Large woody debris and river morphology in scour pool formation, dam removal, and delta formation

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Abstract

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The interactions between large woody debris, fluid flow, and sediment transport are a first-order control on river processes, affecting channel morphology at multiple scales. This thesis investigates how wood geometry and orientation affect scour pool formation around individual pieces of woody debris. We find that the presence or absence of roots on woody debris is the main determinant of scour pool size. The size of scour pools and flow disturbances around woody debris also increases as root cross-sectional area relative to flow increases. The Elwha River Restoration project, which includes two large dam removals, provides an opportunity to investigate how woody debris and logjam dynamics change in response to large-scale wood influxes and changes in channel connectivity. Tracking of individually tagged pieces of woody debris shows wood traveled from the upstream reservoir location to the channel reach downstream of both dams after dam removal. The two former reservoirs followed very different logjam development trajectories, with very little logjam development on the upstream reservoir and unexpectedly rapid log jam development on the downstream reservoir. These differences reflect a greater influx of wood into the downstream reservoir and sediment erosion patterns that exposed 1 - 3 m diameter stumps rooted in the pre-dam valley floor that became anchors for logjam formation. One of the questions for Elwha River Restoration project planning was how woody debris buried in reservoir sediments would affect patterns of reservoir delta erosion during and after dam removal. I use flume experiments to investigate the effects of woody debris on dam removal and delta morphodynamics. Experimental runs with woody debris as compared to experiments without woody debris show increases in channel roughness, channel mobility, and the number of active channels on the delta. Several types of physical aquatic habitats increase with woody debris, including hydraulic variability, number of pools, and lengths of channel edges and delta shorelines. Together these results advance our understanding of how woody debris interacts with channel and delta morphodynamics, and suggest that wood interactions at multiple scales should be considered in dam removals, river restoration projects, and delta restoration projects

TABLE OF CONTENTS

List of Figures

List of Tables

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To mom, dad, and grandma

Ch. 1 Introduction

Woody debris in rivers is common wherever drainage basins have trees. Woody debris are among the largest obstacles in river channels and hence can have a large effect on channel morphology. On a reach scale, woody debris affects sediment scour, deposition, and sorting patterns, and can increase sediment storage (Brooks et al., 2004; Cherry and Beschta, 1989; Davidson and Eaton, 2013). Woody debris also increases the number of pools in a system, increases channel roughness, and increases hyporheic flow (Montgomery et al., 1995; Mutz et al., 2007; Sawyer et al., 2011). Wood that accumulates in logjams can anchor stable islands and change channel planform (Abbe and Montgomery, 2003; Collins et al., 2012). Aquatic habitat increases with woody debris, including the amount of cover (Shirvell, 1990), velocity variability (Beechie et al., 2005), and the number of pools (Montgomery et al., 1995). Increasing hyporheic flow also increases dissolved oxygen in the stream bed, affecting fish eggs and benthic invertebrates (Mutz et al., 2007; Sawyer et al., 2011).

Historical records show large amount of woody debris in rivers, including rafts that blocked the entire channel (Collins et al., 2003). Much of this wood was removed from rivers as salvage wood or to increase navigability (Collins et al., 2002, 2003; Lien, 2000). As the ecological benefits of woody debris have become apparent, wood has been returned to rivers in restoration projects that add individual pieces of woody debris or engineered logjams into channels (Abbe et al., 2003; Kail et al., 2007; Roni et al., 2015).

This dissertation addresses how wood influences the interplay between sediment transport, water, and channel form in river systems. Ch. 2 uses flume experiments and field surveys to test how wood orientation and geometry affect flow patterns and channel morphology around individual pieces of woody debris. Ch. 3 investigates wood transport and logjam dynamics before, during, and after the Elwha River Restoration project dam removals. Ch. 4 addresses how woody debris affects planform and channel morphodynamics in dam removals and deltas.

Individual pieces of wood debris are often the largest obstacle in rivers, affecting flow and channel patterns. Ch. 1 uses flume experiments and field surveys on the Hoh River, Washington state to investigate fluid flow patterns and the shape of scour pools around individual pieces of wood. Experiments and field surveys show that the area and volume of scour pools is correlated to the root blockage area relative to flow. The presence or absence of roots is a key factor controlling how much scour occurs. Model trees with solid, star-shaped, and porous roots all have much larger scour areas than model trees without roots. Similarly, the sediment transport experiments and field surveys all show much deeper scour over a larger area for woody debris with roots than for woody debris without roots. These results suggest that river restoration projects focusing on increasing aquatic habitat by adding individual pieces of woody debris to rivers should emphasize the use of woody debris with roots to maximize habitat changes.

The addition of large amounts of woody debris in channels is often the result of unanticipated events such as dam failures, large landslides, or volcanic eruptions. The Elwha River Restoration project, which includes the removal of Glines Canyon Dam and Elwha Dam offers an opportunity to investigate a planned event that adds large amounts of woody debris to a river system. The Glines Canyon Dam removal is the largest dam removal to date by both height and by the amount of stored sediment (Warrick et al., 2015), storing an estimated 16.1 million m^3 (± 2.4 million m^3) of sediment (Randle et al., 2015). When the dams were in place, woody debris and coarse sediment were trapped in the reservoirs behind both dams, leading to channel coarsening (Pohl, 2004) and less woody debris below both dams (Duda et al., 2011; McHenry et al., 2007; Ward et al., 2008). Elwha Dam and Glines Canyon Dam were taken down in phased dam removals between 2011 and 2014, with the goals of restoring native anadromous fish populations and the Elwha River ecosystem (*Elwha River Ecosystem and Fisheries Restoration Act*, 1992). Although there were no estimates of the amount of woody debris stored in the reservoirs (Chenoweth et al., 2011), the amount of woody debris in the system was expected to increase as buried wood was exhumed from the reservoirs, woody debris from the upstream watershed was transported through former reservoir and dam locations, and increased channel migration downstream of both dams resulted in more erosion of floodplain forest (Duda et al., 2011; McHenry et al., 2007). Management of sediment erosion and floodplain forest development on Mills, the reservoir formed by Glines Canyon Dam, and Aldwell, the reservoir formed by Elwha Dam, were some of the main considerations for dam removal and habitat restoration planning (Chenoweth et al., 2011; Randle and Bountry, 2010; Ward et al., 2008). In the first few years after dam removal, it was expected that channel planform and physical habitat on Mills and Aldwell would be very unstable due to the lack of vegetation (Chenoweth et al., 2011; Ward et al., 2008). Using field surveys and air photos, I measured logjam area in the two former reservoirs and river channels downstream of both dams before, during, and after both dam removals. These data show logjam areas increasing in all sections of the river downstream of the former dam locations. Tracking of individually tagged pieces of woody debris shows that woody debris after dam removal was able to travel from the upper reservoir location through the interdam reach, and through the lower reservoir to the river channel below both dam locations. Logjams developed on both Mills and Aldwell after dam removal but with two very different patterns. There were very few logjams that formed in Mills, until a 12 – year recurrence interval flood in 2015. Contrary to pre-project expectations of unstable reservoir sediment for many years after dam removal, large logjams developed on Aldwell in the first year of dam removal. These logjams are anchored on large old-growth tree stumps on the pre-dam valley floor that were uncovered during dam removal.

During the Elwha dam removal planning process, one of the reservoir sediment erosion questions was how woody debris buried in the reservoir sediments would affect patterns and rates of reservoir sediment exhumation (Randle and Bountry, 2010). The sediment management team expected that buried wood would get exhumed during the removal process (Childers et al., 2000) and hypothesized that it would act as an armor layer restricting lateral channel erosion on reservoir deltas (Randle and Bountry, 2010). Although there has been a considerable amount of research on the effects of woody debris in rivers (Gurnell et al., 2002; Montgomery et al., 2003; Ruiz-Villanueva et al., 2016; Wohl, 2017) very little research has been done on how woody debris affects deltas (Huff, 2015; Phillips, 2012). In Ch. 3 I use flume experiments to investigate how the exhumation of buried woody debris affects dam removal and delta morphodynamics. These experiments show that woody debris increases the rate of lateral channel migration and the number of delta channels, compared to systems without woody debris. Physical aquatic habitat also increases with woody debris, with increases in the number of pools, the amount of channel edge habitat, and the amount of delta shoreline habitat. These results suggest that woody debris can play an important role in dam removals and delta morphodynamics and should be taken into consideration for dam removals and delta restoration projects in forested regions.

Ch. 2 – 4 are written as 3 stand-alone papers that, although primarily my work and analyses, will be submitted for publication with co-authors who helped with field work, flume experiments, and framing the investigations. Ch. 2, on scour pool formation around individual pieces of woody debris will be published with co-author David R. Montgomery. Ch. 3, on logjam development and woody debris dynamics during the Elwha River dam removals, will be published with co-authors Randall McCoy, Mike McHenry, and David R. Montgomery. Ch. 4, on how woody debris interacts with dam removals and deltas, will be published with co-authors David C. Mohrig, Jim L. Buttles, Joel P. Johnson, and David R. Montgomery. Together these chapters document the fundamental role of, and advance understanding of, interactions between woody debris stability and transport, sediment scour and transport, and flow hydraulics at scales from individual pools to the evolution of deltaic systems.

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Ch. 2 The effects of woody debris on streambed morphology: flume experiments on the spatial patterns of fluid flow and sediment transport around individual pieces of wood debris

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Abstract

The interaction of woody debris, fluid flow and sediment transport in rivers creates local streambed morphology, such as large pools that are important fish habitat and sediment deposits that bury and stabilize woody debris. We used two sets of flume experiments and field measurements on a gravel-bedded river to investigate how wood geometry and orientation affect local flow and scour pool formation. For the first set of experiments, fluid flow patterns on the bottom boundary layer, where bedload sediment transport occurs, were visualized using solid dye crystals. The second set of experiments and the field measurements investigated streambed morphology around wood debris, as well as distributions of wood debris geometry and orientation in nature. We find that: 1) the presence of roots on woody debris leads to greater areas of flow disturbance and sediment scour; 2) the size of scour pools and flow disturbances around wood debris increase as the root cross-sectional area, oriented orthogonal to flow, increases. A better understanding of the underlying sediment physics and fluid dynamics around

naturally occurring woody debris in rivers can lead to improved hazard prediction of mobile wood during floods and to improved design criteria for engineered logjams placed to protect infrastructure and improve aquatic habitat.

Introduction

Woody debris has been recognized to have a fundamental role in river dynamics, comparable to the role of water discharge and sediment transport, significantly impacting aquatic habitat (Montgomery et al., 2003). Wood debris also plays a key role in creating physical habitat for fish spawning, feeding and hiding. Individual logs and logjams are significant obstacles in channels, causing local flow disturbances, sediment scour and deposition (Cherry and Beschta, 1989; Daniels and Rhoads, 2003). Wood and logjams increase channel roughness, decrease sediment transport and increase reach scale sediment storage (Davidson and Eaton, 2013; Gippel et al., 1996; Mutz, 2000). At the reach scale, woody debris affects hydraulics, sediment transport and streambed morphology and has a significant effect on aquatic habitat (Gregory et al., 2003). Woody debris increases the hydraulic and topographic complexity of the channel and riparian zone, leading to a greater diversity of aquatic habitats such as pools or slow water refugia (Roni and Quinn, 2001). Large woody debris also helps to retain gravels that are used by spawning salmon (Brooks et al., 2004) and increases hyporheic flow, increasing the dissolved oxygen that reaches salmon eggs incubating within the streambed (Mutz et al., 2007; Sawyer et al., 2011). In forest rivers, many large pools that form important fish habitat, are controlled by scour around large woody debris (Abbe and Montgomery, 2003; Montgomery et al., 1995).

In this study, we use two sets of flume experiments and field measurements on a gravel-bedded river to test how woody debris geometry affects patterns of local sediment scour and deposition and how wood debris orientation relative to flow affects patterns of local sediment scour and deposition. The fluid flow experiments investigate the effects of woody debris on channel morphology by using flow patterns around wood debris as a proxy for sediment erosion and deposition. These flume experiments focus on the flow patterns at the bottom boundary, where sediment transport occurs. The streambed morphology experiments investigate the effects of woody debris on channel morphology by measuring scour and sediment deposition under controlled laboratory conditions. These flume experiments focus on the scour and sediment deposition patterns around woody debris that form under constant uni-directional flow, with uni-modal sediment. The streambed morphology fieldwork investigates scour and sediment deposition around individual pieces of woody debris on a gravel-bedded river. A better understanding of the underlying sediment physics and fluid dynamics around naturally occurring woody debris in rivers can lead to improved hazard prediction of mobile wood during floods and to improved design criteria for engineered logjams placed to protect infrastructure and improve aquatic habitat.

Background

Historically, large woody debris was routinely removed from rivers in the Pacific Northwest to improve navigation, facilitate fish passage and protect infrastructure (Bisson et al., 1987; Collins et al., 2003; Nagayama and Nakamura, 2010). In-stream wood loads were also reduced by anthropogenic activities such as floodplain logging, channelization and levee building that affected local recruitment of riparian trees (Czarnomski et al., 2008; Faustini and Jones, 2003). In many places, wood has been removed from floodzones in order to reduce flood hazards (Comiti et al., 2016). Wood moving in floods can amplify flood risks by altering local flow patterns through logjam formation and the increased impact force from wood moving in the water (Ishikawa et al., 1991; Johnson et al., 2000).

Sediment transport around woody debris is episodic and often occurs during flood events, making it difficult to take active measurements. Combining flume experiments and fieldwork allows for a general understanding of sediment transport around woody debris that includes both the episodic nature of flooding and the complexities of natural systems. Understanding factors controlling how wood debris affects local streambed morphology can provide scientific insights into channel morphodynamics as well as guidance and criteria for use in river restoration and engineering projects.

Wood debris in natural systems is deposited as individual pieces and in logjams. River restoration projects use anchored individual pieces of wood, unanchored individual pieces of wood, and engineered logjam structures (Hilderbrand et al., 1998; Kail et al., 2007; Lester and Boulton, 2008; Roni et al., 2015). Logjams and wood debris can affect flow patterns in a variety of ways, including flow deceleration (Davidson and Eaton, 2013; Nakano et al., 2018), changes in helical motion (Daniels and Rhoads, 2003, 2007), and increased drag (Manners and Doyle, 2008). Pools associated with logjams tend to be short, deeper, and in straighter channel reaches than pools not associated with logjams (Abbe and Montgomery, 1996; Davidson and Eaton, 2013). The shapes of pools associated with logjams varies depending on logjam and channel configurations, with bar apex logjams forming crescent shaped pools, meander logjams forming long, narrow, and deep pools, and bar top logjams seldom forming pools (Abbe and Montgomery, 1996).

While woody debris in the field is most often oriented parallel to flow with the roots pointed upstream, other orientations relative to flow occur as well. Additionally, in low-energy streams with little transport capacity, trees may often remain at whatever angle occurred when they first fell into the stream (Abbe and Montgomery, 2003). Using flume experiments with model wood without roots, Cherry and Beschta (1989) found that for model wood with one end anchored at the stream bank, scour depth, scour area, and scour shape all varied depending on wood orientation relative to flow. The largest amount of scour occurred with wood oriented perpendicular to flow. In field experiments, Hilderbrand et al. (1998) similarly found that adding wood without roots at different orientations relative to flow in a stream resulted in a range of pool shapes and sizes. For individual pieces of woody debris with the roots pointing upstream, Abbe and Montgomery (1996) developed a theoretical model of flow structures around a single key piece in the center of a channel that includes a horseshoe vortex and flow separation around the roots resulting in a crescent shaped scour pool. We are unaware of any experimental research on the effects of wood with roots on scour pools.

Methods

Fluid Flow Experiments

Experimental work was carried out at the Flow Lab at the University of Washington's Friday Harbor Laboratories, in a 70 cm wide paddle wheel driven annular flume with a 6 m long working section. All experiments involved a flat, immobile bed without sediment, and individual, stationary model trees. For each experimental run the flume was turned on and run until flow velocity was no longer increasing. Reynolds numbers for the experiments ranged from 920 to 11,000, and Froude numbers ranged from 0.03 to 0.18. Flow visualization used potassium permanganate crystals which sink to the base of the flow and bleed a magenta dye that shows the direction of local fluid flow. These were used to visualize horizontal flow patterns on the bottom boundary layer, the focus of the experiment since sediment deposition and suspension occurs at the bottom boundary layer of a river. Using the potassium permanganate dye tracers, it's possible to visualize the detailed flow field around the wood debris (Fig. 1a). In particular, it is possible to delineate 'scour zones' where most of the dye is being advected downstream and scour would occur and 'deposition zones' where most of the dye is being slowly recirculated in place and where sediment deposition would occur (Fig. 1b). The advection zones correlate to areas where scour would occur and the recirculation zones correlate to areas where sediment deposition would occur. Overhead photographs for the experiment were taken using a digital camera.

Model trees for the experiments were created from PVC, wood, and wire. Tree trunks were created from 2.1 cm diameter PVC pipe and were 29 cm long. Natural roots on wood debris come in a range of shapes and sizes. Depending on tree age, species, and growth patterns, roots may be an almost solid mass or have a semi-porous structure of interwoven roots. Some species have a star-shaped root structure with a small number of large roots that decrease in diameter as they get farther from the trunk. Root shape also changes over time with smaller roots and roots farther from the trunk breaking off as wood debris is transported and decays. In order to have a more realistic model wood debris, models were created with no roots, solid rootwads, rootwads of wire mesh, to model a uniformly porous rootwad, and rootwads of a solid star shape to model a root structure that decreases in root density as distance from the trunk increases. Finally, semicircular solid and wire mesh rootwads were created to model trees that are partially buried in the river bottom. Due to the low density of the PVC and wooden roots, some of the model trees were weighted with metal rods inside the PVC pipes.

The first set of flume experiments tested the effects of root shape, width, diameter and porosity on the local fluid flow field with all the model trees set parallel to flow with their rootwads pointed upstream. The second set of experiments looks at changes in the local flow field when model trees are set at different angles in the flow. In rivers, individual pieces of woody debris are most often found parallel to flow with their rootwads pointed upstream (Abbe and Montgomery, 2003). Wood debris tends to float downstream with rootwads pointed downstream until the roots ground out and get stuck in the riverbed. At this point the rootwad acts as an anchor and the trunk, which is still floating in the river, continues to move downstream, causing the tree to pivot around the rootwad until the trunk points downstream.

Streambed Morphology Experiments

Experimental work was carried out at the St. Anthony Falls Laboratory of the University of Minnesota, in a 1.22 m wide flume with a 7 m long working section. All experiments involved a 15 cm deep mobile sediment bed, constant discharge and individual stationary trees. Similar to the fluid flow experiments, eight types of model trees were created from plastic, wood and wire mesh, with rootwads in a range of shapes and sizes that corresponded to different types of rootwads found in nature, including model wood debris without roots.

Topographic measurements used vertical sheet lasers set perpendicular to flow (A.1). The lasers and an oblique camera were mounted on a moving cart. Topographic measurements were taken every cm for the areas with greatest scour and sediment deposition and every 10 cm downstream from there. The flume had large low bars that moved during the experiment, so it was not possible to difference the streambed topography at the beginning and end of each experiment to calculate scour or sediment deposition volumes. Scour pool boundaries were manually delineated, and a surface was created using only those points. This top surface and the experimental streambed surface were differenced to calculate the scour volume. For the experiments, model trees were set parallel to the flow with roots pointed upstream, 45° relative to flow, perpendicular to flow, 135° relative to flow, and parallel to flow with roots pointed downstream. Despite the model wood being denser than water and some wood burial occurring during the experiments, some of the model wood moved from the original orientation relative to flow. Each experiment started with water flowing over sediment, then a piece of wood debris was placed in the flume. In the experiments, Reynolds numbers ranged from 5,151 to 14,141, and Froude numbers ranged from 0.53 to 0.71. The flume was drained before topographic measurements were taken.

Streambed Morphology around Individual Pieces of Wood Debris

Field measurements were collected in the Hoh River, in WA state, which has headwaters in the mountains of Olympic National Park, runs through the Hoh Rain Forest, a temperate rain forest, and flows into the Pacific Ocean. The Hoh River watershed is approximately 298 mi^2. Average annual precipitation ranges from 93 – 240 in, depending on location (Klinger et al., 2007). The highest flows typically occur during the late fall/early winter storm season, with moderate flows during the late spring snowmelt, and the lowest flows typically in late summer. In recent decades, peak flows have been increasing while summer flows have been decreasing (Hoh Tribe, 2016).

Field measurements of streambed morphology around woody debris were taken on gravel and cobble bars during low flow and show the cumulative scour and sediment deposition of multiple flow events. Field measurements were taken on several sites on the Hoh River, near the boundary of Olympic National Park during low flow in Sept. 2010 and Aug. – Sept. 2011. Peak discharges in the previous winter storm season were 30,400 cfs in 2010 and 40,300 cfs in 2011. Measurements were taken on cobble bars, banks and side channels that were either dry or had extremely low flow. It was not discernible how long the wood debris had been in place on the cobble bars. A laser theodolite was used to take 30 – 100 topographic points around each piece of wood debris (A.2). Topographic measurements were taken around individual pieces of wood debris that were specifically chosen for having larger amounts of associated scour.

Additionally, the geometry and orientation of every piece of individual wood debris on 4 medium sized bars were surveyed in order to investigate the range of wood debris sizes and deposition orientations that occur in the field site. This survey also included the geometry and orientation of key pieces in logjams where the key pieces were interpreted to be the first pieces of wood deposited, and therefore wood orientation was not affected by other pieces of wood debris. Tree orientation relative to flow is defined so that 0° is parallel to flow, with the roots pointed upstream, and 180° is parallel to flow with the roots pointed downstream. For trees without roots, orientations of 0° vs. 180° and 45° vs. 135° are indistinguishable, and were marked as 0° and 45°, respectively.

Results

In the fluid flow experiments, the scour and deposition zones spanned a range of sizes and shapes. The scour zones were mostly crescent shaped, with the arms of the crescent pointed downstream. For experimental runs with the model tree trunk parallel to flow, the scour zones were quasi-symmetrical (Fig. 4). As root blockage area increased, going from no roots, to mesh roots, star shaped roots and solid roots, the sizes of both the scour zones and the deposition zones increased. The model tree without roots had smaller scour and deposition zones than the model trees with roots. Model trees with porous roots had deposition zones that were farther downstream than model trees with solid roots (Fig. 4). Model trees with solid roots developed a horseshoe vortex wrapped around the roots at the streambed (A.3 A, B). Model trees with porous roots had less coherent flow structures (A.3 C).

For experimental runs with the model tree trunk in a range of orientations relative to flow, the scour and deposition zones varied considerably in shape and size (Fig. 5). The scour and deposition were quasi-symmetrical only when the model wood debris was at 0° or 180°, parallel to the flow direction. The scour zones were mostly crescent shaped, with the arms pointed downstream. The deposition zones are mostly shaped like round-ish blobs superimposed on the roots. For model wood debris with roots, as model wood orientation changes, the root cross-sectional area relative to the flow direction changes. The largest root cross-sectional areas occur when the wood is oriented at 0° and 30°, and smallest root-cross-sectional areas occur when the wood is oriented at 90°. In a few instances where root depth was larger than root diameter, the opposite pattern developed. Larger root cross-sectional areas correspond to larger scour zones and larger deposition zones (Fig. 6).

For streambed morphology measurements, both in the field and experimentally, scour pools had a very well-defined upstream boundary, with a sharp slope change between the pool and the rest of the streambed. In contrast, the scour pools had poorly defined downstream boundaries; as the scour pool gradually became shallower downstream, the sediment deposition was superimposed onto an already uneven streambed surface, and there were no clearly defined slope changes between the pool and the rest of the streambed surface. This only affects scour pool volume measurements a little, since the downstream ends of the pool were very shallow, with most of the scour pool volume on the upstream. Where the downstream boundary was imprecise, it resulted in only small changes in the volume measurements (i.e., <15%). In a few cases, fine sediment was deposited at the downstream end of the woody debris, but since the streambed was mostly gravel and cobble, it is likely that the fine sediment deposition occurred under different flow conditions than when pool scour occurred.

In the streambed morphology experiments, the scour pools around individual pieces of model wood varied considerably in shape, volume, and depth (Fig. 7). For model wood without roots, the scour pools were mostly small and shallow. Scour pool area increased as the model trunk cross-sectional area increased. For model wood with roots, the scour zone was deepest around the roots, and scour pools were larger than the scour areas around model wood without roots. The scour pools are round at the upstream end and have one or two pointed arms at the downstream end. When the model tree trunk is parallel to flow, the scour pools are more symmetrical. Scour pool volumes ranged from 3×10^{-5} m^3 to 1.5×10^{-4} m^3 for model wood without roots and 3×10^{-4} m^3 to 6×10^{-4} m^3 for model wood with roots.

In the streambed morphology measurements in the field, the scour pools around individual pieces of wood varied considerably in shape, volume, and depth (Fig. 8). For pieces of woody debris without roots, the scour pools are mostly small and shallow, while for pieces of wood with roots, the scour pools were larger and deeper. The scour pools around wood with roots were mostly round on the upstream end and had one or two pointed lobes on the downstream end. For both the experimental and the field measurements, scour pool volume systematically increased with increasing root cross-sectional area (Fig. 9).

In the field study site, individual pieces of woody debris were deposited in all orientations relative to the flow direction. For four bars where every individual piece of wood was surveyed, 81% of a total of 118 pieces of woody debris had roots and 19% did not have roots. For woody debris with roots, about half of the pieces, 54%, were deposited at 0° parallel to flow with the root end pointed upstream. Most of the other woody debris, 27%, was deposited at

45° relative to flow, with 9% at 135°, and 7% at 180°. The least common deposition orientation, at 3%, was 90°. For trees without roots, half were orientated at 0°, with most of the rest, 41%, at 45°. As with the woody debris with roots, the least common deposition orientation was 90° relative to flow, at 9% (Fig. 3).

Discussion

We find that the primary control on scour size is the presence or absence of roots. Woody debris geometry and orientation have additional effects on scour depth, volume, and shape. The scour pool volume and the size of flow disturbance around woody debris both increase as root cross-sectional area increases. These controls on scour deposition and size have implications for river restoration planning.

