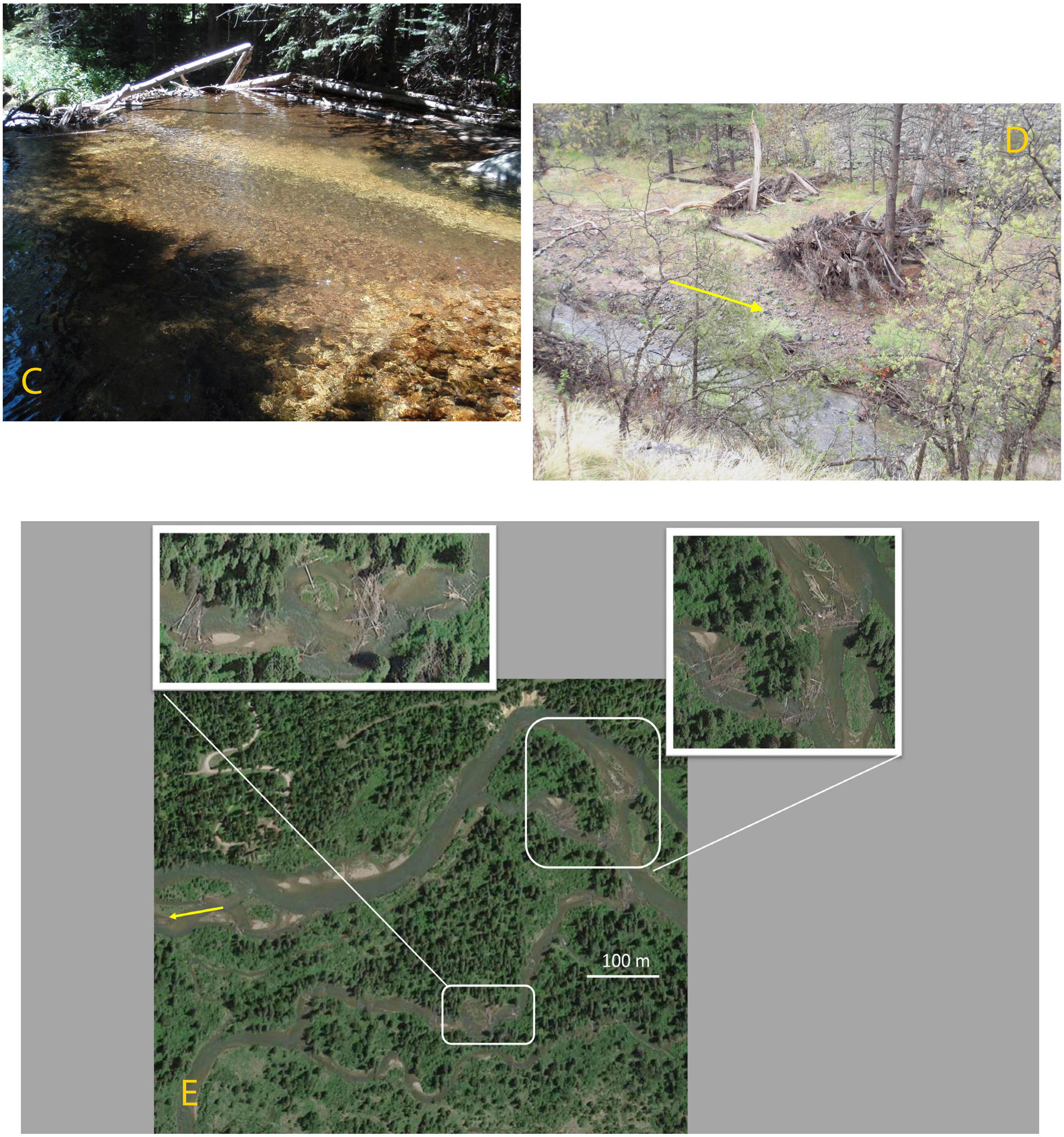


Figure 4a-e. Illustrations of different types of logjams. A) Transport jam, Glacier Creek, Rocky Mountain National Park, Colorado. B) In situ jams formed where a fallen tree mostly or completely spans the channel. C) Channel-spanning jams and backwaters with fine sediment and particulate organic matter. D) Jams are more likely to form on the floodplain where peak flows go overbank and widely spaced living trees can trap wood in transport; Middle Fork Gila River in the Gila National Forest, New Mexico. E) Jams are likely to be restricted to secondary channels where dense floodplain forests limit fluvial transport of wood beyond channel boundaries. Swan River on the Flathead National Forest, Montana. Yellow arrows indicate flow direction.

Figure 5a-c. Examples of beaver dams, illustrating dam construction using diverse sizes of sediment and wood pieces. A) Hague Creek, Colorado. Dam is approximately 1.5 m tall. B) French Creek on the Medicine Bow National Forest, Wyoming. Breached dam with accumulated fine sediment upstream. C) Closer view of wood and sediment along the crest of a dam beside the Duke River, Canada. This dam forms a semi-circular enclosure at the point of a large seep along the valley side wall. The resulting pond is perched 4 meters above the active channel (see figure 7).

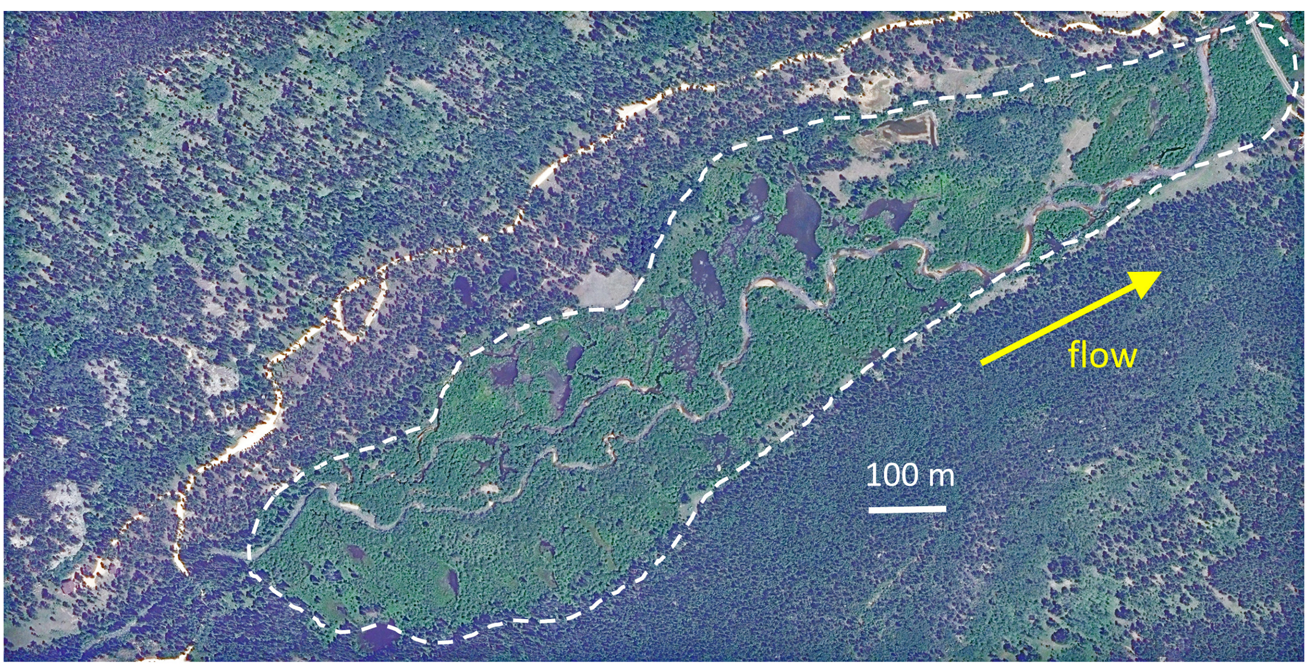


Figure 6. Example of a beaver meadow, here along North St. Vrain Creek in Colorado. Secondary channels and ponds are present within the lighter green area that represents the beaver meadow. Yellow arrow indicates flow direction (image courtesy of Digital Globe).

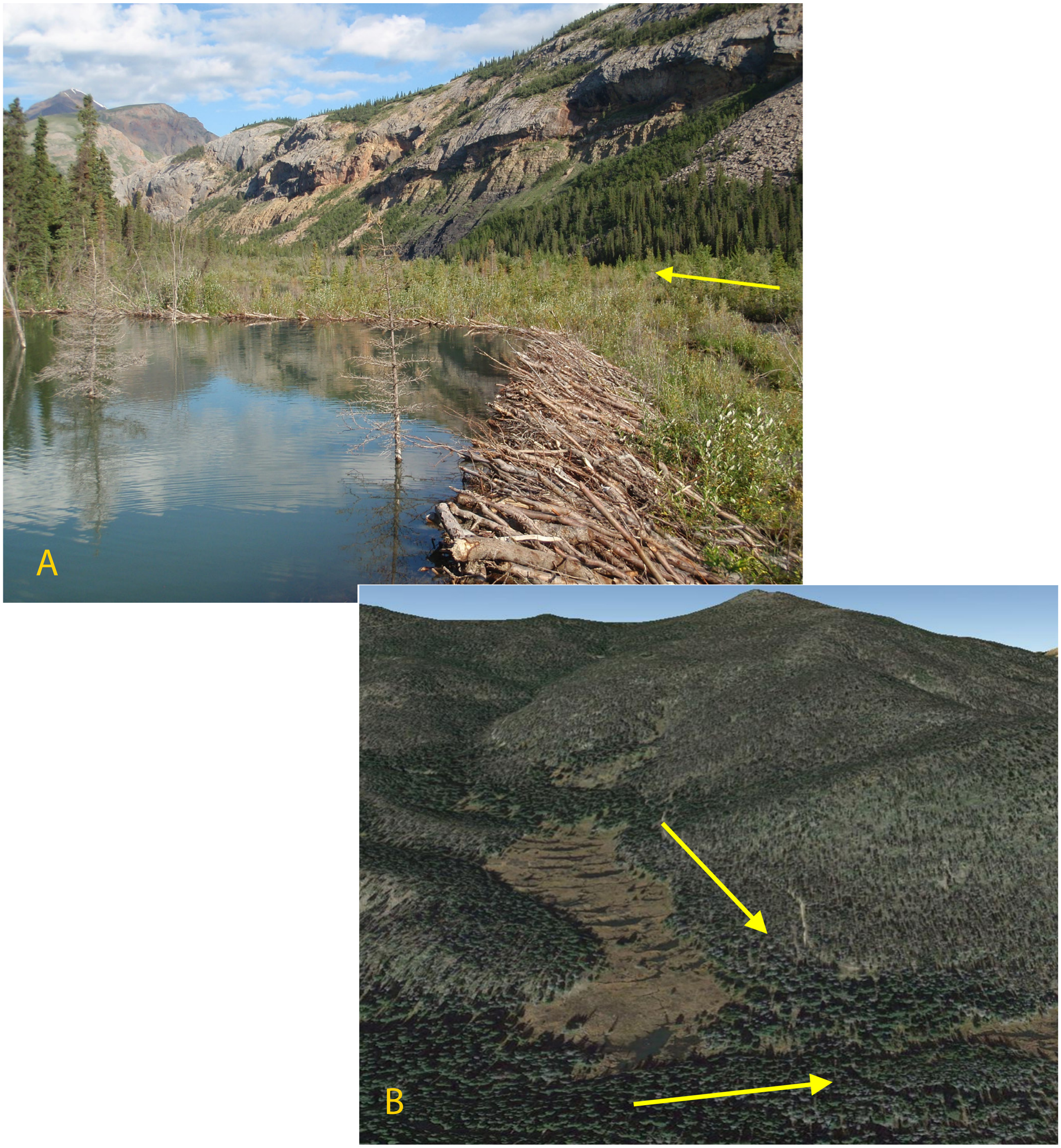


Figure 7a-b. Examples of beaver dams built above the main active channel. A) Beaver dam along the Duke River in Canada. Yellow arrow indicates flow direction and location of main channel, which is about 4 m lower in elevation than the beaver pond along the side of the valley. B) Oblique view of a series of beaver dams and ponds along Spruce Creek, a tributary of St. Louis Creek in the Fraser Experiment Forest, Colorado. Yellow arrows indicate flow direction on each creek.

1.4. Historical Conditions in Stream Corridors of the United States

The earliest written descriptions of stream corridors in forested regions of the United States typically emphasize the substantial quantities of LW in channels and floodplains (e.g., Sedell and Luchessa 1981 for the Pacific Northwest; Wohl 2014 for the southeastern United States) and the abundance of beaver dams. Although LW today may be associated primarily with the Pacific Northwest in the minds of many resource managers in the United States, it is worth emphasizing that substantial quantities of wood were present along forested stream corridors throughout the United States. This includes streams in otherwise tree-less environments such as prairies and deserts, as long as even a slender fringe of riparian forest was present or the headwaters portion of the stream network was forested (e.g., Minckley and Rinne 1985; Andersen et al. 2016).

Among the most distinctive historical features in rivers of the United States were naturally occurring wood rafts (as opposed to log rafts created by floating cut logs downstream). The most well-known wood raft was the Great Raft on the Red River in Louisiana, which was actually a series of wood accumulations that affected nearly 500 km of river, with instantaneous blockage of up to 225 km (Triska 1984). The raft had been in existence at least since the late 1400s at the time it was fully removed in 1873. The raft facilitated overbank sedimentation (Barrett 1996; Patterson et al. 2003) and channel avulsion, leading to the formation of numerous floodplain lakes and bayous that remain in existence today (Reuss 2004). The Great Raft required 40 years to destroy by the process of snagging (removing instream LW) (Williams 2010). Phillips and Park (2009) propose that massive LW recruitment during extreme storms, such as Hurricane Rita in 2005, could initiate wood rafts. Other wood rafts were described on the rivers of the Pacific Northwest, including those in Oregon's Willamette Valley and Washington's Puget Sound lowlands (Sedell and Luchessa 1981; Collins et al. 2002, 2003), and in diverse forested regions of the United States (Wohl 2014) where mass recruitment could occur during tornadoes, microbursts or other intense winds capable of blowing down large numbers of trees, and debris flows and landslides. Although uncommon, wood rafts still occur today (Webster et al. 2002; Erskine et al. 2012; Martín-Vide et al. 2014; Boivin et al. 2015). Buried wood in channels and floodplains record long-term accumulation of wood along stream corridors (Guyette et al. 2008; Davies et al. 2014).

Place names record now-forgotten conditions, as in the case of the Embarras River, a tributary of the Wabash River in Illinois. The name derives from French explorers, who used "embarras" to describe stream blockages associated with instream wood. And of course there are hundreds of "beaver creek" place names throughout the United States, as well as cities named Beverly in Massachusetts, New Jersey, Ohio, Kansas, and elsewhere. Beverly derives from the English phrase "beaver lea," or beaver meadow (Evans 2006).

The earliest indirect form of stream alteration in much of the United States was the commercial trapping of beaver for their fur. Trapping was conducted without regard for survival of beaver populations, leading to local extirpation of the animals along a front that moved progressively westward from the eastern coast of the United States in the late 16th century to the Intermountain West and western coast by the mid-19th century (Naiman et al. 1988). Commercial trapping was largely conducted in response to commercial demand for beaver fur from Europe, where Eurasian beaver (*Castor fiber*) had already been trapped nearly to extinction (Gregory 2003). Scientists estimate that anywhere from 200 to 400 million beaver were present in North America prior to commercial trapping, with a geographic range from northern Alaska to northern Mexico, and along forested stream corridors in otherwise arid regions such as central and southern Arizona (Hill 1982; Naiman et al. 1988; Gibson and Olden 2014). North American beaver numbers fell to an estimated 6 to 12 million by the 20th century (Naiman et al. 1988). Beaver dams fell into disrepair as beaver populations were extirpated in an area, leading to progressive and sustained simplification and drying of stream corridors.

One of the earliest forms of deliberate stream management involved directly removing LW to facilitate navigation and limit overbank flooding (Sedell and Froggatt 1984; Harmon et al. 1986). LW was also indirectly removed in connection with floating of cut logs downstream to sawmills (Sedell and Luchessa 1981; Sedell et al. 1991; Montgomery et al. 2003; Wohl 2014; Higgins and Reinecke 2015) (fig. 8) and as part of navigation improvements that included dredging and channelization (Harmon et al. 1986). Logging of floodplain and upland forests, including logging of forests immediately adjacent to channels to supply fuel for steamboats

Figure 8a-b. Historic photographs of floating cut logs downstream to collection booms and sawmills. A) St. Croix River, Wisconsin, 1886 (source: Minnesota Historical Society. Courtesy of Minnesota Historical Society). B) Medicine Bow National Forest, Wyoming (source: University of Wyoming. Courtesy of American Heritage Center, University of Wyoming).

(Andersen et al. 1996; Wohl 2014), reduced recruitment of LW to stream corridors (Sedell and Froggatt 1984; Wood-Smith and Buffington 1996). Subsequent studies indicate that the great majority of instream and floodplain LW in many rivers comes primarily from adjacent riparian stands (e.g., Lienkaemper and Swanson 1987; McDade et al. 1990; Downs and Simon 2001; May and Gresswell 2003; Latterell and Naiman 2007; Benda and Bigelow 2014; Costigan et al. 2015), although the relative importance of diverse recruitment sources can vary among watersheds and among portions of a watershed (e.g., Swanson, 2003; Wohl et al. 2012; Jensen et al. 2014). Compilations based on federal government records of wood removal indicate that tens of millions of logs were removed over a period of several decades from rivers throughout the United States (Harmon et al. 1986; Wohl 2014).

One of the most significant aspects of these historical activities is their lasting effect, even in channels in which these activities have not occurred for more than a century. Studies throughout the United States indicate that statistically significant differences persist in channels that experienced log floating and wood removal, or even timber harvest in the riparian zone and uplands (e.g., Silsbee and Larson 1983; Sedell et al. 1991; Young et al. 1994; Warren et al. 2007; Nowakowski and Wohl 2008; Ruffing et al. 2015; Livers and Wohl 2016), although the details vary in relation to channel geometry and substrate characteristics (e.g., Scott et al. 2014).

The cumulative effects of substantially greater quantities of LW and much higher population densities of beaver are difficult to imagine when considering most stream corridors in the United States today. Channels and floodplains would have been more spatially heterogeneous and physically complex. Numerous obstructions to flow facilitated enhanced hyporheic exchange and greater connectivity between channels and floodplains. Multiple, subparallel channels and cutoff meanders created diverse aquatic and riparian habitat. Rivers were characterized by numerous downstream alternations between ponded and flowing water where beaver were present. Obstructions to flow and greater overbank flooding promoted attenuation of peak flows, as well as substantial storage of mineral sediment, particulate organic matter, and solutes moving downstream. Floodplain wetlands were likely much more abundant. These physically diverse stream corridors likely supported much greater abundance of aquatic and riparian organisms and greater biodiversity (Sedell and Froggatt 1984; Harmon et al. 1986; Collins et al. 2003), creating stream ecosystems that were more resistant and resilient to natural disturbances such as floods, droughts, and wildfires.

When first coming into contact with a stream corridor that has not experienced historical management, such as old-growth forest or very remote regions in Alaska, even experienced stream scientists can be surprised at the quantity of LW or spatial density of beaver dams. It is worth emphasizing that most people significantly underestimate the volumes of LW and beaver dams that are present in completely natural streams (fig. 9).

Historical removal from streams of once-widespread and abundant large wood and beaver has significantly reduced spatial heterogeneity, physical complexity, and ecosystem function in streams throughout the United States. The cumulative effects of historical removal of large wood and beaver can persist for decades to more than a century after land use ceases.

1.5. Spatial and temporal Patterns of LW in Rivers

Watershed-scale analyses and syntheses of numerous studies suggest that the instream wood load, or cumulative volume of LW per unit area of channel, decreases downstream (Bilby and Ward 1989; Keller et al. 1995; Marcus et al. 2002; Chen et al. 2006; Wohl and Jaeger 2009). This has been interpreted primarily as an effect of increasing transport capacity as channel width and flow depth become greater in the lower portions of a stream network (Martin and Benda 2001). The existence of features such as wood rafts in very large stream segments, however, suggests that observed patterns of downstream decreases in wood load may reflect land-use history as much as changing fluvial transport capacity for LW. Many of the studies conducted in smaller channels focus on relatively unmanaged or old-growth forested environments, whereas such forests are rare along larger rivers, which are also likely to have other human influences such as flow regulation, channelization, or levees. Dryland channels may have greater LW loads downstream if discharge declines downstream because of infiltration and evaporation losses (Jacobson et al. 1999).

Downstream patterns of LW load and function vary greatly between regions as a function of factors such as forest characteristics and piece size of the wood. As noted previously, Gurnell et al. (2002) describe channel size in relation to wood piece size. In small streams, channel width is less than the median wood piece length and much of the LW recruited to the stream corridor has limited mobility. In medium streams, channel width is less than the upper quartile of wood piece length and greater LW mobility can increase the longitudinal non-uniformity of LW distribution, creating jams at sites of lower transport capacity. In large streams (rivers), channel width is greater than the length of all the wood pieces delivered to the channel and most LW is readily mobile above a threshold discharge that inundates wood storage sites along the channel margins. Kramer and Wohl (2017) proposed adding great rivers, which drain areas > 106 km^2 and have vast, seasonally inundated floodplains and the potential for substantial lateral exchange of LW between the channel and floodplain.

This categorization reflects fundamental differences in LW mobility and geomorphic and ecological functions and is flexible enough to incorporate biomes that produce widely different sizes of wood pieces. Rivers, for example, typically have less LW stored in the channel than is introduced annually, with much of the LW stored along the edge of the floodplain and on bars (Piégay and Gurnell 1997; Piégay 2003). Kramer and Wohl (2017) suggest categorizing LW transport regimes as piece-dominated (small streams with rare, episodic LW movement), jam-dominated (medium streams in which piece movement is strongly influenced by the downstream spacing of jams), high-flow-dominated (rivers in which LW is more regularly transported downstream by high flows), or burial-dominated (great rivers in which LW can be trapped and buried within wood rafts). Regardless of the classification used, LW mobility and geomorphic and ecological functions vary systematically in relation to stream size.

At the reach scale, streams are likely to exhibit substantial longitudinal variability in LW loads and the spacing and size of logjams as a function of spatial variations in valley and channel geometry, riparian forest stand age, and watershed structure (i.e., tributary junctions) and temporal variations in LW recruitment and transport (Nakamura et al. 2000; Kraft and Warren 2003; Nakamura and Swanson 2003; Benda et al. 2004b; Young et al. 2006; Cordova et al. 2007; Morris et al. 2007, 2010; Jones and Daniels 2008; Marcus et al. 2011; Wohl and Cadol 2011; Erskine et al. 2012; Benda and Bigelow 2014) (fig. 10). Individual stream reaches that tend to have greater LW loads and longer LW residence times commonly have one


A


B1

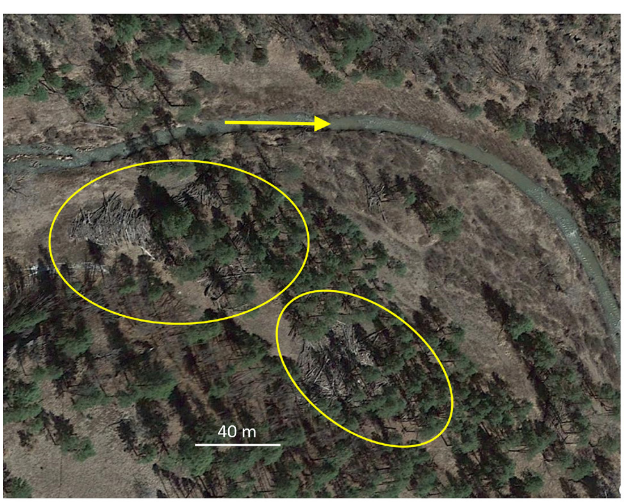

40 m

Figure 9a, b1-b4. (A) Probable historical range of beaver (*Castor canadensis*) indicated in darker gray shading (source: Pollock et al. 2015, figure 1). Although the Great Basin region is excluded from the probably historical range, some of the streams may have had beaver historically. B1-4 includes examples of stream corridors with abundant large wood. Yellow arrows indicate flow direction. (B1) A jam approximately 500 m long and 150 m wide along the margins of the Yukon River at the entrance to a secondary channel. (B2) Aerial view of a portion of the Middle Fork Gila River on the Gila National Forest in New Mexico; yellow ovals highlight substantial accumulations of wood on the floodplain. (B3) Aerial and ground views of a large jam along the Big Thompson River, Colorado. Channel is approximately 20 m wide. (B4) Wood trapped against bridge piers in Kansas.

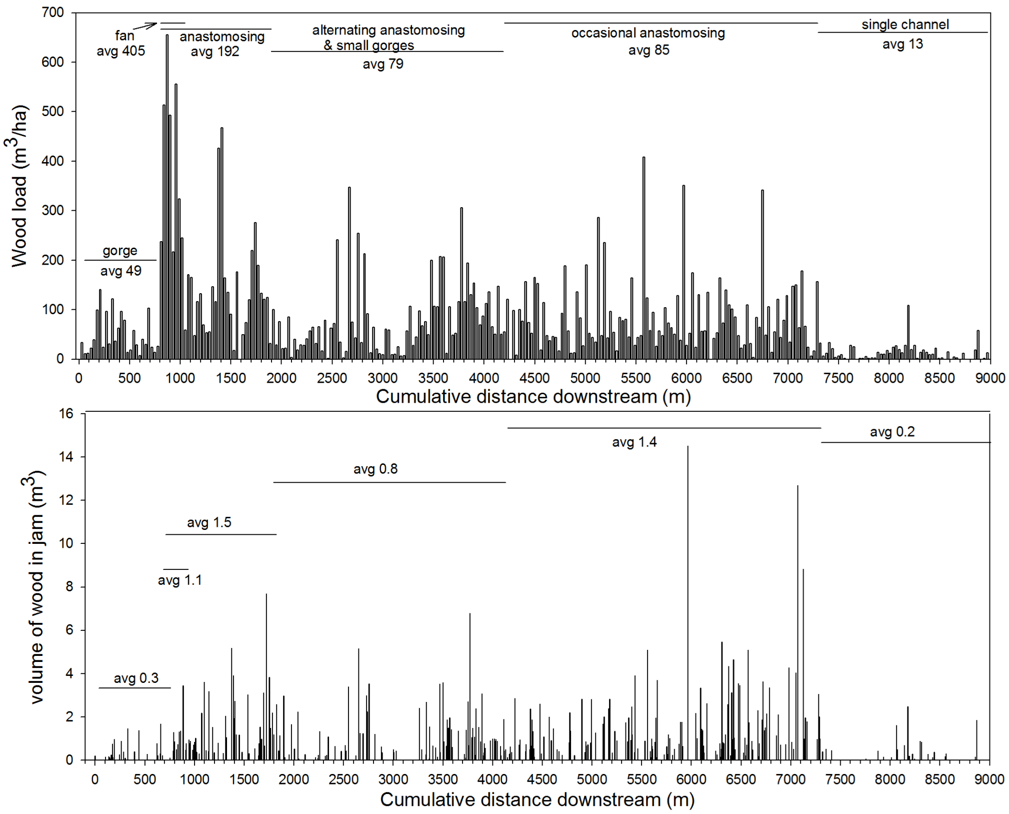


Figure 10. Bar graphs of the distribution of total wood load (individual pieces and jams; upper graph) and the volume of wood within logjams (lower graph) along 9 km of North St. Vrain Creek in Colorado. The substantial longitudinal variations in wood load and jam volume correspond to longitudinal variations in valley and channel geometry noted along the top of the upper graph.

or more characteristics that facilitate LW retention (Hedman et al. 1996; Gurnell 2003; Benda et al. 2004b; Wyzga and Zawiejska 2005; Moulin et al. 2011; Wohl and Cadol 2011). Such characteristics include:

1. lower gradient and greater width in mountainous stream networks and narrower, sinuous channels in lowland networks;
2. older riparian forest and forest with only natural disturbances (rather than contemporary or historical land use);
3. instream and floodplain obstacles such as relatively immobile LW or standing trees; and
4. tributary junctions.

LW jams and associated moist, organic-rich microhabitats can be particularly important for diverse species in ephemeral channels (Jacobson et al. 1999). The presence of longitudinal variations in LW load creates wood-rich hot spots of greater nutrient uptake, biomass, and biodiversity of aquatic and riparian organisms (e.g., Bellmore and Baxter 2014; Herdrich 2016).

Rates of LW recruitment vary substantially through time as a result of natural disturbances such as wildfire (Young 1994; Zelt and Wohl 2004; Bendix and Cowell 2010; King et al. 2013), blowdown (Wohl 2013c), ice or snowstorms (Andrew and Hartman 2015), and hillslope instability (Wohl et al. 2012). Relatively few studies have directly measured LW residence time over a period of multiple years, but studies that have examined this issue indicate that most LW pieces move episodically through a stream network, with relatively long periods of storage interspersed with brief periods of transport (Hyatt and Naiman 2001; Kramer and

Wohl 2017). Residence times vary as a function of: LW load (greater loads equate to longer residence times); flow regime (more frequent or sustained flows exceeding a transport threshold equate to shorter residence times); LW piece size (shorter, narrower pieces tend to have shorter residence times; Merten et al. 2011; King et al. 2013); and position of LW (pieces wholly within the bankfull channel tend to have shorter residence times). Reported residence times vary from less than a year (Wohl and Goode 2008) to decades (Wallace et al. 2001; King et al. 2013), centuries (Keller et al. 1995; Hart 2002), and more than 1,000 years (Nanson et al. 1995; Hyatt and Naiman 2001).

Studies in diverse stream corridors also indicate that the location of storage and relative importance of specific geomorphic and ecological functions of LW vary among stream segments, typically in relation to LW mobility and the ratio of wood piece size relative to channel size (Wohl 2017). LW in small streams, for example, is likely to be primarily *in situ* and to effectively store bedload and particulate organic matter. LW in large rivers is more likely to be transported wood deposited along channel margins or moving in rafts, and which may primarily increase hydraulic resistance and influence lateral channel migration (Gurnell 2013).

Where land uses such as logging have reduced LW recruitment from upstream or riparian sources, studies in diverse environments suggest that at least 200 years of undisturbed forest regrowth–and in some regions substantially longer–are necessary before instream LW loads reach natural or background levels (Webster and Swank 1985; Spies et al. 1988; Murphy and Koski 1989; Bragg 2000; Bragg et al. 2000; Meleason et al. 2003). These studies also emphasize the critical importance of a sufficiently wide forested riparian buffer to provide continuing LW recruitment (e.g., Collins and Montgomery 2002; Boyer et al. 2003). Even a century after logging, instream LW is likely to consist of smaller, more mobile pieces than in otherwise comparable unlogged forest streams (e.g., Ralph et al. 1994; Richmond and Fausch 1995; Bunn and Montgomery 2004). Continued logging or other land uses, including grazing and the presence of roads, are also typically associated with lower wood loads, fewer pools, less diverse habitat, and less sediment storage in channels (e.g., Hogan 1987; Fausch and Northcote 1992; Meredith et al. 2014; Livers and Wohl 2016).

The instream wood load, or cumulative volume of wood per unit area of channel, typically decreases downstream, but downstream patterns of wood load and function vary greatly between regions. Small streams are those in which channel width is less than the median wood piece length and much of the wood recruited to the stream corridor has limited mobility. Channel width is less than the upper quartile of wood piece length in medium streams and greater wood mobility can result in more logjams. Channel width is greater than the length of all wood pieces in large rivers and wood is readily mobile above a threshold discharge. Wood-rich zones include stream segments: of lower gradient and greater width; with older riparian forest and forest with a history of only natural disturbances; with obstacles such as large boulders or living trees in the channel and floodplain; and with tributary junctions.

1.6. Wood Budgets

Effective management of LW in stream corridors requires understanding the processes that recruit LW and the rates at which those processes operate, as well as understanding the factors that mobilize or retain LW. These processes and factors are likely to change through space and time within a stream network or even a segment of river. LW dynamics in rivers of the Yellow-stone ecosystem, for example, vary from 1st and 2nd order streams that are transport limited with respect to LW, to 3rd and 4th order streams that exhibit dynamic equilibrium and LW redistribution during floods, to 6th order and higher streams that are supply-limited with respect to LW (Marcus et al. 2002).

A wood budget can be useful in the context of considering continuing LW recruitment in managed areas (Benda et al. 2003a; Hassan et al. 2005). A wood budget is a simple accounting of inputs, storage, and outputs within a stream reach and can be applied either as a conceptual or quantitative framework. Benda and Sias (2003) proposed the following equation for a wood budget within a channel segment of length x:

$$\Delta S_c = \left[L_i - L_o + \frac{Q_i}{\Delta x} - \frac{Q_o}{\Delta x} - D\right]\Delta t \qquad (1)$$

where
ΔS_c is change in storage within the reach over time interval t,
L_i is lateral wood recruitment into the channel,
L_o is loss of wood to overbank deposition during floods and abandonment of jams,
Q_i is fluvial transport of wood into the reach,
Q_o is fluvial transport out of the reach, and
D is *in situ* decay.

Lateral inputs can be conceptualized as resulting from several processes:

$$L_i = I_m + I_f + I_{be} + I_s + I_e + I_{bd} \qquad (2)$$

where
I_m is chronic individual tree mortality,
I_f is mass mortality (fire, blowdown, insects),
I_s is hillslope instability,
I_{be} is bank erosion,
I_e is exhumation from the floodplain, and
I_{bd} is beaver dams (this term is not in Benda and Sias 2003 but was introduced in Wohl 2016) (fig. 11).

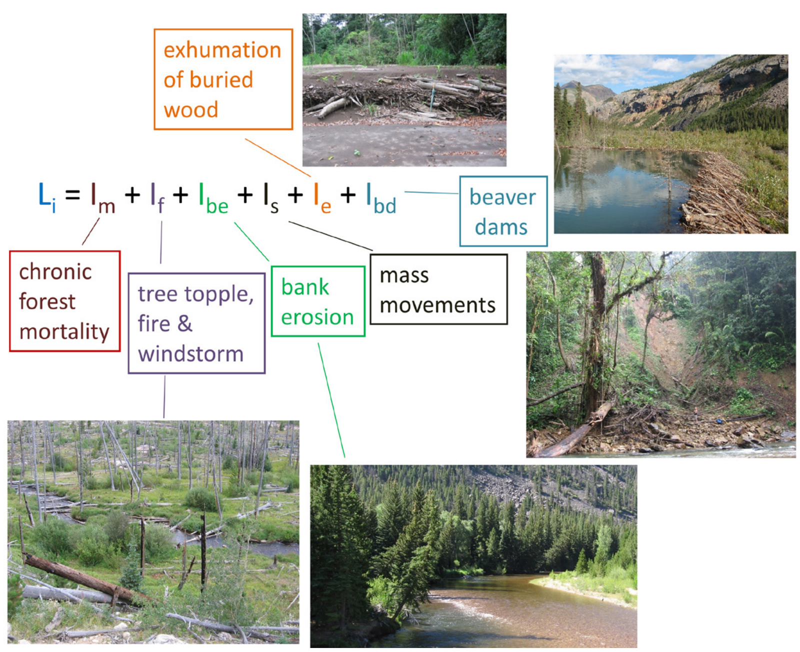


Figure 11. Schematic illustration of the different forms of lateral inputs in a wood budget. Inset photos (clockwise from lower left) illustrate wood recruitment following a wildfire, wood buried in the floodplain being exhumed via bank erosion, wood incorporated into a beaver dam, wood recruited via a landslide, and wood being recruited via bank erosion. Equation for lateral wood inputs modified from Benda and Sias (2003).

Multiple numerical models have been developed to simulate and predict diverse aspects of LW dynamics. Many of the initial models focused on forest stand dynamics that create wood for recruitment to rivers (Gregory et al. 2003). Subsequent models have included more explicit attention to processes that directly cause LW recruitment (e.g., bank erosion) and processes that result in LW transport and redistribution along the stream corridor (Lancaster and Grant 2006; Mazzorana et al. 2009, 2011, 2013; Eaton et al. 2012; Ruiz-Villanueva et al. 2014a, b, c). These models have been calibrated and validated primarily in the Pacific Northwest or European Alpine regions and it remains unclear how well they apply to other regions with different tree size and morphology. Another group of models seeks to predict physical effects, such as flow resistance and bed scour and deposition, associated with LW (e.g., Gippel et al. 1992; Wallerstein 2003; Stewart and Martin 2005; Manners et al. 2007).

In addition to numerical modeling, target wood loads are sometimes defined based on wood loads present in reference channels or the most natural watersheds within a region (e.g., Lester et al. 2006; Fox and Bolton 2007). This typically requires extensive data for a region, however, because of the temporal and spatial variability in LW loads in watersheds without human disturbance. Wohl (2017) summarizes existing datasets on LW loads for rivers in diverse regions.

A wood budget is a simple accounting of inputs, storage, and outputs within a stream reach and can be applied either as a conceptual or quantitative framework.

2. Benefits of Large Wood and Beaver Dams in Stream Corridors

2.1. Benefits of Instream LW

Research into the physical and ecological effects of instream and floodplain LW primarily began in the Pacific Northwest during the 1970s (e.g., Swanson et al. 1976); we know more about LW dynamics in this region than in any other (e.g., Bisson et al. 1987; Maser et al. 1988; Hassan et al. 2005; Fox and Bolton 2007). A substantial body of literature now documents LW characteristics in diverse rivers, although important gaps remain in our knowledge of LW in stream corridors (Wohl 2017). This section briefly reviews the primary benefits associated with LW in rivers.

Large wood in channels and floodplains has diverse influences on physical, chemical, and biotic processes in stream corridors, as summarized in table 1. Each of the following paragraphs in this section briefly reviews a category of these influences.

Hydraulic effects. Individual pieces of LW and jams can directly increase hydraulic resistance in channels and across floodplains by enhancing the irregularity of the surface through the shape of the LW (including branches and rootwads) and the surface roughness of bark (Gippel 1995; Hygelund and Manga 2003; Mutz 2003; Daniels and Rhoads 2004; David et al. 2010; Davidson and Eaton 2013). LW can also indirectly increase hydraulic resistance by changing the downstream spacing and dimensions of bedforms such as steps in high-gradient channels (Keller et al. 1995; Curran and Wohl 2003; MacFarlane and Wohl 2003; Yochum et al. 2012, 2014). Dispersed or jammed LW can create obstructions within a channel that facilitate formation of backwaters and low-velocity zones both upstream and downstream from the wood. LW can also enhance overbank flow. Even in situations where widely dispersed LW does not create substantial backwaters, individual pieces can reduce local flow velocity and increase flow depth, and the cumulative effect of the greater hydraulic resistance can

Table 1—Beneficial effects of large wood in river corridors.

