PERSISTENCE OF STREAM RESTORATION WITH LARGE WOOD, REDWOOD NATIONAL AND STATE PARKS, CALIFORNIA

By

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ABSTRACT

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The conservation and recovery of anadromous salmonids (*Oncorhynchus* sp.) depend on stream restoration and protection of freshwater habitats. In-stream large wood dictates channel morphology, increases retention of terrestrial inputs such as organic matter, nutrients and sediment, and enhances the quality of fish habitat. Historic land use/land cover changes have resulted in aquatic systems devoid of large wood. Restoration by placement of large wood jams is intended to restore physical and biological processes. An important question for scientists and restoration managers, in addition to the initial effectiveness of restoration, is the persistence and fate of large wood installations. In this study I compare channel change and large wood attributes on the East Fork of Mill Creek, a tributary of the Smith River in northern California, eight years after a major instream wood placement effort took place. I compared my results with previously published data from a few months before and one year after large wood installation.

Since the introduction of complex wood jams to East Fork Mill Creek in 2008, this study found an overall increase in floodplain connectivity, bankfull width, and lower channel gradient leading to an increase in hydraulic complexity. Key log jams designs were found to be self-sustaining; creating cover and resting habitat for adult and juvenile salmonids such as side channel access. Furthermore, self-sustaining log jams further improved rearing habitat for juvenile salmonids by trapping and sorting sediments exposing spawning gravel suitable for Chinook, Coho and coastal rainbow trout. The results observed in this study support several common long-term goals. Future restoration efforts in areas equivalent to East Fork Mill Creek with similar long-term goals may find complex log jams, comparable to the log jams installed in this study, benefiting their project area.

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INTRODUCTION

The conservation and recovery of anadromous salmonids (*Oncorhynchus* sp.) in the Pacific Northwest of the United States depend on the restoration and protection of ecological processes that create and maintain freshwater habitats (Reeves et al. 1995). Stream and river systems are interconnected with terrestrial ecosystems and processes. In-stream large wood (i.e. trees in the terrestrial environment that fall into waterways) exemplifies the connectivity between the two systems in the Pacific Northwest In-stream large wood dictates channel morphology, provides storage sites for organic matter and sediment, influences the movement and transformation of nutrients, and enhances the quality of fish habitat (Bisson et al. 1987; Bilby and Bisson 1998). In-stream large wood has been recognized as a key physical element to stream restoration (Reich et al. 2003). Although the role of in-stream large wood in streams has been studied for over 30 years, there is little long-term research on the effects of in-stream large wood placement in stream restoration (Reich et al. 2013). This study evaluates the long-term effects of constructed large wood eight years after placement into the East Fork Mill Creek in Del Norte County, California. Data collected in 2008 and 2009, by Joèl Flannery (2011 and 2017), will be used as a reference point to identify the continual changes of bed sediment size above and below constructed wood jams, residual pool depth, wood volumes, and floodplain connectivity.

In-stream large wood dissipates the energy of flowing water influencing the scour of streambeds, storing and redirecting sediment and surface water. This process creates pools and riffles varying in size and spacing, diversifies bed substrate size and modifies channel width and roughness (Beschta 1979; Bilby 1984; Lisle 1986; Bisson et al. 1987; Fetherston et al. 1995; Dolloff and Warren 2003). The size, placement, and angle of in-stream large wood within a stream channel creates different effects. Pool formation is associated with in-stream large wood aligned perpendicular to the thalweg (Cherry and Beschta 1989; Richmond and Fausch 1995; Hauer et al. 1999). Furthermore, Dolloff and Warren (2003) suggest that large wood located within the wetted perimeter of a channel influences pool formation by directing scour patterns at bank-full flows.

In-stream large wood creates and maintains pool habitat for aquatic organisms. Pools carry low velocities and greater depths at low flows (Dolloff and Warren 2003). Pools associated with in-stream large wood are preferred habitats for various age classes of juvenile Coho salmon (*O. kisutch*), Cutthroat trout (*O. clarki*) and steelhead (*O. mykiss*) (Bisson et al. 1987. Deeper pools provide winter habiat during high flows and summer habitat during low flows for multiple fish species and/or for different ages of the same species (Maser and Sedell 1994). Salmonids and drift-feeding minnows benefit from pool features serving as a refuge and area of food catchment during high flows (Matthews 1998). Furthermore, in-stream large wood provides cover for salmonids from predation and areas for spawning and nesting sites (i.e. spawning gravel) (Dolloff and Warren 2003). In-stream large wood also has considerable influence on sediment transport and storage, an essential component of aquatic habitats (Reeves et al. 1995). In-stream large wood establish sediment storage sites, such as floodplains, which contribute to algae and macroinvertebrate food production for fish. Spawning habitats are promoted by scouring and transporting fine sediments; exposing spawning gravel and creating higher quality habitats for benthic macroinvertebrates (Dolloff and Warren 2003).