The fluid flow experiments, sediment transport experiments, and field measurements all show that scour pool size is strongly dependent on woody debris geometry and orientation. The presence of roots on woody debris results in significantly deeper scour, over a larger area, as compared to woody debris of similar size without roots (Fig. 4, Fig. 7, fig. 8). Woody debris orientation relative to flow affects the volume and shape of scour pools (Fig. 7, Fig. 8), as well as fluid flow patterns around the woody debris (Fig. 4, Fig. 5). The scour pool volume and size of the flow disturbance both increase as the root cross-sectional area increases (Fig. 6, Fig. 9).

While individual pieces of woody debris on the Hoh River were deposited in all possible orientations, wood at 0° (parallel to flow with roots pointing upstream) and 45° were most common by far. Abbe and Montgomery (2003) hypothesized and Davidson and Eaton (2015) found that these preferential orientations occur since woody debris travels during floods with the roots on the downstream end, but as floodwaters recede and flow shallows, the roots act as an anchor against the bed with the trunk still affected by flow and moving downstream until the wood is oriented parallel to flow with the roots pointing upstream. Wood size and shape varies depending on tree species, age, and growing conditions. As woody debris is transported downstream and over time, the rootball also becomes smaller as outer parts are broken during transport or by mobile sediment.

The local effects of streambed scour associated with woody debris influence pre-existing topography such as streambanks and large bars, as well as localized topography that develops concurrently with the woody debris, influenced scour of pools and deposition of dunes and small bars. Scour pools are formed superimposed on this topography, which in some cases affects the shape and size of the scour pool. For example, in both the field and experimental measurements, some of the wood debris was at the base or on the edge of a streambank (Fig. 7, Fig. 8). This led to restricted flow patterns and preferential erosion on the open side of the wood. While this topography forms naturally, it may affect scour pool volume and depth, as compared to wood debris in flatter parts of the streambed.

Discharge variability appears to exert a limited effect on scour pool size. The streambed morphology experiments had a very narrow range of flow conditions and the scour measurements in the field were taken after unknown flow velocities and flow depths, with an unknown sequence of flood events. However both the flume experiments and the field data show a similar relationship between scour volume and root cross-sectional area (Fig. 9).

Differences in scour pool volume and shape affect flow patterns in the channel, and consequently sediment transport patterns and sediment sorting. These differences in channel bed morphology influence the type and availability of aquatic habitats. Increased depth variability and channel roughness from scour pools creates a more diverse range of aquatic habitats.

Preferential sediment sorting can concentrate the gravel sizes important for salmon and other fish that spawn in redds. The increased roughness also drives more hyporheic flow (Mutz et al., 2007; Sawyer et al., 2011), resulting in more dissolved oxygen available for insects, fish eggs, and juvenile fish living in the interstitial gravel spaces in the streambed.

As the relationship between wood and habitat has become better understood, putting wood back into rivers has become a widely accepted tool in river management (Lester and Boulton, 2008; Nagayama and Nakamura, 2010). Wood is reintroduced in rivers either as individual pieces, free-floating or anchored, or as engineered logjams (ELJs) that mimic natural logjams. Engineered logjams have become a widely accepted tool in river management for the purpose of decreasing the rate of riverbank migration and for improving aquatic habitat (Abbe et al., 2003; Brooks et al., 2004; Lester and Boulton, 2008). Sediment deposits around woody debris build up riverbanks and counteracts bank migration on the bank where the wood is located. Logjams and individual logs are also used to create the large pools and complex streambed morphology that are important fish habitat and to accumulate the smaller grain sizes used by spawning anadromous fish (Kail et al., 2007).

Consequently, the different possible scour pool volumes and shapes are important for assessing and restoring aquatic habitat. For example, different fish species and life stages prefer different pool sizes. Hence the species and size of woody debris in a river may result in pools more or less suitable for particular types of fish. River restoration infrastructure may also be designed in order to form the sizes and shapes of scour pools that would have occurred naturally (Roni et al., 2015). Restoration projects focusing on improving aquatic habitat have become increasingly common (Abbe et al., 2003; Kail et al., 2007; Roni et al., 2015) but many structures are placed in orientations that minimize their effects on flow structures and channel morphology

(Kail et al., 2007). If individual pieces of woody debris are added as part of a restoration project, with pieces anchored or cabled in place, trunk orientation will affect the size and shape of scour pools that form. For restoration projects focusing on aquatic habitat that add individual, unconstrained woody debris, projects should plan for the wood to reorient to 0° or 45° relative to flow.

Restoration efforts are also increasingly supplementing woody debris in rivers by adding wood from outside the floodplain. There is often a financial incentive to add woody debris without roots as part of river restoration projects. Trees with roots are more expensive as it requires more time and skill to excavate intact roots. Wood transportation costs are also greater, as trees with roots can't pack as densely on a truck as trees without roots. While wood without roots will still create some fish habitat, wood with roots will create considerably more.

Our experiments and fieldwork focused on wood debris with a single trunk and varying root geometries. In areas where other tree geometries are common, such as trees with multiple large trunks, it is likely that the geometry of the trunks will have as much or greater of an effect than roots on scour pool size(Dixon and Sear, 2014). This study also focuses on a cobble and gravel river. Mutz (2000) found that sand-bedded rivers have fewer logjams, potentially due to sand being more easily erodible. We hypothesize that similar scour patterns would form in sandy rivers but scour depths and volumes would be less than in cobble or gravel rivers. Additionally our results do not take sediment cohesion into account, so it is unlikely that these findings are applicable in silt or mud-rich systems.

Conclusion

Analysis of fluid flow and channel morphodynamics around individual pieces of woody debris reveal the systematic influence and importance of wood geometry and orientation on flow disturbance, scour pool size, and scour pool shape. The presence of roots on woody debris results in significantly deeper scour, over a larger area, as compared to woody debris of similar size without roots. Woody debris orientation relative to flow affects the volume and shape of scour pools, as well as fluid flow patterns around the wood debris. The scour pool volume and size of the flow disturbance both increase as the root cross-sectional area increases. Quantifying the relationships between wood geometry, wood orientation, scour pool size, and scour pool shape can provide insights into channel morphodynamics, as well as guidance and criteria for use in river assessment, restoration, and engineering.

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Figures

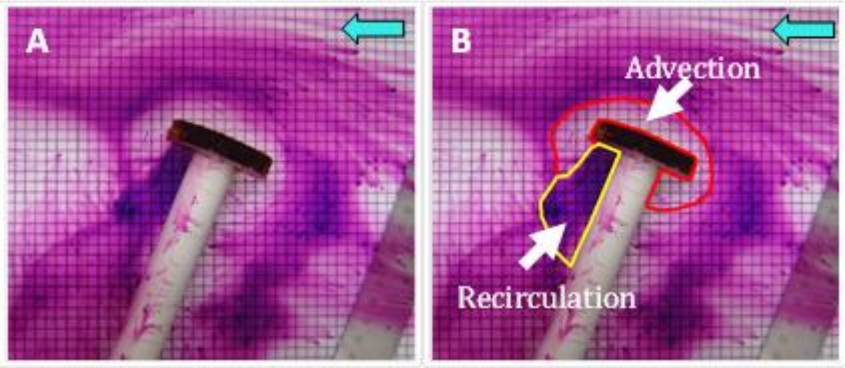


Fig. 1 A) Overhead view of flow visualization around wood debris using potassium permanganate crystals. B) Scour and deposition zones delineated from areas of dye advection and recirculation.

Fig. 2 Model wood debris with varying root sizes and geometries.

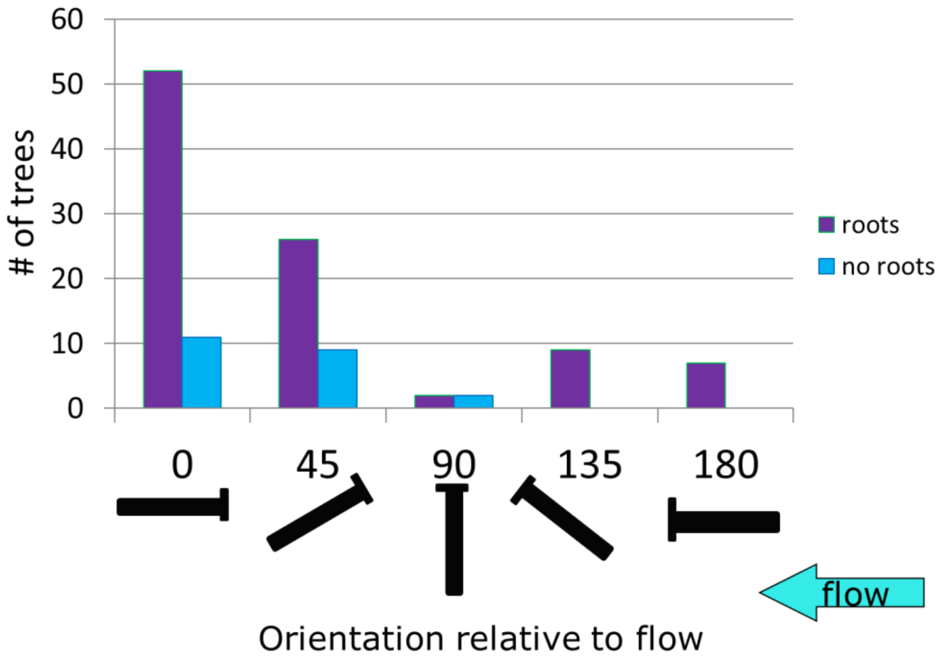


Fig. 3 Wood debris orientation relative to flow, for all individual pieces of wood debris on four bars in the Hoh River.

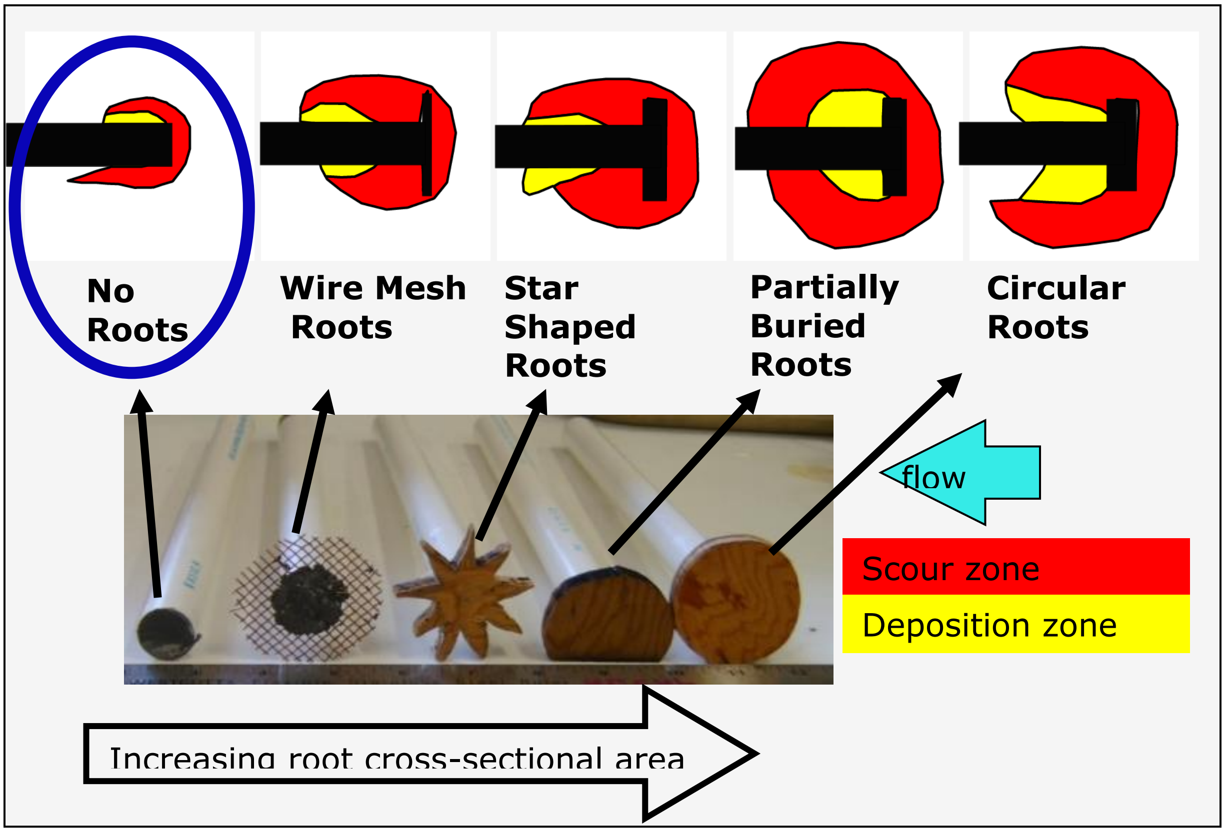


Fig. 4 Scour and deposition zones around wood debris with different types of rootwads. Wood debris without roots has significantly smaller scour and deposition zones as compared to wood debris with any type of roots. Increased root density increases the size of the scour and deposition zones. Additionally the scour zone moves farther away from the roots as root blockage area decreases. Scour and deposition zones are delineated as shown in Fig. 1.

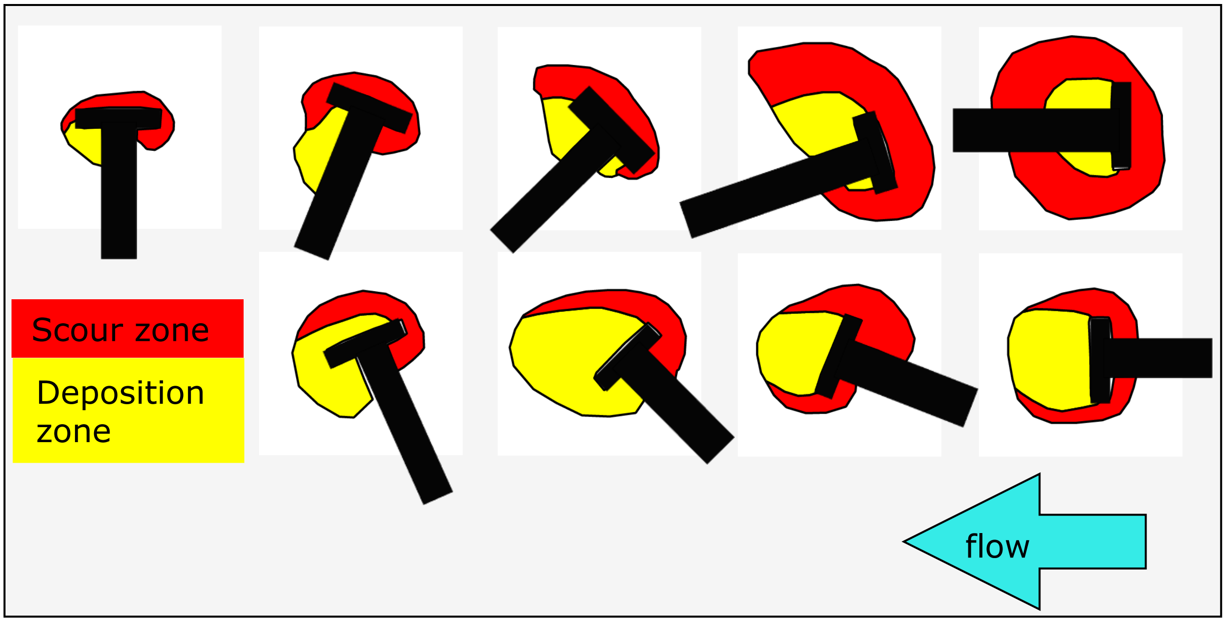


Fig. 5 Wood debris orientation relative to flow affects the size and shape of both the scour and deposition zones. The size of the flow disturbance correlates to the cross sectional area of the wood debris relative to flow. Scour and deposition zones are delineated as shown in Fig. 1.

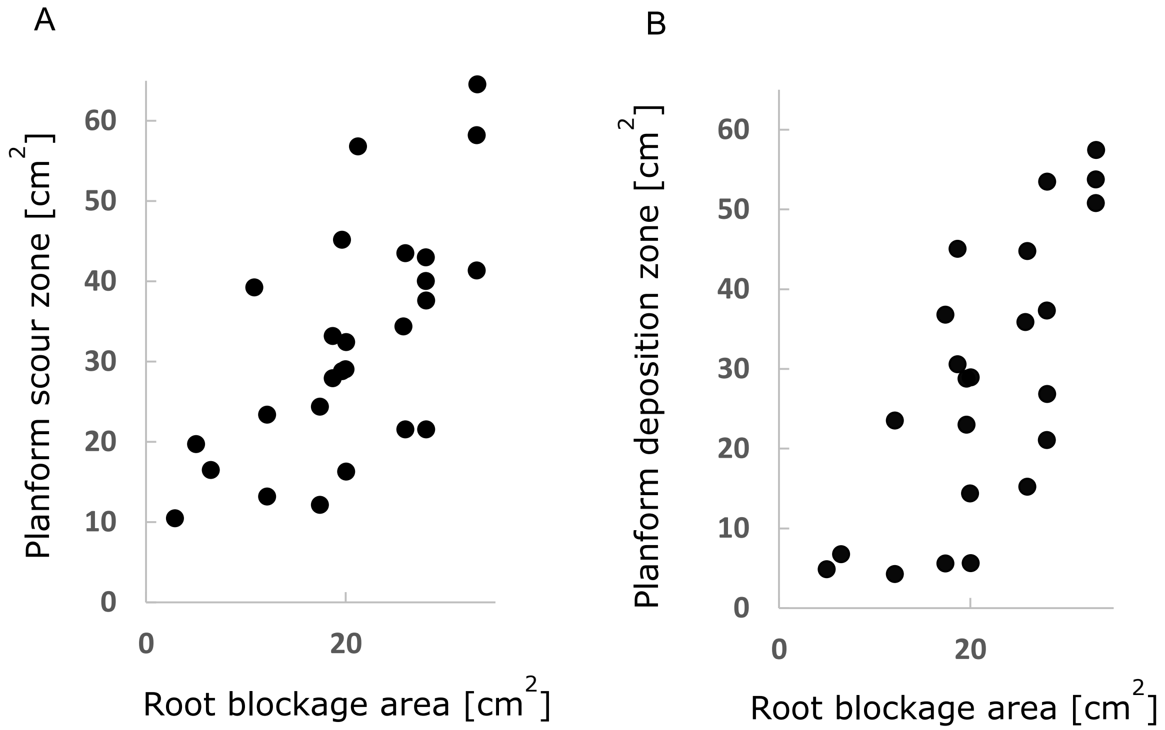


Fig. 6 Planform scour zones (A) and deposition zones (B) plotted against root cross-sectional area relative to flow.

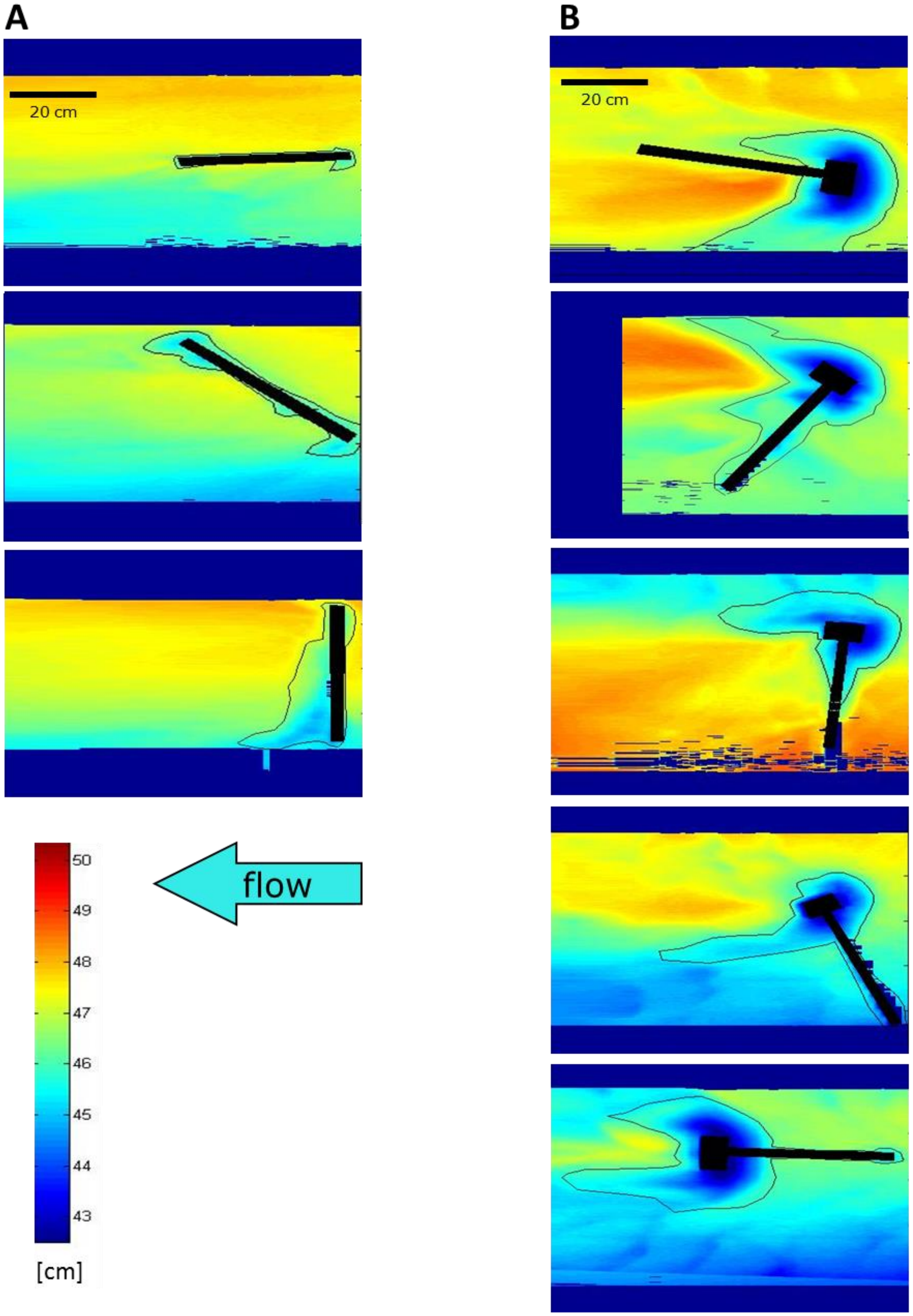


Fig. 7 Bed topography from streambed morphology experiments with wood debris without roots (A) and with roots (B) in a range of orientations. Flow is from right to left. Scour zones are outlined in black. Wood debris without roots (A) has significantly shallower sediment scour and deposition over a smaller area as compared to wood debris with roots (B). Wood debris orientation relative to flow affects the size and shape of scour and sediment deposition.

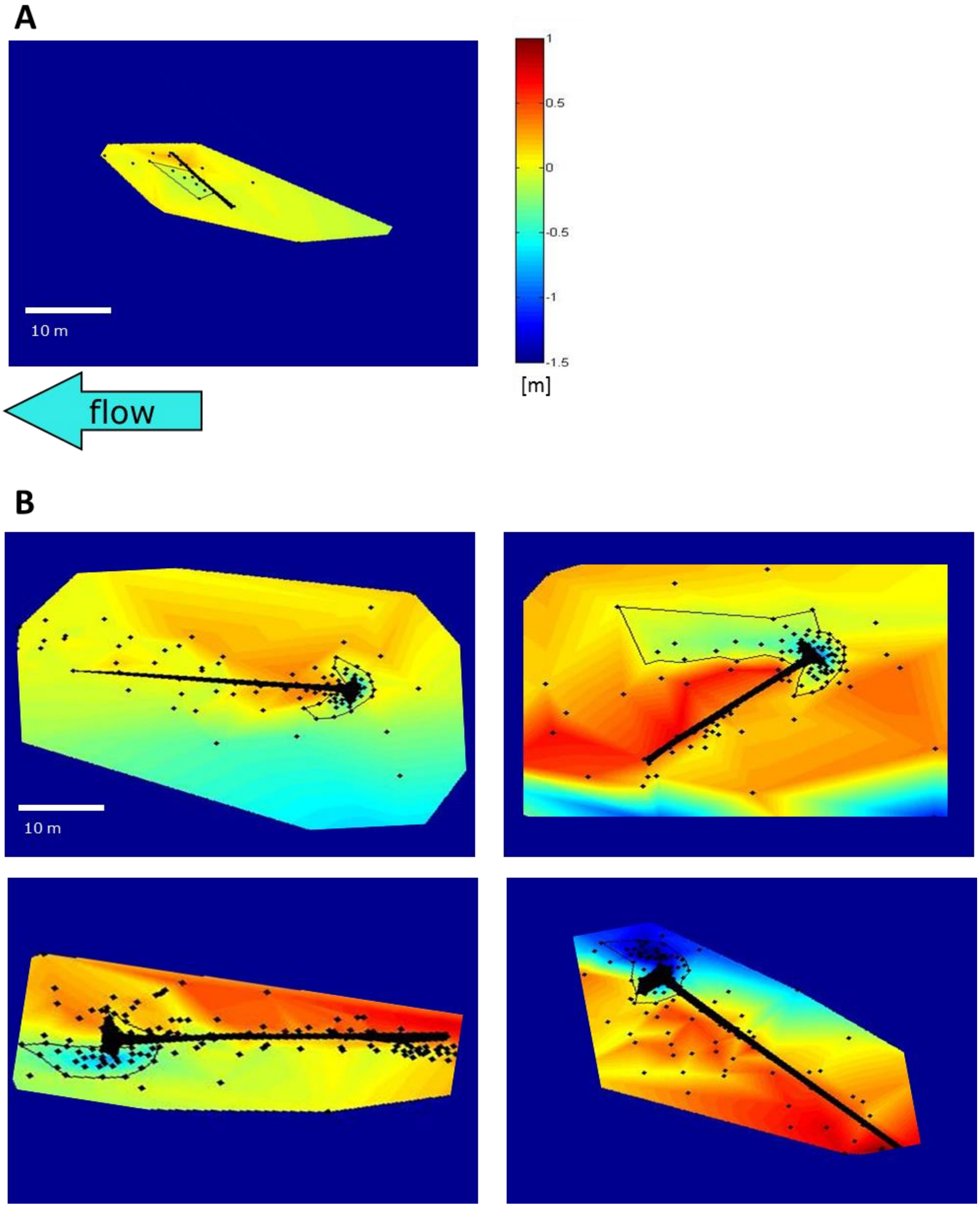


Fig. 8 Field-surveyed streambed morphology around wood debris without roots (A) and with roots (B) with flow direction going from right to left. Black dots are theodolite survey points. Scour zones are outlined in black. Wood debris without roots (A) has significantly shallower sediment scour and deposition over a smaller area as compared to wood debris with roots (B).