Effect	Example references
Channel	
Increased hydraulic resistance directly from LW and indirectly from altered bedforms	Marston, 1982; Keller et al., 1995; Shields and Gippel, 1995; Curran and Wohl, 2003; Yochum et al., 2012; Davidson and Eaton, 2013
Local bed scour	May and Gresswell, 2003; Hassan and Woodsmith, 2004
Decreased flow velocity and increased flow depth	David et al., 2010; Yochum et al., 2014
Obstructed flow with backwater	Richmond and Fausch, 1995; Jackson and Wohl, 2015
Enhanced sediment storage upstream and downstream from LW as a result of flow separation zones	Keller and Tally, 1979; Keller and Swanson, 1979; Ryan et al., 2014
Greater heterogeneity of bed sediment size	Buffington and Montgomery, 1999
Storage of finer sediment on bed	Faustini and Jones, 2003
Formation of forced alluvial reaches	Massong and Montgomery, 2000
Greater width-depth ratio	Zimmerman et al., 1967; Nakamura and Swanson, 1993
Alteration of bedform type and dimensions	MacFarlane and Wohl, 2003
Formation of anabranching channels	Abbe and Montgomery, 2003; O'Connor et al., 2003; Wohl, 2011; Collins et al., 2002, 2012
Increased hyporheic exchange around LW and with LW-induced changes to the bed grain size and channel geometry	Lautz et al., 2006; Sawyer et al., 2011
Improved water quality with storage of particulate and dissolved nutrients and greater hyporheic exchange	Keller et al., 1995; Beckman and Wohl, 2014a
Increased abundance and diversity of habitat for macroinverte-brates, fish, and other aquatic organisms	Triska and Cromack, 1980; Carlson et al., 1990; Keller et al., 1995; Lisle, 1995; Hauer et al., 1999
Increased recreational opportunities (fishing and birding)	
Floodplain	
Increased hydraulic resistance	Hughes, 1997; Florsheim and Mount, 2002
Local scour and deposition	Kochel et al., 1982; Jeffries et al., 2003
Aquatic habitat during periods of floodplain inundation	Benke and Wallace, 1990; Benke, 2001; Braccia and Batzer, 2001
Terrestrial habitat during periods of floodplain exposure	Harmon et al., 1986; Steel et al., 2003; Slaght et al., 2013
Where wood decay is slow, organic carbon sink	Wohl et al., 2012
Increased recreational opportunities (wildlife observation)	
Incorporation of jams into floodplain promotes heterogeneity of floodplain habitat and biota	Fetherston et al., 1995; Naiman et al., 2010; Collins et al., 2012
Beaver dams	
Increased hydraulic resistance and flow obstruction, as well as creation of backwater/lentic habitat	Butler and Malanson, 1995; Green and Westbrook, 2009
Attenuation of floods and increased base flow	Westbrook et al., 2006
Storage of sediment and dissolved and particulate nutrients	Naiman et al., 1986, 1994; Pollock et al., 2007
Enhanced hyporheic exchange	Meentemeyer and Butler, 1999; Lautz et al., 2006
Increased abundance and diversity of aquatic and riparian habitat	Naiman et al., 1988
Increased biomass and biodiversity of various organisms	Wright et al., 2002; Rosell et al., 2005
Increased recreational opportunities (fishing, wildlife observation)	

significantly decrease velocity and increase depth at the reach scale (Brooks et al. 2003; Webb and Erskine 2003; Bocchiola 2011). Manga and Kirchner (2000), for example, found that although dispersed LW pieces covered less than 2 percent of the streambed in a gravel-bed stream of the Oregon Cascades, the LW provided roughly half of the total resistance at the reach scale.

Sediment effects. By increasing hydraulic resistance, obstructing flow, and causing local scour in the stream bed, LW can strongly influence sediment characteristics, including the grain-size distribution, the patchiness of bed sediment (Buffington and Montgomery 1999), and the volume and residence time of sediment stored within the channel (Hassan and Woodsmith 2004; Wohl and Scott 2017). Flume experiments and numerical simulations indicate that scour depth correlates with piece orientation and channel geometry: pieces projecting upstream into the flow and narrow channels relative to the length of the wood piece promote maximum bed scour (Cherry and Beschta 1989; Wallerstein et al. 2001). The most commonly documented effects of LW on bed sediment characteristics are decreased average bed grain size, increased spatial heterogeneity of bed sediment (or patchiness), increased volume of sediment stored within the channel, and increased residence time of sediment where LW is present (Keller and Swanson 1979; Megahan 1982; Keller et al. 1995; Faustini and Jones 2003; Haschenburger and Rice 2004; Ryan et al. 2014; Jackson and Wohl 2015). Comparative studies indicate that LW retains more sediment and for longer periods of time than other channel-margin irregularities such as boulders (Fisher et al. 2010), although piece orientation is important: pieces parallel to flow are less likely to influence hydraulics and sediment dynamics than pieces oriented perpendicular to flow (Magilligan et al. 2008; Laser et al. 2009).

Numerous experiments have demonstrated that when LW is removed, flow resistance declines, bedload mobility increases, and habitat diversity and retention of dissolved and particulate nutrients decrease (e.g., Bilby and Likens 1980; Bilby 1981, 1984; Heede 1985; Shields and Smith 1992; Smith et al. 1993; Raikow et al. 1995; Shields and Gippel 1995; Dudley et al. 1998; Erskine and Webb 2003; Daniels 2006). Similarly, when a piece of LW breaks or becomes mobile or when a logjam fails, a pulse of bedload transport can result (Bugosh and Custer 1989; Adenlof and Wohl 1994). Dumke et al. (2010) document a scenario where a sand-bed channel transitioned to a gravel-bed channel following selective wood removal, and Brooks et al. (2003) describe how a segment of the Cann River (drainage area 1,150 km^2) in south-eastern Australia changed from a sediment-storage zone into a sediment source following removal of LW dispersed across the channel bed.

The manner in which LW affects sediment within channels changes from small, steep channels to large, lowland rivers (Keller and Swanson 1979; Bilby and Ward 1989; Nakamura and Swanson 1993; Le Lay et al. 2013). LW is more likely to form channel-spanning jams in small channels and each jam creates a backwater that stores a wedge-shaped accumulation of sediment that tapers upstream (Keller and Tally 1979; Thompson 1995; Faustini and Jones 2003; Jackson and Wohl 2015). As channel width increases and gradient decreases, dispersed LW pieces are more likely to create local sediment storage, except where a wood raft occurs. Wood rafts can completely span even very large channels and the substantial obstruction associated with the raft enhances overbank flow and floodplain sedimentation (Triska 1984; Wohl 2014) (fig. 12).

In summary, although LW can create local bed and/or bank erosion, the predominant net effect at the reach scale is to increase storage of both fine and coarser sediment in the channel (Brooks et al. 2003; Wohl and Scott 2017). Where sufficient LW is present within the channel

Figure 12. June 2017 view of a wood raft on the St. Jean River, Quebec, Canada. Wood accumulations outlined in dashed white line. Flow is from left to right. Raft is at 48.772358° N, -64.440723° W (image courtesy of Google Earth).

to facilitate overbank flow, floodplain sediment storage can also be increased (Barrett 1996; Jeffries et al. 2003; Patterson et al. 2003). No simple methods exist to predict the net balance between local erosion around individual LW pieces or accumulations and sediment storage at the reach scale, but scour relations developed from physical experiments can be used to estimate the likely location and magnitude of local scour (e.g., Cherry and Bescht, 1989; Wallerstein et al. 2001).

Channel geometry. LW can influence channel geometry, including bedforms, pool volume, cross-sectional geometry, channel planform, and channel mobility. By trapping and storing bed sediment, LW can create forced alluvial reaches in portions of a stream network that have bedrock substrate in the absence of LW (Massong and Montgomery 2000; Montgomery et al. 2003; Lancaster and Grant 2006). LW incorporated into the stream bed can also change the type and dimensions of bedforms present, creating taller, more closely spaced bed-steps in steep channels, for example (MacFarlane and Wohl 2003). Stationary LW can initiate bars within rivers or promote bar growth (Hickin 1984; Piégay 2003; Gurnell et al. 2012; Gurnell 2013; Bertoldi et al. 2013; Mikus et al. 2013). In braided rivers, LW tends to be deposited on existing bars, although the wood can then influence the development of bar morphology (Piégay and Gurnell 1997). By deflecting current toward the banks, LW can enhance local bank erosion and increase channel width-depth ratio (Zimmerman et al. 1967; Nakamura and Swanson 1993).

Channel-floodplain interactions. Logjams blocking the channel can substantially increase overbank flow and sedimentation (Oswald and Wohl 2008; Wohl and Beckman 2014b). Numerous studies document how enhanced bank erosion and overbank flow caused by logjams can lead to a multithread (anabranching or braided) planform (Hickin 1984; O'Connor et al. 2003; Wohl 2011; Little et al. 2013). Collins et al. (2012) conceptualize these interactions among LW, channel planform, and floodplains as the large wood-floodplain cycle hypothesis. In the hypothesized cycle, jams facilitate channel avulsion. The jams then become incorporated into the floodplain as the channel moves laterally away from the jam. The buried jams form a portion of the floodplain more resistant to subsequent stream erosion and provide stable, nutrient-rich substrate for tree germination. The stream channel assumes an anabranching planform in a floodplain with patches of differently aged forest and diverse habitat. The geologic record indicates that stable, multithread, anabranching channels did not occur until the evolution of woody vegetation (Davies and Gibling 2011; Gibling and Davies 2012).

Channel planform. LW can influence rates and directions of meander migration when developing chute cutoffs are blocked by logjams (Hickin 1984). LW in meandering streams is likely to be deposited at the edge of the main channel along the floodplain and along axes of overbank flows within the floodplain (Piégay and Gurnell 1997). Logjams can block and fill distributary channels on deltas (Kramer and Wohl 2015) and promote distributary-channel avulsions (Phillips 2012). LW deposited along lake and marine coastlines can trap sediment; provide germination sites for diverse plants; and strongly influence the rate and characteristics of shoreline progradation, a process that Kramer and Wohl (2015) referred to as "driftcretion."

Hyporheic exchange. LW can directly and indirectly alter hyporheic exchange within channels. Direct alteration comes from individual pieces or jams that create pressure gradients with downwelling at the upstream side of the LW and upwelling downstream from the wood (Lautz et al. 2006; Sawyer et al. 2011). Indirect alteration comes from the effects of LW on bed grain size, bedforms, and channel geometry. By enhancing the amplitude of bedforms, for example, LW can increase pressure gradients near the streambed that drive hyporheic exchange (Wondzell 2006; Hester and Doyle 2008; Buffington and Tonina 2009; Tonina and Buffington 2009; Wondzell et al. 2009).

LW also provides ecological benefits by enhancing hyporheic exchange. Such exchange influences selection of spawning sites by salmonids and increases embryo survival (Baxter and Hauer 2000; Malcolm et al. 2004), as well as providing macroinvertebrate habitat (Stanley and Boulton 1993; Williams 1993). Enhanced hyporheic exchange also creates habitat by promoting thermal diversity within a stream (Sawyer et al. 2012). The greater abundance and diversity of habitat associated with the presence of LW, along with enhanced hyporheic exchange and increased nutrient retention and availability, result in greater biomass and biodiversity of aquatic species in wood-rich portions of a stream (Angradi 1996; Schneider and Winemiller 2008; Kratzer and Warren 2013; Bellmore and Baxter 2014; Herdrich 2016).

Existing studies have focused on the effects of a single piece of LW or a single jam or beaver dam on hyporheic exchange. At this time, the cumulative effects of multiple pieces or sequential jams or dams are not known.

Water quality. LW also indirectly affects water quality by enhancing storage of particulate and dissolved nutrients (Naiman and Sedell 1979; Ward and Aumen 1986; Smock et al. 1989; Beckman and Wohl 2014a); creating vertical drops that oxygenate water; and enhancing hyporheic exchange and thus affecting solute content and water temperature of stream flow. Even very temporary storage of nutrients facilitates biotic uptake of these materials (Battin et al. 2008).

Aquatic habitat. LW is particularly effective at enhancing habitat diversity for aquatic organisms (e.g., Dolloff and Warren 2003; Klaar et al. 2011). Numerous studies document the importance of LW-induced pools and overhead cover for various species of macroinvertebrates and fish (Triska and Cromack 1980; Sechnick et al. 1986; Carlson et al. 1990; Robison and Beschta 1990; Fausch 1993; Beechie and Sibley 1997; Hauer et al. 1999; Buffington et al. 2002; Nagayama et al. 2012 Sechnick et al. 1986; Fausch 1993; Chen et al. 2008; Nagayama et al. 2012). Fish need different habitats during different stages of their life cycle and different times of the year (Schlosser 1991) and LW can help to create habitat diversity by creating low-velocity zones (Fausch 1993; Nagayama et al. 2012), as well as pools and overhead cover (Fausch and Young 2004; Schenk et al. 2015) and favorable spawning habitat (Senter and Pasternack 2011). Macroinvertebrates benefit from the presence of LW as a substrate that can support microbial communities and provide enhanced stability in sand-bed channels (Angermeier and Karr, 1984; Wallace and Benke 1984; Wallace et al. 1995; Benke and Wallace 2003; Wondzell and Bisson 2003; Coe et al. 2009). LW also traps coarse particulate organic matter that larger macroinvertebrate shredders can break down into smaller particles that are used by other organisms (Flores et al. 2011, 2013).

2.1.1. Characteristics of LW

The great majority of studies on instream LW focus on wood that is readily visible within streams. Waterlogged and sunken LW pieces can also be present in large rivers and can create many of the same physical and ecological effects (e.g., Kaeser and Litts 2008) (fig. 13).

Figure 13. Historic drought and low water levels reveal large wood that is normally submerged in the lower Lachlan River of Australia (photo: Rodney Price, New South Wales Department of Primary Industries—Fisheries, Australia.)

Numerical modeling suggests that many of the functions of LW with respect to creating high spatial and temporal variability in sediment transport and storage and channel morphology occur primarily when LW pieces interact to form jams (Eaton et al. 2012), although many of the enhanced effects occur primarily from jams with relatively low porosity (Manners et al. 2007). Formation of jams is facilitated by at least three scenarios:

1. In medium to large streams, jams commonly form in association with particular bedforms such as point bars, alternate bars, or transverse bars (e.g., Abbe and Montgomery 1996).
2. In medium to large streams, jams are more likely to form where congested transport of LW occurs. Congested transport occurs when wood pieces move together as a single mass and occupy more than a third of the channel (Braudrick et al. 1997).
3. In smaller streams, jams are more likely to form when mobile LW is trapped against: relatively immobile obstacles such as bridge or ramp pieces (pieces spanning the bankfull channel or with one end resting above the bankfull channel, respectively) (e.g., Braudrick and Grant 2001; Bocchiola et al. 2006; Beckman and Wohl 2014b); LW pieces with rootwads; or protruding bedrock knobs or very large boulders in the streambed.

In each of these scenarios, something locally reduces transport capacity for LW, allowing a concentration of wood pieces to form a jam. Although jams can form at any point along a stream, they are more common in segments with consistently reduced transport capacity as a result of shallower flow, lower velocity, or congested transport (see section A.2.1).

2.2. Benefits of Floodplain LW

Many of the benefits derived from LW in channels also apply to floodplains (Wohl 2013a). Individual LW pieces or jams on the floodplain surface increase hydraulic resistance and can help to attenuate peak flows (Hughes 1997; Florsheim and Mount 2002; Jeffries et al. 2003; Gurnell and Petts 2006). Floodplain LW creates localized sediment deposition and scour of the floodplain surface (Kochel et al. 1982; Jeffries et al. 2003) and concentrations of LW on the edge of the floodplain next to the channel or at the upstream or downstream end of floodplain channels can limit channel lateral migration and promote or limit avulsion (Zimmerman et al. 1967; Hickin 1984; Piégay and Gurnell 1997; Sear et al. 2010). LW in transport can topple riparian trees, which both recruits new LW to the channel and floodplain and creates germination sites for floodplain species (Johnson et al. 2000). LW deposited along the channel margins during floods can create wood levees (Johnson et al. 2000). Streams with substantial overbank flow and open floodplain woodlands can store wood primarily in overbank areas, especially where standing trees serve as collection points for fluvially transported wood (fig. 4). Streams flowing through densely forested riparian corridors are more likely to have fluvially transported wood present only within the main channel and secondary active or abandoned channels on the floodplain (fig. 4).

Floodplain LW creates habitat for aquatic organisms during periods of floodplain inundation (Benke and Wallace 1990; Benke 2001; Braccia and Batzer 2001) and habitat for terrestrial organisms including insects, amphibians, reptiles, small mammals, and birds during periods when the floodplain is not submerged (Harmon et al. 1986; MacNally et al. 2002; Roni, 2003; Steel et al. 2003; Trainor et al. 2007, 2012; Ballinger et al. 2010; Benjamin et al. 2011; Slaght et al. 2013). Decaying floodplain LW is a particularly important germination site for many floodplain plant species (Schowalter et al. 1998; Hyatt and Naiman 2001; Pettit and Naiman 2006). Water-borne plant propagules can be preferentially deposited against floodplain LW (Schneider and Sharitz 1988). Decaying LW contributes to nutrient cycling and soil formation (Polit and Brown 1996; Zalamea et al. 2007). In floodplain environments where wood decay is very slow, floodplain LW can form an important sink for organic carbon at timescales of hundreds to thousands of years (Hyatt and Naiman 2001; Wohl et al. 2012). Instream jams can become incorporated into the floodplain as channels avulse or migrate laterally. These buried jams form hard points that influence floodplain turnover time, subsequent channel migration, and age of floodplain forests (Fetherston et al. 1995; O'Connor et al. 2003; Montgomery and Abbe 2006; Naiman et al. 2010; Collins et al. 2012).

2.3. Benefits of Beaver Dams

Many of the benefits described earlier for other forms of instream LW also accrue from beaver dams. Beaver dams increase hydraulic resistance and obstruct flow, in the process creating backwater areas of reduced velocity and increased flow depth. These backwater ponds store sediment and dissolved and particulate organic matter (Butler and Malanson 1995; John and Klein 2004; Pollock et al. 2007; Green and Westbrook 2009; De Visscher et al. 2014). Several studies document greatly increased storage and biological uptake of carbon and nitrogen, in particular, in beaver ponds (Naiman and Melillo 1984; Naiman et al. 1986, 1994; Correll et al. 2000; Wohl 2013b; Johnston 2014; Lazar et al. 2015). Beaver dams also enhance hyporheic exchange (Meentemeyer and Butler 1999; Lautz et al. 2006).

Although systematic, quantitative measurements have not yet been made, several studies anecdotally describe the creation of perennial base flow by beaver dams in a previously seasonally intermittent channel (Collier 1959; Albert and Trimble,2000; Gibson and Olden 2014). Other studies document an increase in base flow relative to conditions without beaver dams (Woo and Waddington 1990; Wegener et al. 2017), although the net effect on the water balance will also depend on how beaver ecosystem engineering alters evaporation and transpiration at a particular site. Beaver dams do increase open-water areas within the stream corridor, which can help to buffer against droughts and climate change (Hood and Bayley 2008) (fig. 14).

Beaver dams facilitate overbank flow during higher discharges, leading to attenuation of floods up to at least annual peak flow; floodplain deposition of sediment and particulate organic matter; higher riparian water tables that help to sustain base flow throughout the year; and formation of multithread channels (Meentemeyer and Butler 1999; John and Klein 2004; Westbrook et al. 2006, 2011; Polvi and Wohl 2012, 2013; Westbrook et al. 2013; Levine and Meyer 2014). Ecologists have documented a broad array of organisms that show greater abundance and diversity where beaver dams are present (Naiman et al. 1988), including amphibians (Hossack et al. 2015), aquatic invertebrates (Hood and Larson 2014), terrestrial invertebrates (Rosell et al. 2005), fish (Pollock et al. 2003), reptiles, birds, mammals (Rosell et al. 2005), and herbaceous plants (Wright et al. 2002).

Two of the primary differences between beaver dams and other forms of LW within channels or floodplains are that (1) beaver actively repair dams and can maintain the effects described above even immediately after floods or during periods of drought and (2) beaver can build dams that create these effects even where only limited large woody plants are present. Personal observations suggest that beaver are very capable, for example, of moving fine

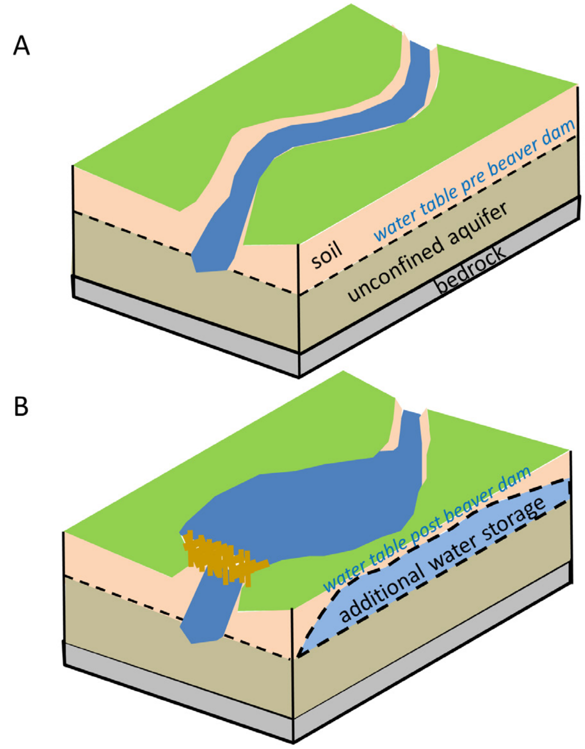


Figure 14a-b. Conceptual illustration of water storage additions pre-beaver dam (A) and post-beaver dam (B) construction to above and below ground water storage. From Hafen and Macfarlane 2016, figure 3)

sediment from stream beds and floodplains to create dams that are largely composed of sediment rather than wood. Beaver thus effectively extend the beneficial effects of LW in stream corridors across greater lengths of time and greater spatial extents of a stream network.

Although individual beaver dams may be maintained for a period of only a few years, at least a few dams are known to have been continuously maintained for several decades (Neff 1959; Butler 2012). More importantly, where sufficient space exists to create and maintain a beaver meadow (Ives 1942), beaver can continuously inhabit the environment for thousands of years (Kramer et al. 2012; Polvi and Wohl 2012). Even after beaver abandon a stream segment, the changes to channel and valley morphology can persist for decades or more, creating a persistent, but lower magnitude, alteration of downstream fluxes of water, sediment, solutes, and organic matter (e.g., Burchsted and Daniels 2014).

A final, distinctive benefit of beaver dams in stream corridors is that many people consider beaver to be charismatic stream megafauna. Although some individuals regard beaver as a nuisance species to be removed wherever possible, other people go out of their way to see beaver, as well as the diverse species of other mammals (e.g., muskrat and otters) and birds attracted to beaver ponds.

2.4. Benefits of LW in Stream Corridors

The preceding sections reviewed benefits of LW specifically in channels or on floodplains. At least two primary additional benefits accrue from the presence of LW, including beaver dams, located throughout stream corridors: sustainability of stream ecosystems and enhanced recreational opportunities. Sustainability of stream ecosystems derives from enhanced storage of nutrients, improved water quality, greater abundance and diversity of habitat, greater biomass and biodiversity, and increased resistance and resilience to natural and human-induced disturbances.

Resistance is the ability of an ecosystem to resist displacement from an equilibrium or reference state (Webster et al. 1975). A resistant channel might change very little during a substantial flood, for example. Resilience is the ability of an ecosystem to return to its prior configuration following a disturbance. A resilient channel experiencing a large flood returns to its pre-flood configuration relatively quickly. Ecologists define a disturbance as a temporary change in environmental conditions that causes a pronounced change in an ecosystem. Natural disturbances affecting stream corridors include floods, droughts, and wildfires. Human-induced disturbances vary from chronic disturbances such as flow regulation associated with dams or diversions, introduction of an exotic, invasive species, or channelization, to acute disturbances such as a spill of toxic material into a river.

By attenuating downstream fluxes of diverse material (water, sediment, organic matter, solutes), increasing channel-floodplain connectivity, and enhancing the spatial heterogeneity of stream corridors, LW can increase the resistance of the stream ecosystem to disturbance, and enhance the resilience of the stream ecosystem following disturbance (Zalewski and Lapinska 2003). Examples come from adjacent stream networks in Rocky Mountain National Park, Colorado.

North St. Vrain Creek and the Big Thompson River both originate near the Continental Divide and flow eastward to join the South Platte River on the Great Plains. North St. Vrain Creek includes an active beaver meadow at the eastern boundary of Rocky Mountain National Park (Figs. 6 and 15). Historic flooding during September 2013 created widespread and substantial erosion and deposition across the portion of the Colorado Front Range that includes the North St. Vrain watershed. Portions of the stream network downstream from the beaver meadow experienced widespread hillslope failure and extensive aggradation of the channel and floodplain. At least one debris flow also occurred upstream from the beaver meadow, but the beaver meadow exhibited almost no changes immediately after the flood. Sand and gravel deposition at the upstream end of the meadow partly buried the base of some willows and small jams of LW formed across the floodplain, but the broad, densely vegetated valley bottoms and the numerous dams and ponds so effectively attenuated the flood waters that none of the beaver dams were breached and the meadow was largely unchanged by the flood. The North St. Vrain beaver meadow apparently substantially increased resistance to the flood as a function of increased surface roughness (dense willow thickets, floodplain topographic relief associated with the presence of active and abandoned beaver dams, surface water storage in ponds and secondary channels). Elsewhere in the National Park and surrounding areas, portions of stream networks in which beaver had been removed (e.g., Fish Creek; fig. 15) subsequently lost many of the beneficial effects described above. The stream corridor experienced widespread erosion during the September 2013 flood.

In contrast, the upper Big Thompson River no longer has active beaver meadows. The Moraine Park portion of the stream network had a very large beaver meadow that has become inactive within the past few decades. As beaver have disappeared from the site, the riparian water table has dropped, grasses have largely replaced the willow carr community, and the stream has altered from an anabranching planform to a single channel (fig. 15). When an illegal campfire triggered an October 2012 fire in Rocky Mountain National Park, the fire burned into the riparian zone along the Big Thompson River, which had lost both the resistance and resilience that were present as long as beaver occupied the site and maintained a high water table and extensive floodplain wetlands.

Figure 15a-c. Examples of the effects of beaver meadows on stream corridors. Yellow arrows indicate flow direction. (A) Details of the active beaver meadow along North St. Vrain Creek in Colorado. Upper photo illustrates multiple small channel anabranches converging. Lower photo illustrates an abandoned, off-channel pond (active channel is at rear of view and not visible). (B) Relict beaver meadow along Fish Creek, Colorado, after a large flood in 2013 caused extensive channel erosion. Dark upper layer in cutbank reflects organic-rich sediment deposited when the beaver were present and beaver dams maintained a high riparian water table. (C) At left, historic air photos show progressive loss of secondary channels between 1964 and 1987 as a result of declining beaver activity along the Big Thompson River, Colorado. Ground photo at right shows the riparian area, which burned during a wildfire in 2012.

Enhanced recreational opportunities come primarily from the ability of LW to attract organisms such as fish and birds. By providing habitat for these animals, LW can enhance recreational fishing and bird-watching, as recognized in numerous publications from sources other than scientific journals (e.g., ODNR 2002; Bottorff 2009; Moore 2013; CDEP 2016; CRWC 2016). On balance, LW in stream corridors greatly increases ecosystem services (Acuna et al. 2013).

Concentrations of large wood in the form of jams and multiple beaver dams that create beaver meadows can create emergent effects within streams, including multiple secondary channels that branch and rejoin downstream, retention of dissolved and particulate nutrients, increased abundance and diversity of aquatic and riparian habitat, and increased biomass and biodiversity.

3. Potential Hazards From Large Wood, Beavers, and Beaver Dams in Stream Corridors

LW, beaver, and beaver dams can create at least five basic types of hazards in stream corridors, and additional hazards that are unique to beavers. Hazards resulting from LW and beaver dams include: increased backwater flooding or inundation of adjacent bottomlands; enhanced local erosion of the channel bed and/or banks; blockage of diversion intakes or culverts; the potential for LW to become mobile and damage infrastructure; and hazards to recreational boaters and tubers. Beaver may also create hazards by cutting down large numbers of riparian trees and affecting stream thermal regime. Hazards from backwater flooding, local erosion, and recreational users come primarily from stationary LW, whereas blockage of structure and impacts or damage to infrastructure such as bridges result primarily from LW in transport. Because of the different types of hazards that result from stationary or mobile LW, it is useful to review the conditions under which LW is likely to be mobile.

3.1. LW mobility

LW can become mobile within a stream corridor for at least three reasons: recruitment, mobilization, and decay or breakage. Recruitment of LW by processes such as bank erosion or blowdown during a storm can create mobile LW. Mobilization can also occur as rising flow stage increases lift or drag forces exerted on a wood piece or logjam stored within the channel or floodplain (Alonso 2004; Merten et al. 2010). Finally, breakage as a result of hydraulic forces, abrasion by sediment in transport, or weakening of the LW through decay can result in smaller pieces that are more easily mobilized (Bilby 2003; Merten et al. 2013). Mobilized LW can float or move by rolling or sliding along the streambed (Buxton, 2010).

Mobilization of an individual LW piece or jam is as difficult to predict precisely as the entrainment of a cobble in a gravel-bed stream. The complex hydraulic forces around LW are site-specific and fluctuations in these forces are likely more important than mean values, creating nonlinear relationships between hydraulics and LW mobility. Patterns have been observed, however. Within the bankfull channel, LW pieces tend to be more stable if they are oriented parallel to flow (rather than transverse); if they have a rootwad; if they are partly buried within the stream bed or banks; if a portion of the piece rests above the bankfull channel; and if the piece length is longer than the width of the bankfull channel, especially where the trunks of standing trees along the channel margins can help to retain LW pieces that protrude across the banks (Braudrick and Grant 2000; Abbe and Brooks 2011).

In flashy, hydrologically variable streams such as those in drylands, living trees within the channel and on the floodplain can be particularly important in trapping and retaining LW (Jacobson et al. 1999; Opperman 2005; Wohl et al. 2011; Dunkerley 2014). LW pieces on a forested floodplain tend to be more stable because the trunks of living trees are likely to limit LW piece mobility during high flows (Wohl et al. 2011). Jams tend to be more stable than dispersed pieces (Wohl and Goode 2008), although many of the pieces within a jam can be exchanged even though the jam remains stationary. Jams can also be quite mobile, breaking up and re-forming on a nearly annual basis (Gregory et al. 1985). In this context, multi-year monitoring of stream segments suggests that individual pieces and jams come and go at timescales of a few years (e.g., Gregory et al. 1985; Wohl and Goode 2008; Dixon and Sear 2014), even if the average volume of LW within the stream segment does not change substantially through time.

Very little has been written specifically about mechanisms of logjam failure. However, our field observations and tangential descriptions in the literature suggest at least three failure mechanisms: scour, lift, and drag, which can occur either independently or in conjunction. During scour, erosion of the bed or bank adjacent to the jam removes the sediment supporting one or more pieces in the jam, causing the jam to fail. Bed erosion can remove sediment trapped upstream of the jam, creating an effect like a plug being pulled from a full bathtub. This can result in high-velocity flow through the jam and failure of the jam. Bed erosion can also result from flow overtopping the jam that creates a plunge pool at the base of the jam. Jams anchored to the bank, floodplain, or valley wall substrate can be rapidly destabilized as flow flanks the jam and erodes the substrate holding key pieces in place. Buoyant forces on a jam during peak flows can lift the entire jam or individual key pieces to the point that the pieces or the whole jam floats and moves downstream. Our time-lapse photography of jams (Scott et al. 2018) indicates that the individual pieces within jams can move apart and rise during peak flow. Although the pieces resettle into an intact jam, pieces can also become dislodged to the point that the entire jam fails. Failure during this buoying is hypothesized to result primarily from changes to jam porosity and the resulting effective force applied on the upstream side (Scott et al. 2018). Drag here refers to the downstream force exerted by stream flows or by debris flows. This force can be sufficient to overcome the frictional resistance and mass of a logjam, causing the jam to fail. An existing difficulty in predicting jam failure is understanding how these mechanisms interact (e.g., buoying leading to a change in jam porosity that increases drag force) to regulate jam stability.

Despite the imprecision of estimating LW mobilization, tools are being developed for such estimates. An example includes the spreadsheet-based Large Wood Structure Stability Analysis Tool of Rafferty (2013, 2017) (fig. 16). Users input basic information on channel dimensions, discharge, bed substrate, and LW characteristics. The tool and supporting documentation are available at http://www.fs.fed.us/biology/nsaec/products-tools.html.

Several studies have monitored LW mobility using techniques such as radio tags and telemetry (Schenk et al. 2014; Ravazzolo et al. 2015), video or time-lapse photography (MacVicar and Piégay 2012; Kramer and Wohl 2014), repeat surveys using ground-based and/or remote sensing data (Wohl and Goode 2008; Curran 2010; Kasprak et al. 2012; Dixon and Sear 2014), LW entering reservoirs (Fremier et al. 2010), or some combination of these techniques (MacVicar et al. 2009; Kramer and Wohl 2017). The results of these studies indicate that there is typically not a simple or linear relationship between discharge and LW transport because of the influence of at least four factors.

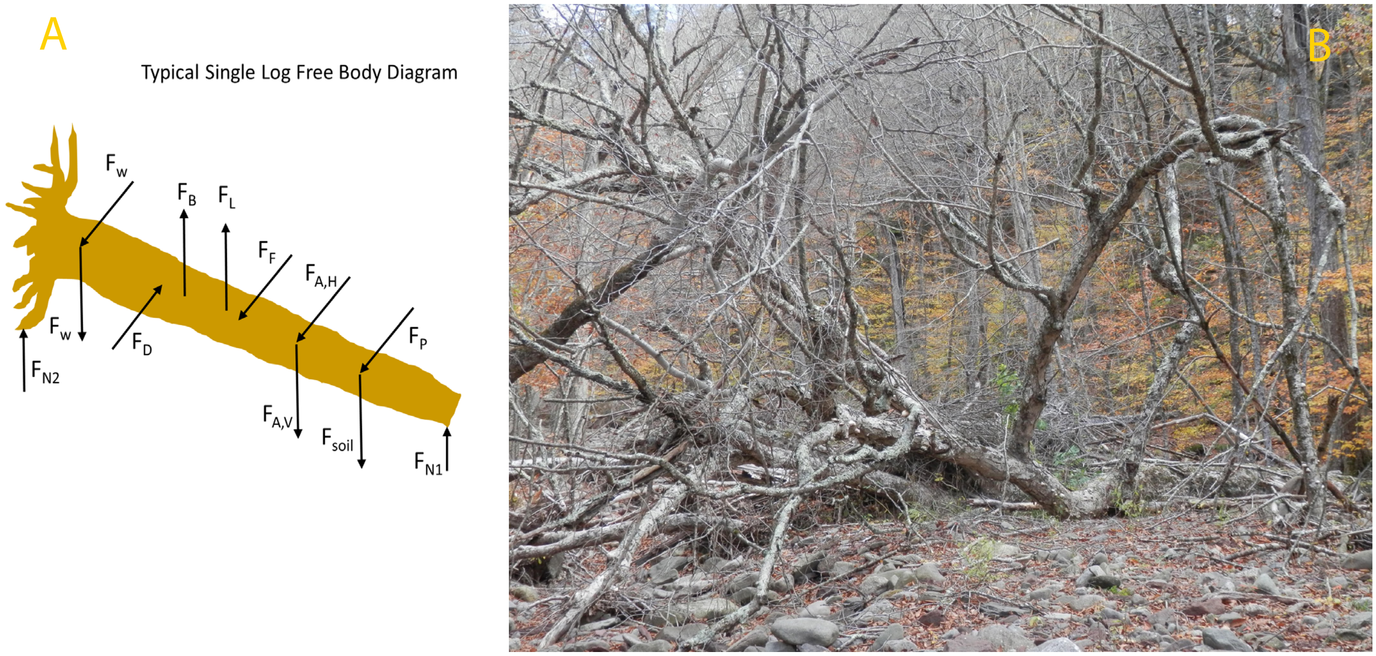


Figure 16a-b. (A) Typical single log free body diagram and log orientation. Forces are as follows: buoyant force (F_B), lift force (F_L), ballast force (F_{soil}), vertical anchor force ($F_{A,V}$), drag force (F_D), passive soil pressure force (F_P), friction force (F_F), horizontal anchor force ($F_{A,H}$), and normal force of soil on structure (F_N) (from Rafferty 2017, figure 1). (B) Natural wood pieces can vary in shape, as illustrated by this complexly branching piece of wood derived from a deciduous tree that has fallen onto the floodplain of Biscuit Brook, in the Catskill region of New York.

The first factor is wood supply and flow history. A large flood can mobilize much of the stored LW along the stream corridor, for example, so that some minimum time must elapse before sufficient LW is recruited again to create substantial wood fluxes (e.g., Haga et al. 2002; Moulin and Piégay 2004). The second factor that complicates relationships between discharge and LW transport is thresholds for LW transport, typically as a function of flow depth at sites where LW is stored between high flows (MacVicar and Piégay 2012; Schenk et al. 2014). A third complicating factor is channel geometry; specifically, the presence of obstacles that tend to retain LW (Haga et al. 2002; Bocchiola et al. 2006; Beckman and Wohl 2014b). A final complicating factor is hysteresis that results from LW mobilized during the rising limb of a flood being trapped near peak flows, with little downstream transport of LW on the falling limb (e.g., MacVicar et al. 2009; MacVicar and Piégay 2012). Most LW is transported during relatively infrequent high flows, but flows under bankfull can transport up to 30 percent of stored LW (mostly the smaller pieces present) within the stream corridor (Kramer and Wohl 2017). Although median mobilization rates of stored LW increase with increasing channel size, maximum mobilization rates are greatest in medium-sized channels, which are commonly 2nd to 4th order (Kramer and Wohl 2017).

LW pieces within a channel tend to be more stable if they are oriented parallel to flow, have a rootwad, are partly buried within the stream bed or banks, and if a portion of the piece rests above the bankfull channel. LW pieces on a forested floodplain tend to be more stable because the trunks of living trees limit LW piece mobility during high flows. Jams tend to be more stable than dispersed pieces.

3.2. Hazards to Infrastructure

Enhanced backwater flooding and overbank inundation can result from LW and beaver dams creating obstructions to flow (USBR and ERDC 2016), as described in the preceding section on beneficial effects. Backwaters and overbank inundation can create ecological benefits but can enhance overbank flooding and create associated hazards to infrastructure near the active channel (Young 1991). Similarly, complete or partial obstruction of flow in the channel can redirect hydraulic force toward the channel banks or bed, enhance local channel erosion, and result in channel widening or lateral channel movement (Comiti et al. 2008). Bank erosion or lateral channel migration can expose or undermine infrastructure including pipelines, roads, bridges, and residential or commercial buildings near active channels. LW that accumulates along channel margins at sites of lower velocity, or beaver dams built at such sites, can block diversion intakes or the entry of side culverts (Blanc et al. 2014). Similarly, channel constrictions associated with bridges or culverts can accumulate LW at the upstream side (e.g., Diehl 1997; Schmocker and Hager 2011; Lagasse et al. 2012), or be dammed by beavers (McKinstry and Anderson 1999; Curtis and Jensen 2004). LW accumulation against bridges can create bed scour that undermines the bridge (Lagasse et al. 2010, 2012) and LW that blocks culverts can force flow over forest roads, leading to slope failure (Furniss et al. 1998). Greater flow depths and higher velocities during peak flows may mobilize LW or wood within beaver dams and carry these wood pieces rapidly downstream, where the pieces may impact infrastructure or riparian vegetation with damaging force (Comiti et al. 2008), or accumulate and create flow obstructions at sites of limited wood transport capacity (Ruiz-Villanueva et al. 2014c). Each of the potential hazards described above is most likely to occur when higher discharges cross a wood transport threshold (Ruiz-Villanueva et al. 2015).

3.3. Hazards to Recreational Users

Stationary LW can also pose hazards to recreational users of rivers. As discussed in detail in Wohl et al. (2016), eight factors influence recreational hazards associated with LW. These can be divided into factors that reflect the characteristics of the stream channel and the recreational user (access, reach characteristics, ability to avoid hazards, prior knowledge) and factors that reflect intrinsic LW characteristics (location, snagging potential, strainers, and anchoring).

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 logjams 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 hazards. 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.

3.4. Hazards Unique to Beavers

Two additional potential hazards unique to the presence of beavers in a stream corridor are the cutting of riparian trees by beavers and alteration of the stream thermal regime. An adult beaver can cut 200-300 trees per year, most of which will be chosen within 30 m of the water’s edge (Baker and Hill 2003). A beaver’s incisor teeth grow continuously, so gnawing wood helps to file the incisors, as well as providing dam-building material and food that beavers in cold climates will cache underwater during the winter. Where landowners or recreational users view riparian trees as a beneficial component of the stream corridor, the removal of large numbers of trees by beavers can be considered deleterious to the stream environment.

It is worth noting in this context that willows (*Salix* spp.), in particular, can benefit from herbivory by beavers. Willows are among the pioneer species that germinate first in newly deposited stream sediment and require high levels of soil nutrients. In the absence of beavers, the shade provided by willows can facilitate the germination and growth of more shade-tolerant woody plant species. The continuous harvesting of early and mid-successional species by beavers can increase light penetration and maintain an environment suitable for early successional species such as willows and alders (Rosell et al. 2005). From an ecosystem perspective, herbivory by beavers is not a hazard to native riparian plants. From an esthetic perspective, however, herbivory by beavers is sometimes considered damage.

Changes in stream thermal regime may result from the ponding of surface water and enhanced hyporheic exchange associated with the presence of beaver dams. Ponding of surface water is likely to result in slightly warmer stream temperatures (McRae and Edwards 1994).

Enhanced hyporheic exchange is likely to result in slightly cooler stream temperatures. Both surface water storage in ponds and enhanced hyporheic exchange may dampen downstream temperature fluctuations (McRae and Edwards 1994). The degree to which changes in water temperature may benefit or harm specific aquatic organisms depends on the geographic setting, the thermal tolerances of specific organisms, and the number and size of beaver impoundments relative to other controls on stream thermal regime, such as air temperature, ground water inputs, and stream shading (Collen and Gibson 2001; Rosell et al. 2005).

Hazards resulting from LW and beaver dams include: enhanced inundation of adjacent bottomlands; enhanced local erosion of the channel boundaries; blockage of diversion intakes or culverts; the potential for LW to become mobile and damage infrastructure; and hazards to recreational boaters and tubers. Beaver also create hazards by cutting down large numbers of riparian trees.

4. Potential Mitigation Measures for Hazards From LW and Beavers

An important consideration is that potential hazards resulting from the presence of LW and beavers in stream corridors cannot always be completely mitigated. Because of encroachment into stream corridors by human communities and associated infrastructure, mobile LW and effects associated with stationary LW (e.g., enhanced scour or sediment deposition, channel avulsion, creation of backwaters) may always present hazards at some sites. Under these circumstances, it is important to carefully evaluate potential benefits versus hazards, as discussed in section C of this document. Here, we review potential mitigation measures that can be used to reduce hazards associated with LW and beavers.

4.1. LW Mobility and Hazards to Infrastructure

European investigators have done much of the research on predicting and modeling mobile LW because of the hazards associated with wood along densely populated and engineered channels in regions such as the Alps. GIS-based models of potential LW recruitment typically rely on parameterizing variables such as forested length of channel, potential for bank erosion and hillslope instability, and LW piece size relative to channel dimensions (e.g., Mazzorana et al. 2011, 2013; Ruiz-Villanueva et al. 2014a, b, c; Piton and Recking 2016).

Mitigation measures designed to limit damage to infrastructure can be passive or active. Passive measures rely on early warning systems or evacuation plans for communities within river corridors, as well as designating hazard zones and planning land use (Schmocker and Weitbrecht 2013). Active measures include removing LW within the channel; stabilizing banks to limit erosion; and infrastructure designed to retain LW or to ensure safe downstream passage of LW. Structures used to trap mobile LW include: rope or wire nets; sectional dams that span only a portion of the active channel and take the form of vertical piles or fins; lattice dams (sometimes called open check dams); slit or slot check dams; and baffles upstream or downstream from the primary overflow portion of a check dam (FHWA, 2005; Schmocker and Weitbrecht 2013; Piton and Recking 2015) (fig. 17; table 2).

Figure 17a-b. Two examples of LW trapping structures used on rivers in the European Alps. Yellow arrows indicate flow direction. (A) Flexible cables are designed to slow and temporarily trap wood that can then be manually removed during low flows. (B) Open or slotted check dam designed to trap large wood and boulders.

Table 2—Structures used to limit the hazards caused by LW culverts and bridges (modified from, National Large Wood Manual, 2016, US Bureau of Reclamation, Table 5-2, pp. 5-23 to 5-25).

Measure	Culverts and Bridges	Additional considerations
Debris deflector	Culvert: Structure that deflects the major portion of the debris away from the culvert entrance. Normally "V"-shaped in plan with the apex upstream. Bridge: Structure placed upstream of the bridge piers to deflect and guide debris through the bridge opening. Normally V-shaped with the apex upstream.	
Debris rack	Culvert: Structure placed across the stream channel to collect the debris before it reaches the culvert entrance. Usually vertical and at right angles to the streamflow, but may be skewed with the flow or inclined with the vertical.	Require regular removal of LW and can cause backwater effects
Debris riser	Culvert: Closed-type structure placed directly over the culvert inlet to cause deposition of flowing debris and fine detritus before it reaches the culvert inlet. Usually built of metal pipe.	Can limit aquatic organism passage
Debris crib	Culvert: Open crib-type structure placed vertically over the culvert inlet in log-cabin fashion to prevent inflow of coarse bed load and light floating LW. Bridge: Walls built between open-pile bents to prevent LW lodging between the bents. Typically constructed out of timber or metal material.	
Debris fin	Culvert: Walls built in the stream channel upstream of the culvert. Purpose is to align the LW with the culvert so that the LW would pass through the culvert without accumulating at the inlet. Bridge: Walls built in the stream channel upstream of the bridge to align large floating trees so that their length is parallel to the flow, enabling them to pass under the bridge without incident. Also referred to as a "pier nose extension."	
Debris dam/ basin	Culvert and bridge: Structure placed across well-defined channels to form basin, which impedes the streamflow and provides storage space for deposits of LW and coarse particulate organic matter.	Can limit aquatic organism passage; requires periodic emptying
River training structures	Bridge: Structure placed in the river flow to create counter-rotating stream-wise vortices in the wake to modify the near-bed flow pattern to redistribute flow and sediment transport within the channel cross section.	
Flood relief sections	Bridge: Overtopping or flow through structure that diverts excess flow and floating LW away from the bridge structure and through the structure.	
Debris sweeper	Bridge: Polyethylene device that is attached to a vertical stainless steel cable or column affixed to the upstream side of the bridge pier. Device travels vertically along the pier as the water surface rises and falls. It is also rotated by the flow, causing the LW to be deflected away from the pier and through the bridge opening.	
Booms	Bridge: Logs or timbers that float on the water surface to collect floating drift. Drift booms require guides or stays to hold them in place laterally.	
Design features	Bridge: Structural features that can be implemented in the design of a proposed bridge structure. The first feature is freeboard, which is a safety precaution providing additional space between the maximum water surface elevation and the low chord elevation of the bridge. The second feature is related to the type of piers and the location and spacing of the piers. Ideally, the pier should be a solid wall type aligned with the approaching flow. It should also be located and spaced such that the potential for LW accumulation is minimized. The third feature involves the use of special superstructure design, such as thin decks, to prevent or reduce the debris accumulation on the structure when the flood stage rises above the deck. The last feature involves providing adequate access to the structure for emergency and annual maintenance.	
Combination devices	Culvert: Combination of two or more debris-control structures at one site to handle more than one type of debris and to provide additional insurance against clogging the culvert inlet.	
Emergency and annual maintenance	Culvert: Although not always feasible for remote culverts or culverts with small drainage areas, maintenance could be a viable option for larger culverts with fairly large drainage basins. Emergency maintenance could involve removing debris from the culvert entrance and/or an existing debris-control structure. Annual maintenance could involve removing debris from within the culvert, at the culvert entrance, and/or immediately upstream of the culvert, or repairing any existing structural measures. Bridge: Emergency maintenance could involve removing debris from the bridge piers and/or abutments; placing riprap near the piers, abutments, or where erosion is occurring due to flow impingement created by the debris accumulation; and/or dredging of the channel bottom. Annual maintenance could involve debris removal and repair to any existing structural measures.	

Key considerations with using structures to trap mobile LW include:

- maintenance – many of these structures must be continually maintained by removing accumulated LW and/or sediment that accumulates at the structure;
- aquatic organism passage – the potential for a structure to limit longitudinal connectivity for diverse aquatic organisms (e.g., insects, amphibians, fish), either as a result of the inherent design of the structure or as a result of LW accumulation at the structure, should be evaluated; as well as potential volume of LW movement – channels in which a substantial volume of LW can be recruited or mobilized during a single event (e.g., flood or landslide) can experience what has been referred to as a wood flood (Kramer et al. 2017), a floating log disaster (Ishikawa et al. 1992), or a wood-laden flow (Ruiz-Villanueva et al. 2019). In this scenario, naturally occurring or human-introduced LW can be abruptly mobilized and can concentrate while moving downstream. The force associated with a large volume of mobile wood can damage infrastructure (e.g., Comiti et al. 2008) within the stream corridor. This type of mobilization is difficult to mitigate with structures designed to trap LW because these structures can become filled or ineffective during a single large flood.

The National Large Wood Manual (USBR and ERDC, 2016) discusses design guidelines and modifications for structures such as bridges and culverts to enhance their ability to pass LW downstream. Among the options are installation of fins designed on the upstream side of bridge piers. The fins are designed to orient logs parallel to flow as the logs approach and pass under the bridge, thus promoting continued LW movement rather than accumulation. Deflectors located upstream from the bridge can create the same effect. Another option is to use various types of "training structure" that are installed on the streambed to induce secondary currents that limit LW accumulation. Examples include micro groins (submerged sills), Iowa vanes, spurs, and meandering ramps. A polyethylene device mounted on a vertical beam and attached at the upstream side of a bridge pier rotates with the motion of the water and deflects LW from the bridge. This device is known as a sweeper.

Investigators have also used data from physical experiments and field observations to propose equations for the probability that a single log or a mass of LW will accumulate at a bridge. The primary variables in these equations tend to be log length and diameter, bridge width or width between bridge piers, and ratio of approach flow depth to bridge height (e.g., Lyn et al. 2003; Schmocker and Hager 2011; DeCicco et al. 2016).

4.2. Hazards to Recreational Users

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.

4.3. Hazards Unique to Beavers

Several approaches have been used to minimize hazards associated with the presence of beavers. A beaver deceiver can be used to prevent the animals from building a dam across the opening of a human structure designed to convey water, such as a culvert or irrigation intake. A beaver deceiver is simply a culvert fence that prevents beaver access to the human structure (Lisle, 2003). A pond leveler can be used to prevent the backwater created by a beaver dam from exceeding a desired stage. A pond leveler is a flexible, perforated pipe that is fenced at the intake end to prevent the beaver from damming the intake (Lisle 2003). Beavers can also be prevented from cutting down riparian trees by simple fencing (e.g., chicken wire) or otherwise protecting the base of selected trees.

Mitigation of hazards resulting from LW and beaver dams can focus on: structures designed to trap and retain mobile LW; infrastructure design to accommodate and/or pass mobile LW; effective communication with recreational users; and, for beavers, structures designed to prevent beavers from damming intakes, limit the water level of beaver ponds, and prevent beavers from felling or damaging selected riparian trees.

Part II. Guidelines for Large Wood and Beaver Retention and Reintroduction

B. Existing Work on Retention, Restoration, and Reintroduction of LW and Beaver Dams

1. Restoration via Emplacement of LW

As recognition has grown among stream scientists, engineers, and managers of the beneficial effects of LW in stream corridors, stream restoration has gradually begun to include active reintroduction of LW. Harmon (2002) called for the recognition of "morticulture," which he defined as a counterpoint to silviculture and which emphasizes the culturing of woody detritus in forest and stream environments.

Several papers report the results of LW addition to rivers that were wood-poor as a result of past land use. The results of these LW additions are mixed. Addition of single logs to first-order streams in the Upper Peninsula of Michigan did not substantially increase organic matter standing stocks after 2 years, but the LW did retain particulate organic matter and increase the abundance of shredding macroinvertebrates (Entrekin et al. 2008). These logs were added "haphazardly" and there was no description of their stability. Other studies report more success. LW additions to a second-order stream in North Carolina increased flow depth, decreased velocity, increased retention of fine sediment and particulate organic matter, and altered invertebrate community structure (Wallace et al. 1995). Log-drop structures installed on small streams in the Colorado Rocky Mountains increased pool volume, depth, and cover, as well as abundance and biomass of trout (Riley and Fausch 1995). A comparison of randomly and deliberately placed LW in low-gradient streams of Virginia indicated that the deliberately placed LW was much more effective at increasing pool volume (Hilderbrand et al. 1997). Deliberately placed pieces are more likely to be perpendicular to flow, thus maximizing flow resistance and bed scour, and to be sufficiently long to include a portion above the bankfull flow, allowing the piece to be more stable and to retain smaller, mobile wood and particulate organic matter (Keim et al. 2000).

Additions of multiple pieces of LW in the form of logjams seem to consistently create at least some of the desired results (e.g., Gallisdorfer et al. 2014; Osei et al. 2015), even though these tend to be very simple and porous structures relative to naturally formed logjams. Engineered logjams, sometimes known as ELJs, can result in lower flow velocity near the jam and higher flow velocity in the main channel, with associated erosion and deposition in the vicinity of the engineered jam (Gallisdorfer et al. 2014). Small jams installed in northern Minnesota altered the richness and abundance of EPT (Ephemeroptera, Plecoptera, Trichoptera) insect taxa. In northern California, stream reaches with engineering wood structures had elevated pool frequencies relative to reaches without such structures. Clustered LW pieces or those with rootwads were most effective at creating pool scour (Lawrence et al. 2013).

The great majority of studies on placed LW indicate improvements in physical habitat (e.g., Brooks et al. 2006), as well as positive responses by salmonid fishes (Roni et al. 2015). However, successful outcomes require consideration of flow and sediment regimes in a watershed. A guideline checklist for reintroduction of wood in rivers, version 2.0 (simplified from Abbe and Brooks, 2011, Figure 7, pp. 444-446):

- Project information (project, owner, location, river system, date, project team)
- Project definition
- Identification of project goals
- Existing/historical site information
- Watershed disturbance
- Identification of opportunities and constraints
- Concept development
- Stakeholders and the community
- Project development
- Design flows
- Substrate
- Wood debris transport and budget
- Hazard delineations
- Alternatives assessment
- Hazard and risk assessment
- Structure design
- Construction planning
- Public safety and signage
- Basis of design or design documentation
- Implementation
- Construction
- Project performance monitoring
- Adaptive management

Review and synthesis papers (Harmon 2002; Abbe et al. 2003; Bisson et al. 2003; Reich et al. 2003) on LW reintroduction note trends through time, including:

- increasing use of "soft" placement techniques that allow some LW movement rather than completely anchoring LW in place;
- emphasis on passive recruitment of LW from natural source areas;
- placing LW in locations where channel geometry and hydraulics favor stability and where additional LW is likely to accumulate;
- careful consideration of likely hydraulic and geomorphic effects of LW placement, including changes in engineered LW structures over time;
- consideration of potential effects on human infrastructure and safety;
- developing restoration targets for wood load that include a watershed-scale perspective and recognize temporal and spatial variability produced by natural disturbances, rather than emphasizing fixed prescriptions for wood load within individual stream segments; and
- greater use of adaptive management, including monitoring of outcomes.

With respect to the latter point, relatively few monitoring studies have been published, despite the increasing number of LW or engineered logjam reintroduction projects in diverse rivers across the United States. This is a problem with all forms of stream restoration

(Bernhardt et al. 2005). Roni et al. (2015) provides one of the few reviews that evaluates success in meeting project objectives across multiple LW-emplacement projects. Roni et al. highlight several gaps in current management practices, including

(1) the rarity of long-term evaluations of placed wood,

(2) the problem that, although LW emplacement may meet short-term restoration objectives, emplacement does not address processes of wood recruitment and natural retention, and

(3) the lack of attention to basic issues such as how and where LW is naturally retained, what characteristics of LW (volume, location) are necessary to obtain desired physical and biological objectives, and how physical processes and biota actually respond to emplaced LW.

As repeatedly emphasized for stream restoration in general, we will not be able to learn from past successes and failures unless monitoring and documentation of results improve (Bernhardt et al. 2005; Roni et al. 2015; Wohl et al. 2015b). In the context of LW and beaver reintroduction, we will not be able to evaluate the effectiveness of these particular restoration measures versus other approaches without more systematic, long-term monitoring.

Effective management of LW in stream corridors requires understanding the processes that recruit LW and the rates at which those processes operate, as well as understanding the factors that mobilize or retain LW. These processes and factors are likely to change through space and time within a stream network or even a segment of river. LW dynamics in rivers of the Yellowstone ecosystem, for example, vary from 1st and 2nd order streams that are transport limited with respect to LW, to 3rd to 5th order streams that exhibit dynamic equilibrium and LW redistribution during floods, to 6th order and higher streams that are supply limited with respect to LW (Marcus et al. 2002).

A wood budget can be useful in the context of considering continuing LW recruitment in managed areas (Benda et al. 2003a; Hassan et al. 2005). A wood budget is a simple accounting of inputs, storage, and outputs within a stream reach and can be applied either as a conceptual or quantitative framework. Benda and Sias (2003) proposed the following equation for a wood budget within a channel segment of length x:

$$\Delta S_c = \left[L_i - L_o + \frac{Q_i}{\Delta x} - \frac{Q_o}{\Delta x} - D\right]\Delta t \qquad (1)$$

where
ΔS_c is change in storage within the reach over time interval t,
L_i is lateral wood recruitment into the channel,
L_o is loss of wood to overbank deposition during floods and abandonment of jams,
Q_i is fluvial transport of wood into the reach,
Q_o is fluvial transport out of the reach, and
D is *in situ* decay.

Lateral inputs can be conceptualized as resulting from several processes:

$$L_i = I_m + I_f + I_{be} + I_s + I_e + I_{bd} \qquad (2)$$

where
I_m is chronic individual tree mortality,
I_f is mass mortality (fire, blowdown, insects),

I_s is hillslope instability,
I_{be} is bank erosion,
I_e is exhumation from the floodplain, and
I_{bd} is beaver dams (this term is not in Benda and Sias 2003 but was introduced in Wohl 2016) (fig. 11).

Multiple numerical models have been developed to simulate and predict diverse aspects of LW dynamics. Many of the initial models focused on forest stand dynamics that create wood for recruitment to rivers (Gregory et al. 2003). Subsequent models have included more explicit attention to processes that directly cause LW recruitment (e.g., bank erosion) and processes that result in LW transport and redistribution along the stream corridor (Lancaster and Grant, 2006; Mazzorana et al. 2009, 2011, 2013; Eaton et al. 2012; Ruiz-Villanueva et al. 2014a, b, c). These models have been calibrated and validated primarily in the Pacific Northwest or European Alpine regions and it remains unclear how well they apply to other regions with different tree size and morphology. Another group of models seeks to predict physical effects, such as flow resistance and bed scour and deposition, associated with LW (e.g., Gippel et al. 1992; Wallerstein 2003; Stewart and Martin 2005; Manners et al. 2007).

In addition to numerical modeling, target wood loads are sometimes defined based on wood loads present in reference channels or the most natural watersheds within a region (e.g., Lester et al. 2006; Fox and Bolton, 2007). This typically requires extensive data for a region, however, because of the temporal and spatial variability in LW loads in watersheds without human disturbance. Wohl (2017) summarizes existing datasets on LW loads for rivers in diverse regions.

In the context of restoring LW, it is worth emphasizing that dispersed pieces or jams can still play an important geomorphic and ecological role even in highly altered streams within developed landscapes (Elosegi and Johnson 2003). Restoration and wood load are not all-or-nothing scenarios in which “natural” wood loads must be replicated to create beneficial effects. Similarly, restoration can effectively focus on limited portions of a stream or watershed in which LW reintroduction or retention is more feasible because of the characteristics of the stream corridor or land use (e.g., Piégay and Landon 1997). This is related to the “string of beads” approach to stream restoration, which focuses on limited lengths of stream – beads – in which it is more feasible to undertake stream restoration and in which restoration is likely to maximize environmental benefits (Stanford et al. 1996). The wood-rich hot spots along rivers that would naturally accumulate and retain more LW form obvious candidates for designation as beads (fig. 18).

Trends through time in large wood reintroduction include:

- increasing use of “soft” placement techniques that allow some wood movement;
- emphasis on passive recruitment of wood from natural source areas;
- placing wood where channel geometry and hydraulics favor stability and where additional wood is likely to accumulate;
- consideration of hydraulic and geomorphic effects of wood placement;
- consideration of potential effects on human infrastructure and safety;
- developing restoration targets for wood load that include a watershed-scale perspective and recognize temporal and spatial variability produced by natural disturbances; and
- greater use of adaptive management, including monitoring of outcomes.

Figure 18. Examples of restored river beads, here along the channelized River Tweed in Scotland. Main channel is approximately 15 m wide during base flow (photo courtesy of Derek Robeson).

2. Guidelines for LW Management in Diverse Regions

Guidelines for location, volume, and characteristics of LW retention and reintroduction of dispersed LW pieces or logjams are increasingly being published for specific regions. For example, addressing management of riparian forests and LW in medium to large rivers in France, Piégay and Landon (1997) suggest identifying different gradients of ecological potential and vulnerability to flooding or erosion based on (1) degree of connectivity (e.g., stream segments with active lateral channel migration that could maintain younger stands of riparian vegetation receive higher priority for protection) and (2) conservation and rehabilitation. Under this approach, stream segments with active lateral channel migration that could maintain younger stands of floodplain vegetation receive higher priority for protection (prioritization based on connectivity). Stream segments receiving priority for rehabilitation include those where the floodplain vegetation is non-existent or stream engineering (e.g., levees) has made the stream corridor too narrow to allow channel-floodplain connectivity and maintenance of diverse floodplain biotic communities (prioritization based on conservation and rehabilitation). Piégay and Landon (1997) also suggest promoting sustainability of LW-related features within channels by prioritizing protection of stream segments

(1) that could supply LW (e.g., via bank erosion),
(2) where logjam formation is most likely, and
(3) that have greatest channel-floodplain connectivity, so that overbank flooding can transport LW between the channel and floodplain and maintain floodplain biotic productivity.

Examining LW reintroduction in sand-bed rivers of southeastern Australia, Erskine and Webb (2003) proposed guidelines based on the understanding that:

- it is easier, less expensive, and more successful to rehabilitate partly disturbed stream segments, and to extend the length of undisturbed segments, than to rehabilitate highly altered segments (Rutherfurd et al. 2000);

- reintroducing LW into stream segments in which the potential for continuing natural LW recruitment is limited is unlikely to be successful over timescales of more than a few years;
- it is vital to consider diverse forms of connectivity within the stream segment, because organisms for which LW creates habitat must be able to reach the protected or restored stream segment;
- the intent of LW reintroduction should govern the placement and orientation of LW pieces with respect to channel morphology and hydraulics (e.g., is the LW intended primarily to stabilize the channel, to promote bed scour, or to perform some other function?);
- creating natural levels of LW load present prior to human disturbance, as well as the distribution of LW pieces with respect to piece size, orientation, and function, is an appropriate management target where processes such as continuing LW recruitment can sustain these LW characteristics; and
- sustainability of LW within the stream segment is facilitated where management maximizes the long-term potential for LW recruitment, for example by protecting riparian forest stands.

Focusing more on hazards associated with LW, Mazzorana et al. (2009) described a multi-step process of

(1) identifying and mapping LW recruitment areas based on recruitment process (e.g., bank erosion versus hillslope failure);
(2) calculating LW transport capacity using numerical models that incorporate LW supply, channel dimensions, and flow regime; and
(3) using a combined approach of GIS software, remote imagery, information on past LW recruitment, and numerical modeling to identify areas with potential hazards from LW recruitment and transport based on LW contributing area, recruitment pathways, and transport within the channel.

Focusing on LW retention and reintroduction, a field manual designed for the Clinton River watershed of Michigan (CRWC 2016) outlines a procedure based on field inventory of LW and field maintenance assessment of LW using an evaluation form of stream segment and LW characteristics. The approach is designed to promote comparison of beneficial and hazardous effects of the presence of LW in order to determine whether LW should be retained, modified, or removed from a particular stream segment. In this, the approach outlined is analogous to that in Wohl et al. (2016), which includes progressively more intensive evaluation methods, from a simple field checklist to use of the Large Wood Structure Stability Analysis Tool (Rafferty 2013, 2017), to determine the most appropriate management of existing LW in channels and floodplains.

Similarly, the online LW management guidelines of the UK Environment Agency emphasize balancing the environmental benefits of LW against the hazards created by the LW and suggest multiple options (retention, removal, modification, repositioning, reintroduction) for LW in rivers (see online resources). Washington's King County developed a checklist for instream project design, as well as a public safety management plan for monitoring, maintenance, and adaptive management of projects involving LW (see online resources), and the county's approach is centered on evaluating benefits versus risk from instream LW.

Of the existing online documents, the *National Large Wood Manual* developed by U.S. Bureau of Reclamation and the Corps of Engineers (USBR and ERDC 2016; see online resources at the end of this document) provides the most thorough discussion of issues around LW in rivers, including assessment of benefit versus risk, design guidelines, and regulatory compliance.

Numerous examples of guidelines for large wood reintroduction now exist. Reintroduction is most likely to be successful if based on the understanding that:

- it is easier, less expensive, and more successful to rehabilitate partly disturbed stream segments, and to extend the length of undisturbed segments, than to rehabilitate highly altered segments;
- reintroducing wood into stream segments in which the potential for continuing natural LW recruitment is limited is unlikely to be successful;
- it is vital to consider diverse forms of connectivity within the stream segment—organisms for which wood creates habitat must be able to reach the stream segment;
- the intent of wood reintroduction should govern the placement and orientation of LW pieces with respect to channel morphology and hydraulics;
- creating natural levels of wood load, as well as the size, orientation, and function of wood pieces, is an appropriate management target where wood recruitment can sustain these characteristics; and
- sustainability of wood within a stream segment is facilitated where management maximizes the long-term potential for wood recruitment.

3. Reintroduction of Beaver and Beaver Dam Analogs

Reintroduction of beaver to a watershed or stream segment from which the animals have been extirpated is typically undertaken to create erosion control (Pollock et al. 2007), enhance aquatic and riparian habitat (e.g., Albert and Trimble 2000), and increase dry-season base flow (Collier 1959). A review of the literature related to stream restoration using beaver suggests cycles of this activity, with periods of active emphasis on beaver reintroduction during:

- the later 1800s to early 1900s (e.g., Morgan 1868; Mills 1913; Dugmore 1914);
- the era of the 1930s Dust Bowl, when the Soil Conservation Service and several State fish and game departments used beaver in stream restoration (e.g., Scheffer 1938);
- the 1980s, when the U.S. Bureau of Land Management and other agencies undertook beaver restoration in at least some western streams (Brayton 1984; Albert and Trimble 2000); and
- a recent emphasis on use of beaver to enhance and restore stream ecosystems, as reflected in publications such as Burchsted et al. (2010), Gibson and Olden (2014), Pollock et al. (2014), and the multi-agency Beaver Restoration Guidebook (Pollock et al. 2017).

Beaver dam analogs are also used either as an initial step in beaver reintroduction or where beaver cannot be reintroduced to a site for some reason (fig. 19). Beaver dam analogs can mimic many of the functions of beaver dams but can be placed at higher densities than those typical of natural beaver dams (Pollock et al. 2014). Beaver dam analogs are channel-spanning structures that mimic or support natural beaver dams. Beaver dam analogs are semi-porous to water, sediment, particulate organic matter, and aquatic organisms and are biodegradable, relatively temporary features (Pollock et al. 2012).

Like real beaver dams, beaver dam analogs function most effectively when constructed in longitudinal sequences. Pollock et al. (2012, 2017) contain detailed descriptions and case studies involving beaver dam analogs. Bouwes et al. (2016) describe an experiment in which beaver dam analogs installed in Oregon's John Day River system resulted in significantly increased density, survival, and production of juvenile steelhead (*Oncorhynchus mykiss*). When placing beaver dam analogs, DeVries et al. (2012) emphasize the importance of choosing locations at which the structures will promote increased frequency of flood connection with floodplain swales and relict channels, such as relatively wide valley bottoms with low gradients.

As with other forms of LW, guidelines have been developed for identifying suitable beaver habitat and for emplacement of beaver dam analogs. As reviewed in several publications (e.g., Howard and Larson 1985; Olson and Hubert 1994; Gurnell 1998; Baker and Hill 2003; Pollock et al. 2017), beaver exhibit preference for certain habitat characteristics. Among these are:

- proximity to a water body or the ability to create a water body, for example by damming seeps and springs;
- sand size or finer bed and bank sediment, as opposed to boulders or bedrock; and
- availability of preferred deciduous woody plants, including willows (*Salix* spp.), aspen and cottonwood (*Populus* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), and maple (*Acer* spp.).

Figure 19a-b. Examples of beaver dam analogs installed along streams in Colorado. (A) Campbell Creek in northern Colorado. (B) Early stages of beaver dam analog installation along South St. Vrain Creek in Colorado. Creek is approximately 15 m wide and flow is left to right (photograph courtesy of Mac Kobza, Boulder County).

Beaver also select habitat based on factors such as channel width (approximately 3-40 m) and valley width (> 50 m), stream gradient (< 6 percent), and flow regime (perennial rivers preferred). It is worth emphasizing that (1) the presence of all of these characteristics does not guarantee that beaver will thrive in a particular stream segment and (2) beaver can thrive where one or more characteristics are lacking. Macfarlane et al. (2014, 2017) describe BRAT (the Beaver Restoration Assessment Tool; http://brat.riverscapes.xyz/), a capacity model designed to assess the limits of stream corridors to support dam-building activities by beaver across diverse landscapes based on the presence of five key factors: a perennial water source; availability of dam-building materials; ability to build a dam at base flow; likelihood of dams to withstand a typical flood; and likelihood that stream gradient will limit or completely eliminate dam building by beavers. Tests of the model in Utah and surrounding States showed strong agreement between predicted beaver habitat and actual presence of the animals along rivers. The model uses databases including the USGS National Hydrography Dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography), LANDFIRE (vegetation; https://www.landfire.gov/), USGS base and 2-year peak flow regression equations, and DEMs to assess the five key factors.

Beaver dam analogs – channel-spanning structures that mimic or support natural beaver dams – can be used either as an initial step in beaver reintroduction or where beaver cannot be reintroduced to a site. Beaver dam analogs can mimic many of the functions of beaver dams but can be placed at higher densities than those typical of natural beaver dams.

Beaver prefer:

- proximity to a water body or the ability to create a water body;
- sand size or finer bed and bank sediment;
- availability of preferred deciduous woody plants, including willows (*Salix* spp.), aspen and cottonwood (*Populus* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), and maple (*Acer* spp.);
- channels approximately 3 to 40 m wide in valley bottoms greater than 50 m wide;
- low-gradient streams (< 6 percent); and
- perennial streams.

C. Guidelines for Identifying Stream Segments that Maximize Environmental Benefits

This portion of the document describes procedures for identifying stream segments that maximize environmental benefits and minimize potential hazards associated with large wood and beaver dams in the context of

(1) reintroducing logjams,
(2) retaining existing, naturally occurring logjams,
(3) reintroducing beaver, and
(4) retaining existing beaver colonies and dams.

Our primary objectives in developing these guidelines were to create relatively simple and inexpensive, field-based evaluation procedures that would facilitate consistency and reproducibility between operators and among regions. Each of the four scenarios listed above involves a 1- to 3-stage procedure (fig. 20). First, in the retention scenario, a Level I checklist is used to evaluate potential hazards that would necessitate removal of a logjam or beaver dam. If a logjam is evaluated as being potentially suitable for retention, three subsequent steps are possible:

(1) a Level II jam stability analysis (see below) can be conducted to more rigorously evaluate potential stability of the logjam;
(2) a Level-II analysis based on decision bands can be used; or
(3) the evaluation can proceed directly to different scenarios for jam retention (fig. 20).

The choice of each of these subsequent steps is governed by time and expertise available for evaluating the logjam. If a beaver dam is evaluated as being potentially suitable for retention, the evaluation can proceed to different scenarios for dam retention (fig. 20). In the reintroduction scenario, a different checklist is used to determine whether to proceed to the design and implementation (logjam) or reintroduction (beaver) phase. The selection of stream segments to evaluate using the checklist or stability analysis can be preceded by a DEM-based analysis of the watershed used to identify generally wider, low-gradient stream segments that could maximize benefits of reintroduction or retention of wood while minimizing potential hazards.

We propose a multi-stage procedure for evaluating either retention of existing logjams or beaver dams, or reintroducing large wood or beaver to a stream segment. The first step involves simple checklists with yes/no questions. This step can be preceded by a DEM-based analysis of stream segments based on gradient as a means of prioritizing sites at which to use the checklist. Depending on the outcome of this level I checklist, evaluation can then proceed to

(1) a Level II jam stability analysis for logjam retention,
(2) a Level II analysis using decision bands, or
(3) the design phase for logjam or beaver reintroduction.

1. Level I Field Checklists for Jams and Dams

The checklists for three scenarios are presented in figures 21A and 21B. The first scenario is initial assessment of retention of wood. The second scenario is initial assessment of beaver dam(s). The third scenario is reintroduction of wood.

Figures 21A and 21B illustrate a multi-step procedure for assessing the retention or reintroduction of LW jams and beaver at selected sites. This checklist is suggested guidance for

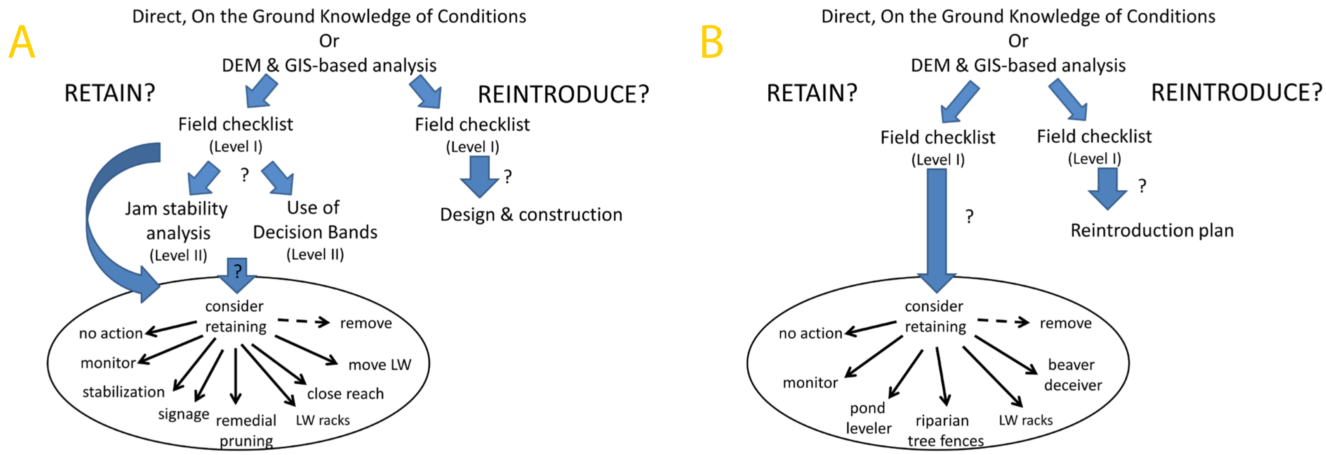


Figure 20a-b. Schematic illustration of multi-step decision process for assessing (A) LW jams (after Wohl et al. 2016, figure 3) and (B) beaver dams. Question marks indicate potential alternative scenarios.

use by land managers, to help structure the decision-making process. Stream segments can be identified from prior knowledge of the watershed or the GIS-based analysis described in section C.2 can be used to identify these stream segments. Once appropriate stream segments are identified, the field checklists can be used for rapid assessment. Logjams can be evaluated with respect to imminent threat to public safety (recreational users), imminent threat to property and infrastructure, and legal requirements (fig. 21A). Decision bands can be used to more objectively weight and analyze the benefits and threats associated with a logjam, as described in section C.4. In situations where a jam potentially creates imminent threats, the jam can be removed or modified in one of several ways (fig. 21A). Management actions include: moving the LW pieces elsewhere (e.g., from the active channel to the floodplain); installing some type of LW retention structure downstream if movement of wood pieces might create hazards; pruning individual pieces of wood or removing a portion of the jam; installing signs to warn recreational users of the presence of the jam; stabilizing the jam; monitoring the jam; or closing the stream segment to recreational users.

Beaver dams can be evaluated with respect to imminent threat to property and infrastructure, and legal requirements (fig. 21B). Management actions (fig. 21B) include: removing the beaver dam or the beaver colony; use of a beaver deceiver; preventing beaver from cutting down riparian trees by fencing or otherwise protecting the base of selected trees; use of a pond leveler; and monitoring the beaver dam.

If the jam under consideration is not judged to be an imminent hazard based on the Level I analysis, the assessment can proceed to Level II with a more detailed assessment of jam stability or the use of decision bands.

Level I checklists provide relatively simple, rapid assessments of potential hazards posed by logjams and beaver dams and provide guidance based on assessed hazard.

Level I checklist for initial assessment of retention of individual LW pieces or accumulations (after Wohl et al., 2016, Figure 4)

1. ***Imminent Threat to Public Safety***

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

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

2. ***Imminent Threat to Property and Infrastructure****

a) Has the wood already damaged a facility or public or private structure?
If yes and no other management alternatives are viable, remove.
If no, or if other management alternatives may be viable, proceed to consider retaining.

b) Could the wood potentially create, or increase the extent of, damage to a facility or public or private structure that may cause loss of function to the facility or structure?
If yes and no other management alternatives are viable, remove.
If no, or if other management alternatives may be viable, 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 spreadsheets and consider retaining.

Level I checklist for initial assessment of beaver dams

1. ***Imminent Threat to Property and Infrastructure***

a) Has backwater flooding from the beaver dam already damaged a facility or public or private structure?
If yes and no other management alternatives are viable, remove.
If no, proceed to consider retaining.

b) Could backwater flooding from the dam potentially create, or increase the extent of, damage to a facility or public or private structure that may cause loss of function to the facility or structure?*
If yes and no other management alternatives are viable, remove.
If no, proceed to consider retaining.

c) Could the presence of beaver lead to blockage of diversion intakes or culverts?
If yes and no other management alternatives are viable, remove.
If no, proceed to retaining.

d) Could cutting of riparian trees by beaver damage private property or reduce esthetic appeal of recreational area?
If yes and no other management alternatives are viable, remove.
If no, proceed to retaining.

2. ***Legalities***

For any reason, are you legally bound to remove the beaver or beaver dams?
If yes, remove.
If no, proceed to consider retaining.

3. ***Overall***

If the answer to all of the preceding questions was a clear 'no,' retain beaver dam.
If the answers involved some qualifications, proceed to Level 2 analysis and consider retaining.

Level I checklist for initial assessment of reintroduction of wood accumulations

1. ***Threat to Public Safety***

a) Would a logjam pose a threat to river recreationists?
If yes, either do not consider site further or evaluate options for minimizing the threat.[1]
If no, proceed to consider reintroducing.

2. ***Threat to Property and Infrastructure****

a) Could the logjam damage a facility or public or private structure?[2]
If yes, either do not consider site further or evaluate options for minimizing the threat.
If no, proceed to consider reintroducing.

b) Could the logjam potentially create, or increase the extent of, damage to a facility or public or private structure that may cause loss of function to the facility or structure?
If yes, either do not consider site further or evaluate options for minimizing the threat.
If no, proceed to consider reintroducing.

3. ***Legalities***

For any reason, are you legally bound to keep the river corridor free of logjams?
If yes, do not consider site further.
If no, proceed to consider reintroducing.

4. ***Overall***

If the answer to all of the preceding questions was a clear 'no,' reintroduce wood.
If the answers involved some qualifications, consider reintroducing in connection with options to minimize potential hazards.