Wood debris orientation relative to flow affects the size and shape of scour and sediment deposition.

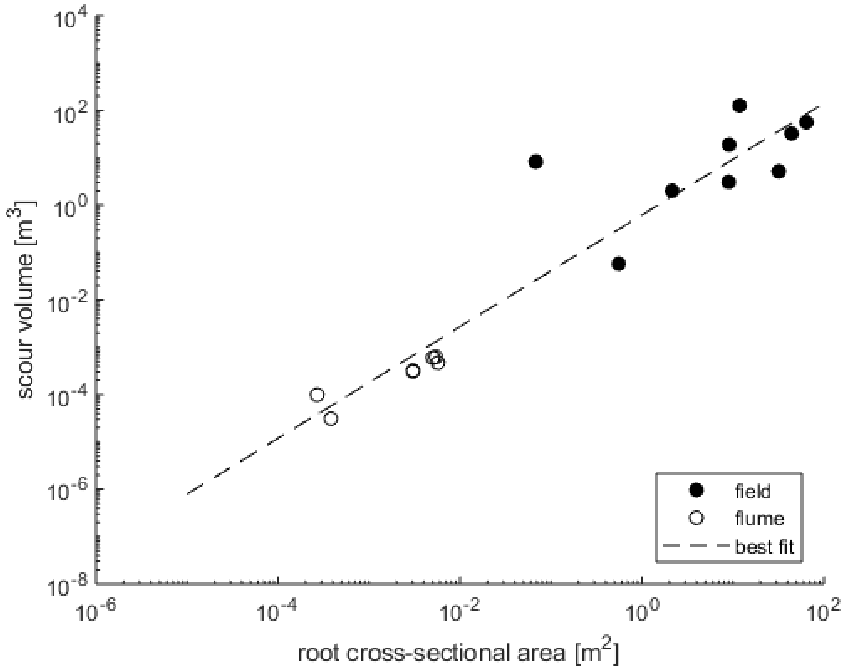
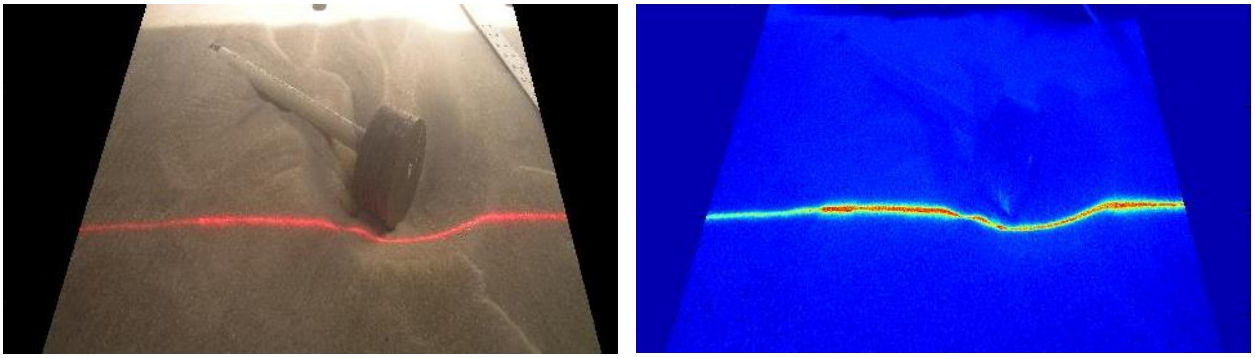


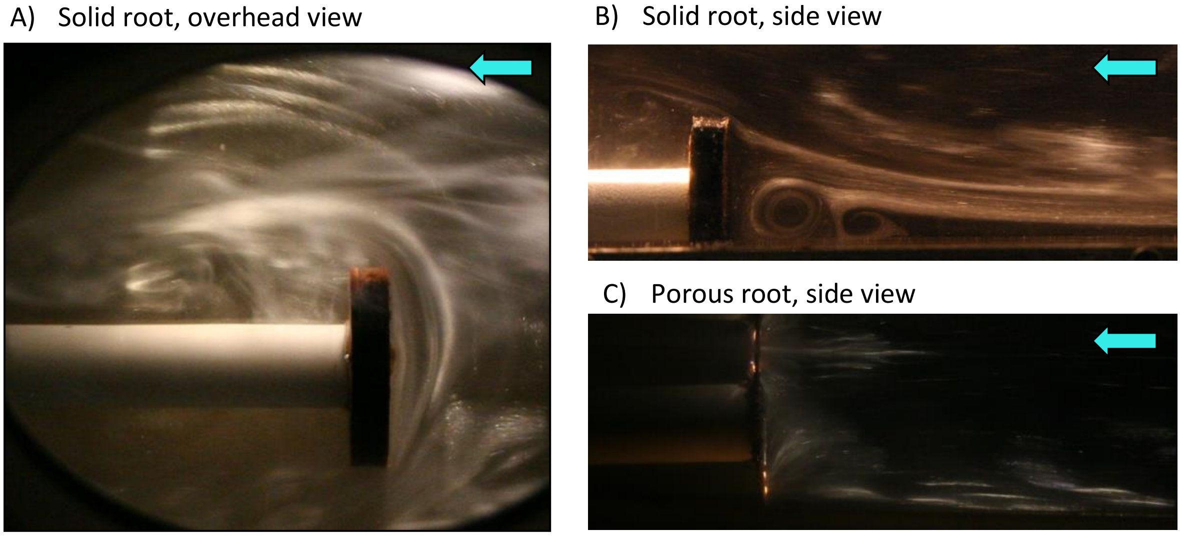
Fig. 9 Scour volume plotted against root cross-sectional area relative to flow, for flume experiments and field measurements. Dashed lines show best fit line, $y = 0.6192x^{1.179}$, calculated by fitting points on a log-log plot.

Appendix



A.1 Topographic measurements in the streambed morphology experiments were taken using vertical sheet lasers set perpendicular to flow.

A.2 Topography measurements were using a laser theodolite. 30-100 points topographic points were taken around each piece of wood debris (blue flags).



A) Solid root, overhead view

B) Solid root, side view

C) Porous root, side view

A.3 Flow structure around model trees, shown with powdered fish scales and a light plane. A) & B) show a horseshoe vortex around a solid root. C) shows a porous root without a horseshoe vortex.

Ch. 3 Wood Debris Sources and Logjam Distribution and Dynamics Before and After Dam Removal, Elwha River, WA

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Abstract

Logjam distribution and dynamics on the Elwha River before, during, and after the Elwha River Restoration project dam removals are measured through aerial photographs and field surveys. Prior to dam removal, local wood recruitment dominated logjam dynamics through bank erosion, channel migration and avulsions. Several large logjams formed in side channels during floods, and gradually revegetated, producing new floodplain forest. Removal of the Elwha and Glines Canyon dams resulted in increased downstream flux of sediment and wood from the upstream watershed and material that was previously stored in the reservoirs behind the dams. During the first year of dam removal, 208 pieces of wood debris were individually tagged in the former Lake Mills, the reservoir behind the Glines Canyon Dam, and the upper part of the Middle Reach (between the dams). After dam removal, 62 tagged pieces were relocated, showing wood transport out of Mills into the Middle Reach, with a few pieces that traveled to the former Lake

Aldwell, the reservoir behind the Elwha Dam, and the Lower Reach (between the Elwha Dam and the coast). During and immediately after dam removal, logjam area increased in the channel main-stem, logjams developed unexpectedly rapidly in the former Lake Aldwell reservoir, and very little logjam development occurred in the former Lake Mills reservoir. In the river channels between Aldwell and Mills (Middle Reach), logjam area increased with increased upstream wood flux and more local recruitment as the higher sediment load increased lateral channel mobility. However, logjam development in the two former reservoirs followed very different trajectories due to rapid erosion of sediment stored in the former Aldwell reservoir, a greater upstream flux of wood into Aldwell, and the presence of rooted 1-3 m diameter tree stumps in the Aldwell sediments that became anchor points for logjam formation.

Introduction

Wood debris has been recognized to significantly impact aquatic habitat and play a fundamental role in forest river dynamics that complements those of water discharge and sediment transport (Gurnell et al., 2002; Montgomery et al., 2003; Ruiz-Villanueva et al., 2016). The interactions among large wood debris, fluid flow and sediment transport in rivers are first-order controls on river processes, affecting channel roughness, streambed morphology and sediment transport (Montgomery et al., 2003).

A number of studies have documented the effects of large-scale wood removal from channels and floodplains due to widespread floodplain logging, dams, levees, and floodplain channelization that affected channel morphodynamics (Collins et al., 2002; Collins and Montgomery, 2002; Sedell and Froggatt, 1984). In contrast, large-scale wood influx events are often unanticipated (e.g., landslides, avulsions, large floods or forest fires) and therefore field investigations of large events are rare. The Elwha River dam removals, the largest dam removal to date, provide an opportunity to quantify how logjam dynamics changed in response to changes in channel connectivity and large scale wood influxes.

In this study, we investigate the effects of dam removal on the Elwha River, Washington, USA on logjam dynamics and analyze rates and patterns of logjam change before, during, and after dam removal to test two hypotheses: (1) that as longitudinal river connectivity is restored after dam removal, there will be an increase in LWD entering the river from the upstream watershed, and an increase in total logjam area in the active channel; (2) new logjams will develop slowly on the former reservoir lakebeds as the high unconsolidated sediment to water ratio and lack of floodplain forest will lead to substantial channel migration and instability before vegetation becomes re-established.

Background

Morphodynamics of wood debris in rivers

Individual logs and logjams are significant obstacles in channels, causing local flow disturbances, sediment scour and deposition (Cherry and Beschta, 1989; Daniels and Rhoads, 2003). At the reach scale, wood and logjams increase channel roughness, decrease sediment transport and increase sediment storage (Davidson and Eaton, 2013; Gippel et al., 1996), and influence streambed morphology and aquatic habitat (Nagayama and Nakamura, 2010). In particular, wood debris increases the hydraulic and topographic complexity of channels and riparian zones, leading to greater diversity of aquatic habitats such as pools or slow water refugia (Nagayama and Nakamura, 2010; Roni and Quinn, 2001). Not only does large wood debris help retain gravel used by spawning salmon (Brooks et al., 2004), but the majority of large pools in forest channels are found in conjunction with large wood debris (Abbe and Montgomery, 2003; Montgomery et al., 1995, 2003).

Across the Pacific Northwest, large wood debris influx into rivers has been greatly reduced due to anthropogenic activities, including upland logging and dams reducing upstream sources of wood, and floodplain logging, levees, channelization, and navigation related snag removal reducing local sources of wood (Collins et al., 2002). In addition, wood currently entering rivers is often smaller than historic wood sizes as most old growth forests have been logged. This reduced wood influx and size has led to fewer, smaller logjams in most rivers (McHenry et al., 1998).

Historically, large wood debris was routinely removed from rivers in the Pacific Northwest to improve navigation and facilitate unimpeded fish passage (Bisson et al., 1987; Collins et al., 2003; Nagayama and Nakamura, 2010). Anthropogenic activities such as floodplain logging, channelization and levee building reduced in-stream wood loads by affecting local recruitment of riparian trees (Czarnomski et al., 2008; Faustini and Jones, 2003). As relationships between in-stream wood and aquatic habitat have become better understood, the practice of putting wood back into rivers has become a widely accepted goal in river management (Lester and Boulton, 2008; Nagayama and Nakamura, 2010). Wood is reintroduced in rivers either as individual pieces, whether free-floating, anchored, or as engineered logjams (ELJs) (Abbe et al., 2003; Kail et al., 2007). Engineered logjams that mimic aspects of natural logjams have been widely used in the Pacific Northwest to decrease riverbank erosion and protect infrastructure from channel migration while improving aquatic habitat (Abbe and Montgomery, 2003). Such approaches have been used to force localized bed scour and thereby create large pools and complex streambed morphology that shape fish habitat, as well as to promote the accumulation of grain sizes used by spawning anadromous fish (Roni et al., 2015).

Study area

The 72-km long Elwha River flows north from the Olympic Mountains to the Strait of Juan de Fuca (Fig. 1), draining a 833 km^2 watershed, the majority of which is within Olympic National Park (Duda et al., 2008). Downstream of the park boundary, the floodplain and watershed are owned by a mix of private, government and tribal entities. Peak discharges occur in the winter storm season between October and March, with secondary peaks in May and June due to snowmelt (Fig. 3a). The 2, 10 and 100-year recurrence interval floods are calculated to be 400, 752 and 1240 m^3/s, respectively, and the median summer discharge is typically 20–40 m^3/s (Duda et al., 2011). Sediment sources include unconsolidated glacial till, glacial outwash, alluvial deposits and proglacial lacustrine deposits (Tabor and Cady, 1978).

This study focused on 4 sections of the Elwha River: the Lower Reach, the former Lake Aldwell, the Middle Reach, and the former Lake Mills (Fig. 2). The 7.4 km-long Lower Reach extends from the Strait of Juan de Fuca to the former Elwha Dam. Here the river is confined to a bedrock canyon for 1.3 km before widening into an anabranching channel with vegetated islands and a patchwork forest floodplain. Aldwell, the site that was formerly Lake Aldwell, is between the former Elwha dam and the 101 highway bridge that crosses the Elwha at rkm 12.1. The Middle Reach stretches between the 101 highway bridge and the former site of the Glines Canyon dam at rkm 21.1. Here the river alternates between confined bedrock canyon reaches and wider anabranching reaches with vegetated islands and multiple channels. Mills, the site that was formerly Lake Mills, is between the former Glines Canyon dam site and Cat Creek at the outlet of Rica canyon at rkm 24.7 in Olympic National Park. Field work reported here builds on extensive research and data collection on the Elwha River basin (Duda et al., 2008, 2011; Ritchie et al., 2018b; Warrick et al., 2015).

With elevations within 200 feet of sea level, the floodplain forest in the study reaches is dominated by Douglas fir (*Pseudotsuga menziesii*) and deciduous species, including bigleaf maple (*Acer macrophyllum*), black cottonwood (*Populus trichocarpa*) and red alder (*Alnus rubra*) (Duda et al., 2011; Kloehn et al., 2008). Younger forests are typically found close to the active river channel and often contain early succession red alder and willow species (*Salix spp.*). Additional conifer species in the floodplain forest include western red cedar (*Thuja plicata*), grand fir (*Abies grandis*) and Sitka spruce (*Picea sitchensis*) (Duda et al., 2011; Shafroth et al., 2016).

The Elwha River was dammed in 1913 and 1927, respectively, by the 32 m tall Elwha Dam at rkm 7.9 and the 64 m tall Glines Canyon Dam at rkm 21.6 (Fig. 1). The dams were originally built for hydropower for paper mills in the area. Downstream of both dams, the Lower Reach had been starved of sediment for almost a century, with the streambed consequently coarsening and becoming armored (Draut et al., 2011; Kloehn et al., 2008). The Lower Reach floodplain has also lost physical and ecological complexity due to human activities, especially floodplain logging and diking (McHenry et al., 2007). Some of the floodplain dikes and other channel modifications have been removed as part of river restoration projects conducted by the Lower Elwha Klallam Tribe (LEKT) Department of Natural Resources (Warrick et al., 2011). Additionally, 45 engineered logjams were constructed in the Elwha River between rkm 1.7 and rkm 3.6 between 1999 and 2014, in order to improve aquatic habitat, protect floodplain infrastructure and promote an anastomosing channel pattern that provides important side-channel habitat for salmonids (McHenry et al., 2007; Natural Systems Design, 2016). Pieces of wood debris used to build ELJs were imported to the floodplain from local tree farms, and consisted of pieces with and without roots in a range of sizes. These were primarily built to increase fish habitat by creating deep pools and increasing the amount of spawning size gravel in the reach. Some ELJs were also built to stabilize banks, protect infrastructure, and direct more flow into side channels. ELJs were built at densities that at the time were considered representative of logjam densities for the Elwha River prior to dam construction. Several types of ELJs were built. Most have posts driven up to 30 ft. into the channel bed, with key pieces cabled into place and buried beneath a large mound of cobbles and gravel as additional ballast for stabilization. Some of the later ELJ's also have pieces of wood sticking out into the flow so that additional, naturally recruited wood pieces will get caught and racked on to the logjam. Several older ELJs constructed with different designs were rebuilt to be more stable after the channel started undermining them. In the first 5 years after dam removal, all ELJs remained stable. Due to construction designs that emphasize stability, ELJ's in this reach behave somewhat differently than natural log jams. The ELJs have very dense cores consisting of crisscrossed logs covered with gravel and cobble-size sediment. The dense core influences flow patterns and pool locations. The ELJs are also both taller and smaller in area than natural log jams.

Elwha River Restoration project history

In 1992 Congress passed the Elwha River Ecosystem & Fisheries Restoration Act, with the goal of restoring the Elwha River ecosystem and native anadromous fisheries in a safe, environmentally sound and cost effective manner, primarily by removing the Elwha and Glines Canyon dams. Project goals included restoring longitudinal river connectivity, restoring anadromous fisheries, increasing marine-derived nutrient cycling, and restoring the reservoirs to conditions consistent with valley and floodplain settings in the rest of the Elwha River valley or similar unaltered rivers in the Olympic Peninsula (Chenoweth et al., 2011; Ward et al., 2008). In September 2011, the Elwha River Restoration project began a multi-year, phased removal of both dams in order to restore ecosystem function and native anadromous fish populations. Elwha Dam was fully removed in September 2012 and Glines Canyon Dam was fully removed in September 2014 (Warrick et al., 2015).

At the beginning of dam removal Lake Aldwell was estimated to store 4.9 +/- 1.4 million m^3 of sediment and Lake Mills was estimated to store 16.1 +/- 2.4 million m^3 of sediment (Randle et al., 2015). One third to half of the stored sediment was predicted to erode in the first few years after dam removal (Randle and Bountry, 2010). Sediment dynamics during dam removal can be divided into 3 parts (Fig. 3b): Stage 1 – where dam removal started on both dams but there were still partial reservoirs behind both dams; Stage 2 – when Lake Aldwell was fully drained and sediment starting spilling downstream of the Elwha Dam site; and Stage 3 – when Lake Mills was fully drained and sediment started spilling downstream of the Glines Canyon dam site (Warrick et al., 2015). A revegetation project involving planting native species and removing invasive species has been underway since 2011 in both former lake beds (Chenoweth et al., 2011).

In order to restore long-term physical processes leading to a natural channel morphology and better quality instream habitat, local sources of wood debris must be developed and maintained, in addition to allowing wood flux from upstream (Chenoweth et al., 2011; Collins et al., 2002; Latterell and Naiman, 2007). Dam removal allowed wood debris from the upstream watershed areas to travel down to the Middle Reach and Lower Reach, instead of settling behind the dams. Additionally, wood that had been stored in the reservoirs was expected to be exhumed from the former lakebeds during and after dam removal (Chenoweth et al., 2011; Ward et al., 2008). Dam removal was expected to increase lateral channel migration due to the high sediment flux as the reservoir sediments started to erode (U.S. Department of the Interior, 1995). Increasing lateral channel migration will erode more forest floodplain, increasing local recruitment of debris (Latterell and Naiman, 2007). Historically, rivers in formerly glaciated valleys in the Pacific Northwest had an anastomosing channel pattern with stable islands developed on and behind large, stable logjams (Collins and Montgomery, 2002). These logjams resisted erosion and could stay intact for thousands of years, creating 'hardpoints' that had enough floodplain stability that trees had time to grow to grow to prodigious sizes (Montgomery and Abbe, 2006). These old growth trees were considerably larger than other wood debris or most other obstacles in the rivers and often initiated and maintained long-term stable logjams (Collins and Montgomery, 2002).

Steps to restore anadromous fisheries have focused on removing migration barriers and in-stream hazards, and improving aquatic habitat for salmon and bull trout (Crain and Brenkman, 2010; Peters et al., 2014; Ward et al., 2008). Physical migration barriers removed included the removal of Glines Canyon Dam, Elwha Dam, and large boulders thought to block or impede most upstream migration (Bountry et al., 2015). Physical habitat improvements resulting from dam removal included increasing the number of deep pools, accumulations of spawning-sized gravels, hyporheic flow through salmon redds, and the amount of side-channel, slack water, and estuary habitat (East et al., 2015; Peters et al., 2017).

Methods

Longitudinal wood distribution methods

We have monitored wood debris and logjams since 2001 on the Lower Reach and since 2012 on Aldwell, the Middle Reach and Mills, providing 10 years of wood monitoring data before dam removal and 5 years of data during and after dam removal. These air photo and field surveys are a continuation of the work discussed in McHenry et al. (2007). In these surveys, logjams were defined as accumulations of at least 10 pieces of debris that are each at least 3 m long and 0.3 m in diameter or are tree stumps at least 0.5 m in diameter. Field surveys took place in late summer and fall, after the spring snowmelt and before the winter storm season. Logjam locations were taken using a Trimble GeoXT, Geo7X or GeoXH. Logjam surveys were conducted by foot and by raft, with stops at each logjam where researchers climbed onto the logjam to make field measurements. Some logjams were inaccessible due to limited launch and landing sites, limited access points by foot, or dense and thorny vegetation. ELJs were not included in logjam area measurements. Field surveys did not include side channels and floodplain to the east or west of mainstem channels, but in some years did include floodplain islands. Therefore floodplain logjam measurements should be considered as a lower bound for the amount of wood stored in the floodplain. Field measurements of average logjam length in the along-stream direction, average logjam width in the cross-stream direction, and average logjam height were taken using a laser range finder. For logjams that were irregularly shaped with large void spaces, the field measurements of logjam dimensions were an estimate of the length, width and height of a densely packed rectangular logjam holding an equivalent volume of LWD. For certain logjams that were inaccessible in the field, or were especially large or complex in shape, the length and width measurements were taken from air photos. If possible, air photos taken in fall or winter were chosen to minimize canopy cover obscuring parts of logjams. Vegetated parts of logjams were considered to be stored floodplain wood and therefore not included in logjam area calculations. Logjam length and width measurements from air photos, following the same logjam size criteria as with field surveys, are combined with field survey data in order to cover the greatest number of sampling times possible. ELJs were not included in these logjam measurements.

Logjams are inherently complex structures with rough and uneven boundaries. Consequently, there are uncertainties to quantifying metrics such as logjam dimensions. We estimate that the measurements of logjam dimensions have a 15 % margin of error. This margin of error is calculated by combining differences in the internal and external boundary points for measuring logjam length, width and height in the field and differences resulting from aligning measurements within 5 degrees of the along-stream and cross-stream directions in the field. Since some logjams were inaccessible to the field surveys, logjam area measurements off air photos are more comprehensive.

Starting in 2013, logjam geomorphic setting was also recorded. Logjam types were based on the geomorphic setting and forcing mechanism for each particular logjam, following the nomenclature of Abbe and Montgomery (2003). Logjam types found on the Elwha River are bar apex, meander, stumps, key piece, live trees, boulder, and channel spanning. A bar apex jam is one where the wood debris is deposited on the topographic high of the front of a bar. A meander jam is one where the wood debris is deposited on the outer curve of a meander bend. Stumps, key pieces, live trees and boulders are logjams where the wood is anchored on each of those things. Channel spanning logjams are logjams that extend fully across a channel.

In 2012, 208 individual pieces of wood debris were marked using numbered aluminum tree tags, expanding on work discussed in McHenry et al. (2007). Each piece of wood debris had two tags hammered in, one at each end of the trunk. Tags were placed 180 degrees from each other, rotated along the trunk axis, in order to increase the chances of spotting a tag in all wood orientations. Only wood debris pieces that were at least 3m long and 0.3m in diameter, or tree stumps at least 0.5 m in diameter were tagged. Pieces of wood debris on the higher terraces in Mills were not tagged, as those terraces were not expected to erode during the study. All other wood debris of that size that were not in logjams and were reachable by foot, a total of 116 pieces, were tagged between rkm 18.4 and rkm 23.3. 30 additional pieces of LWD were tagged at Wolf Creek (rkm 23.8 – 24.6). In the Middle Reach, between rkm 18.4 and rkm 20.4, all wood debris of the right size that were not in logjams and were reachable by foot, a total of 62 pieces, were tagged. In 2015, rkm 0 to rkm 23.5, almost the entire study reach, was re-surveyed for the tagged trees, 62 of which were located.

Logjam evolution methods

Logjam perimeters in upper Aldwell was mapped off of Elwha PlaneCAM air photos (Ritchie et al., 2018a) over four flood events in order to investigate logjam evolution, relative to varying discharges. We focused on the upstream section of Aldwell because it has been the area with the most extensive new logjam development since dam removal began. Before and after photosets were chosen for four flow events: a flood in Mar. 14th, 2015 with peak discharge of 76 m^3/sec as a low-flow ‘control’; two medium floods, a 297 m^3/s flood on Sept. 29th, 2013 before Glines was fully removed and a 230 m^3/sec flood on Feb. 16th, 2016 after both dams were removed; and the largest flood to date since dam removal began, a 733 m^3/sec flood in Nov. 17th, 2015.

For these surveys, more precise logjam area measurements were made by mapping logjam perimeters from Elwha PlaneCAM aerial photosets in ARC GIS. Logjams were mapped using the same criteria as those used in the field surveys. We only considered logjams with at least ten pieces of wood debris, each at least 3m long and 0.3 m in diameter, or stumps at least 0.5 m in diameter. Only logs that were physically touching were considered part of the same logjam. Individual pieces of wood partially sticking out of a logjam were mapped as part of the logjam. Large areas of bare sediment within a logjam were not counted as part of logjam area but small void spaces were included. Logjams were mapped at 1:500 map scale in Arc-GIS. We estimate up to 10 % error associated with human error in mapping logjam perimeters.

Results

Longitudinal wood distributions results

During and after dam removal, logjam area increased in all sections of the field site (Fig. 5b). From 2012 to 2016 logjam area increased steadily in all four river sections, except for a slight decrease in total logjam area from 2013 to 2014. Logjam area per rkm increased in the Lower Reach by 174%, in Aldwell by 245%, in the Middle Reach by 399 %, and in Mills by 3386% between 2012 and 2016 (Table 1). The greatest logjam area increases happened after 2014, following the end of dam removal, except in the Middle Reach where logjam area increased by similar amounts during and after the end of dam removal. Logjam area varies significantly by location, with a one-rkm-long reach having logjam area of 22,695 m^2, many one-rkm-long reaches with logjam area under 5000 m^2, and some reaches without any logjams. Reaches with the lowest concentration of logjams both before and after dam removal include bedrock canyons and straight channel reaches.