[1]Options for minimizing threats posed by introduced logjams include

- anchoring the jam in place
- minimizing crevices within the jam and protruding pieces that could create hazards for recreational users via entrapment or snagging
- placing the jam on the floodplain rather than in the active channel
- placing the jam in a low velocity zone or within a portion of the channel that allows recreational users to avoid the jam
- closing the river reach to recreational use
- posting signs warning recreational users of the presence of the jam
- adding wood retention structures to trap wood pieces that are mobilized from the jam

[2]Threats to property and infrastructure come from

- mobile wood pieces transported downstream
- enhanced overbank flow associated with the obstruction created by the logjam
- directed bed or bank scour associated with the logjam

Figure 21. Checklists for retention of wood, initial assessment of beaver dams, and reintroduction of wood. Several of the steps in this checklist, such as those indicated by an asterisk, are most effectively completed with a simple quantitative analysis using a surveyed channel cross-section and design discharge.

2. GIS Analysis of Stream Gradient and Infrastructure

As noted earlier, total LW load and downstream spacing and volume of jams can vary substantially over stream lengths of hundreds of meters to a few kilometers as a result of downstream variations in LW recruitment and transport capacity related to valley and channel geometry. Similarly, although beaver can build a dam in many parts of a mountainous stream network, beaver meadows and the largest and most persistent dams are likely to be non-uniformly distributed throughout a stream network. Wider, low-gradient stream segments have greater space for beaver dams to create inundated backwaters and ponds, lower unit stream power during peak flows, a more open canopy that can favor deciduous riparian species such as willow (*Salix* spp.) and aspen or birch (*Populus* spp.), and a higher riparian water table associated with groundwater influx from valley-side slopes, which also favors deciduous riparian species and wetland plants. GIS analysis can be used to delineate reaches to aid in selecting sites for wood or beaver management. Here, we describe generally applicable methods of simple GIS analysis that can be used to inform planning. GIS analyses used for management planning should be driven by a clear knowledge of region-specific site characteristics that will maximize the effectiveness of restoration or retention of wood or beaver dams.

The abundance and spatial distribution of these wider, lower gradient valley segments within a stream network can commonly be effectively delineated, at least for approximately 2nd order and larger streams, using a DEM of 10 m or finer resolution. Simple GIS routines can be used to map stream gradient categories over either a fixed length of stream (Wohl et al. 2017) or a fixed elevation. The Fluvial Corridor toolbox, for example, utilizes just a DEM to create a stream network based on a drainage initiation threshold, segment the network into reaches of a desired length, and compute the slope of each reach (Roux et al. 2015). Slope can be classified, if desired, based on field knowledge to attempt to match low-gradient reaches with wide valley bottoms. In the Wohl et al. (2017) analysis of North St. Vrain Creek in Colorado, for example, we classified reaches into high (> 0.10 m/m), medium (0.03-0.10 m/m), and low (≤ 0.03 m/m) gradient classes. Gradient classes were based on analyses of an extensive data set of channel morphology in relation to stream gradient (Livers and Wohl 2015) and effectively distinguish cascade (> 0.10 m/m), step-pool (0.03-0.10 m/m), and pool-riffle or plane-bed (≤ 0.03 m/m) reaches (Mongtomery and Buffington 1997). Another example of mapping reach-scale stream gradient is provided in Buffington and Tonina (2009).

Stream gradient commonly correlates inversely with valley-bottom width in mountainous stream networks, such that higher gradient segments are narrower (Wohl et al. 2007; Buffington and Tonina 2009; Livers and Wohl 2015; Wohl et al. 2017). Consequently, the gradient map derived from a DEM can be used to infer valley geometry (fig. 22A). In addition, valley bottoms can be delineated using a variety of relatively easy-to-use GIS tools (e.g., Roux et al. 2015; Gilbert et al. 2016). Although valley-bottom maps tend to be more dependent on DEM resolution than are slope maps, they can serve as a valuable planning tool to identify unconfined reaches where wood or beaver management could most effectively enhance flood-plain ecosystems. In either case, DEM-based GIS analysis should always be checked using available satellite or aerial imagery, either in a GIS or through publicly available platforms such as Google Earth. Aerial imagery can be used to confirm that slope or valley-bottom maps accurately delineate reaches with desirable characteristics, such as unconfined valley bottoms.

The spatial distribution and characteristics of logjams with respect to valley and channel geometry can vary substantially between regions. In the Intermountain West (regions 1-4), LW storage, channel-spanning logjams, beaver dams, and the environmental benefits associated with these features tend to be greatest in relatively wide, low-gradient stream segments. This distribution reflects the combination of lower transport capacity and greater riparian recruitment potential for LW in wide valley segments, as well as the sustained LW transport associated with annual snowmelt runoff. In the Pacific Northwest (Region 6), in contrast, frequent hillslope instability in addition to riparian recruitment via channel migration recruits substantial LW to stream corridors. In low-order streams of this region, rainfall runoff with higher peak unit discharge (peak discharge per unit drainage area) than commonly occurs during snowmelt can transport LW to choke points in steep, narrow valleys, creating substantial jams with large wedges of sediment stored upstream from the jam. LW also tends to accumulate preferentially at tributary junctions in this region (Benda et al. 2004a,b). Jams in relatively steep, narrow stream segments in the Pacific Northwest can create important pool habitat (Beechie and Sibley 1997; Roni and Quinn 2001;) for fish. However, when such jams are located upstream of wood-poor streams with high wood transport capacity, their failure can pose a substantial hazard to infrastructure. Consequently, the gradient or valley confinement map, combined with infrastructure, wood loading, and other relevant data, can be used to prioritize stream segments for management designed to recruit and maintain LW, or management designed to mitigate potential hazards associated with LW. The remainder of this discussion focuses on the lower gradient segments and opportunities for LW retention.

A GIS platform can be used to overlay the DEM-derived map of stream gradient and/or valley-bottom geometry with additional layers of relevant information, including a map of infrastructure that could be damaged as a result of mobilization of LW or failure of beaver dams (e.g., bridges, culverts, and diversions) or by enhanced inundation caused by beaver dams (e.g., roads, recreational use areas, private property within a National Forest). Other relevant map layers might include the distribution of desired fish species, maps of riparian vegetation communities or forest stand characteristics, maps of instream wood derived from aerial imagery, geomorphic unit maps, or maps of stream segments intensively used for recreation such as fishing or tubing. Overlaying such data can allow for the generation of new spatial data layers representing the magnitude of potential hazards to humans and infrastructure, and the magnitude of potential for improvement of ecological health (or potential for impairment of ecological health if wood were removed) This can be used to prioritize segments for LW/beaver retention or reintroduction, as verified by site visits and the use of the checklists described in the subsequent sections (fig. 22B). After sites are identified for management and the cost of management at potential sites is estimated, this GIS analysis can be used as a foundation for cost-benefit analysis to judge the merit of potential projects.

The DEM-based analysis of channel geometry is used to identify the locations and abundance of relatively unconfined, low-gradient stream segments that are likely to maximize environmental benefits and minimize potential hazards associated with logjams and beaver dams. The channel geometry map can be combined with maps of other relevant stream-corridor characteristics to further target potentially suitable stream segments.

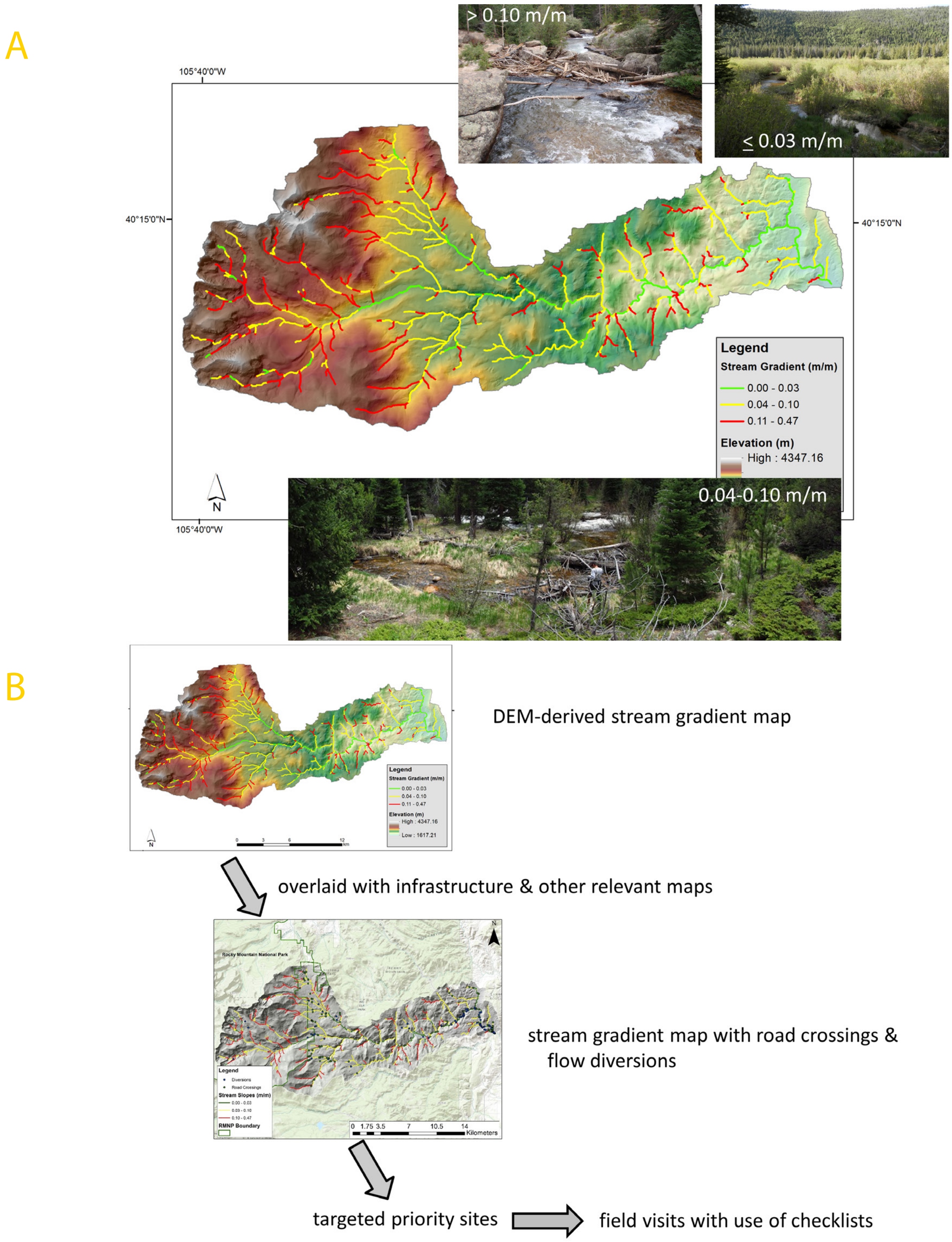


Figure 22a-b. Examples of applying the DEM-based analysis of stream gradient segments within a watershed. (A) Map of segment-scale stream gradient in three categories in the North St. Vrain Creek watershed, Colorado. Inset photos illustrate channel and valley geometry characteristic of each gradient class. (B) Schematic illustration of using the gradient map with other data layers to select stream segments for wood or beaver retention or reintroduction.

2.1. Level II Analysis for Logjam Retention: The Wood Jam Dynamics Database and Assessment Model (WooDDAM)

LW jams are inherently dynamic features that gain and lose wood pieces, especially during high flows (Dixon and Sear 2014). They also expand and contract, which alters their porosity, on both short and long timescales (during floods as well as from year to year). This implies some level of consistent instability, where jams naturally do not capture all LW being transported downstream and do not remain static over substantial periods of time. Management paradigms should accommodate the idea that static LW in streams is rarely a natural or sustainable solution to improving habitat or safety (Kramer and Wohl 2017), although static LW may be the only option in some situations. With that in mind, we define stability as the persistence of a LW jam, but not necessarily all or even most of the wood within the jam, throughout a design flow or during a specified period of time. By this definition, a stable jam will continue to perform geomorphic and potentially ecologic functions over a continued period of time. This definition is designed to accommodate what is most easily measurable about a jam (its presence or absence), as opposed to actually quantifying the degree to which the jam facilitates or impedes the transport of LW downstream.

The *National Large Wood Manual* (USBR and ERDC 2016) suggests the use of a force and moment analysis for evaluating the stability of LW structures. The following discussion comes from chapter 6 of this manual. Forces affecting the stability of LW structures include net buoyancy, friction between the LW and the stream bed, fluid drag and lift, and geotechnical forces on buried portions of the LW. In calculating these forces, the jam is treated as a unit (fig. 23).

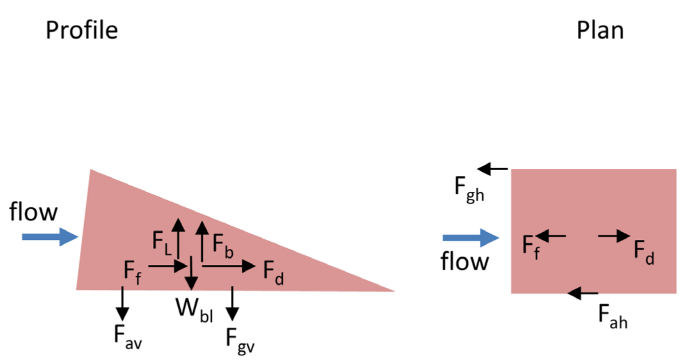


Figure 23. Idealized illustration of the forces acting on a LW structure in a river. F_{av} is restraining force resulting from anchors or other restraints in the vertical direction. W_{bl} is the weight of ballast, if included in the structure. F_{gv} is geotechnical force acting in the vertical direction. F_f is the force of friction between the LW and the river boundary. F_d is drag force, F_L is lift force, F_b is buoyant force, F_{gh} is geotechnical force in the horizontal direction, and F_{ah} is the force resulting from anchors or other restraints in the horizontal direction. The points of application shown for force vectors are arbitrary. From USBR and ERDC 2016, figure 6-13, p. 432.

The net buoyant force, F_b, is the difference between the weight of the jam and the weight of displaced water

$$F_b = [\gamma_d V_d - \gamma_w V_w]$$

where

γ is specific weight,

V is volume, and

the subscripts d and w refer to wood and water, respectively.

V_w is displaced water volume and is equal to V_d if the jam is fully submerged. Estimation of V_d can be difficult because of the complex structure of jams. A simple approximation assumes that each LW piece in a jam is a cylinder and rootwads are cones, and then sums their volumes:

$$V_{wood} = \pi \sum_{k=0}^{n} l_k r_k^2 + \frac{t_{kw_k^2}}{3}$$

where

l_k and r_k represent the length (exclusive of rootwad) and d.b.h. (diameter at breast height) radius of the k^{th} log, respectively, and t_k and w_k represent the thickness (measured in direction parallel to trunk) and radius of the k^{th} rootwad.

Friction between the LW and the stream bed creates a frictional force F_f that resists movement by the LW. The magnitude of this force is equal to the product of the normal force, F_n, and the coefficient of friction between the LW and the bed. If $F_n > 0$

$$F_f = \mu_{bed} F_n$$

In the absence of measured data, $\mu_{bed} = tan\ \varphi$, where φ is the friction angle for the bed sediment (Castro and Sampson, 2001) and

$$F_n = F_b - F_L$$

where F_L is the lift force on the jam.

Fluid drag, F_d, is a force from the horizontal direction that can be estimated using

$$F_d = \frac{C_D A \gamma_w U_o^2}{2g}$$

where

F_d is drag force,

C_D is drag coefficient,

A is area of jam projected in the plane perpendicular to flow, and

U_o is approach flow velocity in the absence of the jam.

Drag coefficients vary greatly between jams but tend to decline to values typical of cylinders (0.5-1.0) when LW becomes so complex that interstitial flow is minimal. C_D values reach a maximum of ~ 1.5 when jams are barely overtopped (Shields and Alonso 2012). In the absence of better information, C_D can be assumed to equal 0.9 for fully submerged conditions and 1.5 when the water surface is within ~ one log diameter of the top of the jam (Shields and Alonso 2012).

$$F_L = \frac{C_L A \gamma_w U_o^2}{2g}$$

Lift force results from flow acceleration above and below a jam and can be computed from

where

F_L is lift force,

C_L is drag coefficient,

A is structure area projected in the plane perpendicular to flow, and

U_o is approach velocity in the absence of the jam.

Although lift forces on jams are typically small relative to buoyant forces, they can be important. In the absence of better information, C_L can be assumed to be 1.0 for complex jams that are submerged. Lift can be assumed to be 0 for LW in contact with the bed that is not fully submerged, and A can be treated as a single body, rather than individual cylinders, if the upstream face of the jam is only slightly porous.

Importantly, the approach outlined above explicitly assumes that the jam will act as a unit, with pieces secured to one another. This approach may not work as well for jams that are porous or unsecured, but it provides a first approximation for estimating the stability of a complex object without the use of a force and moment analysis for each individual log, which could be prohibitively complex or difficult to accomplish given measurement and time constraints. This analysis also does not consider changes in jam characteristics due to wood transport at high flow or the rearrangement of pieces due to bouyancy before mobilization, which has been observed as jams experience flow variability around high flow. Analogous to the findings of studies on the initiation of motion of coarse sediment on the bed of a stream, fluctuating hydraulic forces can exert a particularly important influence on the stability of LW structures. Flume experiments indicate that maximum drag and lift forces can be 2-3 times greater during the rising limb of unsteady flows than the temporal mean values of these forces during steady flow (Shields and Alonso 2012). Drag and lift coefficients are also greatest for simple LW and converge on smaller values typical of blunt bodies as LW complexity (branching) increases.

Conducting field measurements that adequately characterize all of the variables in the preceding equation is difficult, as is determining stability for unsecured (natural) jams or those that strongly interact with immobile objects, living wood, or banks. Therefore, we have developed a simpler and more adaptable approach to analyzing potential jam stability in the field using a machine-learning-based statistical model. Although this approach cannot serve the same function as an analytical approach to determining wood dynamics (e.g., for high risk engineering applications), it represents an effort to bring the most up-to-date understanding of wood jam dynamics to bear in predicting wood jam dynamics using a machine-learning approach.

Force and moment analyses can be very useful in quantitatively estimating the stability of coherent objects such as a single piece of wood. However, because individual pieces of wood within a logjam do not necessarily move as a coherent mass, we suggest evaluating jam stability using a probabilistic, statistical modeling approach, especially when a fully deterministic, analytical prediction is not needed or is infeasible.

Wood jams exhibit significant complexity in terms of their structure, composition, and interactions with sediment, relatively immobile objects (e.g., large boulders and living trees), or various valley-bottom landforms (e.g., bars, valley walls). Although a force and moment stability analysis may be applicable to all jams despite its drawbacks, a simpler, statistical model of jam stability must accomodate variations in the physical characteristics of wood pieces, flow and sediment regimes, network position (e.g., the quantity of LW input from upstream), and disturbance regime. The model described here would ideally be built from information that represents as wide a range of variability in valley-bottom geometry; wood characteristics; jam geometry and characteristics; and flow, sediment, and disturbance regimes as possible. This necessitates a quantity of data that is infeasible for a single team of investigators to collect. In addition, such a static model would be unable to accommodate future data that could otherwise help improve its predictive power. Thus, we have developed a wood jam survey protocol, online database, and accompanying predictive model that will be regularly updated with new data as the model is used and its performance evaluated. New data can be easily added to the database to help improve model predictions simply by utilizing the model as part of restoration/retention design and basic monitoring or research.

We introduce the Wood Jam Dynamics Database and Assessment Model (WooDDAM) to provide a standardized monitoring framework, public database, and predictive model of wood jam dynamics in river corridors (Scott et al. 2018, 2019). We identified three primary objectives that had to be met to ensure the success of this tool. First, data used in the model must be collected using simple methods that are reproducible across multiple operators in all systems and are sufficiently expedient to allow for extensive and cheap data collection. This ensures that multiple investigators can work together to build a dataset for the model, and that data can be collected expediently enough to rapidly develop a large dataset. Second, data must be easily shareable. The model and database, as well as accompanying guidelines for their use, are hosted at https://sites.warnercnr.colostate.edu/woodjam/ to allow data sharing using a user-friendly, public, online interface. This interface facilitates manual supervision of submitted data to help prevent false or erroneous data submission, and it accommodates the data review by a supervisor before being incorporated into the database or predictive models.

Third, submitted data must be analyzed in the context of the environment within which they were collected. This means that data are tracked by variables such as hydrologic regime, region, wood characteristics, and channel characteristics. Outputs such as model predictions for new sites clearly display the confidence of the model for that new site by displaying the similarity of the model's training data to the data being used to make predictions. This ensures that the model presents results that take into account the context of its predictions and reports its applicability to users who seek to use the model for management purposes. By providing an easily interpretable and context-aware tool to predict wood jam dynamics, we aim to allow users to combine model-based predictions with ancilliary data (e.g., GIS analysis, watershed context, historical context, and field observations) to make well-contextualized and informed management decisions.

The wood jam dynamics predictive models use variables describing wood jam and surrounding channel and watershed characteristics to predict a series of binary variables that describe potential changes a wood jam can experience during high flows. The binary variables include whether a jam accumulated wood, lost wood, contracted, expanded, or mobilized. Together, these binary variables cover the breadth of possible changes a wood jam can experience during a high flow. The mobilized variable can be used specifically for analyzing stability, although other mangement or research scenarios may take advantage of the other potential modes of changes.

These modes of change are also non-exclusive, in that a wood jam, during a single high flow, can change in more than one way (e.g., contract and accumulate wood). Model output for a given prediction includes both the prediction of whether a jam will experience each of the five aforementioned modes of change, including mobilization, as well as the interactions between all relevant predictor variables and the predicted response represented as odds ratios, with interpretation guidelines presented with the output. These odds ratios can be used to determine the relative importance of predictor variables in determining wood jam dynamics and help provide background and context to the predictive output.

Our model of wood jam dynamics is trained on a wood jam monitoring database that is publicly accessible and will increase in size with time. This database describing individual wood jams includes variables that describe:

- hydrologic regime (whether flow in the channel is perennial, the flow regime is flashy, high flow peaks are sustained, ice jams regularly occur, and high flows are snow- or glacier-melt driven);
- channel geometry (bankfull width, bankfull depth, channel bed slope);
- reach-scale characteristics (planform, bedform, categorical clast size, whether the channel is a main or side channel, floodplain presence, valley confinement, presence of other wood jams in the reach);
- the relative location of the jam (descriptive location relative to local landmarks, latitude, longitude);
- physical characteristics of the jam (the degree to which it obstructs flow); and
- the average decay class of the wood comprising the jam (Harmon et al. 2011).

The database also describes whether each jam:

- touches the bed, banks (including whether the jam touches the outer or inner bank, if present), floodplain surface, and valley wall;
- occupies the thalweg;
- spans the channel;
- is oriented dominantly parallel or perpendicular to flow;
- is pinned on a relatively immobile object such as living wood or a large boulder and whether that object extends above bankfull depth;
- has key pieces that extend above bankfull depth;
- has key pieces that are oriented at an angle of 15 degrees from horizontal or greater;
- is morphologically impacted the channel by inducing scour or deposition;
- key pieces that are buried in sediment;
- has fine wood or sediment that rest atop key pieces;
- has any key pieces forming the jam that were sourced *in situ* from the bank immediatey surrounding the jam;
- has key pieces that are still attached to rootwads;
- has living wood comprising, growing off of, or growing proximal to the jam; and
- has multiple trunks.

These variables comprehensively describe the channel geometry, bankfull flow hydraulics, jam geometry, characteristics, and location to characterize how the jam will interact with flow during high flows (fig. 24) and how resistant it may be to transport (e.g., a jam pinned against a large living tree may be more stable under high flows than one that sits isolated in the middle of a channel).

The database also includes resurvey data (describing how wood jams change through time), including:

- whether each jam accumulated wood, lost wood, expanded, contracted, or mobilized between surveys;
- the qualitative peak flow magnitude between surveys (below, near, or above bankfull stage);
- the quantitative peak flow magnitude between surveys (if gaging data are available);
- the dates of initial survey and resurvey; and
- a notes section to include other relevant information about each jam.

It is important to note that the database and resulting predictive models can accommodate missing data. For example, if an estimate of peak flow magnitude between resurveys is unavailable, information to improve the predictive modeling can still be gleaned from relating how the jam changed to its initially surveyed characteristics. Database entries with missing data can also serve ancilliary functions as well. For instance, researchers could use the open database in conjunction with other data to explore the longevity of wood jams under variable flow conditions; the relationship between wood jam dynamics and channel dynamics; and other fundamental investigations into interactions between wood jams, human activities, geomorphology, and ecology. The database serves as an informational record that can provide managers and practitioners data regarding typical characteristics of wood jams to aid in decision-making regarding wood retention and reintroduction.

The complete survey protocol, including a full list of measurements that we recommend collecting for characterizing a wood jam and its environment, is documented in Scott et al. (2019), and tools to aid data collection (e.g., printable sheets explaining field measurements) are available at https://sites.warnercnr.colostate.edu/woodjam/. Examples of jams with measurements described can be found in Text Boxes 1 and 14.

WooDDAM depends on users not only characterizing jams using the aforementioned survey protocol (and possibly querying predictions of jam dynamics), but also resurveying jams after high flows and submitting resurvey data to the database to further improve the predictive models. Resurveys involve simply determining whether a wood jam has experienced any of the five binary changes described above; estimating whether peak flows in the period between surveys were below, at, or above bankfull stage (to enable models to account for flow magnitude); and then remeasuring any variables that have changed since the last survey, which facilitates subsequent resurveys. We recommend taking photographs of each wood jam surveyed, ideally from all sides of the jam, to be able to evaluate change after high flows. Photos can be tied to a jam using the date and time the photos were taken, which can be recorded with the other variables listed above for each jam. Scott et al. (2019) provides more detail on field data collection procedures and guidelines. The online user interface accepts tabular data as its input. Therefore, we suggest using a standard spreadsheet for data collection or entering data into this spreadsheet from a notebook. Complete data collection spreadsheets and instructions can be found on the website https://sites.warnercnr.colostate.edu/woodjam/. Data collection, model usage, and data submission to the model can be facilitated by downloading the data collection spreadsheet, entering data into it, and uploading it via the website.

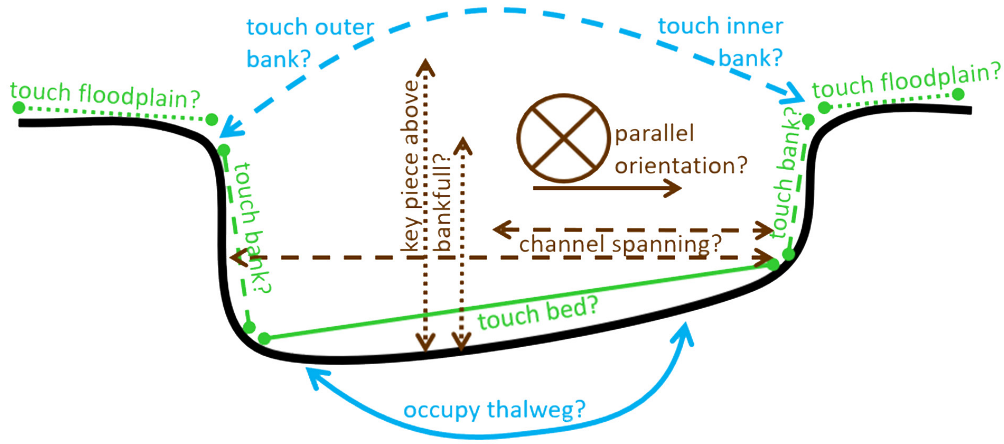


Figure 24. Illustration depicting wood jam geometry and location measurements and how they each determine either where a wood jam is located within a channel cross-section or the relative dimensions of the jam. Blue depicts explicit location metrics. Green depicts channel boundary location metrics. Brown depicts wood jam geometry and orientation metrics. These measurements, when taken together, provide a comprehensive description of the location, size, and orientation of a wood jam relative to the geometry of the channel.

We strongly recommend both visiting the website (https://sites.warnercnr.colostate.edu/woodjam/) and reading Scott et al. (2019) before collecting data or utilizing the wood jam dynamics model. Over time, as the database grows and includes more hydrologic regimes and ecoregions, it will likely become more accurate for predicting wood jam stability. Thus, investigators are highly encouraged to contribute data to the database to facilitate the development of the predictive models and enhance their accuracy at predicting wood jam dynamics in various environments.

Field testing has shown that the variables included in the database are relatively easy to collect in approximately 5-15 minutes per wood jam with a team of 1-2 people. Testing these measurements with multiple operators working simultaneously on the same wood jams has shown these measurements to be reproducible between operators (Scott et al. 2019), which is essential to creating a broad-scale dataset. Although more information could be gleaned from more quantitative measurements, we found that such measurements had high variability depending on who was making the measurement, leading us to increase the number of variables measured while decreasing their complexity (i.e., using binary or categorical variables).

To utilize WooDDAM in the context of decision-making regarding the retention or introduction of wood to valley bottoms, users should treat WooDDAM predictive outputs as a single line of evidence in the context of other information. The output of the predictive models provides contextual information in the form of summary statistics so that users can understand how similar their wood jams of interest are to wood jams used to train the model. Cases that fall generally within the range of data of jams used to train the model are more likely to be correctly predicted than those that are effectively unlike the existing database. The model is expected to work well on wood jams that are similar to wood jams and environmental conditions represented by the data on which the model is trained. As more users in more regions submit data to the database, the model will likely become more accurate in more cases. Users can also browse the public database and view summary statistics to gain a better understanding of the data used to train the model. This context-awareness allows for utilization of both the prediction of wood jam dynamics given by the model and users' own site-specific knowledge to guide management decisions. The model is therefore only a component of a broader analysis to determine stability that should take into account site-specific variables that the model does not capture.

The WooDDAM predictive models and database will be overseen into the future as long as it remains a useful tool for the managerial, practitioner, and research communities. Because the training dataset will be regularly updated with new data, the statistical methods driving the model or the database itself may change to facilitate improvements to the tool.

Data collection for the jam stability and/or dynamics analysis requires completion of simple field measurements during base or low flow conditions. Data are then entered into the statistical model to obtain predictions of stability and dynamics for each surveyed logjam. Users can contribute to the database used to run the model by performing resurveys, or they can utilize the database for other investigations. See Scott et al. (2019) for a comprehensive description of methods to collect data and utilize the database and model.

2.2. Level II Analysis for Logjams Using Decision Bands

The decision bands described here were first presented in Wohl et al. (2016, fig. 5). These bands were developed by a group of civil engineers, fish ecologists, geomorphologists, and recreational boaters, along with staff from the City of Fort Collins and Boulder County (both in Colorado) stormwater utilities and natural areas programs. The bands are designed to assist field-based evaluation of logjams at a more detailed level than the Level I checklists. The decision bands can be used instead of or in conjunction with the Level II jam stability analysis. Individual decision bands focus on aquatic and riparian communities, recreational users, and inhabitants and infrastructure. Suggested weights assigned to each row below the band can be altered by the user. These weights can be used to create a weighted score for comparing different sources of hazards. Use of the decision bands can be adjusted to reflect the characteristics of a site: some sites will have minimal recreational use or potential, for example, or no floodplain habitat.

The band for assessing hazards to aquatic ecosystems associated with wood removal is presented in figure 25A. The first row of this band is designed to help the user determine whether habitat important to sustain fish or aquatic invertebrates, such as deep pools, is likely to decline as a result of jam removal (= high score) or is unlikely to be reduced by jam removal (= low score). The second row (contributions of jam to creating diverse habitats) assesses whether the jam creates multiple types of habitat, such as pool scour and overhead cover for fish, diverse coarse and fine substrates for macroinvertebrates, or backwater pools for fish and macroinvertebrates. If so, removal of the jam results in a high likelihood of reduced habitat diversity. Diverse aquatic habitat is composed primarily of a diversity of flow depth, flow velocity, bed substrate, and complex physical structure created by the jam. Importance of jam-associated habitat includes considerations such as abundance of jams at the reach scale and the need for this habitat by key species. Pools are commonly critical habitat for many fish species, for example, so if jams create the only pool habitat for fish within a particular stream segment, then the importance is high and the likelihood of reducing habitat by removing jam(s) is also high. If jams create no pools or only very small pools, however, then the importance and the hazard can be rated as low. A jam that creates critical habitat for an at-risk or desired species also equates to a higher score for the importance of habitat.

The final row, persistence, assesses whether the jam-related habitat is likely to persist for a short period (< 5 years) or to persist for longer time periods (5-100+ years). If a jam is likely to persist for a long period, then the hazards for aquatic habitat posed by removing it are high.

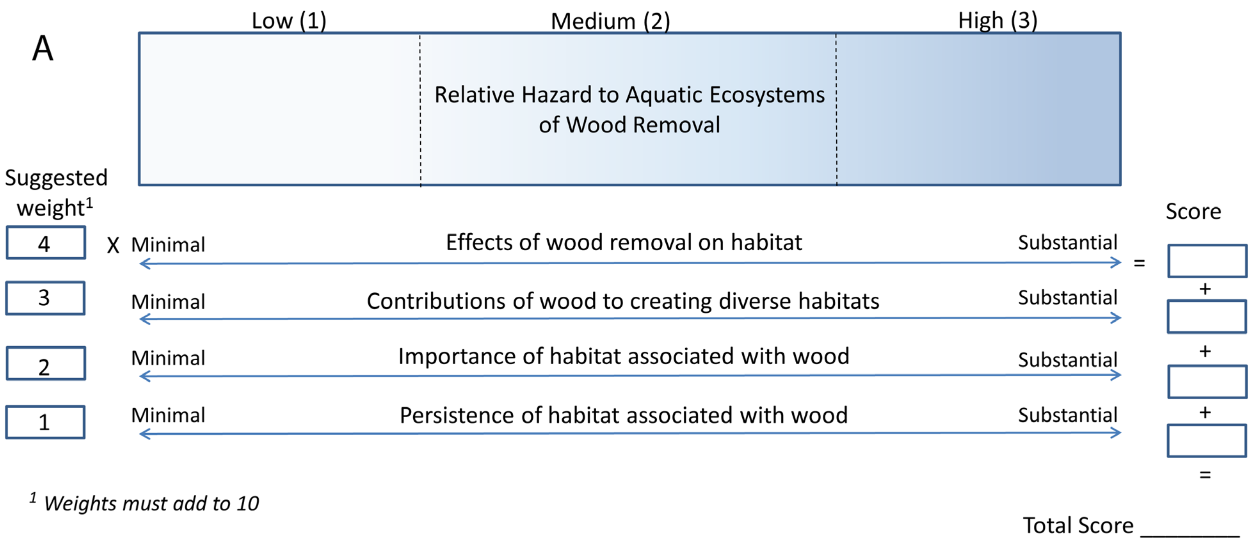
In figure 25B, the basic characteristics of the features (effects of jam removal, contributions, etc.) are the same as described for figure 25A, except that they are applied to riparian organisms. Where a large jam spans the channel and the floodplain, decision bands (A) and (B) should be used together to assess the jam.

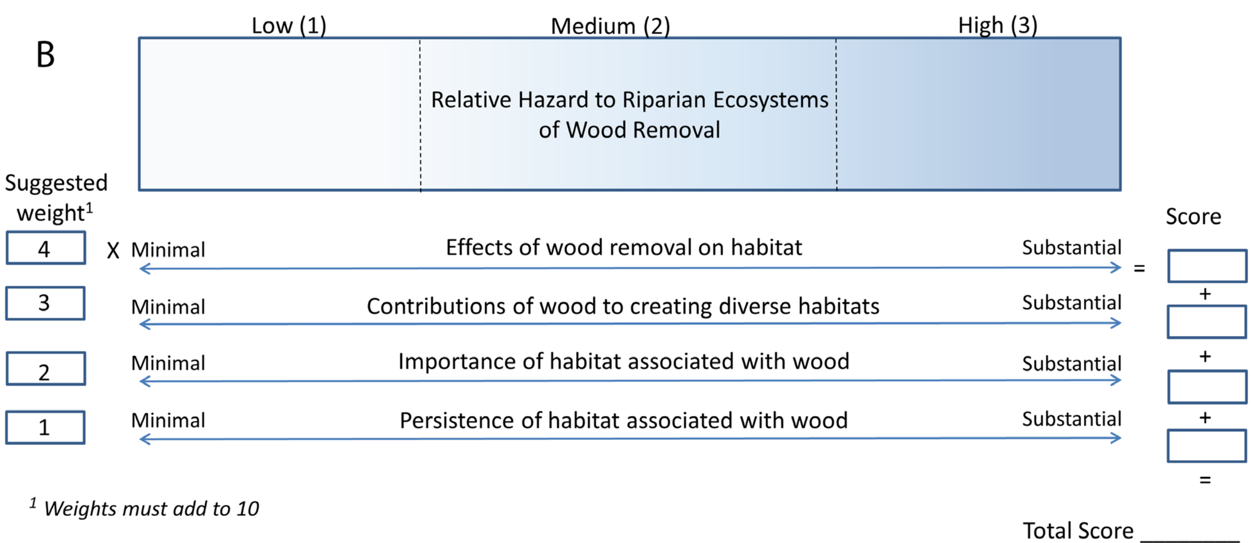
Figures 25C and 25D present decision bands that can be used to assess the potential recreation hazard from jams. Recreation hazard is differentiated with respect to the hazard that a jam poses to a user based on jam characteristics such as placement, size, and type, regardless of user or reach characteristics (fig. 25C) and the hazard to users based on user or reach characteristics and regardless of jam characteristics (fig. 25D). Recognizing and separating recreation hazards in this manner allows flexibility to retain jams that score as potentially hazardous in locations where characteristics of the stream segment and the user reduce the hazard to manageable levels (high hazard in 25C but low hazard in 25D).

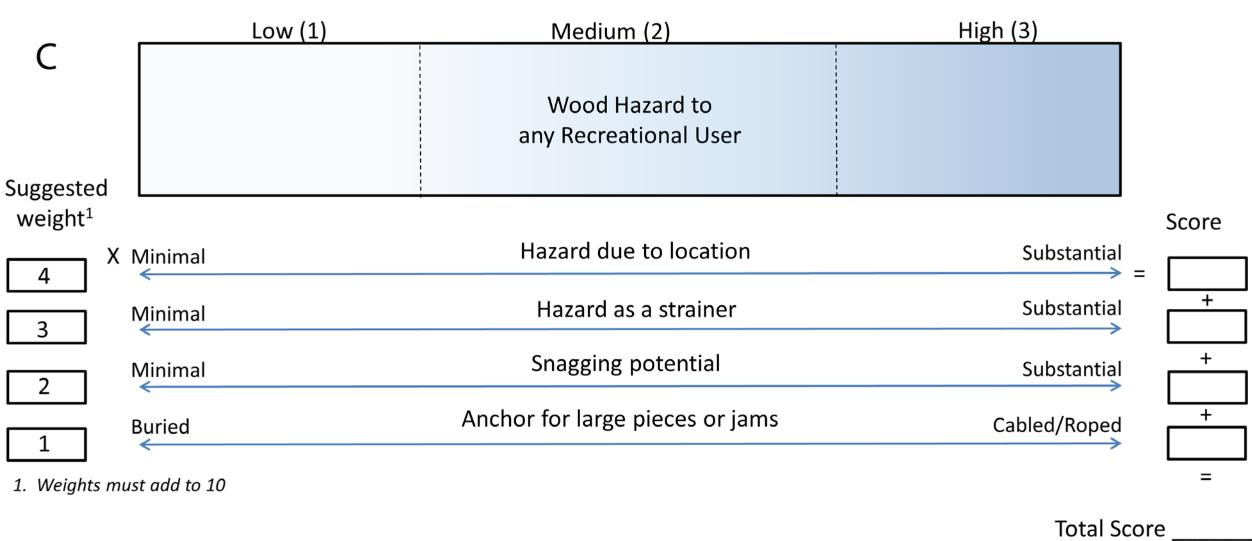
For jam characteristics (fig. 25C), a jam in swift current or on the outside of a bend creates more substantial hazards than a jam in zones of low velocity or on the floodplain. The orientation and shape of the jam, as these influence the ability of the jam to act as a strainer or to snag floating objects, substantially influence hazard. Anchoring with cables or ropes creates high hazards for recreational users if the cables or ropes are ever exposed. For user or stream segment characteristics (fig. 25D), hazard increases in stream segments heavily accessed by less skilled users relative to stream segments lightly accessed by skilled users. A jam creates greater hazards in stream segments that are steeper and swifter, with confined banks or valley walls, than in low-gradient segments with low velocity. Ability and skill to see and avoid a jam greatly reduce hazards, so the upstream visibility of a jam is an important factor. Ability to avoid a jam also depends on the ease with which recreational users can avoid it. The same jam may be difficult for someone floating in an inner tube to avoid but easy for a kayaker. For any recreational user, regardless of skill, prior knowledge of a jam greatly reduces the hazard, while the sudden appearance of a new jam increases hazard.

The potential costs and hazard of negative consequences to property and infrastructure associated with jam retention and placement also depend on site-specific channel and floodplain characteristics (fig. 25E). Encroachment by human development and infrastructure tend to increase potential costs associated with floodplain inundation and stream channel changes. Local encroachment in the vicinity of a jam is thus a fundamental consideration. Assessing hazard also requires an understanding of the physical factors that control flood conveyance. The local extent of channel blockage, flow obstruction, and reduced cross-sectional area that may result from jam retention should be considered. Flow conveyance is also proportional to flow resistance, as expressed by the widely used coefficient for frictional resistance, 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 caused by a jam.

A jam that presents little hazard in its current location may nevertheless produce much greater hazards if pieces of wood or the entire jam are transported downstream to a location


A
Low (1)
Medium (2)
High (3)
Relative Hazard to Aquatic Ecosystems of Wood Removal
Suggested weight[1]
Score
4 X Minimal — Effects of wood removal on habitat — Substantial =
3 Minimal — Contributions of wood to creating diverse habitats — Substantial +
2 Minimal — Importance of habitat associated with wood — Substantial +
1 Minimal — Persistence of habitat associated with wood — Substantial +
=
[1] Weights must add to 10
Total Score ________


B
Low (1)
Medium (2)
High (3)
Relative Hazard to Riparian Ecosystems of Wood Removal
Suggested weight[1]
Score
4 X Minimal — Effects of wood removal on habitat — Substantial =
3 Minimal — Contributions of wood to creating diverse habitats — Substantial +
2 Minimal — Importance of habitat associated with wood — Substantial +
1 Minimal — Persistence of habitat associated with wood — Substantial +
=
[1] Weights must add to 10
Total Score ________


C
Low (1)
Medium (2)
High (3)
Wood Hazard to any Recreational User
Suggested weight[1]
Score
4 X Minimal — Hazard due to location — Substantial =
3 Minimal — Hazard as a strainer — Substantial +
2 Minimal — Snagging potential — Substantial +
1 Buried — Anchor for large pieces or jams — Cabled/Roped +
=
1. Weights must add to 10
Total Score _______

D

Low (1)	Medium (2)	High (3)
	Hazard to Recreational Users from Wood Presence	

Suggested weight[1]		Left	Criterion	Right		Score
4	X	Minimal	Access	Substantial	=	
3		Minimal	Hazard due to reach characteristics	Substantial		+
2		Substantial	User ability to avoid wood	Minimal		+
1		Substantial	User prior knowledge of wood	Minimal		+
						=

1. Weights must add to 10

Total Score _______

E

Low (1)	Medium (2)	High (3)
	Hazard of Water Surface Rise Relative to Adjacent Floodplain	

Suggested weight[1]		Left	Criterion	Right		Score
4	X	Minimal	Adjacent land use/encroachment	Substantial	=	
3		Minimal	Size/area obstructed	Substantial		+
2		Minimal	Increase in roughness	Substantial		+
1		Minimal	Raises water surface elevations above regulatory mandates	Substantial		+
						=

1. Weights must add to 10

Total Score _______

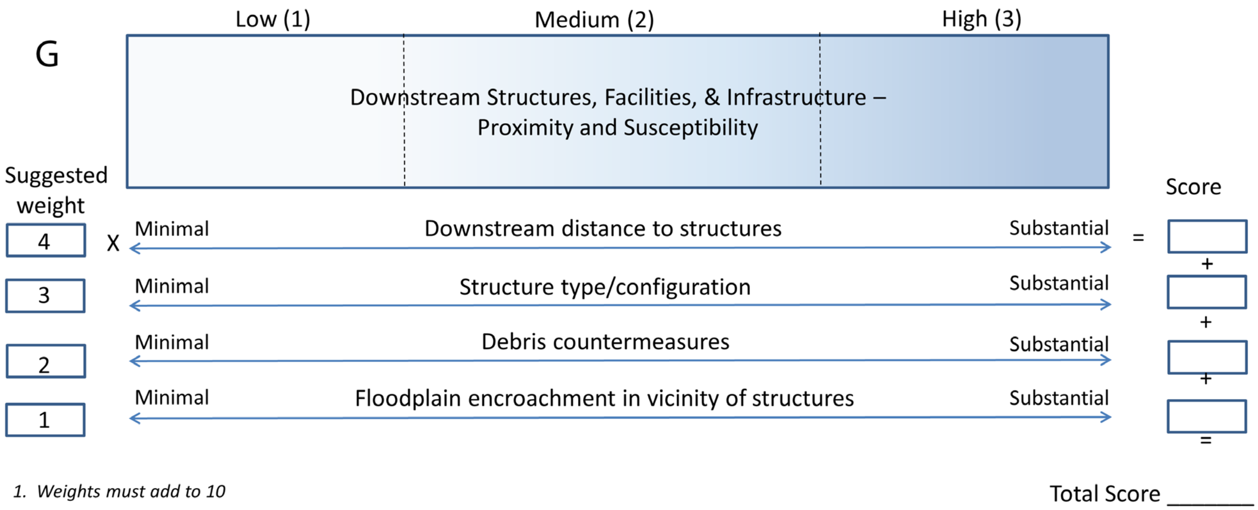
F

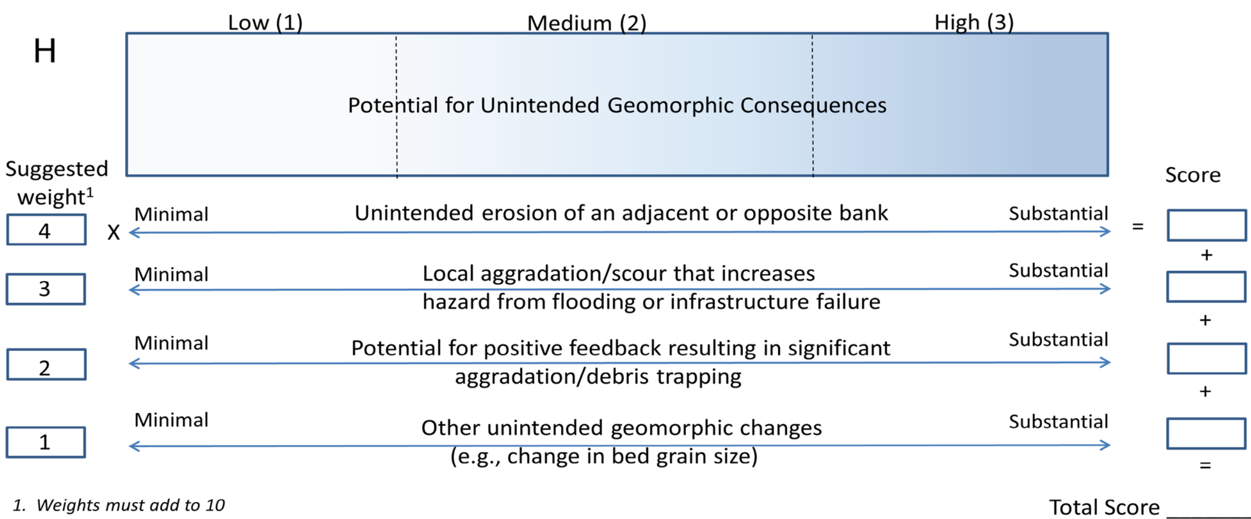
Low (1)	Medium (2)	High (3)
	Wood Stability and Potential Mobility	

Suggested weight		Left	Criterion	Right		Score
4	X	Minimal	Size relative to channel, orientation, & interlocking	Substantial	=	
3		Minimal	Computed force balance	Substantial		+
2		Minimal	Location: floodplain vs. channel	Substantial		+
1		Minimal	Potential for immobilization by floodplain trees	Substantial		+
						=

1. Weights must add to 10

Total Score _______


G
Low (1)
Medium (2)
High (3)
Downstream Structures, Facilities, & Infrastructure –
Proximity and Susceptibility
Suggested weight
Score
4
X
Minimal
Downstream distance to structures
Substantial
=
+
3
Minimal
Structure type/configuration
Substantial
+
2
Minimal
Debris countermeasures
Substantial
+
1
Minimal
Floodplain encroachment in vicinity of structures
Substantial
=
1. Weights must add to 10
Total Score _______


H
Low (1)
Medium (2)
High (3)
Potential for Unintended Geomorphic Consequences
Suggested weight[1]
Score
4
X
Minimal
Unintended erosion of an adjacent or opposite bank
Substantial
=
+
3
Minimal
Local aggradation/scour that increases hazard from flooding or infrastructure failure
Substantial
+
2
Minimal
Potential for positive feedback resulting in significant aggradation/debris trapping
Substantial
+
1
Minimal
Other unintended geomorphic changes (e.g., change in bed grain size)
Substantial
=
1. Weights must add to 10
Total Score _______

Overall Decision Band Score Sheet

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

1. A weighted average could also be applied

Total Score ________

Figure 25a-i. Decision bands for assessing the relative hazards to different components of a stream corridor associated with wood removal or retention. Individual bands relate to (A) aquatic or in-channel ecosystems, (B) riparian or floodplain ecosystems, (C, D) recreational users, (E) water surface rise relative to adjacent floodplain, (F) wood stability and potential mobility, (G) downstream structures, facilities, and infrastructure, (H) potential for unintended geomorphic consequences, and (I) a cumulative assessment for property, infrastructure, and public safety. For each band, the suggested weight in the box at the left in each row is multiplied by one of the numbers at the top of the band (1, 2, or 3) to create a score for that row, and these scores are then summed to create a total score for that decision band. Other weightings are also possible, depending on specific objectives and stakeholder input.

where they could exacerbate flooding and/or threaten property and infrastructure (fig. 25F). This decision band is intended to address the likelihood of a jam being mobilized and transported downstream without reference to specific downstream conditions (addressed in the decision band in figure 25G). The jam characteristics that contribute to relative stability are discussed in section C.3.

Once large wood pieces or a jam is mobilized downstream, its potential for creating hazards depends on the types of hydraulic structures and infrastructure it encounters. The greater the distance large wood must be transported before encountering vulnerable structures, the more likely the wood is to be immobilized and thus provide opportunities for re-stabilization or removal. The inherent susceptibility of hydraulic structures such as bridges or culverts to loss of conveyance, damage, and failure is highly variable (FHWA 2005). Factors that affect a structure's capacity to safely convey large wood include opening width(s) and height(s) relative to wood size, pier spacing, shape, and orientation, backwater effects, the presence of debris countermeasures (Schmocker and Hager 2011), and the transition from the natural channel to the structure (abrupt constrictions are more likely to accumulate LW).

There are many types of structural and nonstructural debris countermeasures for bridges and culverts (FHWA 2005; Schmocker and Weitbrecht 2013). Assessing structure vulnerability and the potential effectiveness of large wood countermeasures requires extensive knowledge of both structures and hydraulic engineering. As described above, encroachment by human development, infrastructure, and other valuable assets tends to increase potential costs associated with floodplain inundation and river channel changes. The decision band in figure 25E focuses on floodplain land use and encroachment in the immediate vicinity of a jam without consideration of potential downstream effects. Accordingly, the decision band in figure 25F requires an evaluation of the potential consequences of reduced flood conveyance and damage to structures if large wood is transported to vulnerable downstream locations.

Jams are widely recognized by river scientists for their capacity to create habitat diversity and channel changes that benefit aquatic ecosystems. However, dynamic channel adjustments are commonly socially unacceptable in stream corridors that are highly constrained by human encroachment. In such situations, it is important to evaluate the potential for a jam to produce channel adjustments that conflict with adjacent property values and floodplain management objectives (fig. 25H).

Potential responses to the presence of a jam 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 a jam can be difficult to predict, even for experienced fluvial geomorphologists and river engineers. Therefore, evaluations of potential geomorphic consequences are best performed by interdisciplinary teams of experts with experience in managing large wood and jams. The decision band in figure 25I integrates the results of decision bands (A) through (H) into an overall assessment score for relative hazard of retaining or removing a jam. Decision band scores consistently in the medium-high range of decision bands (A) and (B) (hazards to aquatic and riparian ecosystems from jam removal) and in the low range of decision bands (C) to (H) (hazards to recreational users, property, and infrastructure from wood presence) suggest options of no action, monitoring, stabilization, or signs (fig. 20A).

In contrast, scores in the low range of decision bands (A) and (B) and the medium-high range of the other decision bands suggest options of remedial pruning, closing the reach to recreational use, or moving a jam. The overall decision band score sheet can be used to compare relative hazards among ecosystems, recreational use, and public infrastructure and safety. Other weightings are possible depending on the priority placed on each, such as in forest wilderness areas where effects on ecosystems may have high priority vs. developed recreational areas where effects on infrastructure and property are paramount. The score sheet can also be used to compare hazards from jams among different stream segments or specific jam locations, to assist in the prioritization and cost-benefit evaluations of restoration or management efforts.

2.3. Level II Analysis for Beaver Reintroduction Using BRAT

BRAT, the Beaver Restoration Assessment Tool, is an ArcGIS-based decision support and planning tool designed to assist managers and researchers in evaluating the potential suitability of river segments for beaver reintroduction (http://brat.riverscapes.xyz/). BRAT is fully described in Macfarlane et al. (2014) and our intent here is to briefly summarize the tool. BRAT calculates the capacity of beaver dams per 300 meter stretch of stream based on existing vegetation, availability of suitable dam building material, land cover and use, stream gradient, bankfull discharge, and baseflow discharge (MacFarlane et al. 2017). The tool thus requires a drainage network layer such as that available through the National Hydrography Dataset (https://nhd.usgs.gov/), hydrography data for the drainage network layer, vegetation-type raster data (such as can be obtained from LANDFIRE, https://www.landfire.gov/), a digital elevation model (such as can be obtained from the U.S. Geological Survey (https://nationalmap.gov/elevation.html), and base and high flow information throughout the drainage network (such as can be obtained from the U.S. Geological Survey's StreamStats program, https://water.usgs.gov/osw/streamstats/), or national stream flow statistics (https://water.usgs.gov/osw/programs/nss/pubs.html). BRAT classifies beaver dam capacity per stream segment as either none (0 dams), rare (0 – 1 dams), occasional (1 – 5 dams), frequent (5 – 15 dams), or pervasive (15 – 40 dams). Matlab files for calculating the beaver dam capacity along a river segment are available through the BRAT website link above.

As with the GIS analysis of stream gradient for logjams, application of BRAT thus requires GIS analyses using existing data layers. The resulting map of beaver dam capacity under existing conditions can be used to estimate the carrying capacity for a river or watershed and to target for management river segments with greater potential carrying capacity. The BRAT website includes examples of output maps for the river network in the Escalante River watershed in Utah and for the entire State of Utah.

D. Field Examples for Application

The USDA Forest Service divides National Forests and Grasslands into nine regions (fig. 26). In the sections that follow, the Rocky Mountain West equates to Regions 1, 2, and 4. The Southeast equates to Region 8; the Northeast to Region 9; Southern California to Region 5; and the Southwest to Region 3. The Pacific Northwest equates to Region 6. We do not include field examples from Alaska (Region 10). For each of these geographic areas, we briefly describe some of the specific characteristics of stream corridors in that area which influence the stability of logjams and beaver dams (e.g., flow regime and wildfire regime) and describe one or two field sites that we assessed using the procedure for evaluating reintroduction of logjams or beaver dams, as outlined in the previous section. Our primary intent in these field examples is to provide actual examples of sites where logjams or beaver dams are not present but could be introduced or managed for. For each region, we provide some background on the characteristics that influence wood in rivers, then provide specific field examples.

Our intent is these field examples is to briefly discuss specific field sites, representing diverse regions of the United States in which logjams or beaver dams could be reintroduced or managed for.

1. Rocky Mountain West

The Rocky Mountain West is characterized by strong gradients in climate, vegetation, and wildfire regime in relation to elevation. With the exception of some National Grasslands, most of the National Forest System lands are in the mountainous portions of the Rocky Mountain West. However, even within a particular National Forest unit or mountain range, the highest elevation watersheds can have very different characteristics than watersheds at the base of the mountains.

Mountain ranges in the Rocky Mountain West can include four primary vegetation zones: alpine tundra, subalpine forest, montane forest, and chaparral woodlands (Bailey 1995). These vegetation zones correspond to differences in the abundance and size of LW, the availability of suitable beaver habitat, and the disturbance regime of the stream corridors.

Alpine tundra is characterized by herbaceous plants and dwarf woody species such as willows (*Salix* spp.). Logjams do not occur in streams of the alpine zone but beaver dams can be present, although they are relatively rare because of typically very small stream size, limited woody vegetation, and very cold winters. Stream flow comes predominantly from snowmelt runoff and groundwater inputs.

The particular tree species present in subalpine forests varies across the Rocky Mountain West but typically include spruce (*Picea* spp.), fir (*Abies* spp.), Douglas-fir (*Pseudotsuga menziesii*), and pine (*Pinus* spp.). Relative to lower-elevation forests, subalpine forests commonly have longer recurrence intervals for wildfire and are likely to include streams dominated by snowmelt runoff. Logjams and beaver dams are likely to be present along streams in the subalpine zone. In some portions of the Rocky Mountain West, blowdowns associated with extreme winds can be an important source of wood recruitment to channels, as can hillslope instability in the form of landslides or debris flows.

Montane forests are likely to be dominated by pines and to have shorter recurrence intervals for wildfires relative to subalpine forests, with a mixed fire regime of more frequent ground fires and less frequent stand-killing fires. Stand-killing fires, in particular, are likely to be associated with flash floods and debris flows during the first year or two after the fire. Wildfires can increase LW recruitment to streams during succeeding decades as standing dead trees gradually fall directly into or are transported from ephemeral channels into perennial streams, but intense fires can also completely burn downed wood and reduce channel or floodplain wood loads (Passovoy and Fulé 2006). Montane watersheds are also more likely to be influenced by rainfall runoff, as well as by snowmelt. Logjams and beaver dams are likely to be present along streams in the montane zone.

Chaparral woodlands at the base of a mountain range can include species such as pinyon pine (*Pinus* spp.) and junipers (*Juniperus* spp.), which grow in stands with mixed deciduous species such as oak (*Quercus* spp.) and a grassy understory. These woodlands typically have relatively frequent wildfires and stream flow is strongly influenced by rainfall runoff. Logjams and beaver dams can be present in streams of the chaparral zone.

Although ephemeral and intermittent streams can be present at any elevation in mountain ranges of the Rocky Mountain West, channels originating at lower elevations are more likely to be ephemeral or intermittent. Ephemeral streams have less abundant and diverse aquatic communities than perennial or intermittent streams, but ephemeral streams can support macroinvertebrate communities (Boulton et al. 1992; Jones et al. 1995) for which LW may be important. Intermittent streams can support abundant, diverse, and unique aquatic communities (Bunn et al. 2006). By facilitating hyporheic exchange, logjams and beaver dams can enhance the ability of ephemeral and intermittent streams to support aquatic and riparian organisms and beaver dams, in particular, can maintain perennial or intermittent flow in what otherwise might be an ephemeral channel (Albert and Trimble 2000; Gibson and Olden 2014; Pollock et al. 2014).

Streams influenced by rainfall runoff can be relatively flashy, depending on the type of rainfall. Some regions in the Rocky Mountain West have strongly seasonal rainfall patterns, such as late winter rain-on-snow events in the northwestern Rockies and summer convective storms in the Middle and Southern Rockies. The magnitude, frequency, and duration of both snowmelt and rainfall runoff exert an important influence on logjam stability. Flashy rainfall runoff can create short duration, high magnitude peak flows that can destabilize jams, but diurnal snowmelt fluctuations over a period of 2 or 3 weeks can also very effectively destabilize jams. Observing jams during snowmelt runoff, for example, we have seen rising flows that lift and expand a jam every night, which can float LW pieces or the entire jam above obstructions that anchor the jam, and reduce internal friction between LW pieces in the jam.

Streams from the upper limits of the subalpine zone down to the chaparral woodlands historically had much greater wood loads and beaver populations than are now present. Extensive timber harvest and floating of cut logs down streams reduced naturally occurring instream LW and logjams and, even where these activities have not occurred for more than a century, wood loads remain lower than those in stream segments of otherwise comparable stream networks with a history of only natural disturbance (Livers and Wohl 2016; Livers et al. 2018). Beaver populations recovered slightly following nearly complete extirpation by the mid-19th century (Frémont 1845; Mills 1913), but populations remain much lower than they were prior to commercial fur trapping.

The field examples for the Rocky Mountain West come from the watershed of the South Fork Cache la Poudre River in Roosevelt National Forest of the Colorado Front Range.

Box 1: Roosevelt National Forest, Colorado (logjam, logjam dynamics analysis)

Site: South Fork of the Cache la Poudre River
Location: 40.68399 °N, 105.44645 °W
Elevation: 2,006 m (6,600 feet)
Drainage area: 289 km^2 (104 mi^2)
Channel characteristics: The South Fork is a perennial river dominated by seasonal snowmelt runoff, although flash floods generated by convective rainfall can occur, most recently in September 2013. At this site the river is narrowly confined within a bedrock canyon, with a bankfull channel width of 11 m and ~ 2 percent stream gradient.
Rationale: A logjam that partially spanned the channel formed here around a ramped piece on the right bank of the channel. Kayakers cut out this jam and much of the other instream LW along this segment of the river in 2009 and the jam has not reformed. This river had log floating during the late 19th century and was wood-poor relative to undisturbed channels in the region even before the vandalism of instream LW. The site is roadless and has no infrastructure downstream to the junction with the mainstem Cache la Poudre River. The site is thus ideal in many respects for reintroduction of logjams because the potential for damage to infrastructure or property is minimal and the environmental benefits are likely to be substantial. Potential conflicts between wood reintroduction and recreationalists could be avoided through the use of signage upstream of the restoration to notify users of the need to portage around the restoration and education efforts to discourage vandalism of the project.

Figure 1.1. Downstream view of the logjam in 2008. Yellow line indicates bankful channel width.

Figure 1.2. Cross-stream view of the logjam in 2008.

Figure 1.3. After the vandalism of the logjam, 2009.

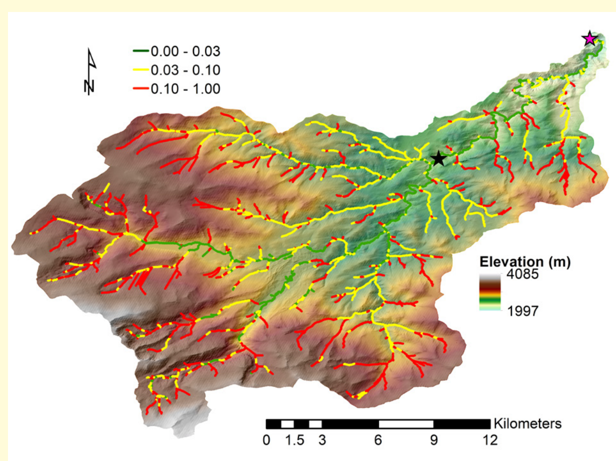


Figure 1.4. Channel gradient map of the South Fork Poudre River basin. The red star indicates the location of the logjam illustrated in figures 1.1-1.3.

Wood jam stability analysis: Between 2008 and 2017, a logjam formed approximately 5 m downstream of this logjam on the left bank. This logjam was surveyed initially in March 2017, then again in September 2017, after high flows due to spring snowmelt. Although many other monitored jams on the South Fork Poudre accumulated wood during that snowmelt, this jam remained unchanged, likely because it does not span the channel, which allows wood transport around the jam. This jam and data describing how it has changed through time can be found in the wood jam dynamics database (https://sites.warnercnr.colostate.edu/woodjam/) under the ID "South Fork Poudre25." This wood jam was measured using a handheld laser rangefinder for channel geometry and took approximately 7 minutes to survey.

Figure 1.5. Logjam surveyed as part of the wood jam dynamics analysis, looking downstream. Notice that although it has an obstruction index of 3 (very low porosity), it only spans a small portion of the channel. This may account for why it did not accumulate wood during the 2017 snowmelt season, while many other channel spanning jams upstream did.

Figure 1.6. Logjam surveyed as part of the wood jam dynamics analysis, looking upstream. Notice that the jam is pinned on a large, likely immobile boulder. This likely stabilizes the jam and has allowed it to accumulate enough material to have a low porosity.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

Box 2: Roosevelt National Forest, Colorado (beaver meadow)

Site: South Fork of the Cache la Poudre River
Location: 40.62635 °N, 105.51958 °W
Elevation: 2,407 m (7,920 feet)
Drainage area: 247 km^2 (89 mi^2)
Channel characteristics: The South Fork at this site lies within a wider and lower gradient portion of the valley. Stream gradient is ~ 1 percent, bankfull channel width is 15 m, and valley-bottom width averages 100 m.
Rationale: Dark, organic-rich soil horizons in cutbanks along the stream and subtle, vegetated berms that are likely former beaver dams suggest that this segment of the valley was formerly a beaver meadow. Limited beaver activity here within the past decade indicates that habitat is potentially suitable for beaver, although the extent of riparian willows is limited, which may partly reflect livestock grazing. Fencing the riparian zone to limit grazing by wild ungulates and domestic animals could help to protect willow communities and allow beaver to fully recolonize the site. An unpaved road along the left margin of the valley is a few meters above the channel, limiting the likelihood of inundation by backwaters behind beaver dams. If inundation did threaten the road, a structure such as a pond-leveler could be used to limit the water-surface elevation near the road.

Figure 2.1. A downstream view of the channel and valley bottom in April 2013.

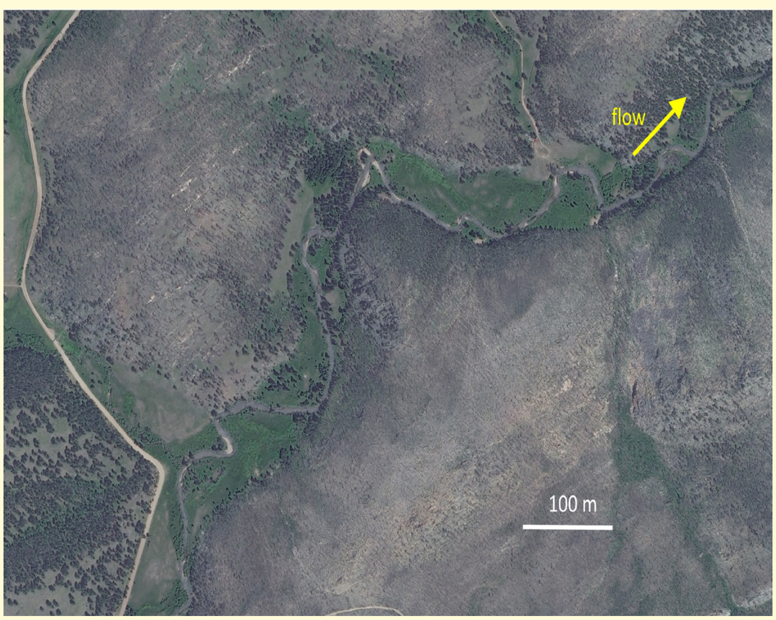


Figure 2.2. 2013 aerial view of the former beaver meadow along the South Fork Poudre River, with white line at left indicating an unpaved road. Downstream, the channel becomes increasingly confined within a bedrock canyon. Image courtesy of Digital Globe.

Figure 2.3. A beaver dam across the channel in October 2012.

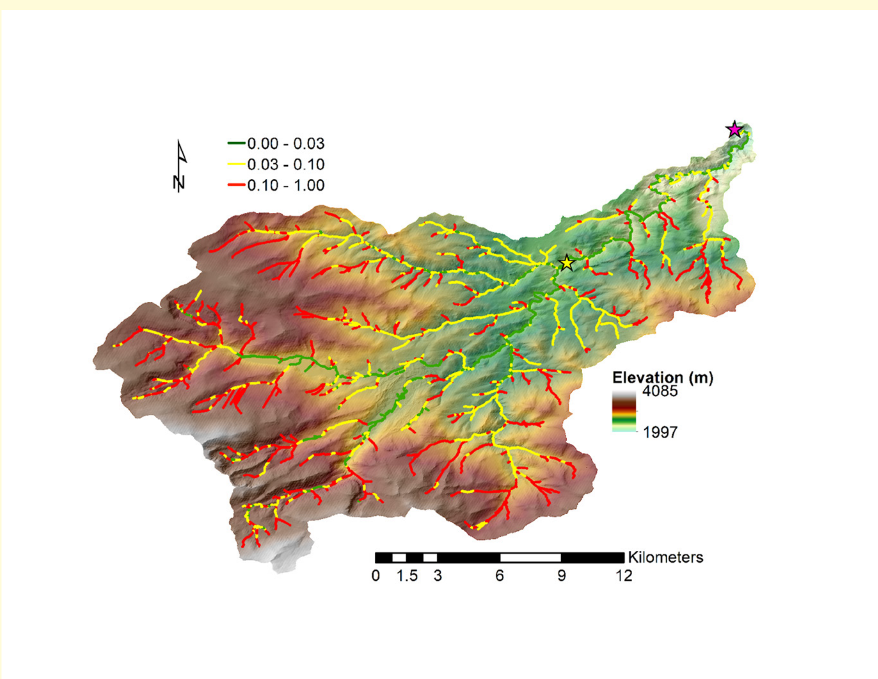


Figure 2.4. Channel gradient map of the South Fork Poudre River watershed. Yellow star indicates the location of the beaver meadow.

Recommendation: An appropriate site at which to reintroduce beavers or protect existing beavers.

2. Southeast

Region 8, the Southern Region of the USDA Forest Service, includes 16 National Forest, Grassland, and recreational units that span the diversity from Virginia south to Florida and Puerto Rico and west to Texas. Some of these units include relatively steep terrain (e.g., El Yunque National Forest in Puerto Rico or Cherokee National Forest in Tennessee), but others are primarily in low-relief terrain, such as the National Forest lands in Alabama.

Mean annual precipitation varies from 430 cm (170 inches) at the highest elevations in Puerto Rico, to 180 cm (70 inches) in the core of this region (Alabama, Mississippi, Louisiana, and Tennessee), to as little as 30 cm (12 inches) in western Texas. The type of rainfall varies substantially across the region. The eastern fringe of Region 8 can experience intense rainfall from dissipating hurricanes, but these storms rarely extend inland beyond the coastal states. All parts of the region can experience convective rainfall associated with relatively localized thunderstorms, as well as more widespread rainfall generated by other types of meteorological systems. The dominance of rainfall-runoff, along with the potential for convective storms and dissipating hurricanes, creates relatively flashy stream flow and high transport capacity for large wood.

Forests in the Southeast commonly include coniferous and deciduous species, with distinct zonation based on elevation and relative soil moisture. Most of these forest lands have experienced timber harvest, including clearcutting, and the legacy of this activity persists in areas that are currently managed as wilderness areas. Consequently, logjam and beaver reintroduction may be appropriate even for areas designated as wilderness. The field example for the Southeast comes from the Little Frog Wilderness in the Cherokee National Forest of Tennessee, which experienced clearcutting prior to wilderness designation in 1986.

Wildfires can occur in the southeastern region, particularly in the drier, western portions, but the primary disturbance to riparian corridors is likely to be flooding or flooding and blowdowns associated with dissipating tropical storms (Phillips and Park 2009). Despite the relatively high precipitation in much of this region, headwater channels can be ephemeral or intermittent and, as in channels of the Rocky Mountain West, the obstructions formed by logjams and beaver dams can be especially important in facilitating hyporheic exchange and greater base flow in channel segments downstream from the jam or dam. Instream LW is particularly important in providing more stable substrate for macroinvertebrates in lowland, sand-bed channels in the Southeast (Wallace and Benke 1984) and much of the work demonstrating the importance of floodplain LW to diverse organisms comes from the Southeast (e.g., Braccia and Batzer 2001). Logjams were likely historically present throughout the southeastern region, including channels in the tropical forest of Puerto Rico (Covich et al. 1991) and the drylands of western Texas (Curran 2010; Phillips 2012). Some of the most vivid historical descriptions of enormous amounts of wood in streams at the time of first European exploration come from the Southeast. An 1818 assessment of Georgia's Oconee River, for example, described the river as "very much infested with logs" (Wohl 2014). Beaver were also likely historically present on mainland channels at all elevations, even in semiarid regions at the western end of this region, as long as at least a forested riparian corridor was present. The only portion of the Southeast that likely did not have beaver historically was the southern half of Florida (Pollock et al. 2017)

The field example for the Southeast comes from the Little Frog Wilderness of the Cherokee National Forest in Tennessee.

Box 3: Cherokee National Forest, Tennessee (logjam)

Site: Rock Creek
Location: 35.07206 °N, 84.45884 °W
Elevation: 413 m (1,360 feet)
Drainage area: 8.9 km^2 (3.2 mi^2)
Channel characteristics: Rock Creek lies within the Little Frog Wilderness in the Cherokee National Forest of Tennessee. The Wilderness is covered in second-growth forest. Logging during the late 1800s was restricted to accessible areas and usually involved selective cutting of high-value lumber such as black cherry (*Prunus serotina*), black walnut (*Juglans nigra*), ash (*Fraxinus* spp.), and yellow poplar (*Liriodendron tulipifera*). Logging operations relied heavily on transport of cut logs in streams, resulting in widespread removal of naturally occurring instream large wood, simplification of channel geometry, and reduction of channel-floodplain connectivity to facilitate downstream movement of logs. Commercial, mechanized logging during the early 20th century involved clearcutting and an increase in fire frequency (Villarrubia 1982; Harden 2004). Consequently, even areas currently managed as wilderness are likely to be depleted in very large, old trees and instream large wood as a result of the legacy of past land use. The area has a warm-temperate rain forest of mixed coniferous and deciduous species. Mean annual precipitation varies from 140 cm at low elevations to 230 cm at higher elevations. Abundant rainfall and well-developed soils support high primary productivity, facilitating continuing wood recruitment to streams. Although this site has a steep valley wall in places, a floodplain is present. Bankfull channel width is ~ 6-10 m and stream gradient is ~ 2 percent. Heavy and prolonged rainfall during the winter and early spring can cause periods of widespread flooding and local flash floods.

Figure 3.1. Upstream view of Rock Creek.

Rationale: Potential transport capacity for instream wood is high in streams such as Rock Creek and natural formation and persistence of logjams may be limited by smaller wood piece size and lower wood abundance as a result of historic timber harvest. Adding wood, particularly large, stable pieces, can help initiate logjams. Logjams may also be more persistent on the forested floodplain. The site is roadless and has no infrastructure downstream to the junction with the Ocoee River; the site is ideal in many respects for reintroduction of logjams because the potential for damage to infrastructure or property is minimal and the environmental benefits are likely to be substantial.

Figure 3.2. Downstream view of Rock Creek showing some wood accumulation at river left.

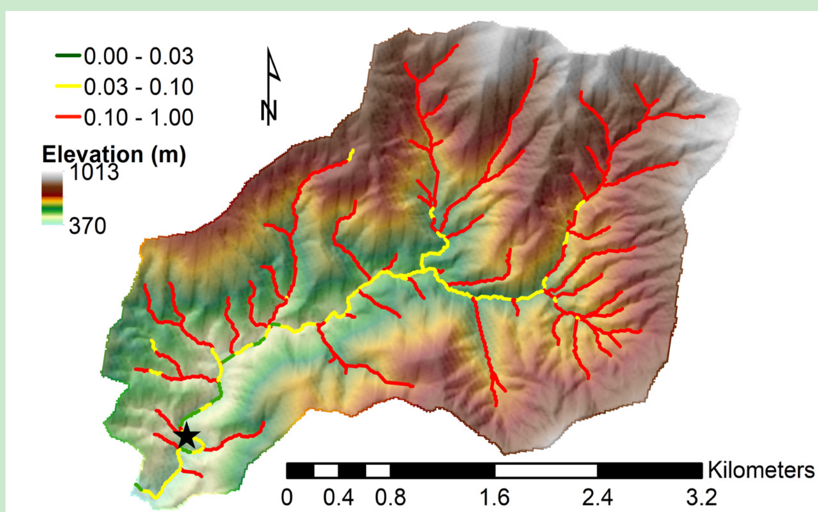


Figure 3.3. Channel gradient map of the Rock Creek watershed. Star indicates the location in figures 3.1 and 3.2.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

3. Northeast

Region 9, the Eastern Region of the USDA Forest Service, includes 15 National Forest and Grassland units. Of these, two-thirds (White Mountain, Green Mountain-Finger Lakes, Allegheny, Huron-Manistee, Midewin, Haiwatha, Ottawa, Chequamegon-Nicolet, Superior, and Chippewa) lie within the area covered by the Laurentide Ice Sheet during the Pleistocene Epoch of geological time. These National Forest units can include exposures of underlying bedrock as well as Quaternary-age sediments that vary from highly compacted glacial till that behaves similarly to bedrock, to glacial lacustrine deposits that can be clay-rich and create sources of hillslope instability and high suspended sediment yields to stream networks.

The National Forests in the northeastern portion of Region 9 typically include steep terrain of the Green and White Mountains, Alleghenies, and Appalachians. Consequently, climate, biotic communities, and stream geometry can vary substantially with elevation within a single National Forest.

Streams in the Northeast can have high flows during summer as a result of thunderstorms and dissipating hurricanes, and during winter in connection with rain-on-snow precipitation. Moisture enters the Northeast primarily from the Atlantic Ocean, sometimes from a northeasterly direction as part of a large, atmospheric recirculation pattern. Moisture can also reach the Northeast from the Great Lakes. Precipitation in the region varies from about 80 to 130 cm (30 to 50 inches) and the proportion that falls as snow versus rain varies with elevation and latitude.

Forests in the Northeast commonly include coniferous and deciduous species, with distinct zonation based on elevation and relative soil moisture. Two characteristics of the trees present in the Northeast are particularly noteworthy relative to other regions of the United States. First, eastern hemlock (*Tsuga canadensis*) trees are largely being eliminated by the introduced wooly adelgid (*Adelges tsugae*), which causes loss of needles and buds that leads to tree mortality. Eastern hemlock is an evergreen canopy tree that functions as a foundational species across eastern North America (Ellison et al. 2005) and conversion of hemlock forests to forests dominated by deciduous species will likely alter large wood recruitment and retention within streams (e.g., Costigan et al. 2015). Second, deciduous trees in northeastern forests commonly have a different trunk and branch morphology than the cylindrical shape commonly assumed for conifers. The presence of multiple, large-diameter branches that can persist after a tree is recruited into a stream creates a more complex LW piece that can trap other LW pieces and sediment differently than a simple, cylindrical piece of wood (fig. 22).

As in the Southeast, wildfires can occur in the Northeast, but the primary disturbance to riparian corridors is likely to be flooding; flooding and blowdowns associated with dissipating tropical storms in the eastern half of the region (Boose et al. 2001; Donnelly et al. 2001); ice storms in the northern half of the region (Kraft et al. 2002); or blowdowns associated with tornadoes in the western two-thirds of the region (Wohl 2014). Headwater channels can be ephemeral or intermittent and, as in other regions, the obstructions formed by logjams and beaver dams can be especially important in facilitating hyporheic exchange and greater base flow in channel segments downstream from the jam or dam. Instream LW is particularly important in providing more stable substrate for macroinvertebrates in lowland, sand-bed channels. Lowland channels from small tributaries to major rivers such as the Illinois were historically described as having clear water and sandy beds (Wohl 2013d). Centuries of land use and associated increased sediment yields to stream networks have created channels characterized by turbid water with abundant silt on the bed (Bhowmik and Demissie 1989). As in the Southeast, logjams may be particularly important in creating stable substrate for benthic organisms in these streams (Johnson et al. 2003).