Starting in March 2012, when Lake Aldwell was fully drained, wood debris from Lake Aldwell and the Middle Reach began to be transported into the Lower Reach (Randle et al., 2015). Starting in October 2014, when Lake Mills was fully drained and sediment started spilling over the remaining ~16 m of Glines Canyon Dam, wood debris from Mills and the upstream watershed began to be transported into and through the Middle Reach.

Logjam area per rkm in the Lower Reach increased from 893 m^2/rkm in 1999 to 5,543 m^2/rkm in 2008, primarily between rkm 1 and 3 where an avulsion happened (Fig. 5a) (Draut et al., 2011). Since then, logjam area decreased in the avulsion reach primarily due to wood accumulations in Hunts Road Island that remained in place and were gradually overgrown with vegetation, thereby becoming stored floodplain wood.

In the Middle Reach, logjam area increased over the majority of the reach. Logjam area in the Middle Reach started out lower than in the Lower Reach. While the amount of logjam area increases were similar in both sections, the greatest proportional increase occurred in the Middle Reach, with a 174 % increase in the Lower Reach and a 399 % increase in the Middle Reach.

The two former reservoirs (Aldwell and Mills) reacted very differently during and after dam removal. By 2012, the first field survey after dam removal began, Aldwell already had 9,340 m^2 of logjams, a significant amount of wood accumulation. By 2014 this increased 46% to 13,643 m^2, with an increase of 245% to 32,213 m^2 by 2016. In contrast Mills only had 3 logjams covering 260 m^2 in 2012 with an increase of 85% to 480 m^2 in 2014, and an increase of 3,376% to 9,036 m^2 in 2016.

In Aldwell, a large number of logjams formed in rkm 10.1 – 12.1, the upstream most 2 km of the former reservoir, but few logjams formed in the rest of the former reservoir. Some logjams developed on higher terraces, forming early on during dam removal when water and dam elevations were higher (Fig. 2). New logjam development after dam removal was concentrated in lower channel elevations where the channel remains active.

After dam removal little happened in Mills in terms of logjam formation in the central part of the reservoir, where the active channel is located. Mills has very large deposits of wood all around the edges of the former reservoir. This was primarily floating wood that was windblown across the reservoir surface and deposited during the initial drawdown. The exhumed wood from Mills and Aldwell had been on or buried in the lake bottom and was presumably waterlogged and therefore had a higher density than the wood in the rest of the river valley. In Mills, a small number of logjams formed during the dam removal but most of the new logjams did not form until after a 12-year recurrence interval flood in 2015. Mills also has stumps, but most of them were buried under lake sediments until after the end of dam removal. High terraces remain on the edge of Mills. Some wood was stranded on these terraces as reservoir water levels dropped, and some wood debris is likely to be buried within the terraces. Larger stumps that were exhumed earlier in the dam removal process were mostly high on the valley walls above the active channel, particularly just upstream of the former dam location and at rkm 24.5 by Wolf Creek.

Both reservoirs contained tree stumps buried in the lake sediment that still had roots in place on the pre-dam valley floor. However, the stumps in Aldwell are considerably larger than most of those in Mills. In Aldwell the stumps reach up to 3 m in diameter, with a substantial number over 1 m in diameter. Mills has a few stumps greater than 1m in diameter, primarily on the valley walls by Wolf Creek, but most are under 1m in diameter, especially in the vicinity of the active channel on the valley floor.

The field site includes several types of logjams, including bar apex logjams, channel-spanning logjams, meander logjams (Abbe and Montgomery, 2003), and logjams anchored by key pieces, boulders, living trees, and tree stumps. Most logjams resulted from several types of geomorphic features. In terms of the primary geomorphic logjam type, most logjam types are represented throughout the study reaches (Fig. 8a). Channel spanning logjams are most common in rkm 3 and include many channels filled with woody debris on a large floodplain island between two branches of the river. The majority of new logjams in Aldwell are anchored by stumps. In 2014, logjam area increased for logjams anchored by stumps, and channel spanning logjam area decreased.

From 2012 - 2014 the largest logjam area increases occurred at rkm 11 & 12 for logjams anchored on stumps, and rkm 17 for logjams anchored by boulders. In Aldwell, at rkm 11 and 12, most of the new logjams formed due to large, old-growth tree stumps uncovered during the dam removal (Fig. 8b). Logjams formed on old-growth tree stumps are extremely rare in the rest of the study site.

A comparison of field and air photo measurements in fall 2012 show that logjam area per rkm measured from air photos is 17% greater than field measurements in the Lower Reach, 39% greater in Aldwell, and 10% less in the Middle Reach (Fig. 4). Logjam area is an imperfect measure of wood accumulation since logjams can range up to 5 or more logs thick. Additionally, many of the logjams in the study area are partially buried. Field observations of logjams in Aldwell with scour pools suggest that up to half of a logjam may be buried beneath sediment. In the 2012 and 2014 field data, logjam area ranged from 10 – 1377 m^2, with the majority of logjams under 400 m². Logjam height ranged from 0.2 – 5.5 m, with the majority of logjams between 0.5 and 3 m in height. There was no discernible relationship between logjam area and logjam height (Fig. 6).

There was considerable downstream transport of the individually tagged pieces of wood debris, with pieces tagged in Mills and the upper part of the Middle Reach travelling downstream to parts of the Middle Reach, Aldwell and the Lower Reach (Fig. 7a). Wood debris length ranged up to 58 m with a median length of 7.2 m. Most of the tagged pieces were transported out of Mills, with only 4 pieces relocated in Mills. Most of the re-found wood, 51 pieces, were deposited in the Middle Reach between rkm 16.2 and rkm 20.4, 5 pieces were deposited in the upstrea end of Aldwell and 2 pieces reached the Lower Reach. The farthest downstream piece of tagged LWD was found in rkm 1. 15 pieces of tagged wood moved 0.1 rkm or less and were interpreted to not have moved. Median wood travel distance was 2.5 rkm and mean travel distance was 3.6 rkm. The farthest wood travel distance was 22.1 rkm.

There are no measurements of the amount of wood exiting the Elwha River into the Strait of Juan de Fuca before or after dam removal. The size of the delta increased after dam removal and initiated sediment accretion on nearby beaches(Gelfenbaum et al., 2015; Warrick et al., 2019).

Logjam evolution

Wood mobility and logjam area changes varied greatly depending on the size of flood events. In upper Aldwell, most of the logjams that were washed away or newly formed were located near areas of active channel migration during floods. About half of the wood debris that was washed away was in an area where the active channel moved to during the flood.

The March 14th, 2015 flood event of 76 m^3/sec was included primarily as a low-flow control to assess the mobility of wood at low flow levels. There was no significant active channel migration, no significant changes in logjam distribution, and no significant changes in total logjam area (Fig. 9a).

The 297 m^3/sec flood on September 28th, 2013 resulted in a moderate amount of active channel movement and some changes in logjam distribution. Three logjams were washed away and 1 larger logjam formed, although the total logjam area did not change significantly (Fig. 9b). Additionally, 1 logjam increased in area, 3 logjams lost wood in some parts but gained a similar amount of wood in other parts, and 6 logjams were not affected by the flood. About half of the wood that mobilized was in an area that the channel moved to after the flood.

The 230 m^3/sec flood on February 16th, 2016 also resulted in a moderate amount of active channel movement but no significant changes in logjam distribution or total logjam area (Fig. 9c). There were very slight increases in logjam area in 4 logjams, very slight decreases in logjam area in 2 logjams and no changes in 7 logjams.

The 733 m^3/sec flood on November 17th, 2015 was the largest flood to date since dam removal began. This flood resulted in substantial active channel movement and a 74% increase in logjam area (Fig. 9d). One logjam grew considerably, two new logjams formed, one lost wood in some parts but gained a similar amount of wood in other parts, and one decreased in size. Four logjams merged into two logjams, and both grew slightly. Two logjams split into four smaller logjams, three of which lost wood in some parts but gained a similar amount of wood in other parts, and one that grew in size. Most of the wood was deposited in the upstream end of the study area. About half of the wood that was washed away was in an area that the channel moved to after the flood.

Discussion

Restoration goals for former dam impoundments

The main physical process restoration goals of the Elwha restoration project were to restore longitudinal river connectivity by removing the Elwha and Glines Canyon dams, and to restore the watershed to a natural condition consistent with the pre-dammed Elwha River (Chenoweth et al., 2011; *Elwha River Ecosystem and Fisheries Restoration Act*, 1992; Randle and Bountry, 2010; Ward et al., 2008). The largest morphodynamic concern related to dam removal involved the coarse sediment impounded in the dam reservoirs for almost a hundred years (Randle and Bountry, 2010; U.S. Department of the Interior, 2005). Project management objectives were to erode as much of this sediment as possible, not raise the downstream flood stage, keep infrastructure intact, and leave the reservoirs with topography that is stable and consistent with natural landscapes (Chenoweth et al., 2011; Randle and Bountry, 2010). Short-term management goals were for sediment exhumation to occur fast enough to minimize sustained sediment impacts on aquatic ecology but slow enough to prevent or mitigate damage to the downstream treatment plant and other infrastructure (Chenoweth et al., 2011; Randle and Bountry, 2010; U.S. Department of the Interior, 2005; Ward et al., 2008). Long-term management goals were to restore floodplain – channel connectivity and ecosystem processes (Chenoweth et al., 2011; Ward et al., 2008), particularly as related to anadromous fish, and to create an anastomosing planform similar to other broader parts of the floodplain, and as is characteristic of rivers in the region (Collins et al., 2012). As expected, the majority of the reservoir sediment erosion occurred in the first 5 years after dam removal (Ritchie et al., 2018b).

Dam removal was expected to leave former lakebed surfaces devoid of vegetation, consisting mainly of unconsolidated sediment (Chenoweth et al., 2011; Randle and Bountry, 2010). Especially in the first few years after removal, it was expected that channel planform and physical habitat would be very unstable (Chenoweth et al., 2011; McHenry and Pess, 2008; Ward et al., 2008). Part of the revegetation plan's purpose was to stabilize sediment and channel banks by planting herbaceous and woody plants in the reservoirs, and potentially by building ELJs, depending on additional funding. It was expected that plant revegetation would occur slowly, especially on high terraces and in the centers of the reservoirs, areas that had more extreme temperatures, wind exposures, and were farthest from seed sources from the surrounding forest (Chenoweth et al., 2011).

New Logjam Formation on the Former Reservoir Lakebeds after Dam Removals

Contrary to pre-project expectations (Chenoweth et al., 2011; McHenry and Pess, 2008), new logjams developed unexpectedly rapidly in Aldwell. Logjams developed more slowly in Mills with very little logjam formation until a 12–year recurrence interval flood in 2015. The presence of large logjams in Aldwell as compared to Mills is likely due to a combination of a larger wood influx, the widespread presence of large old-growth tree stumps in Aldwell, and the timing of sediment exhumation from each reservoir.

Mills lies upstream of Aldwell and its catchment area is therefore smaller. Aldwell received the majority of the exhumed wood from Mills, excluding any pieces temporarily deposited in the Middle Reach. There are not any comparable upstream wood sources for Mills. Additionally, when dam removal began, the Middle Reach underwent 1 – 1.5 m of widespread riverbed aggradation (East et al., 2015) and increased channel sinuosity primarily due to lateral channel migration in unconfined parts of the floodplain (Ritchie et al., 2018b), leading to increased local recruitment from bank erosion. The channel upstream of Mills did not have additional sediment sources to cause increased channel mobility and local recruitment.

The differences in logjam spacing within Aldwell point to the presence of stumps as the primary factor driving large logjam development. The stumps in Aldwell are also considerably larger than most of the stumps in Mills. This stump size difference may be due to the difference in elevation or may be due to Mills having had a narrow and more active floodplain that didn't allow trees to grow as old and large.

Stumps on the valley floor are largest and most closed spaced in rkm 11 and rkm 12, the location with the largest logjam areas per rkm and where the majority of logjams are anchored on stumps, with most logjams anchored on multiple stumps (Fig. 8). While Mills does have some in-place stumps greater than 1 m in diameter, those stumps are concentrated in rkm 24.5, too high on the valley walls to interact with the active channel.

The pre-dam valley bottom in Mills was covered in more sediment for a longer time than the pre-dam valley bottom in Aldwell. Compared to Aldwell's 10-15 ft. of sediment before dam removal, Mills contained a much thicker sediment layer above the pre-dam valley floor, up to 70 ft. thick at the upstream end, primarily because Mills is upstream of Aldwell, and therefore captured most of the coarse sediment between 1927 and 2014 (Randle et al., 2015). Elwha Dam was also fully removed before Glines Canyon dam was fully removed in 2014. Aldwell was a shallower lake with less accumulated sediment and by fall 2012 enough sediment had eroded from the upstream end of Aldwell to expose significant sections of the pre-dam valley floor. In contrast, in Mills parts of the pre-dam valley slopes were exposed in 2012 but most of the pre-dam valley floor was not exposed until after the full dam removal in 2014 (Ritchie et al., 2018a).

Glines Canyon dam was only fully removed in Sept. 2014 as compared to the Elwha Dam’s full removal in spring 2012 for Aldwell. So the sediment eroded over a longer period of time for Mills and the stumps were exposed at a later point.

In Aldwell, the 297 m^3/sec in 2013 and the 230 m^3/sec floods in 2016 showed markedly different responses for wood movement. While both floods produced moderate amounts of active channel migration and similar low levels of total logjam area change, only the 2013 flood was associated with significant changes in wood movement. In 2013 the Glines Canyon dam removal was still in progress so there would be more wood and sediment entering Aldwell from upstream, creating a more dynamic river system. The October 2013 297 m^3/sec flood was also one of the bigger floods since the beginning of dam removal, so we would expect greater change in wood distribution, whereas the March 2016 230 m^3/sec flood was only a few months after the November 2015 733 m^3/sec flood, which was the largest flood on the Elwha since dam removal. Comparatively little wood or sediment likely entered upper Aldwell between November 2015 and March 2016, resulting in a less dynamic system. Hence, the sequencing of flood events matters to wood transport and log jam dynamics.

In upper Aldwell, most of the logjams that were washed away or newly formed were located near areas of active channel migration during floods (Fig. 9). This corresponds to what was seen in flume experiments — wood movement and channel migration are strongly correlated (Ch. 4).

Other factors important in floodplain development and channel planform change include emergent vegetation and succession leading to a floodplain forest (Shafroth et al., 2016). Revegetation of Aldwell and Mills has accelerated since the end of dam removal, with natural revegetation occurring primarily on the lakebed muds, especially on the valley slopes on the edges of the former reservoirs, while the revegetation project has focused on removing invasive species and planting native seedlings on higher terraces, and live staking more active parts of the floodplain (Bountry et al., 2015; Chenoweth et al., 2011). Woody vegetation and forest development typically occurs on decadal timescales, so can only be assessed in the future (Konrad, 2012). Based on logjam development in the former reservoirs depending largely on stable anchor points, we anticipate that long-term logjam locations will correlate with sediment stability and the development of woody vegetation and an anastomosing channel pattern.

Change in longitudinal distribution of wood debris

Before dam removal, the Elwha and Glines Canyon dams allowed water and washload to travel downstream, but prevented most bedload, suspended load, and LWD from traveling downstream (U.S. Department of the Interior, 1995). The river was essentially divided into three systems separated by two reservoirs that blocked downstream transmission of LWD and coarse sediment: 1) the watershed upstream of Lake Mills and Lake Mills delta, 2) the Middle Reach system consisting of the Middle Reach and Lake Aldwell delta, and 3) the Lower Reach system consisting of the Lower Reach and the ocean delta (Fig. 10). As a result the Middle Reach and Lower Reach systems had much larger source areas for runoff than for LWD and sediment. Wood debris recruitment into the Elwha River comes primarily from lateral bank erosion, avulsions, landslides and re-mobilization of previously deposited wood debris (Benda et al., 2003; McHenry et al., 2007). Once in the river, logs are transported primarily during high-flow events and can be stored transiently in logjams and in the floodplain (McHenry et al., 2007; Warrick et al., 2011). A small amount decays and breaks down while in the active channel, a considerable amount of transported wood can be stored in the floodplain, and the rest eventually reaches the delta at the Strait of Juan de Fuca.

Dam removal restored longitudinal channel connectivity for LWD and sediment. Once the reservoirs were fully drained, LWD and coarse sediment from Aldwell and Mills started traveling over the former Elwha Dam and Glines Canyon Dam sites. As dam removal progressed, sediment and wood from the upstream watershed and the Middle Reach also started traveling into and through the former reservoirs.

In the Elwha River channel study reaches, there are several types of wood input, which can be broadly divided into: 1) wood input from the immediate reach and 2) wood input from upstream (Fig. 10). Wood sourced from the immediate reach includes stored floodplain wood that is re-mobilized and local recruitment of live trees as channels expand, migrate, and avulse into floodplain forest. Wood input from upstream can include exhumed reservoir wood, stored floodplain wood re-mobilized from the upstream watershed, landslides in the upstream watershed and local recruitment from the upstream watershed. As very little wood was transported over the dams when they were in operation, we can assume that before dam removal all wood input was from local recruitment and re-mobilized floodplain wood (Duda et al., 2011; McHenry et al., 2007). After dam removal wood entered each reach from both the immediate reach and from upstream sources.

After dam removal wood flux was expected to increase for most sources of LWD, including wood from the upstream watershed, tributaries, exhumed wood, local recruitment and floodplain wood (Randle and Bountry, 2010; Ward et al., 2008). This is consistent with the observed logjam area increases in all four study sections after dam removal (Fig. 5). The trend of logjam area decreasing upriver is also consistent with the size of the watershed supplying LWD to each study section decreasing upstream.

As dam removal progressed, sediment flux increased and likely led to changes in local sources of wood (Magirl et al., 2015; Randle et al., 2015). Floodplain wood and locally recruited wood flux increased due to increased bank erosion, lateral channel migration and avulsions into floodplain forest (Draut et al., 2011; East et al., 2015; Warrick et al., 2015). Increased sediment flux, as expected during dam removals, often increases lateral channel migration and avulsions (Constantine et al., 2014), increasing the amount of locally recruited woody debris. The braiding index of both the Middle Reach and Lower reach increased during the 1st year of dam removal, then decreased during the 2nd year of dam removal (Ritchie et al., 2018b). Main-stem channel sinuosity stayed constant during the first two years of dam removal but increased the last year of dam removal and continued increasing the 2 years following the end of dam removal. Increases in channel sinuosity in the Lower Reach were partially due to new ELJs that directed flow towards a longer anabranch in WY 2015 and 2016, while increases in sinuosity in the Middle Reach were primarily due to lateral channel migration (Ritchie et al., 2018a).

When Glines Canyon Dam and Elwha Dam were in place, water and suspended sediment could travel over the dams (Fig. 10a). Bedload and a small amount of LWD was deposited in deltas on the upstream end of both reservoirs. Most of the LWD entering the reservoirs was unable to travel over the dam sites due to log booms in both reservoirs, except for a few rare releases of LWD over the dams during storms (M. McHenry and P. Crain, personal communication). Some of the wood that floated into the reservoirs slowly became waterlogged, sank in the reservoirs, and became incorporated into lakebed sediments.

In Lake Mills and Lake Aldwell before dam removal, wood debris from tributaries and the upstream watershed entered the lake and were corralled by log booms until they were removed by the dam operators or until they were waterlogged and sank onto the lakebed (Chenoweth et al., 2011). A few small logjams formed on the reservoir delta on the upstream end of both reservoirs (Chenoweth et al., 2011; Childers et al., 2000; Ritchie et al., 2018a).

In Aldwell, during and after dam removal, a few pieces of wood debris with tree trunks were exhumed from the lakebed sediments but most of the wood debris in the lake sediments was old-growth stumps still rooted in the pre-dam valley floor. After dam removal, wood entering Mills could form logjams or be transported downstream into the Middle Reach (Fig. 10). Wood debris was also exhumed from the Mills lakebed during and after dam removal, most of which traveled downstream into the Middle Reach (Fig. 7). Some of the transported wood accumulated in Aldwell and a few pieces reached the Lower Reach (Fig. 7).

In the Middle Reach before dam removal, wood entered from tributaries, local recruitment or as re-mobilized floodplain wood. After dam removal, there was additional wood flux from the upstream watershed, tributaries in Mills and wood exhumed from the Mills lakebed (Fig. 10). Lateral channel mobility also increased after dam removal, potentially leading to more local recruitment and re-mobilized floodplain wood as channels eroded into floodplain forest (Ritchie et al., 2018b).

In the Lower Reach before dam removal, wood flux entered from local recruitment or re-mobilized floodplain wood. The largest wood input occurred after the 1017 m^3/s 40-year flood on Dec. 3rd, 2007 (Fig. 5). By the time dam removal began, most of that wood had been overgrown by trees and was stored in the floodplain. After dam removal, there was additional wood flux from the upstream watershed, Mills, the Middle Reach and Aldwell (Fig. 10).

Before dam removal most wood came from local recruitment during bank erosion, avulsions, and floodplain channel widening during floods (McHenry et al., 2007). Very little wood passed over Elwha Dam or Glines Canyon dam except in rare cases during large floods, as both reservoirs had log booms holding floating wood back in the reservoir (Chenoweth et al., 2011). In 2006 and 2007 during several large floods, including a 40-year recurrence interval flood, the majority of flow at rkm 2.9 switched from the Elwha main channel to the Hunt's Road channel (Draut et al., 2011). Several other channels were also created or widened on islands between the two channels. Large amounts of wood were deposited along channel banks and in some cases logjams completely filled in channels.

In the Lower Reach, logjam area increases during and after dam removal (2012-2016) were of the same magnitude as logjam area increases between 2001 and 2008 resulting from the large channel avulsion. The spatial (longitudinal) pattern of logjam area changes, however, were different before and after dam removal. Logjam area increases before dam removal are concentrated in rkm 2 and 3, in the reaches where the avulsion occurred. In contrast, after dam removal, logjam area increased over a much larger stretch of the Lower Reach, from rkm 2-5 (Fig. 5a).

While it is difficult to separate the post-dam-removal influence of increased upstream wood flux and increased wood input from the immediate reach, both types of wood input increased after dam removal. Local recruitment and re-mobilization of floodplain wood depends on lateral erosion into the floodplain forest, and therefore on flood and flow conditions in the channel (Latterell and Naiman, 2007). The avulsion in the Lower Reach between 2006 and 2009 resulted in a large amount of forested floodplain erosion and local recruitment of wood debris (Fig. 5). The fact that the 40-year flood resulted in more logjam area increases in the Lower

Reach than was seen after dam removal indicates that local recruitment is a primary source of wood in that reach of the Elwha.

Conclusions

The removal of the Elwha and Glines Canyon dams on the Elwha River provided an opportunity to quantify logjam dynamics related to changes in channel connectivity, increased sediment flux and increased wood debris flux. We found logjam area per rkm increased in all parts of the study area, with the greatest increases in rkm 12, the upstream end of Aldwell. Total logjam area in the study reach grew from 28,606 m^3 at the beginning of dam removal to 102,979 m^3 in 2016. In the Lower Reach, logjam area reached 5,543 m^3/rkm after a 40-yr flood, dropped to 1,987 m^3/rkm as floodplain channels reforested, and increased after dam removal to 5,440 m^3/rkm. In the river channels between Aldwell and Mills, logjam area increased with increased upstream wood flux, higher sediment load and increased lateral channel mobility. During and immediately after dam removal, logjam area increased in the channel main-stem, logjams rapidly developed in the former Lake Aldwell reservoir, and very little logjam development occurred in the former Lake Mills reservoir. Logjam development in the two former reservoirs followed very different trajectories due to a greater upstream flux of wood into Aldwell, as well as earlier erosion of sediment stored in the former Aldwell reservoir, exposing 1 -3 m diameter tree stumps in the pre-dam valley floor that became anchor points for logjam formation. The similarities in logjam area per rkm after a 40-yr flood and after dam removal has implications for the preservation of riparian buffer zones and erodible floodplain forest in cases where dam removal is not possible.