Historical descriptions and records of logging and fur harvest indicate that logjams and beaver dams were abundant throughout the region, from headwater channels to large rivers. This history is recorded in names such as the Embarras River in Illinois (embarras is a French-Canadian word for a naturally occurring wood raft; Wohl 2014) and the many "beaver creeks" in the region. The northwestern portion of the region (the western Great Lakes states) experienced extensive clearcutting of the widespread white pine (*Pinus strobus*) forests during circa 1830 to 1920 AD (Wohl 2014). Streams were extensively used for log floating during this period, with cut timber put into headwater channels so narrow that a logger could almost straddle the channel, and enormous rafts of cut logs floated down the largest rivers in the region. Studies of the persistent effects of log floating on streams in the western United States indicate that the streams do not recover the natural spatial heterogeneity of channel boundaries and natural volumes of instream wood for at least a century after log floating ends (Young et al. 1994; Miller 2010; Ruffing et al. 2015), suggesting that streams throughout the Northeast remain impoverished in wood and logjams.

The Northeast region also supported an enormous harvest of beaver furs starting in the 16th century and continuing into the late 18th century (Sandoz 1964; Wohl 2013d). Some of the earliest systematic descriptions of the effects of beaver dams in creating rich alluvial bottomlands come from the Northeast (Morgan 1868; Mills 1913) and early European settlers deliberately sought out beaver meadows for agriculture because of the high soil fertility (Cronon 1983). The contemporary scarcity of beaver dams relative to historical conditions likely represents a fundamental change in the form and function of stream networks throughout the Northeast (Burchsted et al. 2010; Polvi and Wohl 2013).

The two field examples for the Northeast come from the Green Mountain National Forest in Vermont, where we assessed the suitability for reintroducing LW and beaver, respectively.

Box 4: Green Mountain National Forest, Vermont (logjam)

Site: City Stream
Location: 42.87787 °N, 73.09479 °W and 42.88456 °N, 73.11532 °W
Elevation: 578 m (1,900 ft) and 426 m (1,400 ft)
Drainage area: 10 km^2 (3.6 mi^2) and 44 km^2 (15.8 mi^2)
Channel characteristics: At the first location, City Stream is a relatively steep, boulder-bed channel approximately 6-7 m wide and incised 2-3 m below the floodplain. The channel bed has low steps and poorly developed pools. Route 9 occupies much of the historic floodplain, but a pulloff more than 20 m wide at an elevation intermediate between the road and the channel could absorb overbank flow during high discharges. A small logjam that does not span the entire channel could be put into this portion of the channel, but it would likely have to be anchored in place because of high transport capacity during floods. The Route 9 bridge downstream is more than 10 m above the channel and could easily pass mobile LW during floods.

Figure 4.1. Upstream view of City Stream. Route 9 is just visible in the background at upper left.

Figure 4.2. Upstream view of City Stream along Notch Road. Unpaved road is to the right in this view but is not visible.

Less than 1 km downstream, Route 9 leaves the channel for a short distance. Notch Road follows the channel at this site to a private property. This segment of City Stream has a floodplain on river left and a steep hillslope on river right. The slope on the right likely has periodic landslides or debris flows that introduce LW. This process would form logjams and channel avulsion or split flow in the absence of LW removal. The base-flow channel here is approximately 15-20 m wide and the valley bottom is ~ 30 m wide. Channel morphology is a boulder-bed riffle-run to widely spaced low steps. This site is a candidate for emplacement of an anchored logjam that partially spans the channel. The Route 9 bridge downstream is capable of passing mobile LW and only an unpaved road occupies the floodplain. Boulder bars and boulder riprap protect the road from undermining via bank erosion.

Figure 4.3. Downstream view at same location. Route 9 bridge is visible at rear of photo. Steep hillslope on river right can be seen at right.

Figure 4.4. Upstream view of City Stream from an Appalachian Trail foot bridge over the river. This photograph, taken in 2016, shows bank erosion associated with Tropical Storm Irene in 2011.

At the second location, City Stream is ~ 15-20 m wide. The steep, boulder-bed river is incised below the adjacent floodplain, which is ~ 15 m wide on either side of the channel. A logjam partially spanning the channel would increase retention of fine sediment and organic matter, as well as aquatic habitat, but would have to be anchored in place because of high transport capacity during floods.

Figure 4.5. Downstream view from the same footbridge. Floodplain is visible at right, along with a few trees recruited to the channel via bank erosion.

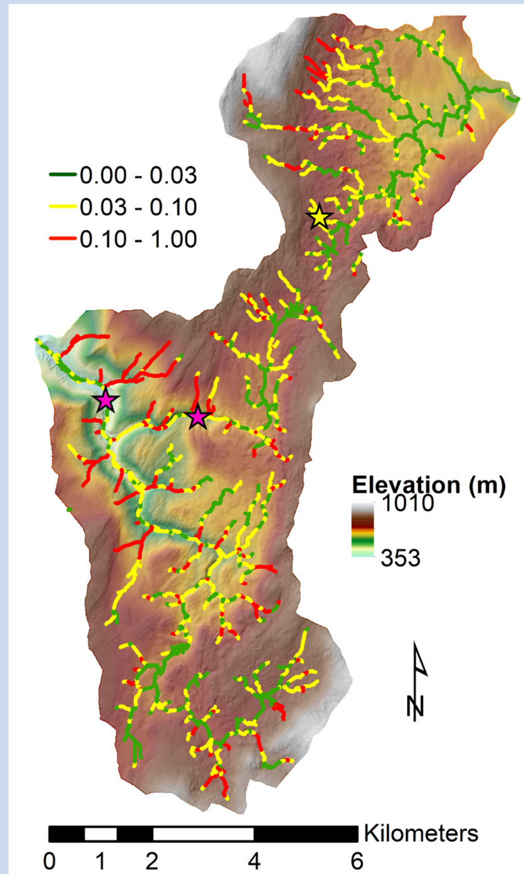


Figure 4.6. Stream gradient map of the City Stream watershed, showing the locations described in the text (pink stars).

Rationale: Green Mountain National Forest includes high elevation but low relief terrain, with numerous smaller channels (typically < 15 m bankfull channel width) that contain abundant logjams that partially or completely span the channel. These jams are formed primarily of small wood pieces and finer organic material such as twigs and leaves, but they nonetheless can promote channel avulsion and formation of split channels. Channels in this portion of the National Forest are highly retentive. As the channels flow from the uplands over steep escarpments and across lower elevations, however, they become relatively steep, narrow channels with much greater transport capacity for LW and narrower and less longitudinally continuous floodplains. This portion of the river network also coincides with more infrastructure in the form of roads, bridges, and private property with residential and commercial development along the valley bottoms. These middle to lower elevation portions of the river network have little or no LW, partly because of transport during high flows such as those associated with hurricanes that affect the entire National Forest (e.g., 1938, 2011) and partly because of active LW removal. However, even these higher energy portions of the river network have the potential for LW reintroduction or retention. The examples illustrated here are portions of the channel beside Route 9 near Woodford, Vermont.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

Box 5: Green Mountain National Forest, Vermont (beaver meadow)

Site: Unnamed tributary of Redfield Brook
Location: 42.90661 °N, 73.05501 °W
Elevation: 699 m (2,300 feet)
Drainage area: 0.3 km^2 (0.1 mi^2)
Channel characteristics: A small channel (bankfull channel width ~ 4 m; gradient ~ 1 percent) with a swale-shaped cross section and abundant particulate organic material and finer sediment over a layer of gravel.
Rationale: The higher elevation, lower relief uplands mentioned in Text Box 5 also have abundant beaver dams that flood extensive areas, commonly in a stair-step configuration of sequential dams and ponds along a channel. Beaver dams were likely historically present in the lower portions of the drainage that have more extensive floodplains, but these areas are now primarily private property with commercial and residential development.

Figure 5.1. 2014 Google Earth view of the series of beaver dams and ponds, with yellow star indicating the site for which latitude and longitude are listed above.

Figure 5.2. Closer view of site (from 2014 imagery, Google Earth).

Figure 5.3. Ground view of the middle pond in the sequence shown in the aerial view (October 2016). Beaver lodge appears as mound at rear center of ponded water.

Recommendation: An appropriate site at which to reintroduce beavers or protect existing beavers.

4. Southern California

The portion of California north of a line between San Francisco and Sacramento is here grouped with the Pacific Northwest region because of similarities of climate and topography. This section deals with the portion of California south of the line, which includes seven National Forests. These lands include low-elevation foothills, mid-elevation montane forests, subalpine forests, and high-elevation alpine environments.

Foothills below ~1,400 m elevation have a Mediterranean climate with mild, wet winters (mean annual precipitation ~60-70 cm) and hot, dry summers. Oak woodland and chaparral shrubland are characteristic of these elevations. Montane forests at elevations of ~1,200 to 2000 m have predominantly winter precipitation (~100-120 cm), including snow. Characteristic tree species include giant sequoia (*Sequoiadendron giganteum*), ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*), sugar pine (*P. lambertiana*), and incense-cedar (*Calocedrus decurrens*). Red fir (*Abies magnifica*) and lodgepole pine (*Pinus contorta*) dominate at higher elevations of the montane zone. Subalpine forests of whitebark (*P. albicaulis*), foxtail (*P. balfouriana*), and limber pine (*P. flexilis*) grow at elevations of ~2000 to 2,730 m. Tree line commonly lies between 2,730 and 3,340 m. Snow is the most common type of precipitation at high elevations and the snowpack can last throughout the year.

Wildfire is one of the most frequent and intense disturbances of forests in Southern California. Lightning-ignited fires started during thunderstorms in July and August have differing effects, depending on elevation. Fires in the chaparral are always stand-replacing, although fire intensity and severity are variable (Keeley and Fotheringham 2001). Historically, fires commonly burned for months before being extinguished by rain or contained by natural barriers, but they did not necessarily burn large areas. Fire return intervals varied highly, with some montane lightning hotspots experiencing fires every few decades. Regional rotation intervals were on the order of 70 years or more for interior (rather than coastal) locations. In the chaparral, the fire regime was generally one of localized fires, punctuated by periodic massive fires (Keeley and Fotheringham 2001). Lower-elevation montane forest species can be sensitive to fire and found only in rocky areas that limit fire. Riparian forests are less exposed to fire and the primary disturbance in these areas can be floods. Upper elevation montane forests include species resilient to or dependent upon fire for regeneration. Ground fires in this zone appear to have had historic recurrence intervals on the order of a decade.

Stream flow is dominated by groundwater inputs and rainfall-runoff at lower to middle elevations, resulting in peak winter flows, and by snowmelt at higher elevations, resulting in early summer peak flows. Channels originating at lower to middle elevations are more likely to be ephemeral or intermittent.

Much of the mountainous terrain in Southern California is underlain by granitic rocks that weather to relatively coarse-grained, well-drained soils. Pleistocene valley glaciation and ice caps created persistent topographic signatures on mountainous landscapes, including those in Sequoia National Forest, where we assessed the suitability for reintroducing LW and beaver. The higher elevations in this and other Southern California National Forests have a stepped terrain, with extensive, gently undulating plateaus dissected by major river valleys. The low-relief plateaus are especially suitable for reintroducing or retaining logjams and beaver dams because of the relatively low stream gradients and wide valley bottoms.

Logjams were likely historically present from headwater channels to large streams from the subalpine zone down to the chaparral, although wood pieces and accumulations were likely more abundant at higher elevations with more dense forests and less flashy hydrographs (Berg et al. 1998; Boughton et al. 2009; Senter and Pasternack 2011). The presence of beaver, however, has been debated. The lack of historical records of beaver and the contemporary absence of beaver have been cited as evidence that beaver do not naturally occur in this region (Lanman et al. 2012, 2013). However, prehistoric beaver remains have been found (James and Lanman 2012) and, given the ubiquity of beaver throughout the rest of North America and the presence of suitable habitat in Southern California, it is difficult to understand why beaver would not have been present.

The two field examples for Southern California come from the Sequoia National Forest.

Box 6: Sequoia National Forest, California (logjam)

Site: Deer Creek
Location: 35.879569 °N, 118.677903 °W
Elevation: 911 m (2,998 feet)
Drainage area: 47 km^2 (17 mi^2)
Channel characteristics: Deer Creek is a perennial river dominated by seasonal rainfall runoff during winter. At this site the river is narrowly confined (valley-bottom width ~ 100 m) within a valley in the foothills region of this National Forest, with a bankfull channel width of 6 m and ~ 2 percent stream gradient. Channel substrate is gravel- to boulder-size clasts.
Rationale: The creek flows past the Leavis Flat Campground at this point. No logjams are present along the channel, but the backwater and obstruction associated with even a channel-spanning jam are unlikely to raise water level sufficiently to exacerbate lateral channel movement or create inundation problems for the campground. The channel is slightly incised at the campground and becomes more incised immediately downstream. The riparian corridor is forested with deciduous trees. The U.S. Geological Survey program StreamStats lists 2-year peak flows of 4.9 m^3/s (176 cfs) and 10-year peak flows of 20.6 m^3/s (735 cfs) for this site. Although flood flows would likely remove a logjam emplaced here, abundant riparian trees in the vicinity could provide source material for a replacement jam.

Figure 6.1. Upstream view of Deer Creek.

Figure 6.2. Downstream view of Deer Creek. Some wood is visible in the channel at the back of the photo.

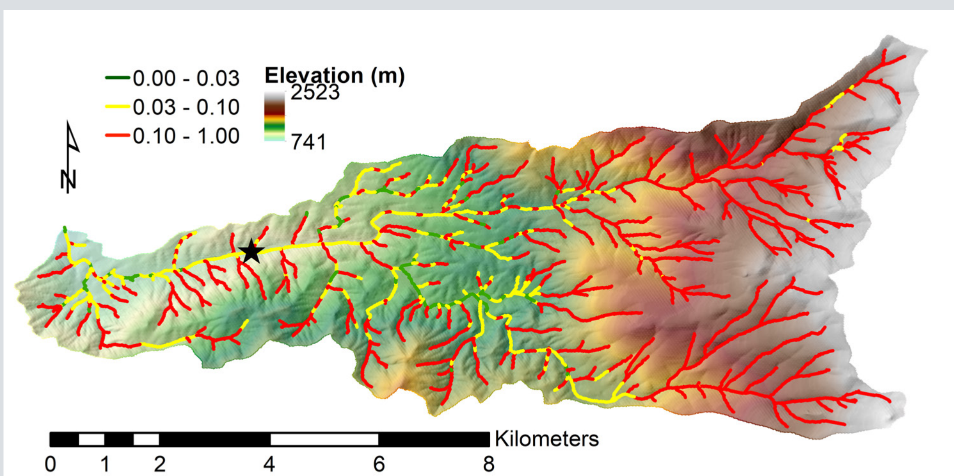


Figure 6.3. Channel gradient map of the Deer Creek watershed. Location of the described site is indicated by star.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

Box 7: Sequoia National Forest, California (beaver meadow)

Site: Unnamed creek **Location: 36.11968 °N, 118.54623 °W**
Elevation: 2,128 m (7,000 feet) **Drainage area:** 1.1 km^2 (0.4 mi^2)
Channel characteristics: This wet meadow is unchannelized but linear in planform (~700 m long, 50-130 m wide), with a very small creek flowing northward into the upper end of the meadow and another very small creek tributary to the meadow from the west. This portion of the drainage network, which is tributary to the South Fork Middle Fork Tule River, is on a high elevation, low relief surface with gently undulating granitic terrain.
Rationale: The existence of this and other wet meadows interspersed along the river networks in this region suggest past occupation by beaver. Subtle down-steps in the meadow longitudinal profile also suggest abandoned, buried beaver dams of the type found elsewhere in sites formerly occupied by beaver (Kramer et al. 2012). The lack of willows in these meadows, along with evidence of past land use for grazing, suggest that beaver might have been eradicated during the period of European settlement. Quaking Aspen Campground borders the site, but the meadow is sufficiently extensive and slightly lower in elevation than the campground, making it unlikely that ponded water or a raised riparian water table would affect the campground. The presence of beaver would be an additional attraction for users of the campground. However, revegetation with willows may be needed to sustain beavers at the site.

Figure 7.1. Wet meadow at higher elevations in Sequoia National Forest with suggestion of past beaver activity (inflection in longitudinal slope of meadow at the point where a downed tree shows in this view at left) but no contemporary beaver activity.

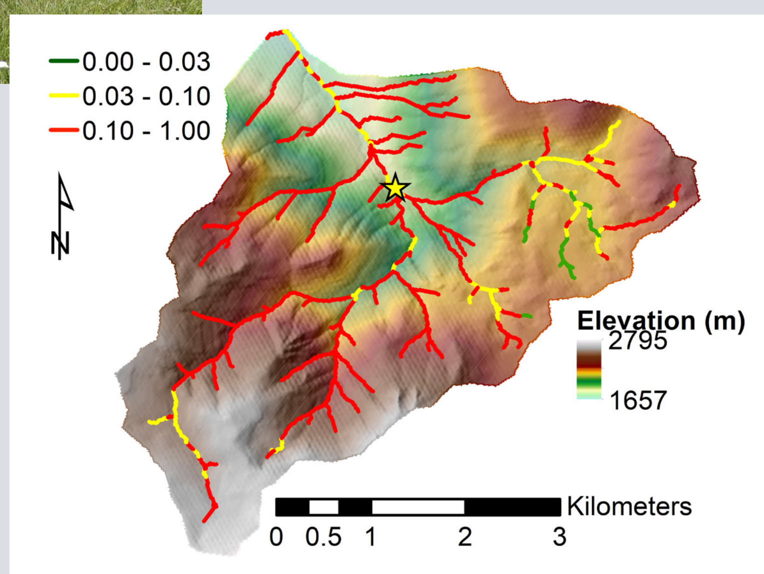


Figure 7.2. Channel gradient map of the area. Beaver meadow location is indicated by a yellow star.

Recommendation: An appropriate site at which to reintroduce beavers or protect existing beavers.

Box 8: Sequoia National Forest, California (existing logjam)

Site: Peppermint Creek
Location: 36.08296 °N, 118.53434 °W
Elevation: 2,150 m (7,080 feet)
Drainage area: 9.2 km^2 (3.3 mi^2)
Channel characteristics: Perennial channel ~ 8 m wide with ~ 2 percent gradient and step-pool bedforms. Existing logjam partly spans the channel and creates a backwater in which finer sediment has accumulated.
Rationale: This logjam could usefully be enhanced by additional wood introduction. The existing jam is ~ 30 m downstream from the Highway 190 road crossing and a large culvert beneath the road impedes downstream LW transport to the site (as well as aquatic organism passage up- and downstream). No infrastructure immediately downstream that could be damaged by LW mobilized from jams. Channels banks downstream from jam are lined with dense riparian willows that would also effectively trap larger, mobile wood. The channel has few jams, likely partly because the road culvert impedes LW transport from the upstream portions of the catchment, which are completely forested.

Figure 8.1. Logjam on Peppermint Creek. Flow is toward right. Note sand-size sediment accumulated upstream from jam.

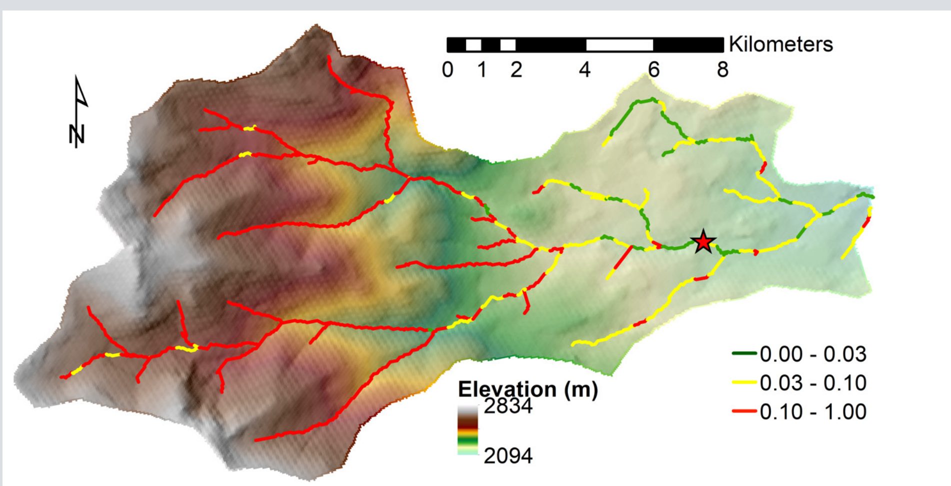


Figure 8.2. Channel gradient map for the Peppermint Creek watershed. Location of the logjam indicated by a red star.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

5. Southwest

Many of the characteristics described for the Rocky Mountain West are also present in watersheds of the Southwest. National Forest System lands in the Southwest can include alpine tundra, subalpine forest, montane forest, and chaparral woodlands, as well as grasslands. Higher elevations are more likely to be influenced by snowmelt runoff and have longer wildfire recurrence intervals, whereas lower elevations are likely to have predominantly rainfall runoff, more frequent wildfires, and more ephemeral and intermittent channels. In general, the Southwest is influenced by frontal storms during winter, convective storms during summer, and dissipating tropical storms from the Baja California region during autumn.

Like Southern California, the Southwest is highly prone to wildfires. Many of the National Forests in the region are dominated by ponderosa pine forests that are characterized by frequent ground fires, as well as longer recurrence interval stand-killing fires and associated debris flows and flash floods. These relatively infrequent, high-magnitude events have sufficient transport capacity to move LW from channels onto floodplains, creating persistent floodplain jams that influence lateral channel migration and hydraulics during overbank flows, as well as providing habitat for terrestrial and riparian organisms (Minckley and Rinne 1985). The flashy hydrology of many streams in the Southwest limits the stability of instream logjams. Although flash floods can destroy beaver dams, the abundance of beaver in streams of this region at the time of first exploration by people of European descent suggests that beaver are quite capable of adapting to high-magnitude floods and of rebuilding dams destroyed by such floods. Historical descriptions and fur trapping records suggest that beaver were present on perennial and intermittent channels at all elevations within the Southwest (Pollock et al. 2015) and that logjams were also present even along desert channels, if a riparian forest was present or if higher elevation portions of the watershed were forested (Minckley and Rinne 1985).

The two field examples from the Southwest come from the Gila Wilderness Area in the Gila National Forest of New Mexico.

Box 9: Gila Wilderness Area, Gila National Forest, New Mexico (beaver meadow)

Site: Snow Canyon
Location: 33.45156 °N, 108.50349 °W
Elevation: 2,267 m (7,460 feet)
Drainage area: 14.2 km² (5.1 mi²)
Channel characteristics: Spring-fed perennial channel ~ 1 m wide and 15-20 cm deep at base flow, with pool-riffle bedforms.
Rationale: At the time of the 2016 visit, the site was still affected by a 2012 wildfire and 2013 flood/debris flow, but valley geometry and channel characteristics suggest that the site could support logjams, or beaver dams if the riparian water table is high enough to support willow carrs. The valley-bottom is sufficiently moist to limit encroachment of conifers. Dark soil in cutbanks suggests a former beaver meadow here. No infrastructure immediately downstream that could be damaged by LW mobilized from jams or dams.

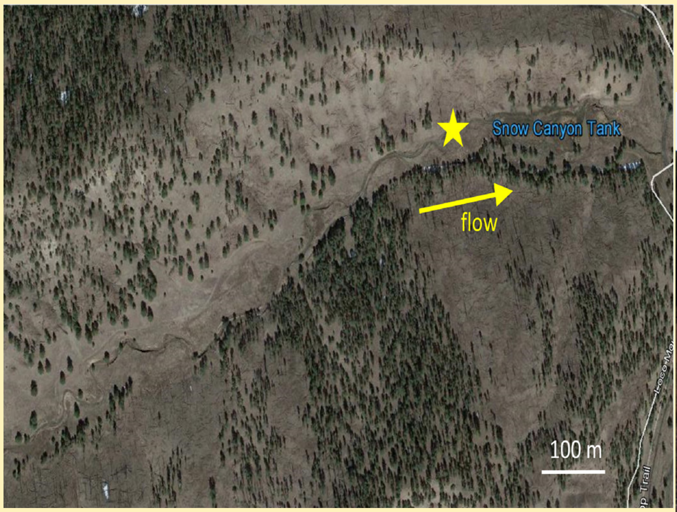


Figure 9.1. 2016 view of the site, indicated by a yellow star. Unpaved road at right shows as white line. Image courtesy of Google Earth.


Figure 9.2. Upstream view in May 2016.


Figure 9.3. Downstream view in May 2016.


Figure 9.4. View of channel farther downstream (33.45161 N, 108.49821 W).

An intermittent tributary enters from the north. The appearance suggests that the channel could support jams in a pool-riffle reach downstream from this location. Even if the channel avulsed around the jam, this would increase spatial heterogeneity and physical complexity in the river corridor.

Figure 9.5. View farther downstream (33.45010 N, 108.49709 W), below where the channel stops being incised. The creek here no longer flows to Snow Lake, but likely did before sedimentation associated with the 2013 flood.

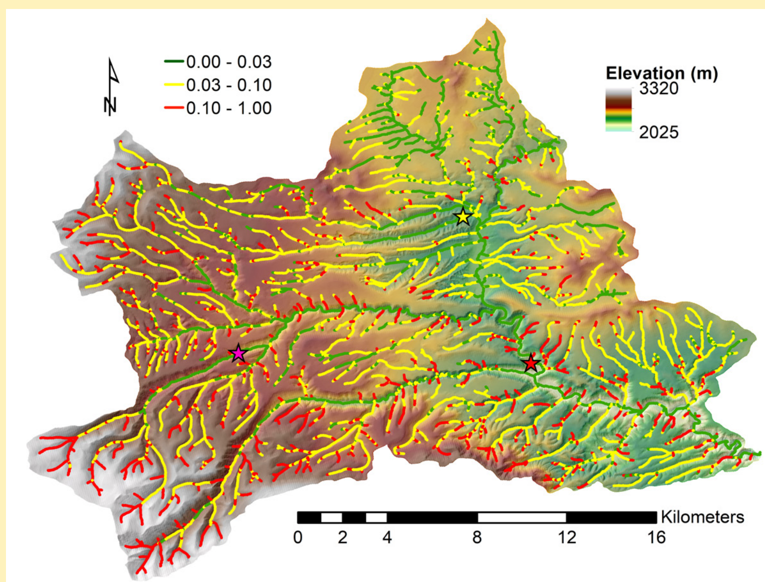


Figure 9.6. Channel gradient map of the vicinity of the beaver dam and logjam sites in the Gila National Forest. The beaver dam site is indicated by a yellow star.

Recommendation: An appropriate site at which to reintroduce beavers or protect existing beavers.

Box 10: Gila Wilderness Area, Gila National Forest, New Mexico (logjam)

Site: Willow Creek at Ben Lilly Campground
Location: 33.39682 °N, 108.59371 °W
Elevation: 2,444 m (8,040 feet)
Drainage area: 23.9 km^2 (8.62 mi^2)
Channel characteristics: A perennial, cobble-bed, pool-riffle channel, with an unpaved road at river left. The bankfull channel is ~ 6 m wide (1%) and the valley bottom is ~ 50 m wide.
Rationale: LW in the channel has been cut out. The channel flows through a primitive campground that is unlikely to be damaged by LW mobilization or by limited channel avulsion: the creek already has a dry secondary channel, perhaps from a 2013 flood. Riparian forest of mixed pine, spruce, and fir along the stream is capable of providing LW to the stream corridor.

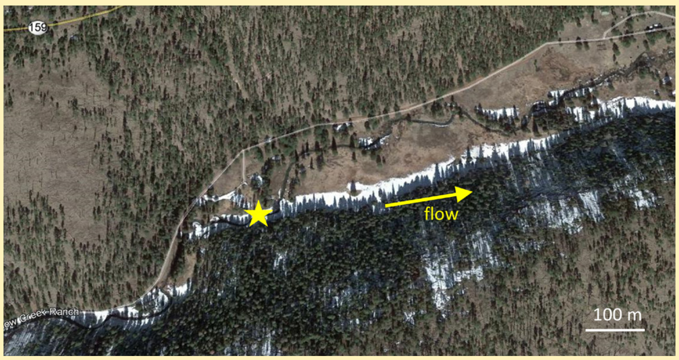


Figure 10.1. 2016 aerial view of site, shown as yellow star. Unpaved road parallel to channel is white line above (north) of channel and valley bottom. Image courtesy of Google Earth.

Figure 10.2. Channel and floodplain.

Figure 10.3. Upstream view of channel.

Figure 10.4. Downstream view of channel.

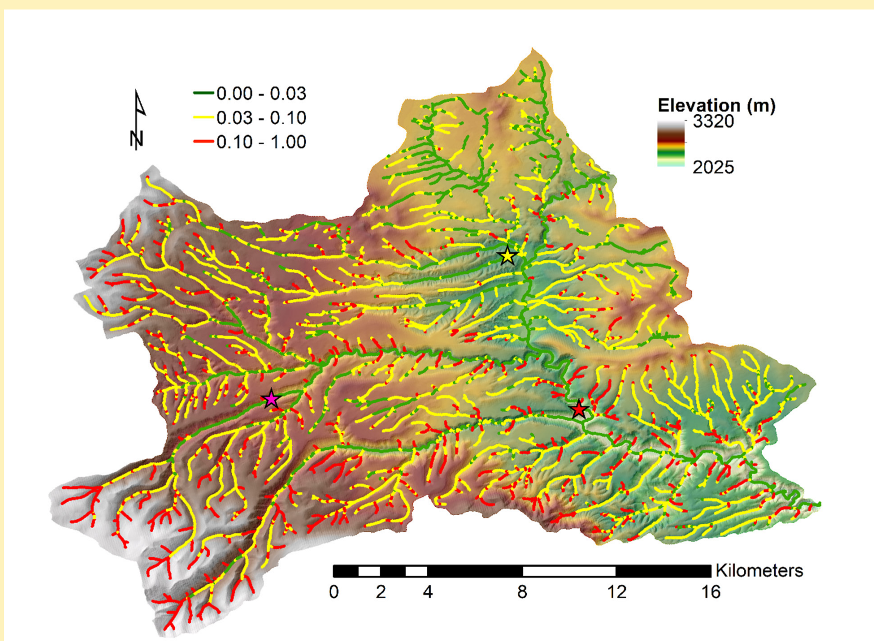


Figure 10.3. Channel gradient map of the portion of the Gila National Forest that includes the sites in Text Boxes 9, 10, and 11. The logjam on Willow Creek is the pink star at lower left. The logjam on the Middle Fork Gila River is the pink star at lower right.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

Box 11: Gila Wilderness Area, Gila National Forest, New Mexico (existing floodplain logjam)

Site: Middle Fork Gila River
Location: 33.392839 °N, 108.476222 °W
Elevation: 2,150 m (7,080 feet)
Drainage area: 367 km^2 (132 mi^2)
Channel characteristics: A perennial, cobble-bed, pool-riffle channel. The bankfull channel is ~ 8 m wide, gradient is ~1 percent, and the valley bottom is ~ 50 m wide. Jam is 25 m long, 12 m wide, and 2.2 m tall, with an estimated 50 percent porosity.
Rationale: This is an example of the numerous jams present on the floodplain following a 2012 fire and a large flood in 2013. The majority of LW present in the river corridor is located on the floodplain rather than in the channel. Although LW will not be removed in this wilderness area, this large floodplain jam presents an ideal example of a jam because it provides habitat for various plants and animals on the floodplain and it is stabilized by the presence of a grove of cottonwood trees immediately downstream, which likely caused the wood to accumulate at this location during the 2013 flood.

Figure 11.1. Downstream view of floodplain jam on river right along the Middle Fork Gila River.

Figure 11.2. Aerial view of the logjam, indicated by the dashed white circle. Yellow arrow indicates flow direction.

Recommendation: An appropriate site at which to protect existing logjams.

6. Pacific Northwest

The Pacific Northwest region is characterized by wet, high-relief terrain to the west of the Cascade Mountains and drier, more moderate-relief terrain to the east. For the purposes of these field examples, we focus on the western portion of the Pacific Northwest region. National Forest System lands are dominantly in the mountainous and foothills portions of this region, and as such include a variety of streams ranging from steep, cascade to step-pool channels to relatively low gradient, meandering to anastomosing channels as rivers reach the mountain front. The legacies of Pleistocene glaciation and volcanism in the Cascades lead many stream systems in this region to be rich in sediment whether draining glacial or volcanic sediment.

Dominant tree species in this region include spruce (*Picea* spp.), hemlock (*Tsuga* spp.), fir (*Abies* spp.) Douglas-fir (*Pseudotsuga menziesii*), cedar (*Thuja* spp.), red alder (*Alnus rubra*), and maple (*Acer* spp.). Mean annual precipitation ranges from approximately 150 to 450 cm, falling as a mixture of rain and snow. Although the hydrograph is dominated by rain, with a wet September through June and a dry summer, snowmelt peaks are regularly observed. As such, floods are regularly flashy, posing a high potential for wood transport, especially in larger streams. Although smaller streams receive high wood inputs in many parts of the region, their transport capacity is low relative to larger streams (Bilby and Ward 1989). Natural disturbance is most commonly via wind throw, landsliding, or debris flows, which can deliver large quantities of wood to channels (Benda et al. 2003b). Logging, especially clearcutting, is widespread in the region and likely impacts wood loads (Bisson et al. 1987; Bilby and Ward 1991) both by the input of slash to channels and the removal of riparian trees that could be sourced as instream wood.

Due likely to the large trees found in this region, wood jams can be stable on timescales up to 10^3 years, acting as hard points in valley bottoms that generate forested islands (Fetherston et al. 1995, Collins et al. 2012). Due to wood removal, such long-lived logjams are relatively rare compared to past conditions, resulting in the widespread shift of many medium to large streams from anastomosing to meandering. In medium-size streams, logging and wood removal have likely reduced pool habitat essential to fish (Bisson et al. 1987). Wood and beaver reintroduction are likely necessary for habitat restoration throughout river networks, although the best style and construction of such restoration probably differs strongly depending on stream size. For instance, larger rivers may need the restoration of more large wood jams that can drive morphologic change, combined with increasing the width available for the stream to migrate, whereas small streams may simply need the restoration of riparian wood and sufficient instream wood necessary to drive recruitment and sustainable wood loads.

Box 12: Olympic National Forest, Washington (logjam)

Site: Sitkum River
Location: 47.955179 °N, 124.239943 °W
Elevation: 130 m (427 feet)
Drainage area: 66 km^2 (25 mi^2)
Channel characteristics: Perennial, cobble- to boulder-bed, pool-riffle channel with a bankfull with of ~ 30m and a slope of ~ 1 percent. It is confined by its valley margins. The site drains a basin that has been extensively clearcut over the last century.
Rationale: This site is representative of many reaches in the Sitkum basin, where logging, either through direct wood and roughness element removal from the channel or the harvest of riparian zones that contain trees that can be recruited by the channel, has significantly decreased wood loads relative to similar, unlogged basins in the region. There is no infrastructure nearby that would be at risk if wood was placed in this reach, and white-water recreation is minimal. Because the channel currently has a high transport capacity for wood, the introduction of large roughness elements along with wood jam structures that could act to trap wood may be an effective strategy to encourage wood jam formation in the reach. Because recent logging operations have not harvested near the channel recently, there is a supply of wood that can be recruited to the channel upstream, allowing for continued, natural maintenance of wood within the reach provided roughness elements are present to trap wood. Increasing the wood load in this reach could lead to improved fish and macroinvertebrate habitat while posing little to no risk to humans or infrastructure.

Figure 12.1. Upstream view of the site.

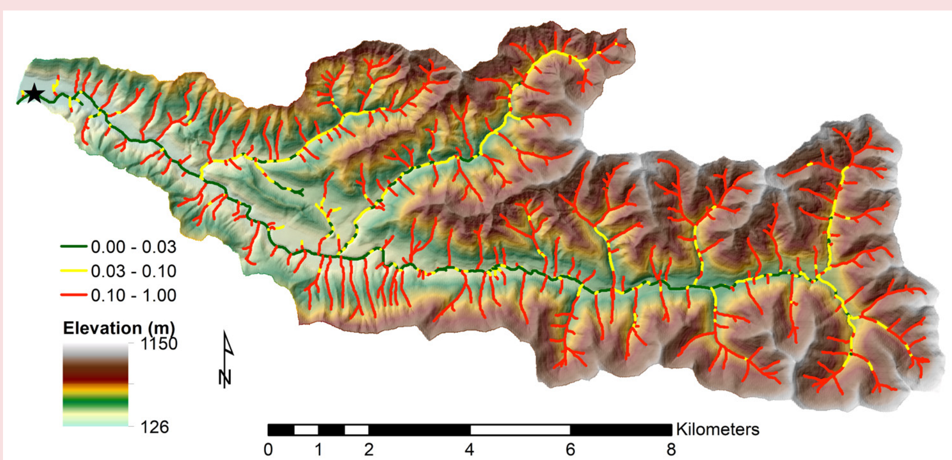


Figure 12.2. Channel gradient map of the Sitkum watershed. Location described in the text indicated by a star.

Recommendation: An appropriate site at which to reintroduce logjams or protect existing logjams.

Box 13: Mt. Baker-Snoqualmie National, Washington (beaver meadow)

Site: Tributary to Middle Fork Snoqualmie River **Location:** 47.519805 °N, 121.636099 °W
Elevation: 361 m (1,184 feet) **Drainage area:** 5.9 km² (2.3 mi²)
Channel characteristics: This wetland resides on glacial till and is largely unchannelized. It exhibits a slope of 1-3 percent, but is drained by multiple small channels of higher gradient (3-5 percent). The wetland is dominated by beaver dams that are likely currently inactive, possibly due to forestry and mining activity nearby and upstream.
Rationale: This site is a good example of a wetland where watershed-scale management (addressing possible impacts on the site from surrounding forestry and mining) could allow for beaver reintroduction and the reactivation of the beaver dam complex here and in nearby wetlands. The surrounding Middle Fork Snoqualmie watershed still has beaver activity, although the beaver population in the watershed is likely reduced from pre-European settlement levels, and restoring beaver could increase the capacity of wetlands such as this one to store organic matter and potentially enable beaver restoration in nearby wetlands.

Figure 13.1. Upstream view of site. Picture was taken standing on an abandoned road bed.

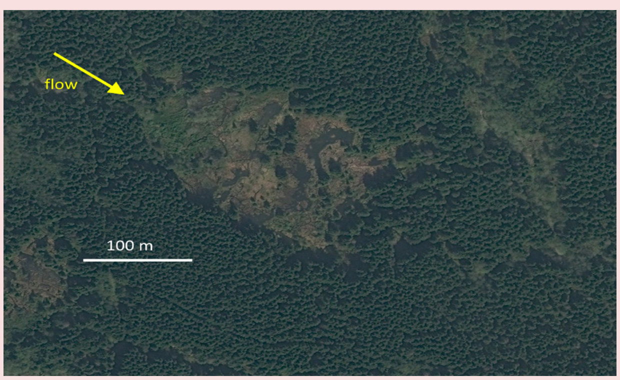


Figure 13.2. Digital Globe image of site. Notice the roads surrounding the site.

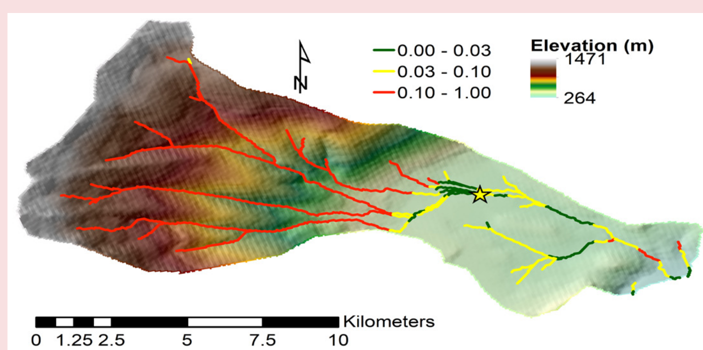


Figure 13.3. Channel gradient map of the watershed. The beaver site is indicated by a yellow star.