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Figures

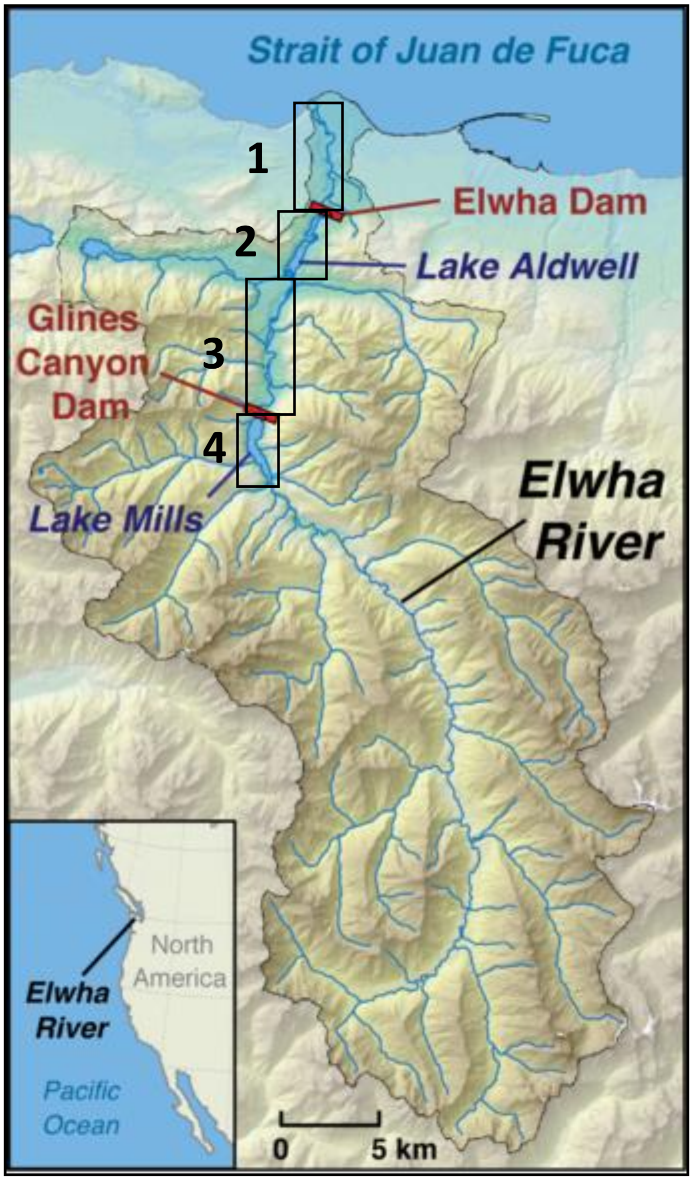

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Fig. 1 Elwha River location map. Boxes show locations of study reaches: 1) Lower Reach, 2) Aldwell, 3) Middle Reach, and 4) Mills. Basemap adapted from Map of the Elwha river in the state of Washington, by U.S. Geological Survey, accessed May 5th, 2019, retrieved from <https://www.usgs.gov/media/images/map-elwha-river-state-washington>. Public Domain

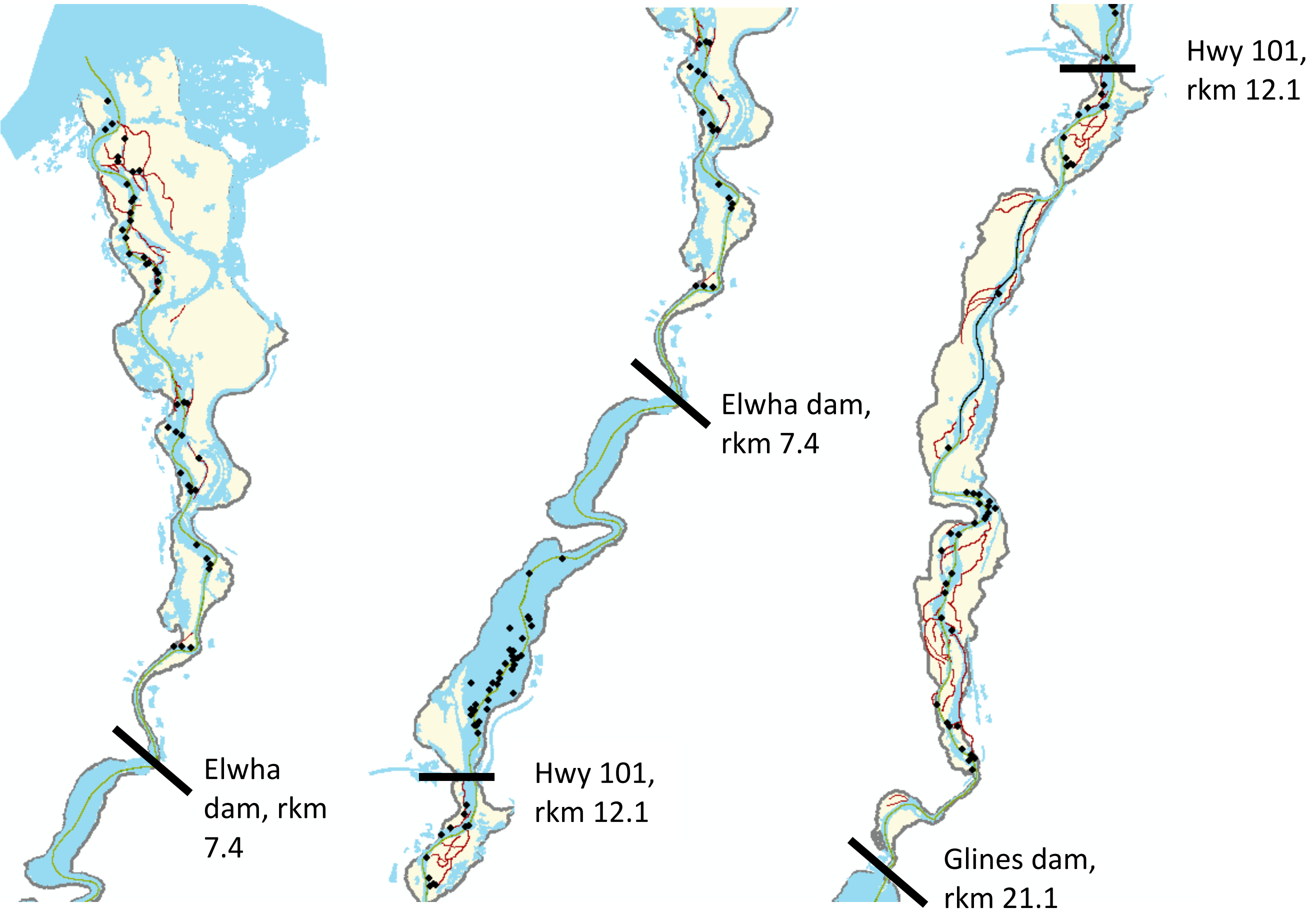


Fig. 2 Study area map showing forest cover (tan), the mainstem river channel (green), side channels (magenta), 2014 logjam locations (black dots), and boundaries between the Lower Reach, Aldwell, the Middle Reach, and Mills (black bars).

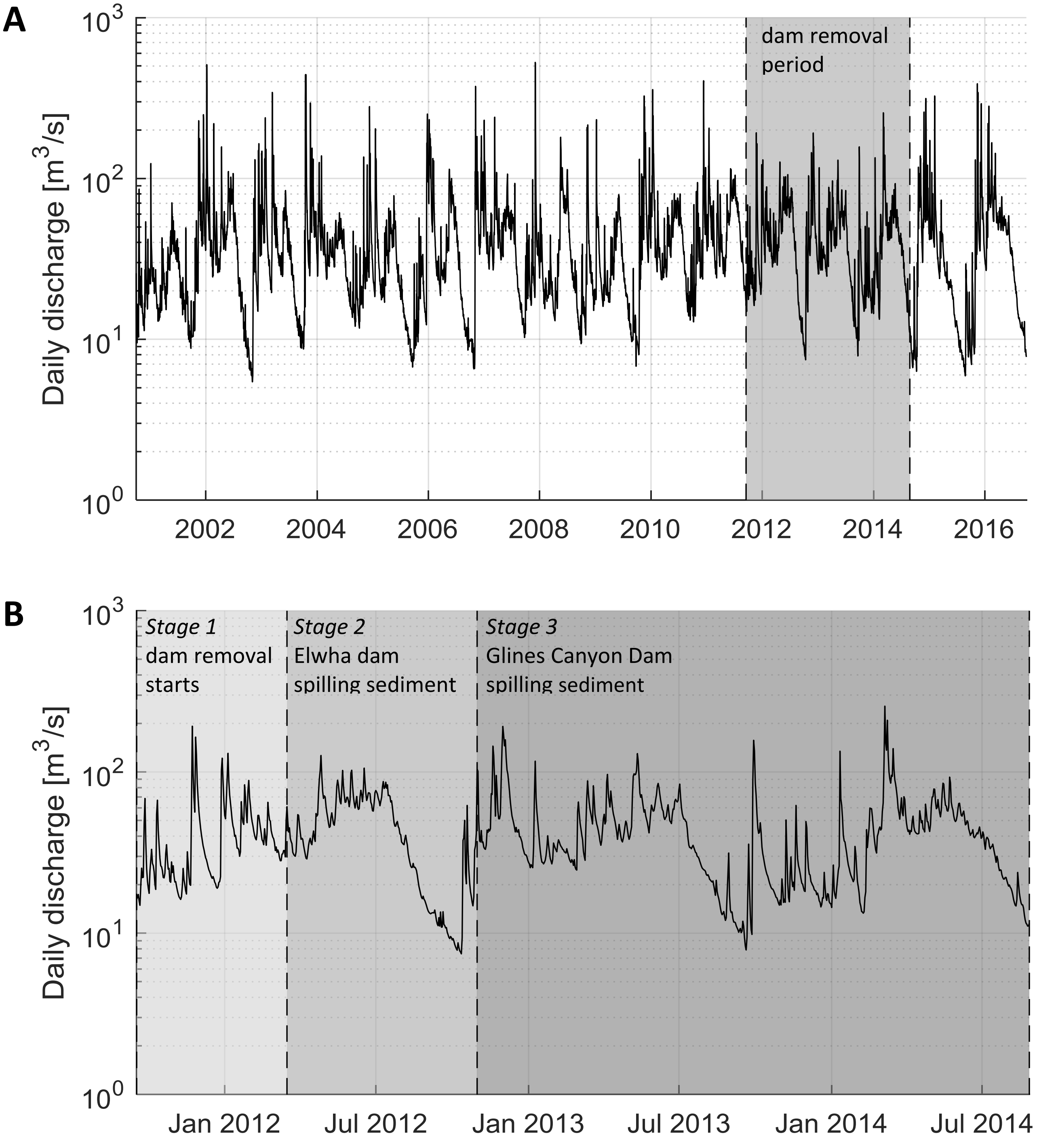


Fig. 3 Daily discharge measured at USGS station 12045500 Elwha River at McDonald Bridge, near Port Angeles, WA for **A)** water years 2011-2016, and **B)** during the 3 stages of dam removal.

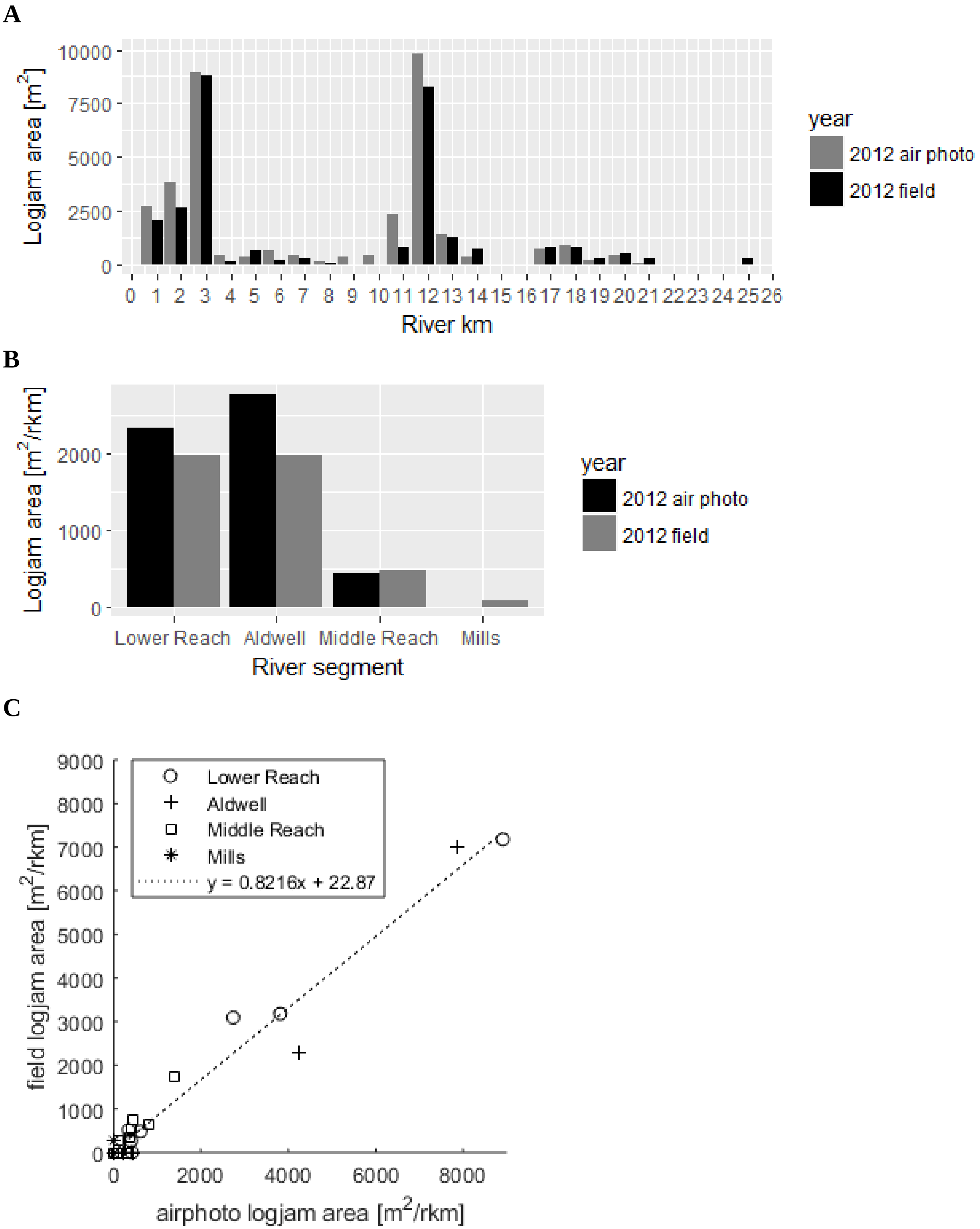
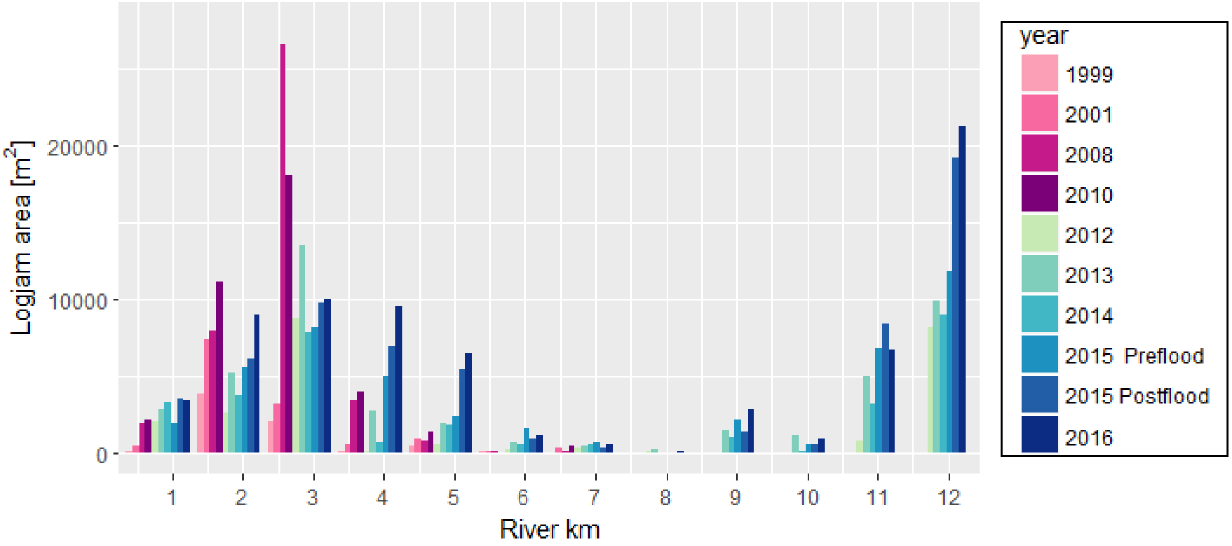
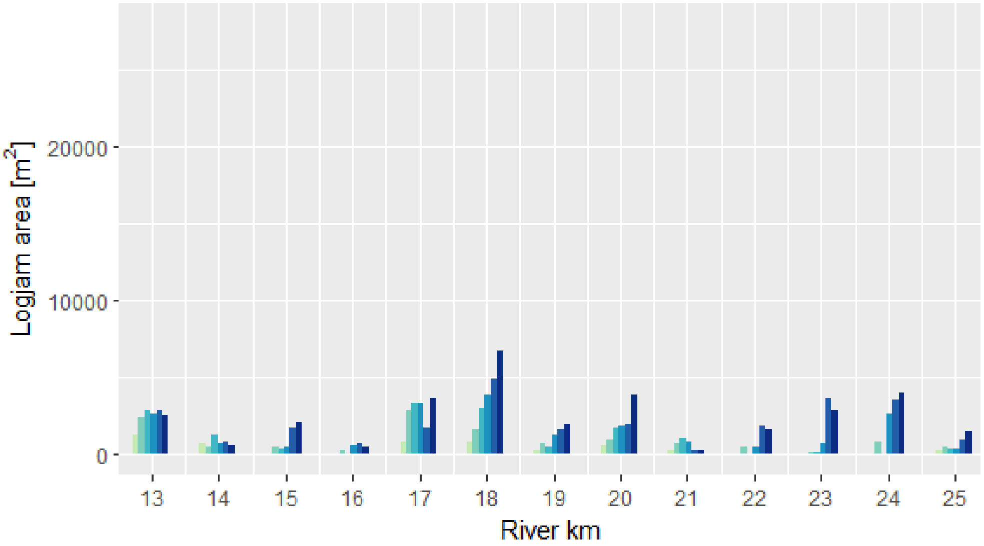


Fig. 4 Comparison of logjam area measurements in the field and logjam area measurements from air photos by: A) river km, B) river segment, and C) best fit line of $y = 0.8216x + 22.87$

Lower Reach and Aldwell



Middle Reach and Mills



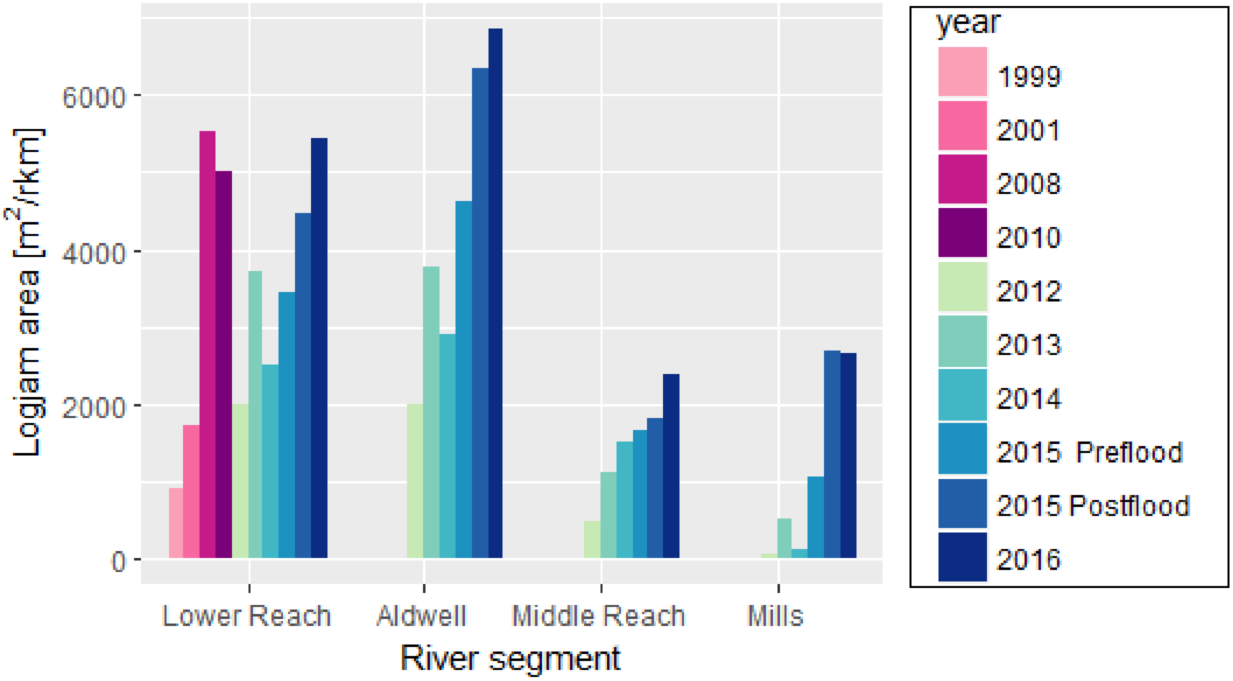


Fig. 5 Logjam area by river kilometer before (pink/purple) and after dam removal (blue/green). Data before dam removal only exists for the Lower Reach. The rapid logjam area increase in rkm 3 in 2008 was related to an avulsion of the main channel and side channels that widened and developed channel-spanning logjams. After dam removal, all rkms in the Lower Reach showed a gradual increase in logjam area. The largest accumulations of logjams after dam removal occurred in rkm 11 and 12, on the upstream end of Aldwell.

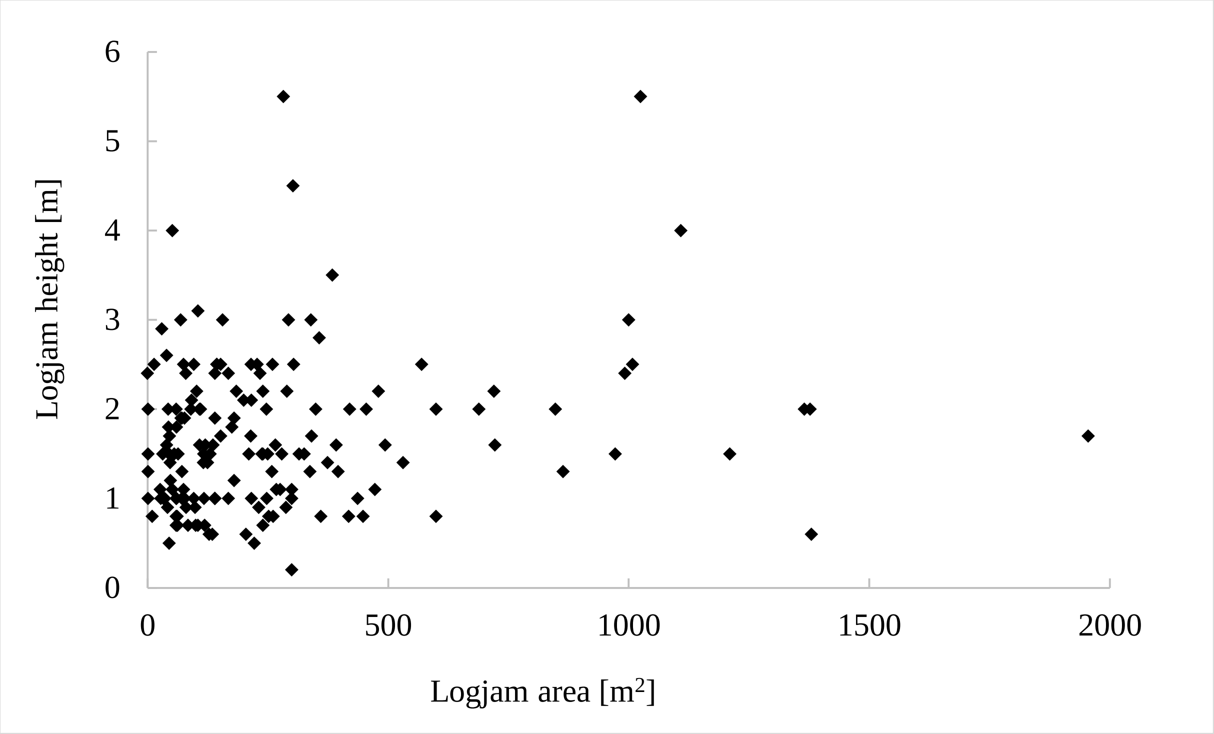


Fig. 6 In the 2012 and 2014 field data, logjam area ranged from 10 – 1955 m², with the majority of logjams under 400 m². Logjam height ranged from 0.2 – 5.5 m, with the majority of logjams between 0.5 and 3 m in height. There was no discernible relationship between logjam area and logjam height.

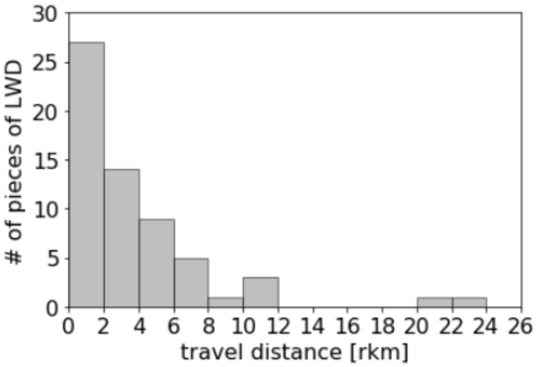


Fig.7 Travel distance between 2012 and 2015 for individually marked pieces of wood.

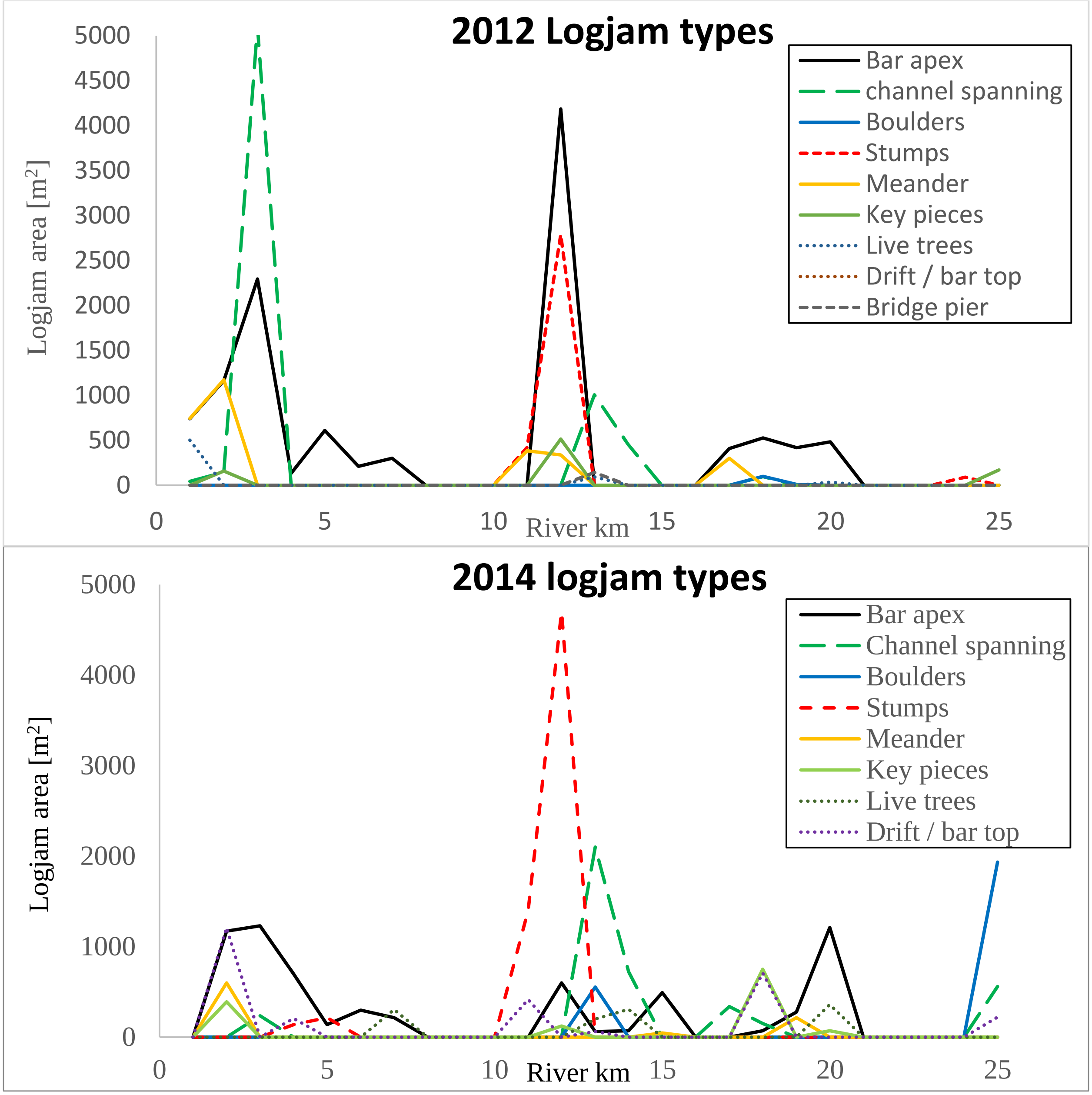


Fig. 8 Logjams area by type and position in the study area. Channel spanning logjams are most common in rkm 3 and logjams anchored by stumps are most common in rkm 11 and 12. In 2014, logjam area increased for logjams anchored by stumps and decreases in channel spanning logjams.

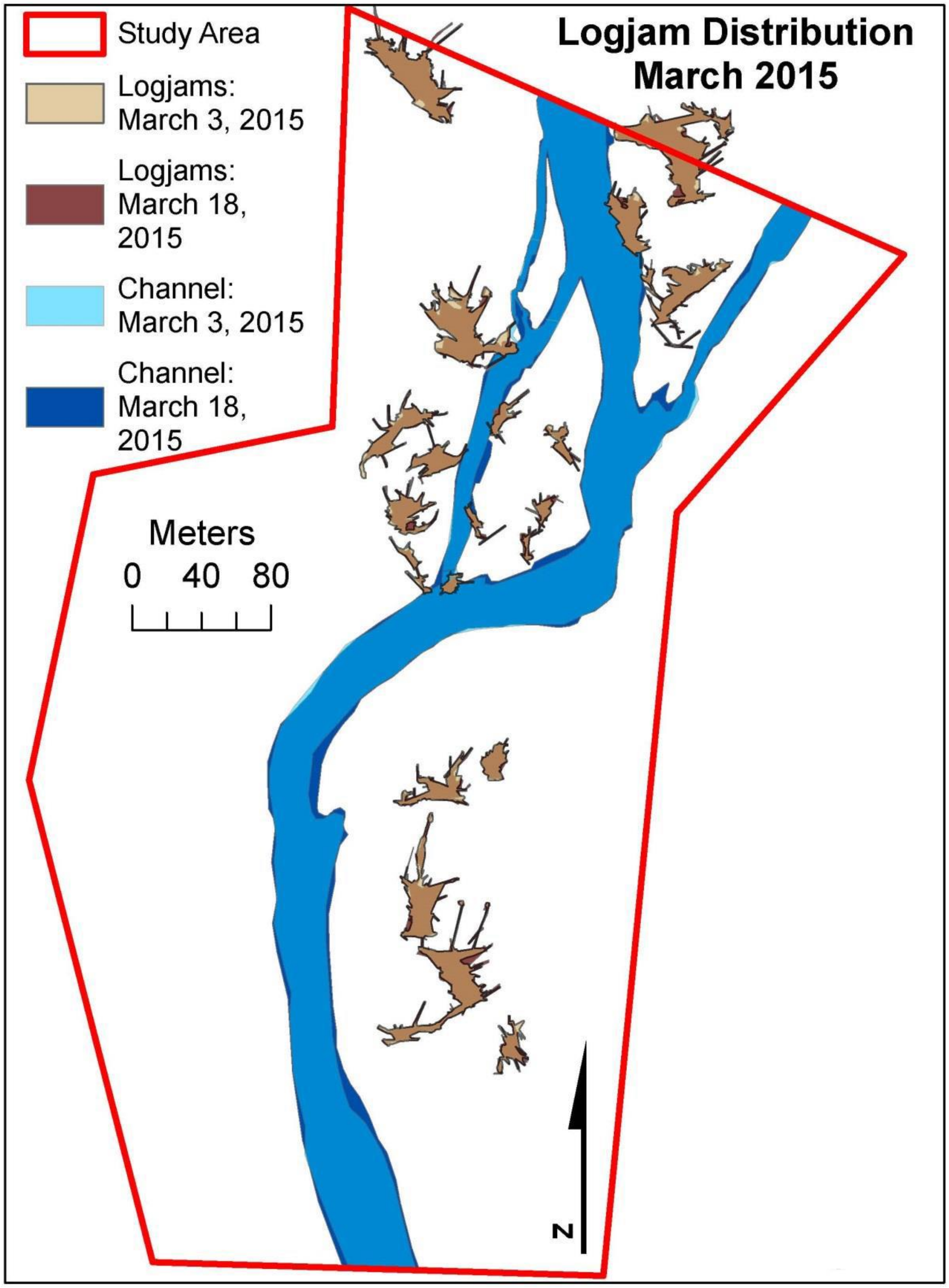


Fig. 9a Logjam distributions and active channel locations before and after a 76 m^3/sec flood on March 14th 2015.

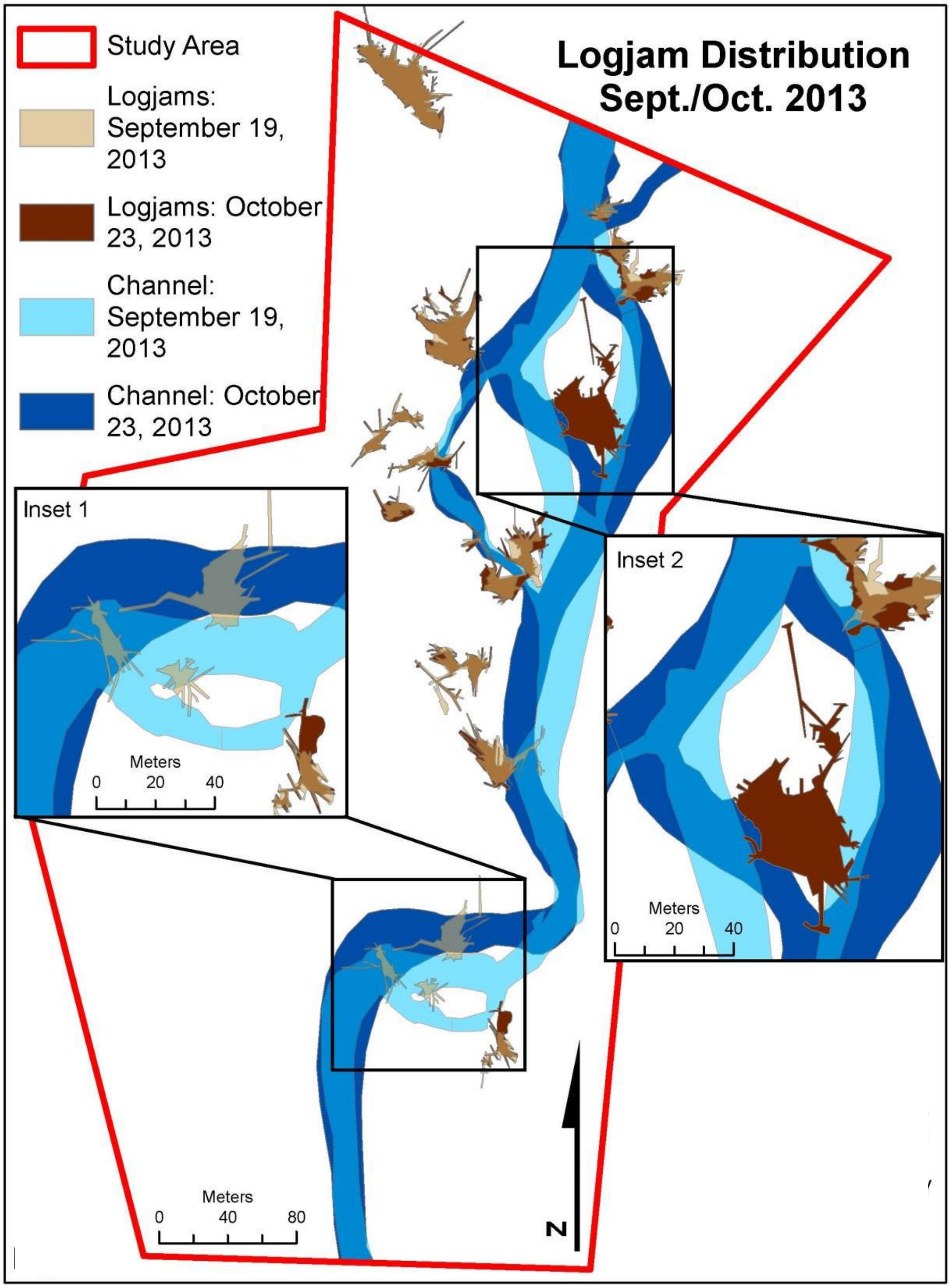


Fig. 9b Logjam distributions and active channel locations before and after a 297 m^3/sec flood on Sept. 29th, 2013

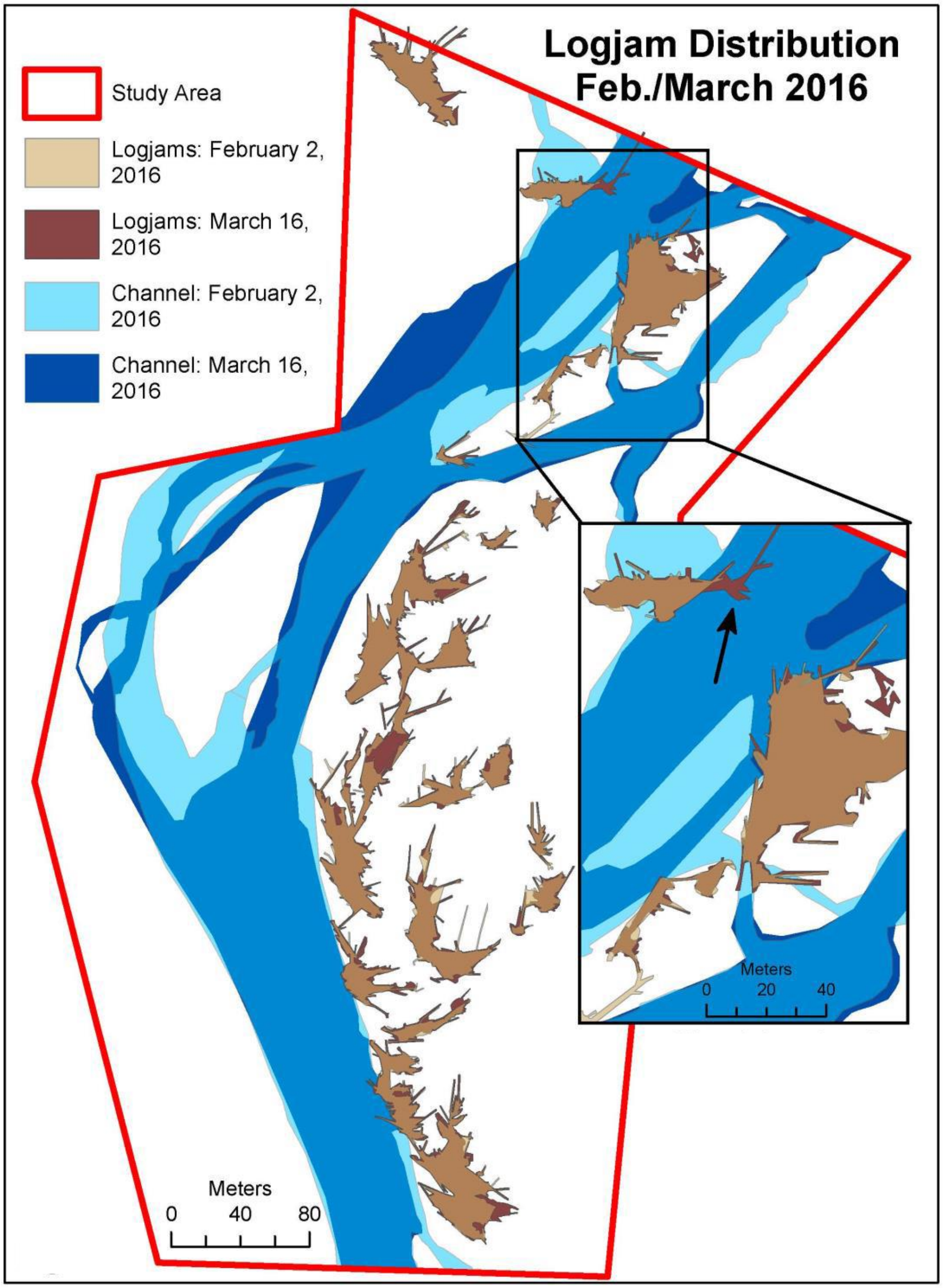


Fig. 9c Logjam distributions and active channel locations before and after an 230 m^3/sec flood on Feb. 16th, 2016.

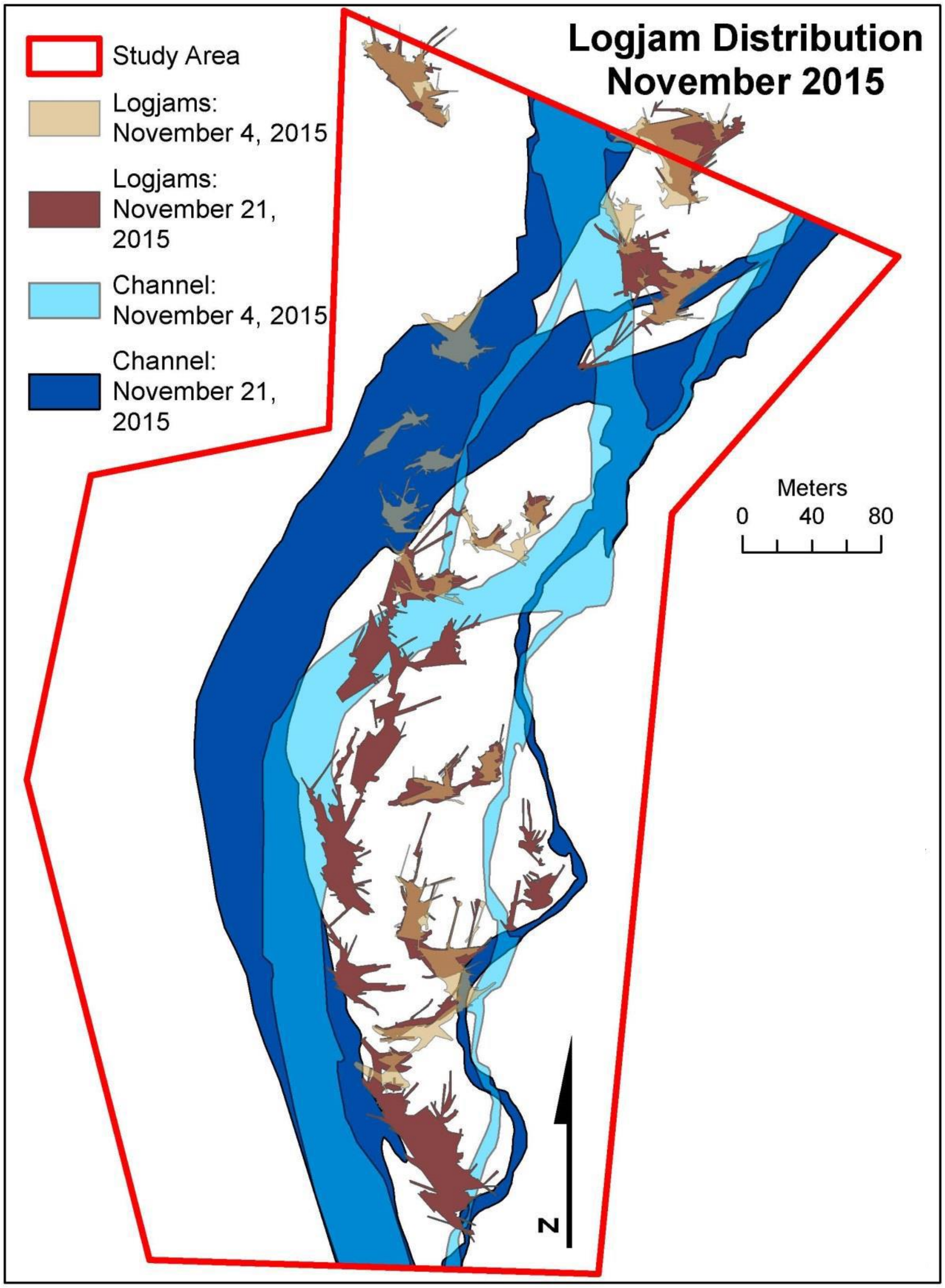


Fig. 9d Logjam distributions and active channel locations before and after a 733 m^3/sec flood on Nov. 17th, 2015.

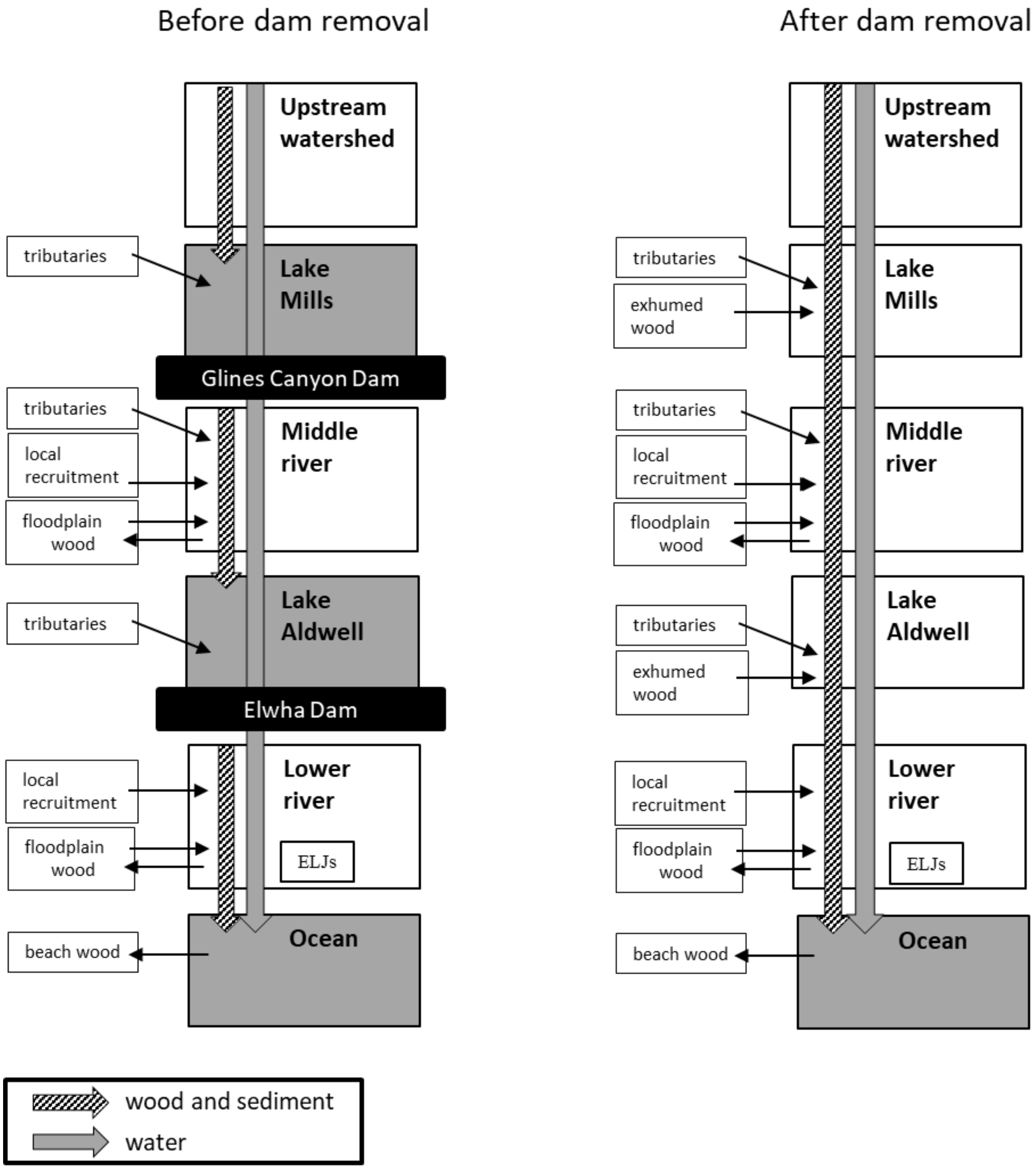


Fig. 10 Conceptual wood budget for Elwha River. Grey arrows represent water discharge, diagonal striped arrows represent wood and sediment transport.

Tables

River reach	Logjams 2012 [m^2/rkm]	Logjam 2016 [m^2/rkm]	Logjam area/rkm % increase
Lower Reach	1,987	5,440	174
Aldwell	1,987	6,854	245
Middle Reach	478	2,386	399
Mills	72	2,510	3,386

Table 1. Logjam area per rkm in 2012 and 2016 by river reach.

Ch. 4 Flume experiments on the effects of buried wood debris on delta processes and sediment exhumation during a phased base-level drop

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Abstract

The interactions between large woody debris, fluid flow and sediment transport in rivers are a first-order control on river processes, affecting channel roughness, streambed morphology and sediment transport. While there has been a large body of research on how wood debris interacts with channel morphodynamics there has been very little research on how wood affects dam removals. We use flume experiments to investigate the effects of buried wood on delta during staged base level drops, similar to the phased Glines Canyon dam removal on the Elwha River. Experimental runs with buried wood show significant changes in delta morphodynamics compared to the control experimental run with only sediment, including increases in channel roughness, channel mobility, the number of active channels on the delta, and delta area. Ecologically, this suggests that increased wood loading leads to increases in aquatic habitat quality and quantity with increased cover, increased depth variability, more logjams and pools, increased channel-edge length, and greater delta area.

Introduction

Dam removals have become an increasingly common alternative for older unsafe or obsolete dams that also provides a way to rehabilitate river ecosystems (Cheng and Granata, 2007; Duda et al., 2011; Major et al., 2012; Pizzuto, 2002; Tsutsumi and Laronne, 2017). Often these dams have significant amounts of sediment and, in forested watersheds, wood debris stored in the reservoirs (Duda et al., 2011; Pearson et al., 2011; Walter and Merritts, 2008). Much of the modeling, experimental and field studies of dam removals has focused on how sediment will be evacuated during and after dam removal (Bromley, 2008; Cui et al., 2014; Pizzuto, 2002; Sawaske and Freyberg, 2012). Numerical and experimental modeling on dam removals have suggested that as reservoir water level drops during a dam removal, a single channel will incise rapidly, with a knickpoint that moves upstream (Cantelli et al., 2004). In staged dam removals, during the stages where a reservoir pool remains behind the dam, a delta forms on the upstream end of the reservoir pool. These models and theories have thus far not taken into account the interactions between wood debris, sediment and rapidly falling base level that would occur during a dam removal. While there has been a large body of research on how wood debris interacts with channel morphodynamics (Collins et al., 2012; Comiti et al., 2016; Gurnell et al., 2002; Montgomery and Abbe, 2006; Wohl, 2017), there has been very little research on how wood affects dam removals (Pearson et al., 2011; Tsutsumi and Laronne, 2017; Warrick et al., 2015) or delta morphodynamics (Huff, 2015; Phillips, 2012).

Here we report the results of a set of physical experiments that explored how exhumed wood debris affects delta morphodynamics during a phased base level drop. We identify some of the key changes in channel mobility and delta morphodynamics related to wood debris that affects delta planform and habitat quality. These experiments, which are broadly based upon the multi-stage removal of the Glines Canyon Dam on the Elwha River, provide a way to isolate the effect of wood debris on delta morphodynamics in a net erosional, falling base level system. Dam removal and drainage of the reservoir (Lake Mills) occurred through a multi-stage removal process over three years, in order to protect downstream infrastructure, protect downstream anadromous fish populations during more susceptible life stages, and evacuate as much sediment as possible during the dam removal process (Ward et al., 2008). Sediment management predictions for the Glines Canyon dam removal were that a single channel would incise rapidly as water level dropped. Several ‘hold periods’, with constant water level, were planned so that the channel had time to erode laterally across the reservoir pool delta and remove more sediment (Bromley, 2008; Randle and Bountry, 2010). Our experiments are an idealized and simplified model of the first phase of dam removal, during which partial sections of the dam were removed, followed by 2-4 week ‘holding periods’ when the lake (reservoir) level was held constant. In this phase of dam removal suspended sediment was transported over the dam but bedload sediment transport mostly stayed within the reservoir.

These experiments were designed to investigate the effects of wood debris on channel dynamics and delta planform during a partial dam removal and focus on the interactions between wood, sediment and water in natural rivers. While the experiments are broadly based on the phased baselevel drops during the Glines Canyon dam removal on the Elwha River, these experiments are simplified analog models, where none of the runs were intended to replicate details of actual conditions.

Background

There is very limited field data on the effects of woody debris on dam removals and reservoir erosion (Tsutsumi and Laronne, 2017). In the Merrimack Village Dam removal on the Souhegan River (New Hampshire), large woody debris was recruited from vegetated reservoir banks as the channel widened (Pearson et al., 2011). This woody debris induced minor amounts of sediment deposition, forming a pool and a riffle, and initiating point bar deposits. During later high flows, the woody debris armored banks, limiting channel widening (Pearson et al., 2011). During the planning process for the Elwha River dam removals, the adaptive sediment management plan for the removal included provisions to increase erosion using high-pressure hoses if woody debris were to induce bank armoring (Randle and Bountry, 2010). Woody debris and in-place stumps exhumed during the dam removal process contributed to increases in logjam area downstream of the dams (Warrick et al., 2015). We are unaware of any experimental research on the effects of woody debris on dam removal morphodynamics.