Recommendation: An appropriate site at which to reintroduce beavers or protect existing beavers.

Box 14: Mt. Baker-Snoqualmie National Forest, Washington (wood jam dynamics analysis)

Site: South Fork Snoqualmie River
Location: 47.41051 °N, 121.57965 °W
Elevation: 454 m (1,490 feet)
Drainage area: 106 km^2 (41 mi^2)
Channel characteristics: Perennial, cobble- to boulder-bed, pool-riffle anastomosing channel with a bankfull width of ~ 30 m and a slope of ~ 0.1 percent. This channel is confined on its right side by riprap protecting Interstate 90. Riparian forest includes dominantly red alder (*Alnus rubra*). The wood jam at this site is comprised of dominantly red alder (*Alnus rubra*) as well.
Wood jam stability analysis: This logjam was surveyed initially in June 2016, then again in July 2017, after high flows during winter and spring of 2016/2017. This jam is relatively dispersed, with a low obstruction index and no pinning objects to stabilize it, although it does have rootwads attached to key pieces. This jam both lost wood (the large log on the left side of the jam visible in fig. 14.1, circled in red) and accumulated wood (the small material racked on the right side of the jam visible in fig. 14.1, circled in blue) during rain-driven high flows. The loss of wood was likely due to the lack of anchoring (e.g., by pinning objects) and the perpendicular orientation of the key pieces relative to flow. This jam and data describing how it has changed through time can be found in the wood jam dynamics database (https://sites.warnercnr.colostate.edu/woodjam/) under the ID "South Fork Snoqualmie7." This wood jam was measured using a handheld laser rangefinder for channel geometry and took approximately 8 minutes to survey.

Figure 14.1. Before and after photographs of wood jam looking downstream. Top panorama was taken in June 2016. Bottom panorama was taken in July 2017. Red circle denotes part of the jam that was mobilized during high flow. Blue circle denotes wood that accumulated during high flow. Note that the portion of the jam that was lost was closer to the thalweg (potentially exposed to higher velocity flow) than the portion that accumulated wood.

Recommendation: An appropriate site at which to protect existing logjams.

E. Concluding Remarks

After more than a century of actively removing wood and beaver from streams throughout the continental United States, stream management paradigms are gradually shifting toward a recognition that instream pieces of wood, logjams, and beaver dams create numerous environmental benefits and consequently should be retained or actively managed for when possible (Wohl et al. 2016). The Pacific Northwest region is leading the country in this regard. Stream habitat restoration guidelines published by the State of Washington, for example, include detailed recommendations for reintroducing large wood, logjams, and beaver (Cramer 2012). Federal agencies have now also published guidelines for retaining and reintroducing large wood (USBR and ERDC 2016) and beaver (Pollock et al. 2017). The presence of large wood and beaver dams within a stream, however, can also potentially create damage to infrastructure and property. Consequently, it is important to evaluate the relative benefits of removing, retaining, or reintroducing wood and beaver on a site-by-site basis. This document describes alternative procedures requiring differing levels of time and expertise for undertaking such evaluations. Our intent is to provide tools that can be used to move away from management practices in which logjams and beaver dams are immediately assumed to create sufficient hazards that warrant automatic removal and toward more nuanced stream management that explicitly recognizes the many beneficial effects of logjams and beaver dams and builds on this recognition to retain jams and dams or to reintroduce LW and beaver to streams where feasible.

F. Glossary

active channel: a portion of the valley bottom that can be distinguished based on the three primary criteria of (1) channels defined by erosional and depositional forms created by stream processes, (2) the upper elevation limit at which water is contained within a channel, and (3) portions of a channel without mature woody vegetation

avulsion: formation of a new channel that is commonly parallel or subparallel to the existing channel(s)

bankfull: the portion of the channel below the top of the banks, with top of banks defined by a break in slope between relatively high-angle banks and relatively flat overbank portions of the valley bottom

bar: a large-scale bedform, the dimensions of which are controlled by flow width and depth; subdivided based on shape and position within the channel into alternate bars, point bars, transverse bars, braid bars, etc.

beaver meadow: a spatially extensive complex of multiple dams and ponds in varying states of activity or abandonment

bedform: a deposit on the stream bed, formed by fluvial processes, and typically repeated downstream (e.g., pool, riffle, point bar, alternate bar, ripple, and dune)

carr: saturated, wooded terrain that commonly represents a successional stage between open water or marsh and forest

channel migration zone: the width of the valley bottom across which main and secondary channels can migrate and have migrated under the contemporary flow regime

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

disturbance: a temporary change in environmental conditions that causes a pronounced change in an ecosystem (e.g., flood)

fine wood: definitions of piece dimensions vary between references; here, wood pieces smaller than 10 cm in diameter and 1 m in length

floodplain: a relatively flat sedimentary surface adjacent to the active channel that is built by stream processes and inundated frequently

hyporheic zone: the portion of unconfined, near-stream aquifers where stream water is present; this zone is a flow-through subsurface region in which flow paths originate and terminate at the river

instream wood: large wood within the bankfull channel

key piece: any wood piece in a logjam that is interpreted to be essential to forming the jam (i.e., that retains other wood pieces)

large wood (LW): wood pieces greater than or equal to 10 cm in diameter and 1 m in length

livewood: living woody vegetation (trunks, stems, and branches) within the bankfull channel; can help to trap and retain otherwise mobile LW

logjam: a cluster of three or more LW pieces in contact with one another; types include channel-spanning, in situ, and transport

overbank flow: flow that overtops the channel and inundates the floodplain or adjacent valley bottom

resilience: the tendency of a channel to return to its pre-flood configuration following a large flood; a resilient channel returns to its pre-flood configuration relatively quickly

resistance: the ability of an ecosystem to resist displacement from equilibrium or a reference state

riparian zone: lands adjacent to rivers that are transitional between terrestrial and aquatic ecosystems, through which surface and subsurface hydrology connects stream waters with their adjacent wetlands, non-wetland waters, or uplands

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

stream corridor: the portion of any landscape that has been created by stream erosion and deposition through time and that remains connected to the contemporary stream at least during ordinary floods

G. Online Resources

Clinton River Watershed, New York, field manual for maintenance of LW:
http://www.hrwc.org/wp-content/uploads/2013/03/LWD%20Manual%20Final.pdf
King County, Washington, LW management guidelines:
http://your.kingcounty.gov/dnrp/library/water-and-land/flooding/natural-large-wood/procedures-for-managing-naturally-occurring-wood-2013.pdf
King County Independent Review Report for Projects Involving LW Emplacements:
http://your.kingcounty.gov/dnrp/library/2015/kcr2733.pdf
UK Environment Agency LW management guidelines:
http://evidence.environment-agency.gov.uk/FCERM/en/SC060065/MeasuresList/M5/M5T3.aspx?pagenum=2
US Bureau of Reclamation LW Design Guidelines – National Manual:
http://www.usbr.gov/research/projects/detail.cfm?id=2754
Beaver Restoration Assessment Tool:
https://water.usgs.gov/osw/programs/nss/pubs.html
The Beaver Restoration Guidebook:
https://lccnetwork.org/resource/beaver-restoration-guidebook-version-20

H. References

Abbe T, Brooks A. 2011. Geomorphic, engineering, and ecological considerations when using wood in river restoration. In: Simon A, Bennett SJ, Castro JM (eds.), Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. American Geophysical Union Press, Washington, DC, 419-451.

Abbe TB, Brooks AP, Montgomery DR. 2003. Wood in river rehabilitation and management. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 367-389.

Abbe TB, Montgomery DR. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management 12, 201-221.

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

Acuna V, Diez JR, Flores L, Meleason M, Elosegi A. 2013. Does it make economic sense to restore rivers for their ecosystem services? Journal of Applied Ecology 50, 988-997.

Adenlof KA, Wohl EE. 1994. Controls on bedload movement in a subalpine stream of the Colorado Rocky Mountains, USA. Arctic and Alpine Research 26, 77-85.

Albert S, Trimble T. 2000. Beavers are partners in riparian restoration on the Zuni Indian Reservation. Ecological Restoration 18, 87-92.

Alonso CV. 2004. Transport mechanics of stream-borne logs. In: Bennett SJ, Simon A (eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union Press, Washington, DC, 59-69.

Andersen DC, Stricker CA, Nelson SM. 2016. Wood decay in desert riverine environments. Forest Ecology and Management 365, 83-95.

Andersen O, Crow TR, Lietz SM, Stearns F. 1996. Transformation of a landscape in the upper mid-west USA: the history of the lower St. Croix River valley, 1830 to present. Landscape and Urban Planning 35, 247-267.

Andrew RG, Hartman KJ. 2015. Uneven inputs of woody debris to Appalachian streams from superstorm Sandy. Canadian Journal of Fisheries and Aquatic Sciences 72, 1-6.

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.

Angradi TR. 1996. Inter-habitat variation in benthic community structure, function, and organic matter storage in 3 Appalachian headwater streams. Journal of the North American Benthological Society 15, 42-63.

Aumen NG, Hawkins CP, Gregory SV. 1990. Influence of woody debris on nutrient retention in catastrophically disturbed streams. Hydrobiologia 190, 183-192.

Bailey RG. 1995. Descriptions of the ecoregions of the United States. USDA Forest Service Misc. Publ. no. 1391, Washington, DC.

Baker BW, Hill EP. 2003. Beaver. In: Feldhammer GA, Thompson BC, Chapman JA (eds.), Wild Mammals of North America: Biology, Management, and Conservation, 2nd edition. The Johns Hopkins University Press, Baltimore, Maryland, 288-310.

Ballinger A, MacNally R, Lake PS. 2010. Decay state and inundation history control assemblage structure of log-dwelling invertebrates in floodplain forests. River Research and Applications 26, 207-219.

Barrett ML. 1996. Environmental reconstruction of a 19th century Red River raft lake: Caddo Lake, Louisiana and Texas. American Association of Petroleum Geologists Bulletin 80, 1495 (abstract).
Battin TJ, Kaplan LA, Findlay S, Hopkinson CS, Marti E, Packman AI, Newbold JD, Sabater F. 2008. Biophysical controls on organic carbon fluxes in fluvial networks. Nature Geoscience 1, 95-100.
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, 1470-1481.
Beckman ND, Wohl E. 2014a. Carbon storage in mountainous headwater streams: the role of old-growth forest and logjams. Water Resources Research 50, 2376-2393.
Beckman ND, Wohl E. 2014b. Effects of forest stand age on the characteristics of logjams in mountainous forest streams. Earth Surface Processes and Landforms 39, 1421-1431.
Beechie TJ, Sibley TH. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126, 217-229.
Bellmore JR, Baxter CV. 2014. Effects of geomorphic process domains on river ecosystems: a comparison of floodplain and confined valley segments. River Research and Applications 30, 617-630.
Benda L, Bigelow P. 2014. On the patterns and processes of wood in northern California streams. Geomorphology 209, 79-97.
Benda L, Miller D, Sias J, Martin D, Bilby R, Veldhuisen C, Dunne T. 2003a. Wood recruitment processes and wood budgeting. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 49-73.
Benda L, Veldhuisen C, Black J. 2003b. Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington. Bull. Geol. Soc. Am. 115, 1110–1121. doi:10.1130/B25265.1
Benda L, Andras K, Miller D, Bigelow P. 2004a. Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resources Research 40, W05402. Doi:10.1029/2003WR002583.
Benda L, Poff NL, Miller D, Dunne T, Reeves G, Pess G, Pollock M. 2004b. The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54, 413-427.
Benda LE, Sias JC. 2003. A quantitative framework for evaluating the mass balance of in-stream organic debris. Forest Ecology and Management 172, 1-16.
Bendix J, Cowell CM. 2010. Fire, floods and woody debris: interactions between biotic and geomorphic processes. Geomorphology 116, 297-304.
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, Wallace JB. 1990. Wood dynamics in coastal plain blackwater 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. In, Gregory SV, Boyer KL, Gurnell AM (eds.), Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 149-177.
Berg N, Carlson A, Azuma D. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. Canadian Journal of Fisheries and Aquatic Sciences 55, 1807-1820.
Bernhardt ES, Palmer MA, Allan JD, Abell R, Alexander G, Brooks S, et al. 2005. Synthesizing U.S. river restoration efforts. Science 308, 636-637.
Bertoldi W, Gurnell AM, Welber M. 2013. Wood recruitment and retention: the fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources. Geomorphology 180-181, 146-155.
Bhowmik NG, Demissie M. 1989. Sedimentation in the Illinois River Valley and backwater lakes. Journal of Hydrology 105, 187-195.
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. 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry 82, 609-613.
BIlby RE. 2003. Decomposition and nutrient dynamics of wood in streams and rivers. In, Gregory SV, Boyer KL, Gurnell AM (eds.), Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 135-147.
Bilby RE, Likens GE. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61, 1107-1113.
Bilby RE, Ward JW. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118, 368-378.
Bilby RE, Ward JW. 1991. Characteristics and Function of Large Woody Debris in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington. Can. J. Fish. Aquat. Sci. 48, 2499–2508. doi:10.1139/f91-291
Bisson PA, Bilby RE, Bryant MD, Dolloff CA, Grette GB, House RA, Murphy ML, Koski KV, Sedell JR. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo EO, Cundy TW (eds.), Streamside Management: Forestry and Fishery Implications. Institute of Forest Resources, University of Washington, Contrib. No. 57, 143-190.
Bisson PA, Wondzell SM, Reeves GH, Gregory SV. 2003. Trends in using wood to restore aquatic habitats and fish communities in western North American rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 391-406.
Blanc J, Wallerstein N, Arthur S, Wright G. 2014. Analysis of the performance of debris screens at culverts. Water Management 167, 219-229.
Bocchiola D. 2011. Hydraulic characteristics and habitat suitability in presence of woody debris: a flume experiment. Advances in Water Resources 34, 1304-1319.
Bocchiola D, Rulli MC, Rosso R. 2006. Transport of large woody debris in the presence of obstacles. Geomorphology 76, 166-178.
Boivin M, Buffin-Belanger T, Piégay H. 2015. The raft of the Saint-Jean River, Gaspe (Quebec, Canada): a dynamic feature trapping most of the wood transported from the catchment. Geomorphology 231, 270-280.

Boose ER, Chamberlin KE, Foster DR. 2001. Landscape and regional impacts of historical hurricanes in New England. Ecological Monographs 71, 27-48.

Bottorff J. 2009. Snags, Coarse Woody Debris, and Wildlife. Washington State Department of Natural Resources. Accessed 30 June 2016. http://forestry.wsu.edu/wp-content/uploads/2014/02/SNAGS.pdf

Boughton DA, Fish H, Pope J, Holt G. 2009. Spatial patterning of habitat for Oncorhynchus mykiss in a system of intermittent and perennial streams. Ecology of Freshwater Fish 18, 92-105.

Boulton AJ. 1999. An overview of river health assessment: philosophies, practice, problems and prognosis. Freshwater Biology 41, 469-479.

Boulton AJ, Valett HM, Fisher SG. 1992. Spatial distribution and taxonomic composition of the hyporheos of several Sonoran Desert streams. Archives fur Hydrobiologie 125: 37-61.

Bouwes N, Weber N, Jordan CE, Saunders WC, Tattam IA. Volk C, Wheaton JM, Pollock MM. 2016. Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (Oncorhynchus mykiss). Scientific Reports 6, 28581. doi:10.1038/srep28581.

Boyer KL, Berg DR, Gregory SV. 2003. Riparian management for wood in rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 407-420).

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

Bragg DC. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology 81, 1383-1394.

Bragg DC, Kershner JL, Roberts DW. 2000. Modeling large woody debris recruitment for small streams of the central Rocky Mountains. USDA Forest Service General Technical Report RMRS-GTR-55, Fort Collins, CO.

Braudrick CA, Grant GE. 2000. When do logs move in rivers? Water Resources Research 36, 571-583.

Braudrick CA, Grant GE. 2001. Transport and deposition of large woody debris in streams: a flume experiment. Geomorphology 41, 263-283.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: a flume experiment. Earth Surface Processes and Landforms 22, 669-683.

Brayton DS. 1984. The beaver and the stream. Journal of Soil and Water Conservation 39, 108-109.

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 of south-eastern Australia. Geomorphology 79, 395-422.

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.

Buffington JM, Montgomery DR. 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35, 3507-3521.

Buffington JM, Tonina D. 2009. Hyporheic exchange in mountain rivers II: effects of channel morphology on mechanics, scales, and rates of exchange. Geography Compass 3, 1038-1062.

Bugosh N, Custer SG. 1989. The effect of a log-jam burst on bedload transport and channel characteristics in a headwaters stream. In: Headwaters Hydrology. American Water Resources Association, Bethesda, MD, 203-211.

Bunn JT, Montgomery DR. 2004. Patterns of wood and sediment storage along debris-flow impacted headwater channels in old-growth and industrial forests of the western Olympic Mountains, Washington. In: Bennett SJ, Simon A. (eds.), Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union Press, Washington, DC, 99-112.

Bunn SE, Davies PM, Mosisch TD. 1999. Ecosystem measures of river health and their response to riparian and catchment degradation. Freshwater Biology 41, 333-345.

Bunn SE, Thoms MC, Hamilton SK, Capon SJ. 2006. Flow variability in dryland rivers: boom, bust and the bits in between. River Research and Applications 22: 179-186.

Burchsted D, Daniels MD. 2014. Classification of the alterations of beaver dams to headwater streams in northeastern Connecticut, USA. Geomorphology 205, 36-50.

Burchsted D, Daniels M, Thorson R, Vokoun J. 2010. The river discontinuum: applying beaver modifications to baseline conditions for restoration of forested headwaters. BioScience 60, 908-922.

Butler DR. 2012. Characteristics of beaver ponds on deltas in a mountain environment. Earth Surface Processes and Landforms 37, 876-882.

Butler DR, Malanson GP. 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology 13, 255-269.

Buxton TH. 2010. Modeling entrainment of waterlogged large wood in stream channels. Water Resources Research 46, W10537. doi:10.1029/2009WR008041.

Carlson JY, Andrus CW, Froehlich HA. 1990. Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in northeastern Oregon, USA. Canadian Journal of Fisheries and Aquatic Sciences 47, 1103-1111.

Castro JM, Jackson PL. 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. Journal of the American Water Resources Association 37, 1249-1262.

Castro J, Sampson R. 2001. Incorporation of Large Wood into Engineering Structures. Natural Resource Conservation Service Engineering Technical Note Number 15. USDA, Boise, ID.

CDEP (Connecticut Department of Environmental Protection). Large Woody Debris Fact Sheet. Inland Fisheries Division, Habitat Conservation and Enhancement Program, 6 pp: accessed 30 June 2016. http://www.ct.gov/deep/lib/deep/fishing/restoration/largewoodydebrisfactsheet.pdf

Chen X, Wei X, Scherer R, Luider C, Darlington W. 2006. A watershed-scale assessment of in-stream large woody debris patterns in the southern interior of British Columbia. Forest Ecology and Management 229, 50-62.

Chen X, Wei X, Scherer R, Hogan D. 2008. Effects of large woody debris on surface structure and aquatic habitat in forested streams, southern interior British Columbia, Canada. River Research and Applications 24, 862-875.

Cherry J, Beschta RL. 1989. Coarse woody debris and channel morphology: a flume study. Water Resources Bulletin 25, 1031-1036.

Chin A, Daniels MD, Urban MA, Piégay 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.

Chin A, Laurencio LR, Daniels MD, Wohl E, Urban MA, Boyer KL, Butt A, Piégay H, Gregory KJ. 2014. The significance of perceptions and feedbacks for effectively managing wood in rivers. River Research and Applications 30, 98-111.
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
Coles JM, Orme BJ. 1983. Homo sapiens or Castor fiber? Antiquity LVII, 95-102.
Collen P, Gibson RJ. 2001. The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. Reviews in Fish Biology and Fisheries 10, 439-461.
Collier E. 1959. Three Against the Wilderness. E.P. Dutton and Co., Inc, New York.
Collins BD, Montgomery DR. 2002. Forest development, wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington. Restoration Ecology 10, 237-247.
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.
Collins BD, Montgomery DR, Sheikh AJ. 2003. Reconstructing the historical riverine landscape of the Puget Lowland. In: Montgomery DR, Bolton S, Booth DB, Wall L (eds.), Restoration of Puget Sound Rivers. University of Washington Press, Seattle, 79-128.
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.
Comiti F. 2012. How natural are Alpine mountain rivers? Evidence from the Italian Alps. Earth Surface Processes and Landforms 37, 693-707.
Comiti F, Mao L, Preciso E, Picco L, Marchi L, Borga M. 2008. Large wood and flash floods: evidence from the 2007 event in the Davča basin (Slovenia). WIT Transactions on Engineering Sciences 60, 173-182.
Cordova JM, Rosi-Marshall EJ, Yamamuro AM, Lamberti GA. 2007. Quantity, controls and functions of large woody debris in Midwestern USA streams. River Research and Applications 23, 21-33.
Correll DL, Jordan TE, Weller DE. 2000. Beaver pond biogeochemical effects in the Maryland Coastal Plain. Biogeochemistry 49, 217-239.
Costigan KH, Soltesz PJ, Jaeger KL. 2015. Large wood in central Appalachian headwater streams: controls on and potential changes to wood loads from infestation of hemlock woolly adelgid. Earth Surface Processes and Landforms 40, 1746-1763.
Covich AP, Crowl TA, Johnson SL, Varza D, Certain DL. 1991. Post-Hurricane Hugo increases in Atyid shrimp abundance in a Puerto Rican montane stream. Biotropica 23, 448-454.
Cramer ML (ed.) 2012. Stream Habitat Restoration Guidelines. Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and the U.S. Fish and Wildlife Service. Olympia, Washington, http://wdfw.wa.gov/publications/01374/
Cronon W. 1983. Changes in the Land: Indians, Colonists, and the Ecology of New England. Hill and Wang, NY.

CRWC (Clinton River Watershed Council). 2016. Field Manual on Maintenance of Large Woody Debris for Municipal Operation and Maintenance Crews, 50 pp. Accessed 30 June 2016. http://www.hrwc.org/wp-content/uploads/2013/03/LWD%20Manual%20Final.pdf

Culp JM, Scrimgeour GJ, Townsend GD. 1996. Simulated fine woody debris accumulations in a stream increase rainbow trout fry abundance. Transactions of the American Fisheries Society 125, 472-479.

Curran JC. 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. Geomorphology 116, 320-329.

Curran JH, Wohl EE. 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. Geomorphology 51, 141-147.

Curtis PD, Jensen PG. 2004. Habitat features affecting beaver occupancy along roadsides in New York State. Journal of Wildlife Management 68, 278-287.

Daniels MD. 2006. Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. Geomorphology 77, 286-298.

Daniels MD, Rhoads BL. 2004. Effects of large woody debris configuration on three-dimensional flow structure in two low-energy meanders bends at varying stages. Water Resources Research 40, W11302. doi:10.1029/2004WR003181.

David GCL, Wohl E, Yochum SE, Bledsoe BP. 2010. Controls on spatial variations in flow resistance along steep mountain streams. Water Resources Research 46. DOI: 10.1029/2009WR008134.

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.

Davies NS, Gibling MR. 2011. Evolution of fixed-channel alluvial plains in response to Carboniferous vegetation. Nature Geoscience 4, 629-633.

Davies NS, Gosse JC, Rybczynski N. 2014. Cross-bedded woody debris from a Pliocene forested river system in the High Arctic: Beaufort Formation, Meighen Island, Canada. Journal of Sedimentary Research 84, 19-25.

DeCicco PN, Paris E, Solari L. 2016. Wood accumulation at bridges: laboratory experiments on the effect of pier shape. Proceedings, 8th River Flow Congress, St. Louis, Missouri.

De Visscher M, Nyssen J, Pontzeele J, Billi P, Frankl A. 2014. Spatiotemporal sedimentation patterns in beaver ponds along the Chevral River, Ardennes, Belgium. Hydrological Processes 28, 1602–1615.

DeVries P, Fetherston KL, Vitale A, Madsen S. 2012. Evaluating riverine landscape controls of beaver in stream restoration. Fisheries 37, 246-255.

Diehl TH. 1997. Potential Drift Accumulation at Bridges. US Department of Transportation, Publ. FHWA-RD-97-028, McLean, VA.

Dixon SJ, Sear DA. 2014. The influence of geomorphology on large wood dynamics in a low gradient headwater stream. Water Resources Research 50, 9194-9210.

Dolloff CA, Warren ML. 2003. Fish relationships with large wood in small streams. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 179-193.

Donnelly JP, Bryant SS, Butler J, et al. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. Geological Society of America Bulletin 113, 714-727.

Downs PW, Simon A. 2001. Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, central Mississippi, USA. Geomorphology 37, 65-91.
Dudley SJ, Fischenich JC, Abt SR. 1998. Effect of woody debris entrapment on flow resistance. Journal of the American Water Resources Association 34, 1189-1197.
Dugmore AR. 1914. The Romance of the Beaver. J.B. Lippincott Company, Philadelphia.
Dumke JD, Hrabik TR, Brady VJ, Gran KB, Regal RR, Seider MJ. 2010. Channel morphology response to selective wood removals in a sand-laden Wisconsin trout stream. North American Journal of Fisheries Management 30, 776-790.
Dunkerley D. 2014. Nature and hydro-geomorphic roles of trees and woody debris in a dry-land ephemeral stream: Fowlers Creek, arid western New South Wales, Australia. Journal of Arid Environments 102, 40-49.
Dunne T, Aalto RE. 2013. Large river floodplains. In, E Wohl (ed.), Fluvial geomorphology, vol. 9 of Treatise on geomorphology, JF Shroder (ed.), Elsevier, 645-677.
Eaton BC, Hassan MA, Davidson SL. 2012. Modeling wood dynamics, jam formation, and sediment storage in a gravel-bed stream. Journal of Geophysical Research 117, F00A05, doi: 10.1029/2012JF002385.
Ellison AM, MS Bank, BD Clinton, EA Colburn, K Elliott, CR Ford, DR Foster, BD Kloeppel, JD Knoepp, GM Lovett. 2005. Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Frontiers in Ecology and the Environment 3: 479-486.
Elosegi A, Johnson LB. 2003. Wood in streams and rivers in developed landscapes. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 337-353.
Entrekin SA, Tank JL, Rosi-Marshall EJ, Hoellein TJ, Lamberti GA. 2008. Responses in organic matter accumulation and processing to an experimental wood addition in three headwater streams. Freshwater Biology 53, 1642-1657.
Erskine WD, Saynor MJ, Chalmers A, Riley SJ. 2012. Water, wind, wood, and trees: interactions, spatial variations, temporal dynamics, and their potential role in river rehabilitation. Geographical Research 50, 60-74.
Erskine WD, Webb AA. 2003. Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia. River Research and Applications 19, 233-249.
Evans CK. 2006. The Great Big Book of Baby Names. Publications International Ltd, NY.
Fairweather PG. 1999. State of environment indicators of 'river health': exploring the metaphor. Freshwater Biology 41, 211-220.
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, Northcote TG. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49, 682-693.
Fausch KD, Young MK. 2004. Interactions between forests and fish in the Rocky Mountains of the USA. In: Northcote TG, Harman GF (eds.), Fishes and Forestry: Worldwide Water-shed Interactions and Management. Blackwell Science, Oxford, UK, 463-484.
Faustini JM, Jones JA. 2004. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. Geomorphology 51, 187-205.

Fetherston KL, Naiman RJ, Bilby RE. 1995. Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. Geomorphology 13, 133-144.
FHWA (Federal Highway Administration). 2005. Debris Control Structures Evaluation and Countermeasures. Hydraulic Engineering Circular No. 9. Publication No. FHWA-IF-04-016. Available at http://www.fhwa.dot.gov/engineering/hydraulics/pubs/04016/.
Fisher GB, Magilligan FJ, Kaste JM, Nislow KH. 2010. Constraining the timescales of sediment sequestration associated with large woody debris using cosmogenic 7Be. Journal of Geophysical Research 115, F01013. doi:10.1029/2009JF001352.
Flores L, Diez JR, Larranaga A, Pascoal C, Elosegi A. 2013. Effects of retention site on breakdown of organic matter in a mountain stream. Freshwater Biology 58, 1267-1278.
Flores L, Larranaga A, Diez JR, Elosegi A. 2011. Experimental wood addition in streams: effects on organic matter storage and breakdown. Freshwater Biology 56, 2156-2167.
Florsheim JL, Mount JF. 2002. Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California. Geomorphology 44, 67-94.
Fox M, Bolton S. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forest basins of Washington State. North American Journal of Fisheries Management 27, 342-359.
Fremier AK, Seo JI, Nakamura F. 2010. Watershed controls on the export of large wood from stream corridors. Geomorphology 117, 33-43.
Frémont JC. 1845. Report of the Exploring Expedition to the Rocky Mountains in the Year 1842 and to Oregon and North California in the Years 1843-'44. Gales and Seaton, Printers, Washington, DC.
Furniss M, Ledwith T, Love M, McFadin B, Flanagan S. 1998. Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California. USDA Forest Service, Technology and Development Program, Corvallis, OR.
Gallisdorfer MS, Bennett SJ, Atkinson JF, Ghaneeizad SM, Brooks AP, Simon A, Langendoen EJ. 2014. Physical-scale model designs for engineered log jams in rivers. Journal of Hydro-environment Research 8, 115-128.
Gibling MR, Davies NS. 2012. Palaeozoic landscapes shaped by plant evolution. Nature Geoscience 5, 99-105.
Gibson PP, Olden JD. 2014. Ecology, management, and conservation implications of North American beaver (*Castor canadensis*) in dryland streams. Aquatic Conservation: Marine and Freshwater Ecosystems 24, 391-409.
Gilbert JT, Macfarlane WW, Wheaton JM. 2016. The Valley Bottom Extraction Tool (V-BET): A GIS tool for delineating valley bottoms across entire drainage networks. Computers and Geosciences. 97, 1-14. doi:10.1016/j.cageo.2016.07.014.
Gippel CJ. 1995. Environmental hydraulics of large woody debris in streams and rivers. Journal of Environmental Engineering 121, 388-395.
Gippel CJ, O'Neill IC, Finlayson BL. 1992. The Hydraulic Basis of Snag Management. Land and Water Resources Research and Development Corporation, Rural Water Commission, Victoria, Australia.
Gooseff MN. 2010. Defining hyporheic zones – advancing our conceptual and operational definitions of where stream water and groundwater meet. Geographical Compass 4, 945-955.

Graf WL. 2001. Damage control: restoring the physical integrity of America's rivers. Annals of the Association of American Geographers 91, 1-27.
Green KC, Westbrook CJ. 2009. Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. BC Journal of Ecosystems and Management 10, 68-79.
Gregory KJ. 2003. The limits of wood in world rivers: present, past, and future. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 1-19.
Gregory KJ, Gurnell AM, Hill CT. 2012. The permanence of debris dams related to river channel processes. Hydrological Sciences Journal 30, 371-381.
Gregory SV, Meleason MA, Sobota DJ. 2003. Modeling the dynamics of wood in streams and rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 315-335.
Gurnell AM. 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography 22, 167-189.
Gurnell AM. 2003. Wood storage and mobility. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 75-91.
Gurnell AM. 2013. Wood in fluvial systems. In: Shroder J (ed. in chief), Treatise on Geomorphology, vol. 9, Wohl E (ed.), Fluvial Geomorphology. Academic Press, San Diego, 163-188.
Gurnell AM, Petts G. 2006. Trees as riparian engineers: the Tagliamento River, Italy. Earth Surface Processes and Landforms 31, 1558–1574.
Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. Freshwater Biology 47, 601-619.
Gurnell AM, Tockner K, Edwards P, Petts G. 2005. Effects of deposited wood on biocomplexity of river corridors. Frontiers in Ecology and Environment 3, 377-382.
Gurnell AM, Bertoldi W, Corenblit D. 2012. Changing river channels: the roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. Earth-Science Reviews 111, 129-141.
Guyette RP, Dey DC, Stambaugh MC. 2008. The temporal distribution and carbon storage of large oak wood in streams and floodplain deposits. Ecosystems 11, 643-653.
Hafen K, Macfarlane WW. 2016. Can beaver dams mitigate water scarcity caused by climate change and population growth? Stream Notes, p. 1-5. (The Technical Newsletter of the National Stream and Aquatic Ecology Center, Fort Collins, Colorado).
Haga H, Kumagai T, Otsuki K, Ogawa S. 2002. Transport and retention of coarse woody debris in mountain streams: an in situ field experiment of log transport and a field survey of coarse woody debris distribution. Water Resources Research 38. Doi:10.1029/2001WR001123.
Harden CP. 2004. Fluvial response to land-use change in the Southern Appalachian Region: a century of investigation. Physical Geography 25: 398-417.
Harmon ME. 2002. Moving towards a new paradigm for woody detritus management. In: Laudenslayer WF, Shea PJ, Valentive BE, Weatherspoon CP, Lisle TE (eds.), Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests. USDA Forest Service General Technical Report PSW-GTR-181, Albany, CA, 929-944.

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.

Harmon ME, Woodall C, Sexton J. 2011. Standing and Downed Dead Tree Wood Density Reduction Factors : A Comparison Across Decay Classes and Tree Species. Research Paper NRS-15.

Harris JH, Silveira R. 1999. Large-scale assessments of river health using an Index of Biotic Integrity with low-diversity fish communities. Freshwater Biology 41, 235-252.

Hart EA. 2002. Effects of woody debris on channel morphology and sediment storage in headwater streams in the Great Smoky Mountains, Tennessee-North Carolina. Physical Geography 23, 492-510.

Harvey JW, CC Fuller. 1998. Effect of enhanced manganese oxidation in the hyporheic zone on basin-scale geochemical mass balance. Water Resources Research 34, 623-636.

Haschenburger JK, Rice SP. 2004. Changes in woody debris and bed material texture in a gravel-bed channel. Geomorphology 60, 241-267.

Hassan MA, Hogan DL, Bird SA, May CL, Gomi T, Campbell D. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. Journal of the American Water Resources Association 41, 899-919.

Hassan MA, Woodsmith RD. 2004. Bed load transport in an obstruction-formed pool in a forest, gravelbed stream. Geomorphology 58, 203-221.

Hauer FR, Poole GC, Gangemi JT, Baxter CV. 1999. Large woody debris in bull trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watersheds in northwest Montana. Canadian Journal of Fisheries and Aquatic Sciences 56, 915-924.

Hedman CW, Van Lear DH, Swank WT. 1996. In-stream large woody debris loading and riparian forest seral stage associations in the southern Appalachian Mountains. Canadian Journal of Forest Research 26, 1218-1227.

Heede BH. 1985. Channel adjustments to the removal of log steps: an experiment in a mountain stream. Environmental Management 9, 427-432.

Herdrich AT. 2016. Effects of Habitat Complexity Loss on Eastern Slope Rocky Mountain Brook Trout Populations. MS thesis, Colorado State University, Fort Collins.

Hester ET, Doyle MW. 2008. In-stream geomorphic structures as drivers of hyporheic exchange. Water Resources Research 44, W03417. Doi:10.1029/2006WR005810.

Hickin EJ. 1984. Vegetation and river channel dynamics. Canadian Geographer 28, 111-126.

Higgins D, Reinecke S. 2015. Effects of historical logging on rivers in the lake states. USDA Stream Notes, Nov. 2015, 12 pp.

Hilderbrand RH, Lemly AD, Dolloff CA, Harpster KL. 1997. Effects of large woody debris placement on stream channels and benthic macroinvertebrates. Canadian Journal of Fisheries and Aquatic Sciences 54, 931-939.

Hill EP. 1982. Beaver. In: Chapman JA, Feldhamer GA (eds.), Wild Mammals of North America. The Johns Hopkins University Press, Baltimore, MD, 256-281.

Hogan DL. 1987. The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. In: Erosion and Sedimentation in the Pacific Rim. IAHS Publication no. 165, Wallingford, UK, 343-353.

Hood GA, Bayley SE. 2008. Beaver (Castor canadensis) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. Biological Conservation 141, 556-567.
Hood GA, Larson DG. 2014. Beaver-created habitat heterogeneity influences aquatic invertebrate assemblages in boreal Canada. Wetlands 34, 19-29.
Hossack BR, Gould WR, Patla DA, Muths E, Daley R, Legg K, Corn PS. 2015. Trends in Rocky Mountain amphibians and the role of beaver as a keystone species. Biological Conservation 187, 260-269.
Howard RJ, Larson JS. 1985. A stream habitat classification system for beaver. Journal of Wildlife Management 49, 19-25.
Hughes FMR. 1997. Floodplain biogeomorphology. Progress in Physical Geography 21, 501–529.
Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications 11, 191-202.
Hygelund B, Manga M. 2003. Field measurements of drag coefficients for model large woody debris. Geomorphology 51, 175-185.
Ishikawa Y, Kusano S, Fukuzawa M. 1991. Flood and deposition characteristics of the mud-flow and flooding logs, and mechanism of damage to houses in Ichinomiya Town, Kumamoto Prefecture. Civil Engineering Journal 34, 40-45.
Ives RL. 1942. The beaver-meadow complex. Journal of Geomorphology 5, 191-203.
Jackson KJ, Wohl E. 2015. Instream wood loads in montane forest streams of the Colorado Front Range, USA. Geomorphology 234, 161-170.
Jacobson PJ, Jacobson KM, Angermeier PL, Cherry DS. 1999. Transport, retention, and ecological significance of woody debris within a large ephemeral river. Journal of the North American Benthological Society 18, 429-444.
James CD, Lanman RB. 2012. Novel physical evidence that beaver historically were native to the Sierra Nevada. California Fish and Game 98, 129-132.
Jansson R, Zinko U, Merritt DM, Nilsson C. 2005. Hydrochory increases riparian plant species richness: a comparison between a free-flowing and a regulated river. Journal of Ecology 93, 1094-1103.
Jeffries R, Darby SE, Sear DA. 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. Geomorphology 51, 61-80.
Jensen CK, Leigh DS, Jackson CR. 2014. Scales and arrangement of large wood in first-through fifth-order streams of the Blue Ridge Mountains. Physical Geography 35, 532-560.
John S, Klein A. 2004. Hydrogeomorphic effects of beaver dams on floodplain morphology: avulsion processes and sediment fluxes in upland valley floors (Spessart, Germany). Quaternaire 15, 219-231.
Johnson LB, Breneman DH, Richards C. 2003. Macroinvertebrate community structure and function associated with large wood in low gradient streams. River Research and Applications 19: 199-218.
Johnson SL, Swanson FJ, Grant GE, Wondzell SM. 2000. Riparian forest disturbances by a mountain flood – the influence of floated wood. Hydrological Processes 14, 3031-3050.
Johnston CA. 2014. Beaver pond effects on carbon storage in soils. Geoderma 213, 371-378.
Jones JB, Fisher SG, Grimm NB. 1995. Vertical hydrologic exchange and ecosystem metabolism in a Sonoran Desert stream. Ecology 76: 942-952.

Jones TA, Daniels LD. 2008. Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills. Forest Ecology and Management 256, 1751-1759.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. In Dodge DP, ed., Proceedings of the International Large River Symposium. Canadian Special Publications in Fisheries and Aquatic Sciences 106, 110-127.

Kaeser A, Litts TL. 2003. An assessment of deadhead logs and large woody debris using side scan sonar and field surveys in streams of southwest Georgia. Fisheries 33, 589-597.

Karr JR. 1999. Defining and measuring river health. Freshwater Biology 41, 221-234.

Kasprak A, Magilligan FJ, Nislow KH, Snyder NP. 2012. A lidar-derived evaluation of watershed-scale large woody debris sources and recruitment mechanisms: coastal Maine, USA. River Research and Applications 28, 1462-1476.

Keeley JE, Fotheringham CJ. 2001. Historic fire regime in Southern California shrublands. Conservation Biology 15, 1536-1548.