Similarly, there is very little research on how woody debris interacts with delta morphodynamics, although there is a small amount of research on how woody debris interacts with estuaries. On the Brazos River (Texas), Huff (2015) found that woody debris stabilized delta morphology by decreasing longshore transport. Areas of the delta with a volumetric concentration of woody debris greater than 0.4 resulted in delta progradation rather than erosion (Huff, 2015). On the San Antonio River delta (Texas), Phillips (2012) found that channel spanning logjams sometimes displaced flow and triggered crevasses but that a large recurring logjam at an ongoing avulsion was not the cause of the avulsion. In estuaries, Gonor et al. (1988) theorized that woody debris affect local flow patterns, created riffles, and provided cover in estuaries. In the Snowy River estuary, Hinwood and McLean (2017) found that woody debris led to very localized scour and sediment deposition but did not have large scale impacts on estuary hydrology or geomorphology. They theorized that woody debris impacts were so low because tidal channels in the estuary were wide and deep relative to the wood, water velocities were low, and woody debris was deposited as single pieces, not in logjams. In an estuary restoration project, Cornu et al. (2008) found that woody debris added to a tidal wetland redirected flow and caused channel scour but it was unclear which changes would persist since woody debris in the project moved upstream and downstream during extreme winter high tides. We are unaware of any experimental research on the effects of woody debris on delta morphodynamics.

Woody debris may interact with channel morphodynamics in dam removals and deltas in ways similar to wood debris interactions with channel form in rivers. River channel planform and floodplain morphology affects a range of geomorphic and ecological characteristics, including water and sediment routing, methods of channel migration and the structure and abundance of riparian and aquatic habitats. Traditionally, river channel planform has been explained by the physics of water and sediment discharge and floodplain cohesion. Recent research has shown the influence of vegetation and large wood on river planform and floodplain morphology (Collins et al., 2012; Gurnell et al., 2002; Montgomery and Abbe, 2006; Wohl, 2011). At a valley scale, stable wood and logjams accumulate sediment and can form the basis for stable islands that divert flow, cause avulsions, and create an anastomosing river pattern (Collins et al., 2012; Sear et al., 2010; Wohl, 2011). The multiple channels and stable islands in anastomosing rivers result in increased diversity of hydrologic environments, geomorphic features, hyporheic exchange, floodplain elevations, riparian environments and aquatic habitat. Historical and field studies have shown that river channel planforms can change from multichannel anastomosing to wider braided systems when riparian logging and removal of in-channel wood occurs (Collins et al., 2012). These changes in river channel planform likely result from loss of in-stream wood from direct removal and decreased wood recruitment and decreased bank cohesion due to the loss of riparian trees. Flume experiments on vegetation in rivers have demonstrated that riparian vegetation and root cohesion can create stable islands and multiple narrower channels (Tal and Paola, 2007). When wood debris is introduced as well, flume experiments suggest that island and bank stability increase even more (Bertoldi et al., 2015).

Methods

Each experiment started with a hand-built initial lakebed surface with a top set slope of 5.5° and a filled model lake (Fig. 1). Model wood was set in the lakebed in a quasi-horizontal manner, mimicking the way wood sinking into a lakebed would deposit primarily horizontally, by taking handfuls of mixed wet sediment and model wood and smoothing each handful down onto the lakebed. Dam level and lake level in the experiments were controlled by removable foam blocks set in the model dam. During each experiment base level was reduced by 3.5 cm, and then the lake level was held constant during a 3-hour long 'hold period', followed by another 3.5 cm base level drop and subsequent 3 hour long holding time (Fig. 2). The foam blocks were slowly removed by hand and attempts were made for all of the 1st base level drops to take approximately 45 min. and all of the 2nd base level drops to take approximately 23 min. During hold periods, base water level was held constant, so the experimental delta behavior is more analogous to natural deltas.

We report results from three experiments, the Sediment Only Run, the 2% Wood Run and the 3.5% Wood Run, in which the only variable that differed was the amount of model wood debris buried in the reservoir lakebed at the start of the experiment (wood percentages are measured by percentage of the surface covered in wood). Historically, estuaries and deltas have been places where extremely large log rafts have formed (Collins et al., 2003; Collins and Montgomery, 2002). Logjams, rafts, and single pieces of wood are transported, deposited, and remobilized differently from each other, but the amount of wood in historical records suggests that the 2% and 3.5% wood debris used in the experiment are plausible. Fig. 3 shows similar distributions of wood in the 2% Wood Run as compared to individual pieces of wood in Mills on the Elwha River after dam removal. Wood in a lakebed is likely to have deposited more random orientations than in fluvial reaches, since the wood floats around the reservoir before sinking to the lakebed without being subjected to the currents and channel topography that affect logjam formation. All channel and delta morphodynamics in the experiment are a result of sediment and woody debris being reworked from the original initial surface as sediment and woody debris were not fed into the upstream end of the experiment.

Data reported in this paper come from time lapse photography collected using an overhead digital camera. Images were corrected for lens distortion. Upstream water discharge was mixed with a blue dye source, allowing for color-based image classification of wetted channel area. Dye intensity varied over time in the experiments. Channel occupation over time and channel mobility was calculated based on mapping wetted channel area maps. Topography was measured at 9 times in each experiment using a Keyence laser pointing vertically down, mounted on a robotic cart set to a 2 mm by 2mm measurement grid for the Sediment Only Run and the 2 % Wood Run, and a Leica C-10 LIDAR, set above and downstream of the experiment and pointed obliquely towards the experiment, for the 3.5% Wood Run. Error associated with the Keyence laser is +/- 300 microns and error associated with the Leica lidar is +/- 3 mm. The lasers measured the surface of the sediment and model wood, which include any air gaps behind or under model wood. Additionally, for the Sediment Only Run and the 2% Wood Run, any banks that are under cut will not show in the topography scans. The flume was drained before each topographic measurement.

The only differences between the experimental runs were the amount of buried wood in the delta at the beginning of the experiments. All other variables were held constant. The experiments thus show the effect of exhumed wood on channel and delta morphodynamics during a rapid, phased base level drop.

Results

Each experiment developed two distinct sections: an upstream erosional section and a depositional delta section. As model wood was exhumed during the experiments for the 2% Wood and 3.5% Wood runs, some pieces would travel downstream and some would be partially or completely exposed but remain in place. Some of the mobile pieces traveled directly to or past the delta, some traveled downstream in multiple “hops”, and some agglomerated with other pieces of wood to form logjams. Smaller logjams of 2 – 4 pieces were often less stable, unless anchored by a piece that was partially buried in the channel bank. The 3.5% Wood Run rapidly developed many small logjams in the fluvial section that grew into channel-spanning logjams. The deltas in all three experiments were more mobile than the upstream fluvial channels, and logjams on deltas tended to be smaller and less stable than logjams in the fluvial sections.

The upstream erosional channel had different channel cross-section shapes in the three experiments. The Sediment Only Run and the 2% Wood Run had more rectangular cross-sections while the 3.5% Wood Run had more rounded channel cross-sections (Fig. 4). Compared to the Sediment Only Run, channels were wider in the 2% Wood Run, and narrower and deeper in the 3.5% Wood Run (Fig. 4, Fig. 5).

A significant morphologic difference between the three experimental runs arose in the number of bifurcations and channels on the delta surface. In the Sediment Only Run a single main channel developed on the delta for the majority of the experiments (Fig. 5A). There were only two instances where the channel bifurcated, once during the first dam segment removal and again during the second dam segment removal. In the 2 % Wood Run and the 3.5 % Wood Run bifurcations were extremely common, with multiple channels on the delta surface for the majority of the experiments (Fig. 5B, 5C). The 2 % Wood Run fluctuated between one to five channels on the delta surface and the 3.5 % Wood Run fluctuated between one to six channels on the delta surface. Multiple channels were common starting from about halfway through the first dam segment removal and continuing through both hold periods and the second dam segment removal. These channels concentrate flow and sediment deposition, leading to “lobe-ier” deltas in the experiments with wood (Fig. 5).

A major difference between the three experimental runs was in the amount and type of channel mobility. Fig. 6 shows the changes in wetted area between time steps. The Sediment Only Run’s lateral channel mobility primarily comes about through incremental lateral bank erosion, shown in Fig. 6 as a lower level of wetted area change per time. The 2 % Wood and 3.5 % Wood runs have lateral channel mobility that includes both incremental lateral bank erosion as well as abrupt avulsions and bifurcations creating new channels. Fig. 6 shows a higher overall level of wetted area change for both wood runs, as well as spikes corresponding to major avulsions and new channels being created. Additionally, the amount of time that different parts of the delta are covered in channels varies greatly by experiment. Channel occupation maps of the last 90 min. of the second hold period (Fig. 7) show that in the Sediment Only run there is a single main channel and it stays predominantly in the same section of the delta during this time period. Conversely, for the 2% and 3.5% Wood runs there are multiple narrower channels that migrate often and cover a much greater fraction of the total delta area (Fig. 7).

In these experiments abrupt channel movements correlate with wood movement. In the Sediment Only Run the single main channel moved slowly, sweeping side to side across the delta during the hold periods. Figure 7, which includes data from the last 90 min. of the 2nd hold period, shows that in the Sediment Only Run the main channel stayed primarily in the same location on the delta during that entire time period. In contrast both the 2 % Wood Run and the 3.5 % Wood Run exhibited more frequent channel movements (Fig. 6) that covered a larger fraction of the delta (Fig. 7). These larger, abrupt channel migrations correlated to wood debris movement, as individual pieces of wood debris moving downstream affect thalweg position and channel location. Pieces of wood debris often deflected flow across the channel or caused flow divergences that created islands in the flow or a channel bifurcation. When that wood debris was eroded there were no longer any obstacles causing flow deflection or flow divergence at that location, which often led to a change in the thalweg position or channel planform. Similarly when pieces of wood debris deposited in a new location there were thalweg and channel planform changes that initiated from the flow deflections and divergences caused by the wood in the new location. In certain circumstances there was enough accumulated sediment from the original flow divergences that the channel planform continued to be directed by the topographic changes even after the wood debris was eroded. In the upstream fluvial section during the last 90 min. of the second hold period, the 3.5 % Wood Run had no wood debris movement while the 2 % Wood Run had pieces of wood debris that eroded and deposited within the section. Fig. 7 shows that the upstream erosional section was extremely stable in the 3.5 % Wood Run with almost no channel movements while the 2 % Wood Run had a considerable amount of channel shifting.

The 3.5 % Wood Run also had stable wood debris that correlated with the most stable channel planform. The upstream erosional section of the 3.5 % Wood Run had almost no wood movement during the last 90 min. of the 2nd hold period and the channel stayed in effectively the same location during that entire time (Fig. 7). At 55 min. into the 1st hold period a channel spanning logjam formed at the upstream end of the delta. For the remainder of the first hold period that logjam stayed intact and there was effectively no wood movement on the delta surface downstream of the logjam. There were two channels on the delta that bifurcated from the channel spanning logjam when it first formed. These two channels fluctuated in width and very occasionally had small, ephemeral offshoot channels that developed during the remainder of the first hold period but primarily stayed in the same location and did not form any major bifurcations. During the second dam segment removal the two pre-existing delta channels both prograded as base level fell (Fig. 8C). Both channels had secondary bifurcations and avulsions that formed as wood debris was exhumed from the delta surface but the upstream delta channel planform stayed stable throughout the dam segment removal and into the 2nd hold period until a newly exhumed piece of wood debris blocked of the left-hand channel of the main bifurcation.

Discussion

Woody debris interactions with channel shape and distribution

Experimental runs with wood debris exhibited increased roughness affecting sediment transport, modes of channel mobility, and overall channel behavior and delta planform. Increased amounts of exhumed wood led to increased channel roughness, both directly from individual pieces of woody debris and indirectly from increased channel splitting in the runs with woody debris (Fig. 9). The increased roughness led to increased flow deflection, channel bifurcation, and avulsion, resulting in a more mobile, multithreaded delta planform pattern. Individual pieces of wood and small logjams caused both local sediment accumulation immediately downstream and sharp deflections of the thalweg across the active channel. These effects cumulatively increased the number of bifurcations and avulsions. The amount of lateral bank erosion also increased as the thalweg was directed toward banks for a much greater percentage of time.

Together this means that even though the overall system is incisional, with falling base level, a steady discharge and no upstream sediment inputs, conditions where we would normally expect relatively immobile incising channels on the delta, channels instead rapidly avulsed across the delta. Every time pieces of wood move downstream or logjams formed, broke up, gained or lost pieces, changes in the pattern of local sediment accumulation and thalweg location resulted in much more dynamic and active channel systems. Conversely, when wood did not move, channel planform generally did not change. The largest and most stable logjam in the experiments, a channel spanning logjam in the 3.5 % Wood Run, was able to control flow at a bifurcation even in an active, incising system. Delta area also grew faster with the increased channel mobility and avulsions creating channels angled away from the original channel (Fig. 8).

Channel cross-sections in the upper erosional channel were narrower and deeper in the 3.5% Wood Run but wider in the 2% Wood Run, in comparison to the Sediment Only Run (Fig. 4). Previous field and flume experiments showed that individual pieces of wood can deflect flow and erode both downwards into the streambed and laterally into streambanks (Ch. 1). When there is less wood in the channel, most small logjams or individual pieces not in contact with other pieces of wood tend to deflect flow laterally across the channel. These flow deflections increase the flow velocity directed towards channel edges and thereby increase channel width. As wood concentration increases, individual pieces of wood and logjams also act to protect banks from erosion by blocking high flow velocities from reaching the channel edge, resulting in narrower channel widths. These experiments are all net erosional in the fluvial channel section, as there was no sediment fed into the upstream end of the experiment. If a high enough spatial density of wood is protecting channel banks from erosion, the channels also deepen as the streambed becomes easier to erode than channel banks. In these experiments wood was placed quasi-horizontally to correspond to the most likely wood orientations in nature for waterlogged wood sinking onto a lakebed. It is likely that logs buried in floodplains are also mostly horizontal as most wood is transported downstream and deposited individually or in logjams horizontally. As such, eroding and un-burying a piece of wood on the streambed requires scouring vertically down to the depth of the trunk or root diameter. Eroding and un-burying a piece of wood laterally from a streambank requires scouring the entire length of the tree trunk.

Implications for ecology, dam removals, and deltas

These experiments suggest significantly improved aquatic habitat as exhumed wood concentration increases. Logjams correlate to the number of pools in the system, which is important for fish feeding, and rearing, and as cold water refugia during summer low flow conditions. Pools associated with logjams are especially useful for feeding fish as they combine cover with proximity to food sources. The experimental runs with wood debris also show more overall depth variability in the channel, contributing to more types of microhabitats and more boundaries between different habitat zones, things important for creating productive feeding zones (Fig. 10). The increased number of channels on the delta translates to an increase in the total length of channel edges, an important aspect of aquatic habitat as they typically combine cover, slower flow and proximity to multiple food sources. Similarly, reaches with more wood had greater total shoreline lengths, leading to more shoreline edge habitat. Finally the total delta area increases as exhumed wood percentage increases so the total habitat area also increases.

These experiments suggest that future dam removals may experience increased lateral delta erosion in reservoir sediments, if sufficient amounts of wood are stored in the impoundment. Depending on reservoir geometry, increased lateral erosion during dam removal can result in the erosion of 40% or more of impounded sediments (Tsutsumi and Laronne, 2017). In some cases, sediment management goals may be to decrease rates of sediment evacuation in order to remediate contaminated sediment (U.S. Environmental Protection Agency, 2004). In the case of the Elwha River Restoration, sediment management goals for the dam removals included eroding and redistributing coarse delta sediments over the reservoir so that the resulting floodplain topography would be stable and suitable for new plant growth (Randle and Bountry, 2010). The sediment management plan included the removal of a logjam to increase lateral erosion and adaptive management criteria to erode islands and break up channel bed armoring with high-pressure hoses. The sediment management team was particularly concerned that woody debris exhumed from the reservoir would armor channel banks and prevent lateral erosion (T. Randle and J. Bountry personal communication 2011). Unfortunately it is difficult to estimate the volume of a woody debris buried in a reservoir without extensive coring or geophysical surveys of reservoir deposits (Tsutsumi and Laronne, 2017). In some cases the amount of woody debris in a reservoir can be estimated based on the amount of floating wood in a reservoir or based on woody debris exposed during a reservoir drawdown (Chenoweth et al., 2011). In such cases, woody debris interactions with dam removal morphodynamics may be considered during sediment management planning for dam removals.

These experiments suggest that woody debris can have an important role in delta morphodynamics, affecting channel planform, sediment routing, and delta evolution. In the case of incisional systems with dropping base level, woody debris can create multiple channels on a delta (Fig. 5) instead of a single channel incising into delta deposits (Cantelli et al., 2004). Woody debris increases bar formation, channel bifurcations, and avulsions, leading to lateral channel mobilitiy (fig. 6) and wider deltas (Fig. 8). These patterns are similar to how woody debris interacts with fluvial systems, with woody debris increasing the number of active channels (Collins et al., 2012; Sear et al., 2010; Wohl, 2011) and facilitating bar and island formation (Abbe and Montgomery, 1996; Bertoldi et al., 2015; Collins et al., 2012). Understanding interactions between woody debris, sediment transport, and delta channel networks is important for predicting delta evolution and for planning delta restoration projects that aim to reduce coastal flooding (Kim et al., 2009; Paola et al., 2011) or create new habitat (Cornu et al., 2008).

Limitations

These experiments were run at a constant discharge, without sediment fed into the system. Experimental conditions are most similar to staged dam removals taking place during low discharges. Dam removals often occur during these times, so that the removal is more controlled but oftentimes other scheduling constraints, such as fish migrations, result in dam removals occurring during higher or more variable discharges (Tsutsumi and Laronne, 2017). Wood mobilization is most likely to happen by mobilization of in-channel wood and from wood recruited from the floodplain and floodplain forest as avulsions occur. Wood recruitment from local bank erosion also increases as discharge increases. Wood that was stored in the floodplain can be remobilized as scour and erosion occur. Once in motion, wood transport distances are greater than during low flow, as increased water depth reduces the amount of contact in transit wood has with streambed topography. In-flux wood is much more likely to interact with floodplain vegetation during high discharges. During higher discharges, sediment transport and changes in channel form are greater than during lower discharges. The amount of the floodplain that interacts with the active channel is likely to increase, both from overbank flow and from increased flow in side channels and abandoned channels. Wood flux generally increases as discharge increases. Wood flux during floods is often supply limited (Comiti et al., 2016), so increases in wood transport are highly dependent on upstream conditions, particularly whether there are landslides on forested hillslopes. Depending on the increase in wood flux, wood transport may be congested (Braudrick et al., 1997), leading to more trees uprooted from the floodplain and greater deposition of wood levees that constrain channel flow (Johnson et al., 2000). Bertoldi et al. (2015) found that at constant discharges in flume experiments, the amount of wood stored in the channel depends on log input rate, with a non-linear threshold effect, in which the amount of stored wood increased sharply when larger logjams start to form. At peak discharge, mobile wood will deposit only in the most stable locations, creating more large logjams. As larger logjams are more stable, they can deflect larger amounts of flow farther laterally, and may increase the number and spacing of active channels. The logjam and channel planform changes during the largest floods are most likely the upper limits of channel mobility and channel distribution changes possible in the system.

In these experiments, sediment primarily travelled as bedload, with a barely detectable amount of sediment traveling as suspended load. As a consequence, delta dynamics are dominated by delta top and delta front progradation, with very little of the prodelta developed. The delta front is very steep, at the angle of repose, at almost all times in the experiment. In contrast, natural systems have a considerable amount of suspended load. Turowski et al. (2010) found that often 0 - 50% of sediment is transported as bedload in natural systems, with high variability between events and years, and that the percentage of sediment traveling as bedload increased during floods (Turowski et al., 2010). These experiments also only used non-cohesive sand, in contrast to natural systems which often contain a mix of cohesive and non-cohesive sediments. Using simulations in Delft3D, van der Vegt et al. (2016) found that changes in the percentage of bedload and suspended load transport, and the percentage of cohesive and non-cohesive sediments affect delta shape, delta channel cross-sections, and avulsion frequency. Bedload and non-cohesive sediment dominated deltas have a more extensive delta top with a steeper delta front, while suspended load and cohesive sediment dominated deltas have a more developed prodelta with a shallower delta front. Delta channels are shallower and wider on bedload and non-cohesive sediment dominated systems, and deeper and narrower on suspended load and cohesive dominated systems. Avulsions occur more frequently on bedload and non-cohesive sediment dominated systems than on suspended load and cohesive sediment dominated systems. Consequently, bedload and non-cohesive sediment dominated systems are reworked more frequently and have a smoother delta contour. In suspended load and cohesive sediment dominated systems, delta channels are able to extend farther over time, resulting in a more lobate delta. Our experiments indicate that wood load also influences delta morphology.

The Sediment Only Run in these experiments does not have sediment fed in with the water discharge, although sediment eroded from the erosional section travels to the depositional delta section. Sediment grain size is also uniform in these experiments unlike in natural systems. Consequently, channel mobility in these experiments is dominated by lateral bank erosion, with very few avulsions or bifurcations. Wood debris greatly increases channel roughness, resulting in increased topographic and hydraulic variability and heterogeneous sediment storage. Sediment can accumulate in the lee of wood debris, leading to more bifurcations, avulsions and a more lobate delta front. In a system with wood debris that is also suspended load or cohesive sediment dominated, there would likely be a more developed prodelta than in a bedload, non-cohesive sediment, or bedload, non-cohesive sediment, and wood debris dominated system but a less developed prodelta than in a suspended load or cohesive sediment dominated system without wood debris. Bifurcations and avulsions would be less frequent than in bedload, non-cohesive sediment, or bedload, non-cohesive sediment, and wood dominated systems, leading to a more lobate delta planform. Channel cross sections shape and delta top growth rates would likely be between that of bedload or noncohesive sediment and suspended load or cohesive sediment dominated systems.

Conclusions

This investigation provides insight into channel development, delta morphodynamics, and physical processes related to wood debris during base level drops, such as in dam removals or reservoir drawdowns. In the upstream erosional sections, channel cross-sections are shallower, wider, and less stable when there is a small amount of wood debris, and deeper, narrower, and more stable when there is a large amount of wood debris. Increased roughness from wood deflected flow, increased hydraulic variability, and increased the number of bifurcations and avulsions, resulting in a more mobile, multi-threaded delta planform. The largest and most stable logjam in the experiments, a channel spanning logjam in the 3.5 % Wood Run, was able to control flow at a bifurcation even in an active, incising system. When there was wood in the system, experimental deltas developed up to six delta channels that migrated rapidly laterally and frequently bifurcated and avulsed. In contrast, the single main delta channel only slowly migrated laterally and only bifurcated twice during the entire experiment. Several types of physical aquatic habitat increased in the presence of wood, including hydraulic variability, pools, side-channel habitat, channel edge habitat and delta shoreline habitat. The changes in channel planform and channel mobility in these experiments suggest that wood debris can play an important role in dam removal and delta morphodynamics, and should be considered in planning for dam removals and delta restoration projects.

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Figures

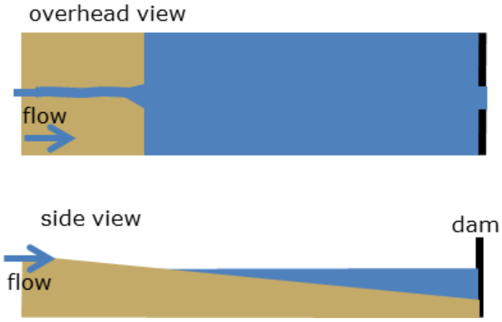

Fig. 1 Schematic illustration of flume and experiment setup.

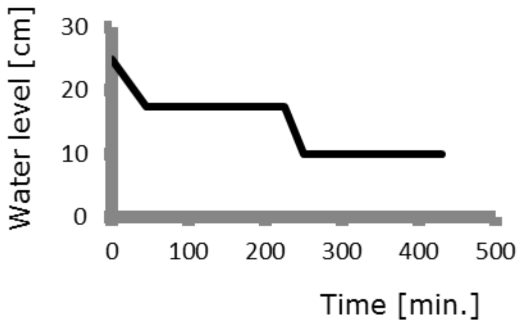

Fig. 2 Variation in experimental lake levels over time during experimental runs.