Keim RF, Skaugset AE, Bateman DS. 2000. Dynamics of coarse woody debris placed in three Oregon streams. Forest Science 46, 13-22.

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

Keller EA, Tally T. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In, DD Rhodes and GP Williams (eds.), Adjustments of the fluvial system, Kendall/Hunt, Dubuque, Iowa, 169-197.

Keller EA, MacDonald A, Tally T, Merrit NJ. 1995. Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek, northwestern California. U.S. Geological Survey Professional Paper 1454-P.

King L, Hassan MA, Wei X, Burge L, Chen X. 2013. Wood dynamics in upland streams under different disturbance regimes. Earth Surface Processes and Landforms 38, 1197-1209.

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

Kochel RC, Ritter DF, Miller J. 1987. Role of tree dams in the construction of pseudo-terraces and variable geomorphic response to floods in Little River valley, Virginia. Geology 15, 718-721.

Kondolf GM. 2006. River restoration and meanders. Ecology and Society 11(2): 42. http://www.ecologyandsociety.org/vol11/iss2/art42/

Kraft C, Schneider R, Warren D. 2002. Ice storm impacts on woody debris and debris dam formation in northeastern US streams. Canadian Journal of Fisheries and Aquatic Sciences 59, 1677-1684.

Kraft CE, Warren DR. 2003. Development of spatial pattern in large woody debris and debris dams in streams. Geomorphology 51, 127-139.

Kramer N, Wohl E. 2014. Estimating fluvial wood discharge using time-lapse photography with varying sampling intervals. Earth Surface Processes and Landforms 39, 844-852.

Kramer N, Wohl E. 2015. Driftcretions: the legacy impacts of driftwood on shoreline morphology. Geophysical Research Letters 42, 5855-5864.

Kramer N, Wohl E. 2017. Rules of the road: a qualitative and quantitative synthesis of large wood transport through drainage networks. Geomorphology 279, 74-97.

Kramer N, Wohl EE, Harry DL. 2012. Using ground penetrating radar to 'unearth' buried beaver dams. Geology 40, 43-46.
Kramer N, Wohl E, Hess-Homeier B, Leisz S. 2017. The pulse of driftwood export from a very large forested river basin over multiple time scales, Slave River, Canada. Water Resources Research 53, 1928-1947.
Kratzer JF, Warren DR. 2013. Factors limiting brook trout biomass in northeastern Vermont streams. North American Journal of Fisheries Management 33, 130-139.
Kreutzweiser DP, Good KP, Sutton TM. 2005. Large woody debris characteristics and contributions to pool formation in forest streams of the Boreal Shield. Canadian Journal of Forest Research 35, 1213-1223.
Lagasse PF, Clopper P, Zevenbergen L, Spitz W, Girard LG. 2010. Effects of Debris on Bridge Pier Scour. Federal Highway Administration, Washington, DC.
Lagasse PF, Zevenbergen LW, Spitz WJ, Arneson LA. 2012. Stream Stability at Highway Structures, 4th ed. Hydraulic Engineering Circular No. 20. Publication No. FHWA-HR-12-004.
Lancaster ST, Grant GE. 2006. Debris dams and the relief of headwater streams. Geomorphology 82, 84-97.
Lanman CW, Lundquist K, Perryman H, Asarian JE, Dolman B, Lanman RB, Pollock MM. 2013. The historical range of beaver (*Castor canadensis*) in coastal California: an updated review of the evidence. California Fish and Game 99, 193-221.
Lanman R, Perryman H, Dolman B, James C, Osborn S. 2012. The historical range of beaver in the Sierra Nevada: a review of the evidence. California Fish and Game 98, 65-80.
Laser M, Jordan J, Nislow K. 2009. Riparian forest and instream large wood characteristics, West Branch Sheepscot River, Maine, USA. Forest Ecology and Management 257, 1558-1565.
Latterell JJ, Naiman RJ. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17, 1127-1141.
Lautz LK, Siegel DI, Bauer RL. 2006. Impact of debris dams on hyporheic interaction along a semi-arid stream. Hydrological Processes 20, 183-196.
Lawrence JE, Resh VH, Cover MR. 2013. Large-wood loading from natural and engineered processes at the watershed scale. River Research and Applications 29, 1030-1041.
Lazar JG, Addy K, Gold AJ, Groffman PM, McKinney RA, Kellogg DQ. 2015. Beaver ponds: resurgent nitrogen sinks for rural watersheds in the northeastern United States. Journal of Environmental Quality 44, 1684-1693.
Le Lay Y-F, Piégay H, Moulin B. 2013. Wood entrance, deposition, transfer and effects on fluvial forms and processes: problem statements and challenging issues. In: Shroder J (ed. in chief), Treatise on Geomorphology, vol. 12, Butler DR, Hupp CR (eds.), Ecogeomorphology. Academic Press, San Diego, CA, 20-36.
Leopold LB, Wolman MG, Miller JP. 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco.
Lester R, Wright W, Jones-Lennon M. 2006. Determining target loads of large and small wood for stream rehabilitation in high-rainfall agricultural regions of Victoria, Australia. Ecological Engineering 28, 71-78.
Levine R, Meyer GA. 2014. Beaver dams and channel sediment dynamics on Odell Creek, Centennial Valley, Montana, USA. Geomorphology 205, 51-64.

Lienkaemper GW, Swanson FJ. 1987. Dynamics of large woody debris in stream in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17, 150-156.

Lisle S. 2003. The use and potential of flow devices in beaver management. Lutra 46, 211-216.

Lisle TE. 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruptions of Mount St. Helens, Washington. Water Resources Research 31, 1797-1808.

Little PJ, Richardson JS, Alila Y. 2013. Channel and landscape dynamics in the alluvial forest mosaic of the Carmanah River valley, British Columbia, Canada. Geomorphology 202, 86-100.

Livers B, Wohl E. 2015. An evaluation of stream characteristics in glacial versus fluvial process domains in the Colorado Front Range. Geomorphology 231, 72-82.

Livers B, Wohl E. 2016. Sources and interpretation of channel complexity in forested subalpine streams of the Southern Rocky Mountains. Water Resources Research 52, 3910-3929.

Livers B, Wohl E, Jackson KJ, Sutfin NA. 2018. Historical land use as a driver of alternative states for stream form and function in forested mountain watersheds of the Southern Rocky Mountains. Earth Surface Processes and Landforms 43, 669-684.

Lyn DA, Cooper T, Yi YK, Sinha R, Rao AR. 2003. Debris accumulation at bridge crossings: laboratory and field studies. Report No. FHWA/IN/JTRP-2003/10. Joint Transportation Research Program, Purdue University, West Lafayette, Indiana.

MacFarlane WA, Wohl E. 2003. Influence of step composition on step geometry and flow resistance in step-pool streams of the Washington Cascades. Water Resources Research 39, 1037. doi:10.1029/2001WR001238.

Macfarlane WW, Wheaton JM, Jensen ML. 2014. The Utah Beaver Restoration Assessment Tool: A Decision Support & Planning Tool. Ecogeomorphology and Topographic Analysis Lab, Utah State University, Prepared for Utah Division of Wildlife Resources, Logan, Utah, 142 pp. Available at: http://etal.usu.edu/BRAT/

Macfarlane WW, Wheaton JM, Bouwes N, Jensen ML, Gilbert JT, Hough-Snee N, Shivik JA. 2017. Modeling the capacity of riverscapes to support beaver dams. Geomorphology 277, 72-99.

MacNally R, Horrocks G, Pettifer L. 2001. Experimental evidence for potential beneficial effects of fallen timber in forests. Ecological Applications 12, 1588-1594.

MacVicar B, Piégay H. 2012. Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). Earth Surface Processes and Landforms 37, 1272-1289.

MacVicar BJ, Piégay H, Henderson A, Comiti F, Oberlin C, Pecorari E. 2009. Quantifying the temporal dynamics of wood in large rivers: field trials of wood surveying, dating, tracking, and monitoring techniques. Earth Surface Processes and Landforms 34, 2031-2046.

Maddock I. 1999. The importance of physical habitat assessment for evaluating river health. Freshwater Biology 41, 373-391.

Magilligan FJ, Nislow KH, Fisher GB, Wright J, Mackey G, Laser M. 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. Geomorphology 97, 467-482.

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.

Manga M, Kirchner JW. 2000. Stress partitioning in streams by large woody debris. Water Resources Research 36, 2373-2379.
Manners RB, Doyle MW, Small MJ. 2007. Structure and hydraulics of natural woody debris jams. Water Resources Research 43, W06432. doi:10.1029/2006WR004910.
Marcus WA, Marston RA, Colvard CR, Gray RD. 2002. Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. Geomorphology 44, 323-335.
Marcus WA, Rasmussen J, Fonstad MA. 2011. Response of the fluvial wood system to fire and floods in northern Yellowstone. Annals of the Association of American Geographers 101, 21-44.
Marston RA. 1982. The geomorphic significance of log steps in forest streams. Annals of the Association of American Geographers 72, 99-108.
Martin DJ, Benda LE. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society 130, 940-958.
Martín-Vide JP, Amarilla M, Zárate FJ. 2014. Collapse of the Pilcomayo River. Geomorphology 205, 155-163.
Maser C, Tarrant RF, Trappe JM, Franklin JF (eds.) 1988. From the Forest to the Sea: A Story of Fallen Trees. USDA General Technical Report PNW-GTR-229, Portland, OR.
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.
May CL, Gresswell RE. 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, USA. Canadian Journal of Forest Research 33, 1352-1362.
Mazzorana B, Zischg A, Largiader A, Hübl J. 2009. Hazard index maps for woody material recruitment and transport in alpine catchments. Natural Hazards and Earth System Science 9, 197-209.
Mazzorana B, Hübl J, Zischg A, Largiader A. 2011. Modelling woody material transport and deposition in alpine rivers. Natural Hazards 56, 425-449.
Mazzorana B, Comiti F, Fuchs S. 2013. A structured approach to enhance flood hazard assessment in mountain streams. Natural Hazards 67, 991-1009.
McDade MH, Swanson FJ, McKee WA, Franklin JF, Van Sickle J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20, 326-330.
McKinstry MC, Anderson SH. 1999. Attitudes of private- and public-land managers in Wyoming, USA, toward beaver. Environmental Management 23, 95-101.
McRae G, Edwards CJ. 1994. Thermal characteristics of Wisconsin headwater streams occupied by beaver: implications for brook trout habitat. Transactions of the American Fisheries Society 123, 641-656.
Meade RH. 2007. Transcontinental moving and storage: the Orinoco and Amazon Rivers transfer the Andes to the Atlantic. In, Gupta A, ed., Large Rivers: Geomorphology and Management. John Wiley and Sons, Chichester, UK, 45-63.
Meentemeyer RK, Butler DR. 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. Physical Geography 20, 436-446.

Megahan WF. 1982. Channel sediment storage behind obstructions in forested drainage basins draing the granitic bedrock of the Idaho Batholith. In, Swanson FJ, Janda RJ, Dunne T, Swanston DN, eds., Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141, Portland, OR, 114-121.
Meleason MA, Gregory SV, Bolte JP. 2003. Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications 13, 1212-1221.
Meredith C, Roper B, Archer E. 2014. Reductions in instream wood near roads in the interior Columbia River basin. North American Journal of Fisheries Management 34, 493-506.
Merten EC, Finlay J, Johnson L, Newman R, Stefan H, Vondracek B. 2010. Factors influencing wood mobilization in streams. Water Resources Research 46, W10514. doi:10.1029/2009WR008772.
Merten EC, Finlay J, Johnson L, Newman R, Stefan H, Vondracek B. 2011. Environmental controls of wood entrapment in upper Midwestern streams. Hydrological Processes 25, 593-602.
Merten EC, Vaz PG, Decker-Fritz JA, Finlay JC, Stefan HG. 2013. Relative importance of breakage and decay as processes depleting large wood from streams. Geomorphology 190, 40-47.
Mikus P, Wyzga B, Kaczka RJ, Walusiak E, Zawiejska J. 2013. Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. Geomorphology 202, 115-127.
Miller RR. 2010. Is the Past Present? Historical Splashdam Mapping and Stream Disturbance Detection in the Oregon Coastal Province. MS thesis, Oregon State University, Corvallis.
Millington CE, Sear DA. 2007. Impacts of river restoration on small-wood dynamics in a low-gradient headwater stream. Earth Surface Processes and Landforms 32, 1204-1218.
Mills EA. 1913. In Beaver World. Houghton Mifflin, Boston.
Minckley WL, Rinne JN. 1985. Large woody debris in hot-desert streams: an historical review. Desert Plants 7, 142-153.
Montgomery DR, Abbe TB. 2006. Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. Quaternary Research 65, 147-155.
Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109, 596-611.
Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 21-47.
Montgomery DR, Massong TM, Hawley SCS. 2003. Influence of debris flows and log jams on the location of pools and alluvial channel reaches, Oregon Coast Range. Geological Society of America Bulletin 115, 78-88.
Morgan LH. 1868. The American beaver and his works. J.B. Lippincott & Co., Philadelphia.
Moore A. 2013. Why fish love 'large woody debris.' Trout Unlimited blog post: http://www.tu.org/blog-posts/why-fish-love-large-woody-debris
Morris AEL, Goebel PC, Palik BJ. 2007. Geomorphic and riparian forest influences on characteristics of large wood and large-wood jams in old-growth and second-growth forests in northern Michigan, USA. Earth Surface Processes and Landforms 32, 1131-1153.

Morris AEL, Goebel PC, Palik BJ. 2010. Spatial distribution of large wood jams in streams related to stream-valley geomorphology and forest age in northern Michigan. River Research and Applications 26, 835-847.
Moulin B, Piégay H. 2004. Characteristics and temporal variability of large woody debris trapped in a reservoir on the River Rhone (Rhone): implications for river basin management. River Research and Applications 20, 79-97.
Moulin B, Schenk ER, Hupp CR. 2011. Distribution and characterization of in-channel large wood in relation to geomorphic patterns on a low-gradient river. Earth Surface Processes and Landforms 36, 1137-1151.
Murphy ML, Koski KV. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9, 427-436.
Mutz M. 2003. Hydraulic effects of wood in streams and rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, 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.
Naiman RJ, Bechtold JS, Beechie TJ, Latterell JJ, Van Pelt R. 2010. A process-based view of floodplain forest patterns in coastal river valleys of the Pacific Northwest. Ecosystems 13, 1-31.
Naiman RJ, Johnston CA, Kelley JC. 1988. Alteration of North American streams by beaver. BioScience 38, 753-762.
Naiman RJ, Melillo JM. 1984. Nitrogen budget of a subarctic stream altered by beaver (*Castor canadensis*). Oecologia 62, 150-155.
Naiman RJ, Melillo JM, Hobbie JE. 1986. Ecosystem alteration of boreal forest streams by beaver (*Castor canadensis*). Ecology 67, 1254-1269.
Naiman RJ, Pinay G, Johnston CA, Pastor J. 1994. Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology 75, 905-921.
Naiman RJ, Sedell JR. 1979. Benthic organic matter as a function of stream order in Oregon. Archives fur Hydrobiologie 87, 404-422.
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.
Nakamura F, Swanson FJ. 2003. Dynamics of wood in rivers in the context of ecological disturbance. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 279-297.
Nakamura F, Swanson FJ, Wondzell SM. 2000. Disturbance regimes of stream and riparian systems – a disturbance-cascade perspective. Hydrological Processes 14, 2849-2860.
Nanson GC, Barbetti M, Taylor G. 1995. River stabilisation due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. Geomorphology 13, 145-158.
Neff DJ. 1959. A seventy-year history of a Colorado beaver colony. Journal of Mammalogy 40, 381-387.

Nihlgard BJ, WT Swank, MJ Mitchell. 1994. Biological processes and catchment studies. In, B Moldan, J Cerny, eds, Biogeochemistry of small catchments: a tool for environmental research. Wiley and Sons, Chichester, 133-161.
Norris RH, Thoms MC. 1999. What is river health? Freshwater Biology 41, 197-209.
Nowakowski AL, Wohl E. 2008. Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. Environmental Management 42, 557-571.
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.
ODNR (Ohio Department of Natural Resources). 2002. Large Woody Debris in Streams. Ohio Stream Management Guide No. 21. Accessed on 30 June 2016. http://soilandwater.ohiodnr.gov/portals/soilwater/pdf/stream/stfs21.pdf
Olson R, Hubert WA. 1994. Beaver: Water Resources and Riparian Habitat Manager. University of Wyoming, Laramie.
Opperman JJ. 2005. Large woody debris and land management in California's hard-wood-dominated watersheds. Environmental Management 35, 266-277.
Opperman JJ, Meleason M, Francis RA, Davies-Colley R. 2008. Livewood: geomorphic and ecological functions of living trees in river channels. BioScience 58, 1069-1078.
Osei NA, Harvey GL, Gurnell AM. 2015. The early impact of large wood introduction on the morphology and sediment characteristics of a lowland river. Limnologica 54, 33-43.
Osterkamp WR. 2008. Annotated definitions of selected geomorphic terms and related terms of hydrology, sedimentology, soil science and ecology. USGS Open File Report 2008-1217, Reston, VA.
Oswald EB, Wohl E. 2008. Wood-mediated geomorphic effects of a jökulhlaup in the Wind River Mountains, Wyoming. Geomorphology 100, 549-562.
Parrish JD, DP Braun, Unnasch RS. 2003. Are we conserving what we say we are? Measuring ecological integrity within protected areas. BioScience 53, 851-860.
Passovoy MD, Fulé PZ. 2006. Snag and woody debris dynamics following severe wildfires in northern Arizona ponderosa pine forests. Forest Ecology and Management 223, 237-246.
Patterson LJ, Muhammad Z, Bentley SJ, et al. 2003. 210Pb and 137Cs geochronology of the Lake Fausse Pointe region of the lower Atchafalaya Basin. Gulf Coast Association of Geological Societies, Transactions 53, 668-675.
Petit F, Pauquet A. 1997. Bankfull discharge recurrence interval in gravel-bed rivers. Earth Surface Processes and Landforms 22, 685-693.
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.
Phillips JD. 2012. Log-jams and avulsions in the San Antonio River delta, Texas. Earth Surface Processes and Landforms 37, 936-950.
Phillips JD, Park L. 2009. Forest blowdown impacts of Hurricane Rita on fluvial systems. Earth Surface Processes and Landforms 34, 1069-1081.
Piégay H. 2003. Dynamics of wood in large rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 109-133.
Piégay H, Gurnell AM. 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. Geomorphology 19, 99-116.
Piégay H, Landon N. 1997. Promoting ecological management of riparian forests on the Drôme River, France. Aquatic Conservation: Marine and Freshwater Ecosystems 7, 287-304.

Piégay H, Gregory KJ, Bondarev V, Chin A,Dahlstrom N, Elosegi A, Gregory SV, Joshi V, Mutz M, Rinaldi M, Wyzga B, Zawiejska J. 2005. Public perception as a barrier to introducing wood in rivers for restoration purposes. Environmental Management 36, 665–674.

Piton G, Recking A. 2016. Design of sediment traps with open check dams. II: Woody debris. Journal of Hydraulic Engineering 142, 04015046. Doi: 10.1061/(ASCE)HY.1943-7900.0001049.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. BioScience 47, 769-784.

Polit JI, Brown S. 1996. Mass and nutrient content of dead wood in a central Illinois flood-plain forest. Wetlands 16, 488-494.

Pollock MM, Wheaton JM, Bouwes N, Volk C, Weber N, Jordan CE. 2012. Working with beaver to restore salmon habitat in the Bridge Creek intensively monitored watershed: design rationale and hypotheses. National Oceanic and Atmospheric Administration, Technical Memorandum no. NMFS-NWFSC-120.

Pollock MM, Beechie TJ, Jordan CE. 2007. Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon. Earth Surface Processes and Landforms 32, 1174–1185.

Pollock MM, Heim M, Werner D. 2003. Hydrologic and geomorphic effects of beaver dams and their influence on fishes. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 213-233.

Pollock MM, Beechie TJ, Wheaton JM, Jordan CE, Bouwes N, Weber N, Volk C. 2014. Using beaver dams to restore incised stream ecosystems. BioScience 64, 279-290.

Pollock MM, Lewallen G, Woodruff K, Jordan CE, Castro JM (eds.). 2017. The Beaver Restoration Guidebook: Working With Beaver to Restore Streams, Wetlands, and Flood-plains, v. 2.0. US Fish and Wildlife Service, Portland, OR, 219 pp. http://www.fws.gov/oregonfwo/ToolsForLandowners/RiverScience/Beaver.asp

Polvi LE, Wohl E. 2012. The beaver meadow complex revisited – the role of beavers in post-glacial floodplain development. Earth Surface Processes and Landforms 37, 332-346.

Polvi LE, Wohl E. 2013. Biotic drivers of stream planform: implications for understanding the past and restoring the future. BioScience 63, 439-452.

Rafferty M. 2013. Development of a Computational Design Tool for Evaluating the Stability of Large Wood Structures Proposed for Stream Enhancement. MS Independent Study, Colorado State University, Fort Collins, CO. http://www.fs.fed.us/biology/nsaec/products-tools.html

Rafferty M. 2017. A Computational Design Tool for Evaluating the Stability of Large Wood Structures. TN-103.2, https://www.fs.fed.us/biology/nsaec/products-publications-technotes.html

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

Ralph SC, Poole GC, Conquest LL, Naiman RJ. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Canadian Journal of Fisheries and Aquatic Sciences 51, 37-51.

Ravazzolo D, Mao L, Picco L, Lenzi MA. 2015. Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. Geomorphology 228, 226-233.

R Core Team. 2017. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.

Reich M, Kershner JL, Wildman RC. 2003. Restoring streams with large wood: a synthesis. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 355-366.

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

Richmond AD, Fausch KD. 1995. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. Canadian Journal of Fisheries and Aquatic Sciences 52, 1789-1802.

Richter BD, Davis MM, Apse C, Konrad C. 2012. A presumptive standard for environmental flow protection. River Research and Applications 28, 1312-1321.

Riley SC, Fausch KD. 1995. Trout population response to habitat enhancement in six northern Colorado streams. Canadian Journal of Fisheries and Aquatic Sciences 52, 34-53.

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.

Ron, P., Quinn TP. 2001. Density and size of juvenile salmonids in response to placement of large woody debris in western Oregon and Washington streams. Canadian Journal of Fisheries and Aquatic Sciences, 58(2), 282–292. https://doi.org/10.1139/cjfas-58-2-282

Roni P, Beechie T, Pess G, Hanson K. 2015. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences 72, 466-478.

Rosell F, Bozser O, Collen P, Parker H. 2005. Ecological impact of beavers Castor fiber and Castor canadensis and their ability to modify ecosystems. Mammal Review 35, 258-276.

Roux C, Alber A, Bertrand M, Vaudor L, Piégay H. 2015. “FluvialCorridor”: A new ArcGIS toolbox package for multiscale riverscape exploration. Geomorphology 242, 29-37. doi:10.1016/j.geomorph.2014.04.018.

Ruffing CM, Daniels MD, Dwire KA. 2015. Disturbance legacies of historic tie-drives persistently alter geomorphology and large wood characteristics in headwater streams, southeast Wyoming. Geomorphology 231, 1-14.

Ruiz-Villanueva V, Bodoque JM, Diez-Herrero A, Blad E. 2014a. Large wood transport as significant influence on flood risk in a mountain village. Natural Hazards 74, 967-987.

Ruiz-Villanueva V, Diez-Herrero A, Ballesteros JA, Bodoque JM. 2014b. Potential large woody debris recruitment due to landslides, bank erosion and floods in mountain basins: a quantitative estimation approach. River Research and Applications 30, 81-97.

Ruiz-Villanueva V, Castellet EB, Diez-Herrero A, Bodoque JM, Sanchez-Juny M. 2014c. Two-dimensional modeling of large wood transport during flash floods. Earth Surface Processes and Landforms 39, 438-449.

Ruiz-Villanueva V, Wyzga B, Zawiejska J, Hajdukiewicz M, Stoffel M. 2015. Factors controlling large-wood transport in a mountain river. Geomorphology.

Ruiz-Villanueva V, Mazzorana B, Mao L, Ravazzolo D, Wohl E, Burkli L, Iribarren-Anacona P, Nakamura F, Stoffel M. 2019. Characterization of wood-laden flows in rivers. Earth Surface Processes and Landforms 44, 1694-1709.
Ryan SE, Bishop EL, Daniels JM. 2014. Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado. Geomorphology 217, 73-88.
Sandoz M. 1964. The Beaver Men: Spearheads of Empire. Hastings House, NY.
Sawyer AH, Bayani Cardenas M, Buttles J. 2011. Hyporheic exchange due to channel-spanning logs. Water Resources Research 47, W08502. Doi: 10.1029/2011WR010484.
Sawyer AH, Bayani Cardenas M, Buttles J. 2012. Hyporheic temperature dynamics and heat exchange near channel-spanning logs. Water Resources Research 48, W01529. doi:10.1029/2011WR011200.
Scheffer PM. 1938. The beaver as an upstream engineer. Soil Conservation 3, 178-181.
Schenk ER, McCargo JW, Moulin B, Hupp CR, Richter JM. 2015. The influence of logjams on largemouth bass (Micropterus salmoides) concentrations on the lower Roanoke River, a large sand-bed river. River Research and Applications 31, 704-711.
Schenk ER, Moulin B, Hupp CR, Richter JM. 2014. Large wood budget and transport dynamics on a large river using radio telemetry. Earth Surface Processes and Landforms 39, 487-498.
Schmidt JC, Parnell RA, Grams PE, Hazel JE, Kaplsinki MA, Stevens LE, Hoffnagle TL. 2001. The 1996 controlled flood in Grand Canyon: flow, sediment transport, and geomorphic change. Ecological Applications 11, 657-671.
Schmocker L, Hager WH. 2011. Probability of drift blockage at bridge decks. Journal of Hydraulic Engineering 137, 470-479.
Schmocker L, Weitbrecht V. 2013. Driftwood: risk analysis and engineering measures. Journal of Hydraulic Engineering 139, 683-695.
Schneider KN, Winemiller KO. 2008. Structural complexity of woody debris patches influences fish and macroinvertebrate species richness in a temperate floodplain-river system. Hydrobiologia 610, 235-244.
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 5 years of decomposition. Ecography 21, 3-10.
Scott DN, Montgomery DR, Wohl EE. 2014. Log step and clast interactions in mountain streams in the central Cascade Range of Washington State, USA. Geomorphology 216, 180-186.
Scott DN, Wohl E, Yochum SE. 2019. Wood jam dynamics database and assessment model (WooDDAM): A monitoring protocol for an evolving, public database and predictive model 35, 1466-1477. doi:10.31223/osf.io/jxzpc
Sear DA, Millington CE, Kitts DR, Jeffries R. 2010. Logjam controls on channel:floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology 116, 305-319.
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, Froggatt JL. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and streamside forest removal. Verhandlungen Internationale Verein. Limnol. 22, 1828-1834.
Sedell JR, Leone FN, Duval WS. 1991. Water transportation and storage of logs. In: Meehan WR (ed.), Influence of Forest and Rangeland Management on Salmonid Fishes and their Habitats. American Fisheries Society Special Publication 19, Bethesda, MD, 325-368.
Sedell JR, Luchessa KJ. 1981. Using the historical record as an aid to salmonid habitat enhancement. In: Armantrout NB (ed.), Acquisition and utilization of aquatic habitat inventory information. American Fisheries, Society, Bethesda, MD, 210-223.
Senter AE, Pasternack GB. 2011. Large wood aids spawning Chinook salmon (*Oncorhynchus tshawytscha*) in marginal habitat on a regulated river in California. River Research and Applications 27, 550-565.
Shields FD, Gippel CJ. 1995. Prediction of effects of woody debris removal on flow resistance. Journal of Hydraulic Engineering 121, 341-353.
Shields FD, Alonso CV. 2012. Assessment of flow forces on large wood in rivers. Water Resources Research 48, W04516. Doi: 10.1029/2011WR011547.
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.
Silsbee DG, Larson GL. 1983. A comparison of streams in logged and unlogged areas of Great Smoky Mountains National Park. Hydrobiologia 102, 99-111.
Simon A, Dickerson W, Heins A. 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? Geomorphology 58, 243-262.
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.
Smith RD, Sidle RC, Porter PE. 1993. Effects on bedload transport of experimental removal of woody debris from a forest gravel-bed stream. Earth Surface Processes and Landforms 18, 455-468.
Smock LA, Metzler GM, Gladden JE. 1989. Role of debris dams in the structure and functioning of low-gradient headwater streams. Ecology 70, 764-775.
Spies TA, Franklin JF, Thomas TB. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69, 1689-1702.
Stanford JA, JV Ward. 1988. The hyporheic habitat of river ecosystems. Nature 335, 64-66.
Stanford JA, Ward JV, Liss WJ, Frissell CA, Williams RN, Lichatowich JA, Coutant CC. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research and Management 12, 391-413.
Stanley EH, Boulton AJ. 1993. Hydrology and the distribution of hyporheos: perspectives from mesic rivers and desert streams. Journal of the North American Benthological Society 12, 79-83.
Steel EA, Richards WH, Kelsey KA. 2003. Wood and wildlife: benefits of river wood to terrestrial and aquatic vertebrates. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 235-247.
Stewart TL, Martin JF. 2005. Energy model to predict suspended load deposition induced by woody debris: case study. Journal of Hydraulic Engineering 131, 1011-1016.

Swanson FJ. 2003. Wood in rivers: a landscape perspective. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 299-313.
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, Corvallis, OR.
Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19, 397-441.
Thompson DM. 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. Geomorphology 11, 235-244.
Tonina D, Buffington JM. 2009. Hyporheic exchange in mountain rivers I: mechanics and environmental effects. Geography Compass 3, 1063-1086.
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.
Triska FJ, Cromack K. 1980. The role of wood debris in forests and streams. In: Waring RH (ed.), Forests: Fresh Perspectives from Ecosystem Analysis. Oregon State University Press, Corvallis, 171-190.
USBR and ERDC (Bureau of Reclamation and US Army Engineer Research and Development Center). 2016. National Large Wood Manual: Assessment, Planning, Design, and Maintenance of Large Wood in Fluvial Ecosystems: Restoring Process, Function, and Structure.
Villarrubia CR. 1982. Movement Ecology and Habitat Utilization of Black Bears in Cherokee National Forest, Tennessee. MS thesis, University of Tennessee, Knoxville.
Wallace JB, Benke AC. 1984. Quantification of wood habitat in subtropical coastal plain streams. Canadian Journal of Fisheries and Aquatic Sciences 41, 1643-1652.
Wallace JB, Webster JR, Eggert SL, Meyer JL, Siler ER. 2001. Large woody debris in a headwater stream: long-term legacies of forest disturbance. Internat. Rev. Hydrobiol. 86, 501-513.
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.
Wallerstein NP. 2003. Dynamic model for constriction scour caused by large woody debris. Earth Surface Processes and Landforms 28, 49-68.
Wallerstein NP, Alonso CV, Bennett SJ, Thorne CR. 2001. Distorted Froude-scaled flume analysis of large woody debris. Earth Surface Processes and Landforms 26, 1265-1283.
Wallerstein NP, Thorne CR. 2004. Influence of large woody debris on morphological evolution of incised, sand-bed channels. Geomorphology 57, 53-73.
Ward GM, Aumen NG. 1986. Woody debris as a source of fine particulate organic matter in coniferous forest stream ecosystems. Canadian Journal of Fisheries and Aquatic Sciences 43, 1635-1642.

Warren DR, Bernhardt ES, Hall RO, Likens GE. 2007. Forest age, wood and nutrient dynamics in headwater streams of the Hubbard Brook Experimental Forest, NH. Earth Surface Processes and Landforms 32, 1154-1163.
Webb AA, Erskine WD. 2003. Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. Geomorphology 51, 109-126.
Webster JR, Stanford JA, Chaffin JL. 2002. Large wood jam in a fourth-order Rocky Mountain stream. Verh. Internat. Verein. Limnol. 28, 1-4.
Webster JR, Swank WT. 1985. Within-stream factors affecting nutrient transport from forested and logged watersheds. In: Blackmon BG (ed.), Proceedings of Forestry and Water Quality: A Mid-South Symposium. Little Rock, Arkansas, 18-40.
Webster JR, Waide JB, Patten BC. 1975. Nutrient recycling and stability of ecosystems. In: Howell FG, Gentry JB, Smith MH (eds.), Mineral Cycling in Southeastern Ecosystems. US Energy Research and Development Administration. Washington, DC, 1-27.
Wellnitz T, Kim SY, Merten E. 2014. Do installed stream logjams change benthic community structure? Limnologica 49, 63-72.
Westbrook CJ, Cooper DJ, Baker BW. 2006. Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Research 42, W06404. Doi:10.1029/2005WR004560.
Westbrook CJ, Cooper DJ, Baker BW. 2011. Beaver assisted river valley formation. River Research and Applications 27, 247–256.
Westbrook CJ, Cooper DJ, Butler DR. 2013. Beaver hydrology and geomorphology. In: Shroder J (ed. in chief), Treatise on Geomorphology, Butler DR, Hupp CR (eds.), vol. 12, Ecogeomorphology. Academic Press, San Diego, CA, 293-306.
Williams DB. 2010. November 27, 1873: Red River logjam removed for good. Earth, 74-76.
Williams DD. 1993. Changes in freshwater meiofauna communities along the groundwater-hyporheic water ecotone. Transactions of the American Microscopical Society 112, 181-194.
Williams GP. 1978. Bank-full discharge in rivers. Water Resources Research 14, 1141-1154.
Wohl E. 2011. Threshold-induced complex behavior of wood in mountain streams. Geology 39, 587-590.
Wohl E. 2013a. Floodplains and wood. Earth-Science Reviews 123, 194-212.
Wohl E. 2013b. Landscape-scale carbon storage associated with beaver dams. Geophysical Research Letters 40, 1-6.
Wohl E. 2013c. Redistribution of forest carbon caused by patch blowdowns in subalpine forests of the Southern Rocky Mountains, USA. Global Biogeochemical Cycles 27, 1205-1213.
Wohl E. 2013d. Wide Rivers Crossed: The South Platte and the Illinois of the American Prairie. University Press of Colorado, Boulder.
Wohl E. 2014. A legacy of absence: wood removal in U.S. rivers. Progress in Physical Geography 38, 637-663.
Wohl E. 2015. Of wood and rivers: bridging the perception gap. WIREs Water 2:167-176.
Wohl E. 2017. Bridging the gaps: an overview of wood across time and space in diverse rivers. Geomorphology 279, 3-26.
Wohl E, Beckman N. 2014a. Controls on the longitudinal distribution of channel-spanning logjams in the Colorado Front Range, USA. River Research and Applications 30, 112-131.

Wohl E, Beckman ND. 2014b. Leaky rivers: implications of the loss of longitudinal fluvial disconnectivity in headwater streams. Geomorphology 205, 27-35.
Wohl E, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC. 2015a. The natural sediment regime in rivers: broadening the foundation for ecosystem management. BioScience 65, 358-371.
Wohl E, Lane SN, Wilcox AC. 2015b. The science and practice of river restoration. Water Resources Research 51, 5974-5997.
Wohl E, Cooper D, Poff L, Rahel R, Staley D, Winters D. 2007. Assessment of stream ecosystem function and sensitivity in the Bighorn National Forest, Wyoming. Environmental Management 40, 284-302.
Wohl E, Bledsoe BP, Fausch KD, Kramer N, Bestgen KR, Gooseff MN. 2016. Management of large wood in streams: an overview and proposed framework for hazard evaluation. Journal of the American Water Resources Association 52, 315-335.
Wohl E, Bolton S, Cadol D, Comiti F, Goode JR, Mao L. 2012. A two end-member model of wood dynamics in headwater neotropical rivers. Journal of Hydrology 462-463, 67-76.
Wohl E, Cadol D. 2011. Neighborhood matters: patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA. Geomorphology 125, 132-146.
Wohl E, Cenderelli DA, Dwire KA, Ryan-Burkett SE, Young MK, Fausch KD. 2010. Large instream wood studies: a call for common metrics. Earth Surface Processes and Landforms 35, 618-625.
Wohl E, Goode JR. 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. Water Resources Research 44, W09429, doi:10.1029/2007WR006522.
Wohl E, Jaeger K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surface Processes and Landforms 34, 329-344.
Wohl E, Dwire K, Sutfin N, Polvi L, Bazan R. 2012. Mechanisms of carbon storage in mountainous headwater rivers. Nature Communications 3, 1263, doi:10.1038/ncomms2274.
Wohl E, Polvi LE, Cadol D. 2011. Wood distribution along streams draining old-growth floodplain forests in Congaree National Park, South Carolina, USA. Geomorphology 126, 108-120.
Wohl E, Rathburn S, Chignell S, Garrett K, Laurel D, Livers B, Patton A, Records R, Richards M, Schook D, Sutfin N, Wegener P. 2017. Mapping longitudinal stream connectivity in the North St. Vrain Creek watershed of Colorado. Geomorphology 277, 171-181.
Wohl E, Scott DN. 2017. Wood and sediment storage and dynamics in river corridors. Earth Surface Processes and Landforms 42, 5-23.
Wohl E, Kramer N, Ruiz-Villanueva V, Scott DN, Comiti F, Gurnell AM, Piegay H, Lininger KB, Jaeger KL, Walters DM, Fausch KD. 2019. The natural wood regime in rivers. BioScience 69, 259-273.
Wolman MG, Leopold LB. 1957. River flood plains: some observations on their formation. U.S. Geological Survey Professional Paper 282-C.
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.
Wondzell SM, Bisson PA. 2003. Influence of wood on aquatic biodiversity. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 249-263.

Wondzell SM, LaNier J, Haggerty R, Woodsmith RD, Edwards RT. 2009. Changes in hyporheic exchange flow following experimental wood removal in a small, low-gradient stream. Water Resources Research 45, W05406. Doi:10.1029/2008WR007214.

Woo M-K, Waddington JM. 1990. Effects of beaver dams on subarctic wetland hydrology. Arctic 43, 223-230.

Wood-Smith RD, Buffington JM. 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impacts on channel condition. Earth Surface Processes and Landforms 21, 377-393.

Wright JP, Jones CG, Flecker AS. 2002. An ecosystem engineer, the beaver, increases species richness at the landscape scale. Oecologia 132, 96-101.

Wyzga B, Zawiejska J. 2005. Wood storage in a wide mountain river: case study of the Czarny Dunajec, Polish Carpathians. Earth Surface Processes and Landforms 30, 1475-1494.

Yochum SE, Bledsoe BP, David GCL, Wohl E. 2012. Velocity prediction in high-gradient channels. Journal of Hydrology 424-425, 84-98.

Yochum SE, Bledsoe BP, Wohl E, David GCL. 2014. Spatial characterization of roughness elements in high-gradient channels of the Fraser Experimental Forest, Colorado, USA. Water Resources Research 50, 6015-6029.

Young MK. 1994. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. Canadian Journal of Forest Research 24, 1933-1938.

Young MK, Haire D, Bozek MA. 1994. The effect and extent of railroad tie drives in streams of southeastern Wyoming. Western Journal of Applied Forestry 9, 125-130.

Young MK, Mace EA, Ziegler ET, Sutherland EK. 2006. Characterizing and contrasting instream and riparian coarse wood in western Montana basins. Forest Ecology and Management 226, 26-40.

Young WJ. 1991. Flume study of the hydraulic effects of large woody debris in lowland rivers. Regulated Rivers: Research and Management 6, 203-211.

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.

Zalewski M, Lapinska M. 2003. Fish relationships with wood in large rivers. In: Gregory SV, Boyer KL, Gurnell AM, eds., The Ecology and Management of Wood in World Rivers. American Fisheries Society Symposium 37, Bethesda, MD, 195-211.

Zelt RB, Wohl EE. 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. Geomorphology 57, 217-233.

Zimmerman RC, Goodlett JC, Comer GH. 1967. The influence of vegetation on channel form of small streams. In: Tison LJ (ed.), Symposium on River Morphology, IAHS Publ. no 75, Gentbrugge, Belgium, 255-275.

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