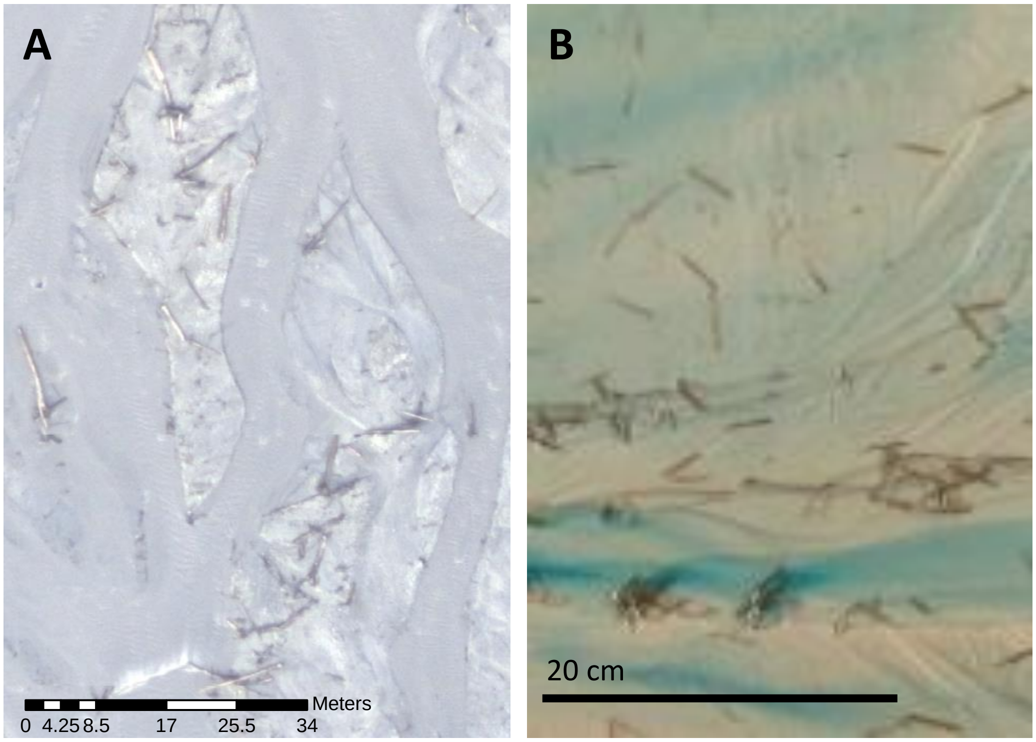

Fig. 3 Comparisons between flume-scale and field-scale spatial patterns of wood distribution for: A) 2% Wood Run and B) individual pieces of LWD in Mills on the Elwha River after dam removal,

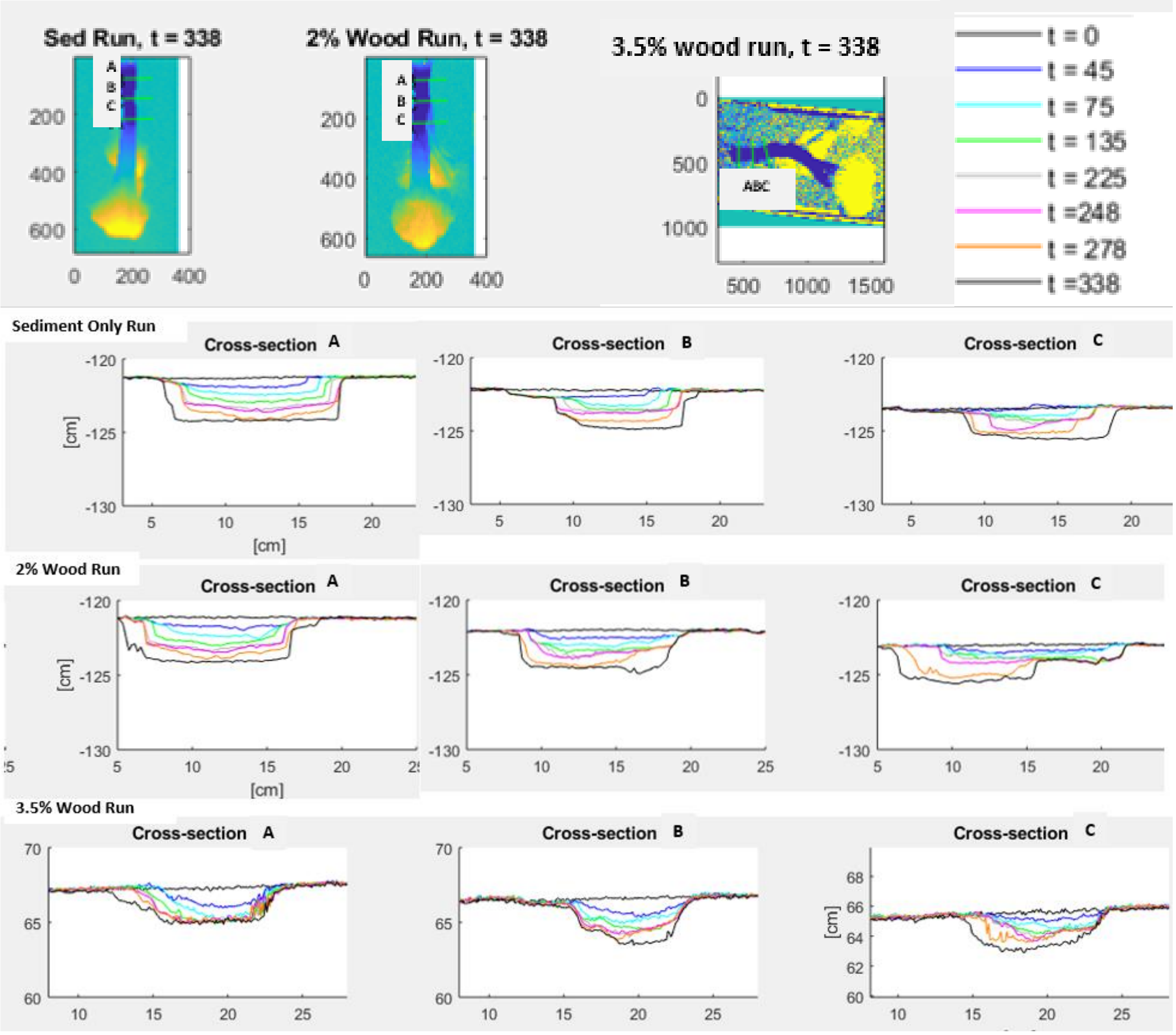

Fig. 4 Channel cross-sections at 9 times in each experiment, for 3 places in the upstream fluvial sections.

A) Sediment Only Run
B) 2 % Wood Run
B) 3.5% Wood Run

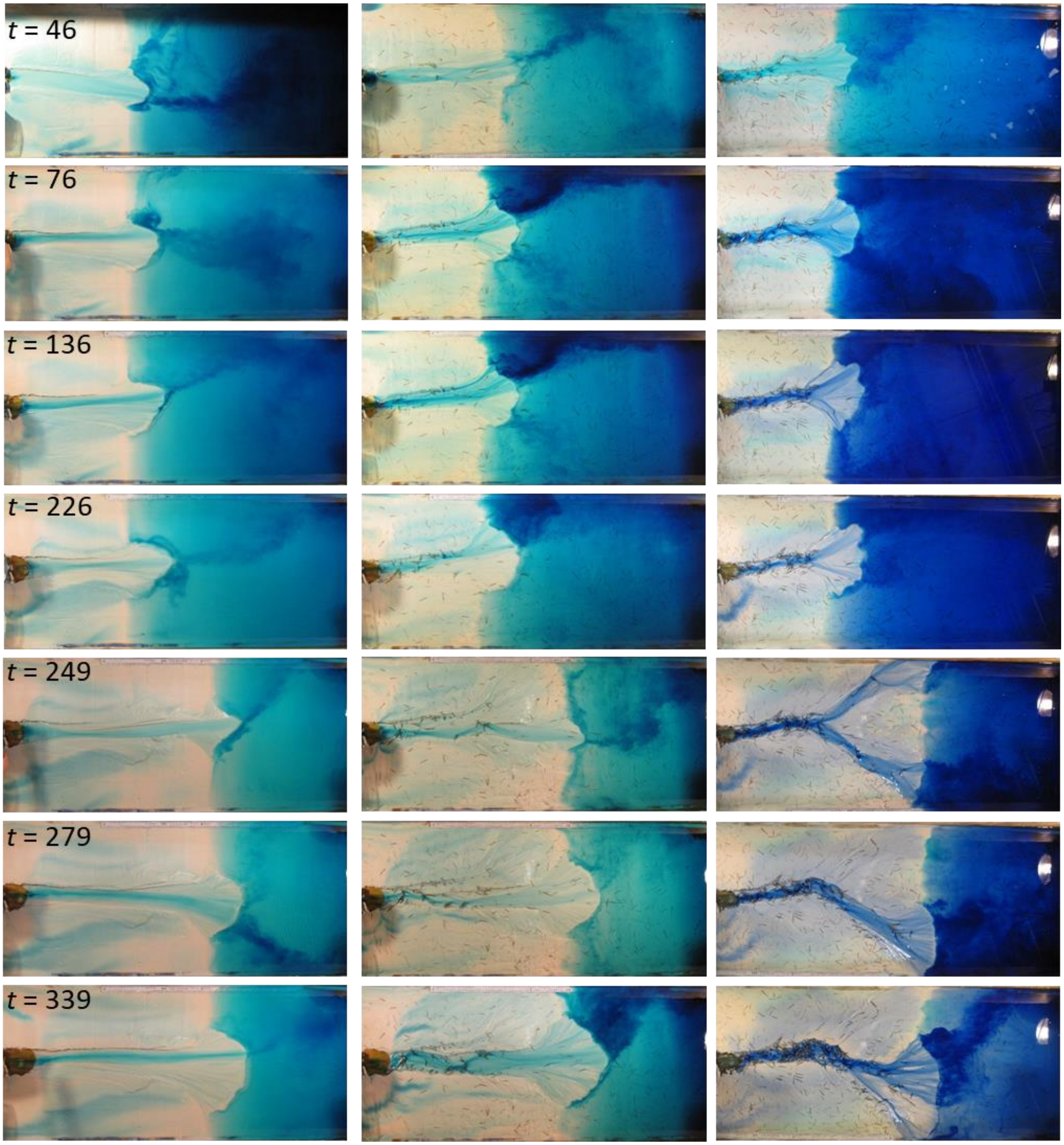

Fig. 5 Channel and delta planform at specific times in the experiments, corresponding to times that topography measurements were taken. Column A is the Sediment Only Run, column B is the 2% Wood Run and column C is the 3.5% Wood Run.

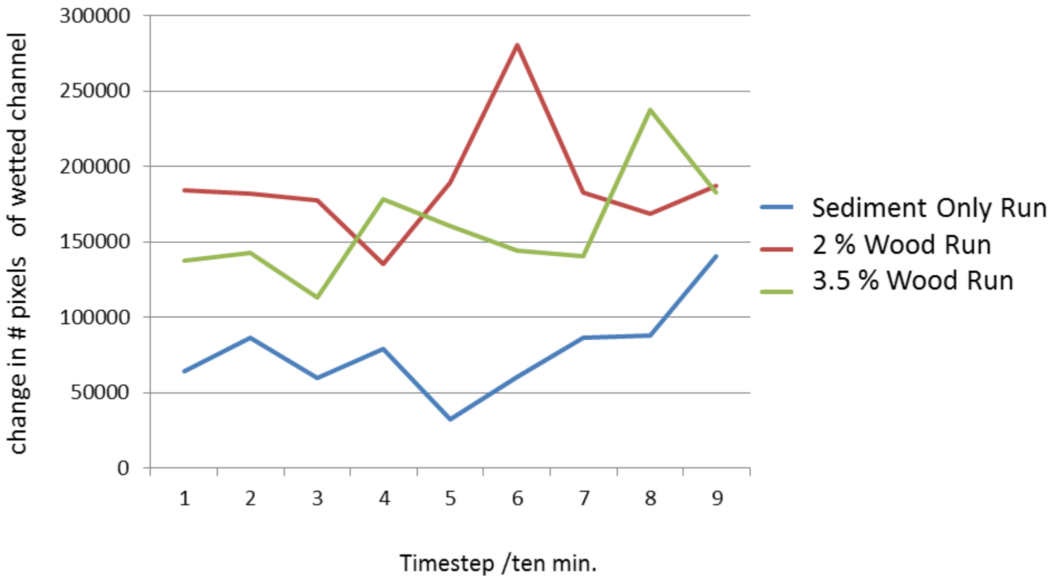

Fig. 6 Channel mobility during the last 90 minutes of the 2nd hold period showing greater channel mobility in the two experimental runs with exhumed wood debris. Change in wetted channel area (by pixels) is plotted against time.

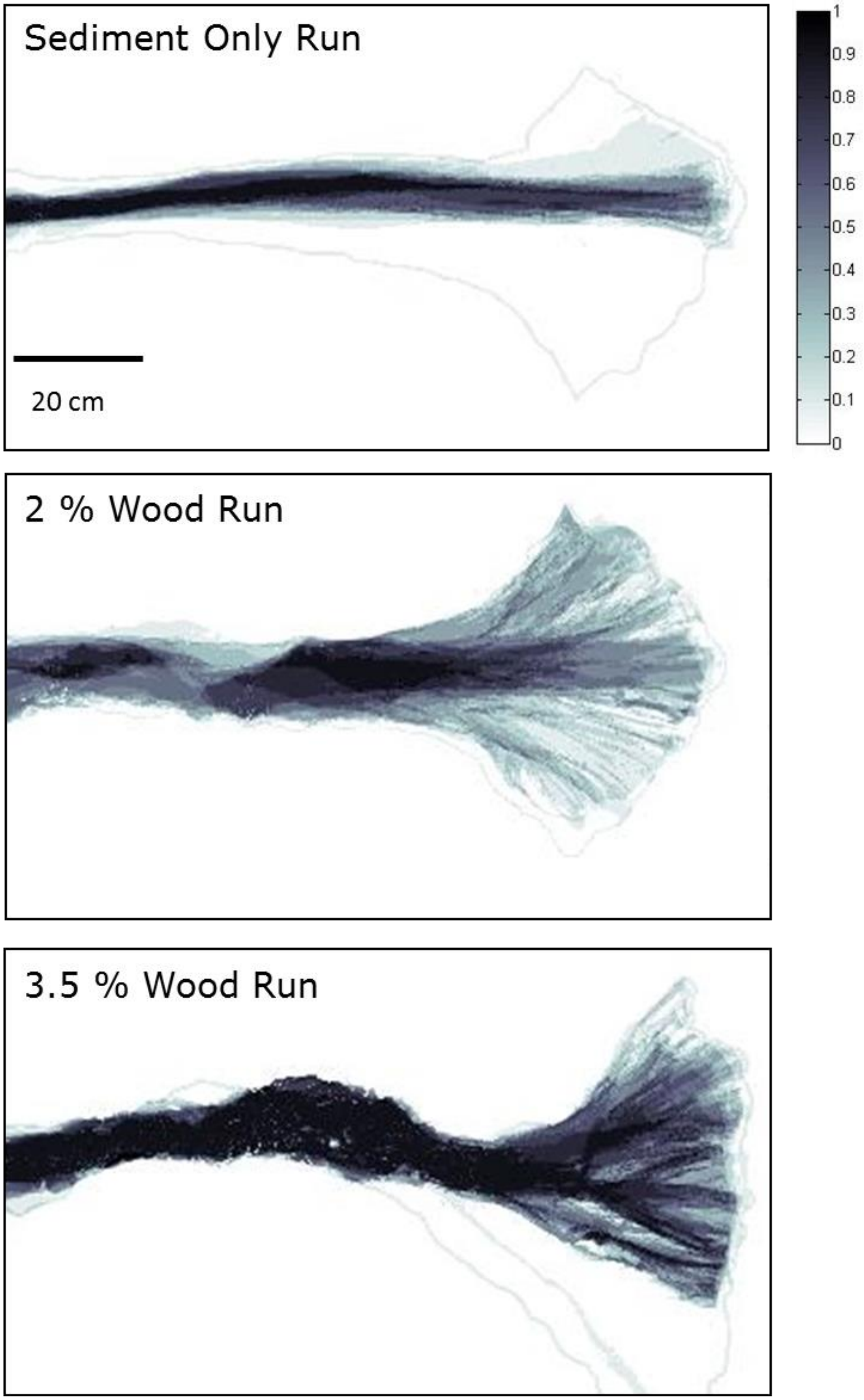

Fig. 6 Channel occupation maps of the last 90 min. of the 2nd hold period. Black and dark grey shows areas where the wetted channel is the majority of the time and light grey shows areas where the wetted channel is for less of the time.

A) Sediment Only Run
B) 2 % Wood Run

C) 3.5% Wood Run

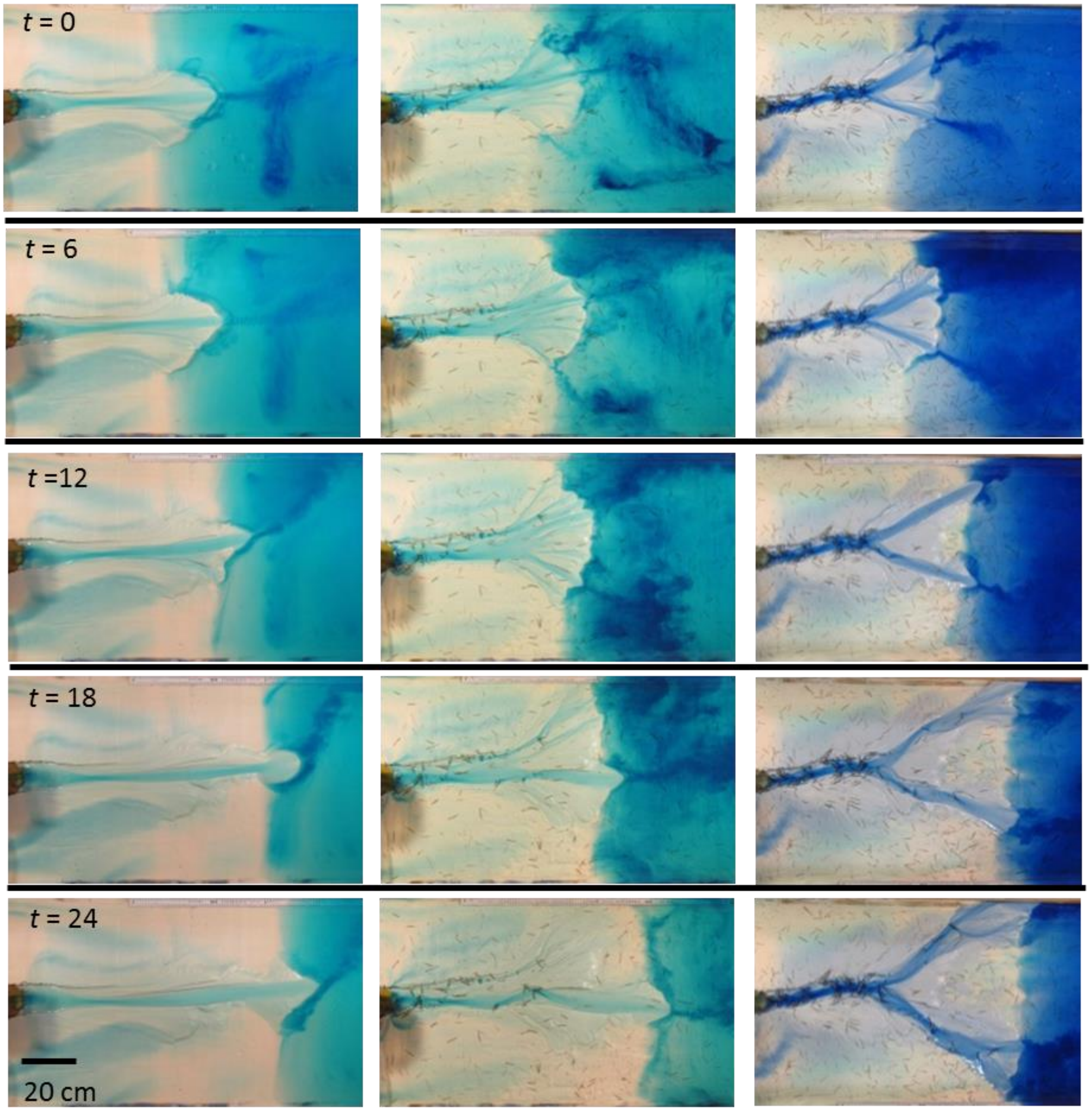

Fig. 8 Overhead photo sequences of the 2nd dam segment removal, with photos taken every 6 minutes. The Sediment Only Run (column A) had a single main channel that prograded as base level droped. The 2 % Wood Run (column B) had multiple channels that prograded simultaneously as base level dropped. The 3.5 % Wood Run (column C) had a stable bifurcation during the dam segment removal and both channels of that bifurcation prograded as base level dropped. Additional channel bifurcations also developed farther along the delta as base level dropped. The 3.5 Wood Run developed a significantly larger delta at the end of the 2nd dam segment removal as compared to the other two experimental runs.

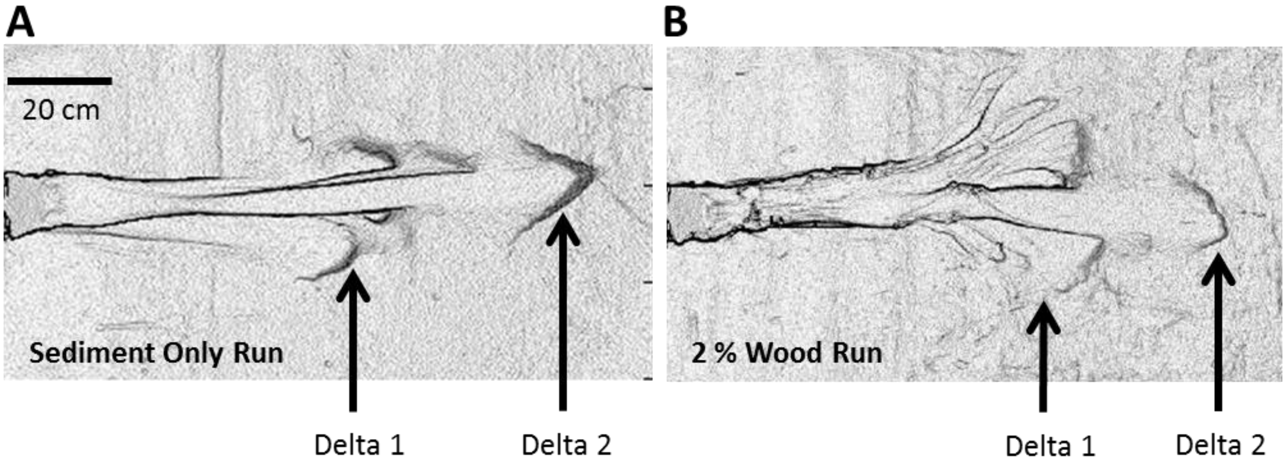

Fig. 9 Slope-maps of the (A) Sediment Only Run and (B) the 2 % Wood Run at the end of the 2nd hold period showing increased channel roughness in the 2 % Wood Run. Delta 1 is the delta formed during the 1st dam segment removal and 1st hold period and Delta 2 is the delta formed during the 2nd dam segment removal.

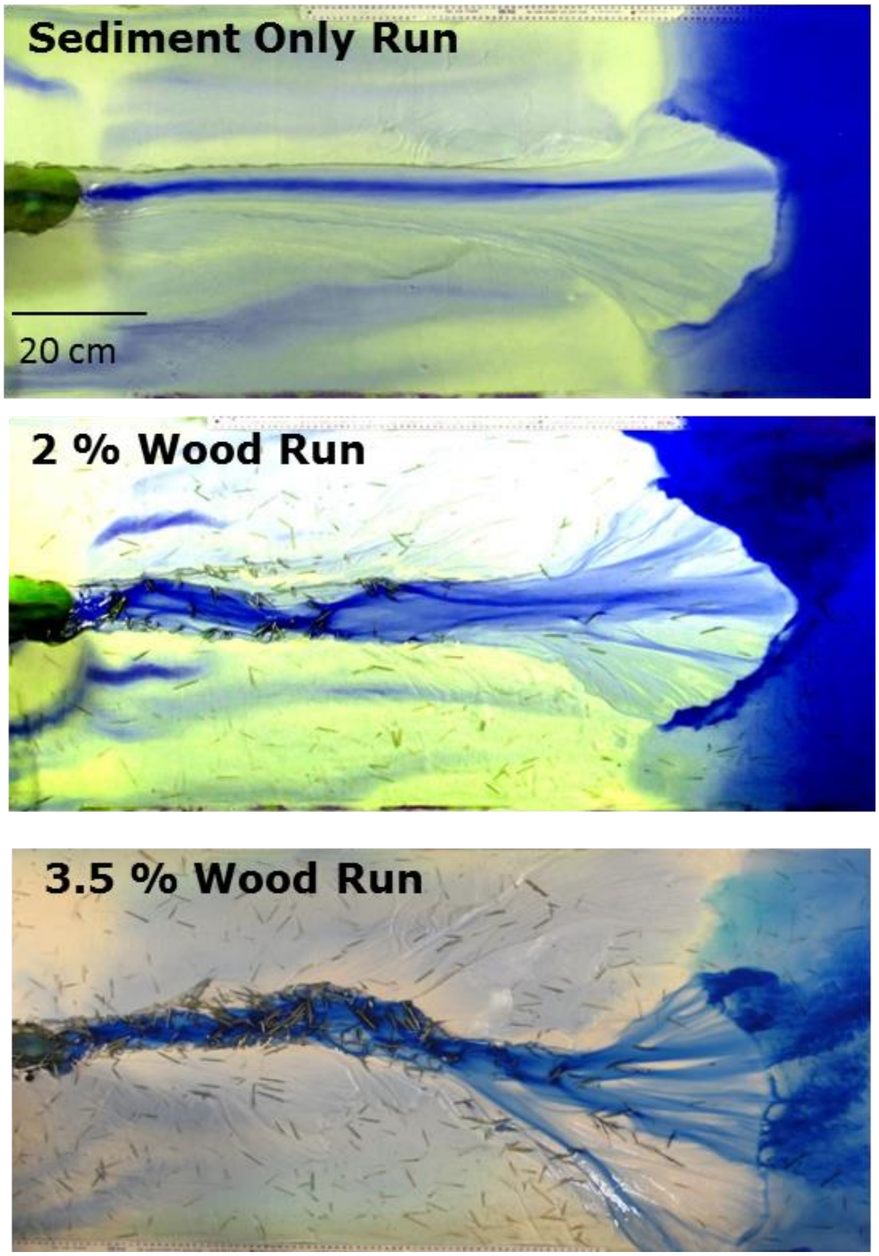

Fig. 10 Overhead photos during the 2nd hold period showing increased bifurcations and multiple simultaneously occupied channels on the delta for the experimental runs with exhumed wood debris. Experimental runs with exhumed wood show more pools, more logjam complexity, more topographic depth variability, more channel edge lengths and more delta shoreline length.

Ch. 5 Conclusions

Woody debris interacts dynamically with river systems, creating pools, stabilizing floodplains, and changing channel planform. In turn, wood mobility, deposition, and logjam formation are affected by flow, sediment transport, and existing channel morphology. These influences occur at multiple scales, from individual pieces of woody debris at reach scales, to logjams, channel planform, and the evolution of deltaic systems. At the local level, the presence or absence of roots is the main determinant for scour pool size. An individual piece of woody debris with any type of root will create a larger scour pool than a piece of woody debris without roots. The scour pool size is also correlated with the root cross-sectional area relative to flow. On the Elwha River, logjams have developed unexpectedly rapidly on former reservoir surfaces after dam removal. Logjam area has increased in all sections of the river downstream of the former dam locations. In the Lower Reach, below both dams, logjam area increases after dam removal are similar in magnitude to logjam area increases after an avulsion associated with a 40-year flood. However logjam area only increased in the two rkm nearest to the avulsion, in contrast to logjam area increasing after dam removal in every part of the river except for bedrock canyon reaches. For reservoir sediment morphodynamics during dam removals and delta morphodynamics, relatively small amounts of woody debris can have large effects on channel plan form, channel mobility, and delta development. Woody debris can play an important role in dam removals and delta morphodynamics and should be taken into consideration for dam removals and delta restoration projects in forested regions. Flume experiments with woody debris have up to six delta channels that avulse and migrate rapidly, in contrast to experiments with only sediment where one main channel rarely bifurcates and migrates far more slowly. Ecologically, this suggests that more woody debris leads to increases in aquatic habitat quality and quantity with increased cover, increased depth variability, more logjams and pools, increased channel-edge length, and greater delta area. Together, these results broaden the geomorphic understanding of interactions between woody debris stability and transport, sediment scour and transport, and flow hydraulics at scales from individual pools to the evolution of deltaic systems.