Dynamic stream flows and floodplain connectivity result in elevated biodiversity and primary productivity (Junk et al. 1989; Tockner and Stanford 2002). Stream velocity typically slows as it enters onto the floodplain during inundation periods allowing sediment deposition. This results in less turbid water granting greater rates of aquatic vascular plant and algae production (Ahearn et al. 2006). Increased primary productivity supports the productivity of zooplankton and aquatic invertebrates (Junk et al. 1989). Shallow, low-velocity floodplains with vegetated habitats are beneficial for salmonids to take refuge from fast, turbid waters during high flows and rear offspring within a sheltered food-rich area (Welcomme 1979; Sommer et al. 2001). Bayley (1991) found a higher yield of fish per area in rivers with connected floodplains that received unaltered flood pulses.

The lack of adequate wood in stream systems increases homogeneity in stream structures, reducing habitat complexity and species diversity (Dolloff and Warren 2003). Poorly developed streams have low residual pool depth and therefore tend to support fewer species, exhibit simple trophic structures, and result in higher variability of fish abundance (Schlosser 1987; Lisle and Hilton 1992). Throughout the Pacific Northwest, river and stream systems have been altered by human activity including timber harvest, and stream wood cleaning (Bisson et al. 1992; Wooster and Hilton 2004).

Timber harvest in the Pacific Northwest reduced the potential of large wood availability and delivery into the stream systems (Hicks et al. 1991; Reeves et al. 1993; Ralph et al. 1994). Therefore, in an event of harvest-related hillslope failures, the primary material delivered into the channel is sediment (Hicks et al. 1991). In-stream large wood creates complexities in river channel geomorphology by trapping sediment directly upstream and changing the movement of water directly downstream. These complexities are beneficial for various aspects of fish habitat. Timber harvest has decreased stream channel complexity (Reeves et al. 1995).

In the early 1980's, initial stream restoration efforts focused on migrational barriers of anadromous fish. Wood jams were considered a barrier to fish passage and the cause of erosion (Wooster and Hilton 2004). Therefore, steam cleaning occurred (i.e. removal of in-stream large wood) at a rate of 100 miles per year in the Pacific Northwest. These salmonid restoration efforts were funded through California’s Energy Resources Fund of 1980 and the 1981 Bosco-Keene Assembly Bill 951 (California Resource Agency 1982). Stream cleaning efforts removed all in-stream large wood below a stream’s high-water mark (Wooster and Hilton 2004). Natural recruitment of wood decreased via removal through riparian tree harvesting and in-stream large wood removal, which resulted in an alteration of riparian habitats and nutrient cycles, increased sediment and organic matter transport, simplified stream channel complexities and caused loss of fish habitat (Likens and Bilby 1982; Bilby and Bisson 1998; Reich et al. 2003). By 1987, however, the model for stream restoration moved away from complete in-stream large wood removal to selective removal and replacement of in-stream large wood (Wooster and Hilton 2004).

In-stream large wood placement in areas of stream channels and floodplains provide a range of ecological functions and habitat diversity (Bilby and Likens 1980; Sedell and Beschta 1991). Recognition of the ecological importance of in-stream large wood by research scientists and land managers led to advocacy for the reintroduction of in-stream large wood and creation of riparian buffers for future large wood recruitment (Reich et al. 2003). Placement of large logs and rootwads, either individually or in combination with smaller logs, provide a secure foundation for restoring in-stream structures and cover (Maridet et al. 1996; Bisson et al. 2003). The intention of the reintroduction of large wood is to re-establish natural processes and conditions that create and sustain physical complexity (Maridet et al. 1996, Abbe et al. 2003). Several studies of stream restoration projects included the reintroduction of in-stream large wood such as Cederholm et al. (1997), Solazzi et al. (2000), Roni and Quinn (2001), and Roni (2003). These studies found an increase in numbers of Coho salmon juveniles and smolts in complex habitats created by in-stream large wood placement. Brookes et al. (1996) concluded that the placement of in-stream large wood alters hydrodynamics and influences deposition spawning gravel in the vicinity of in-stream large wood structures.

In 2006 and 2008, California State Parks implemented in-stream large wood placement as part of the East Fork Mill Creek In-stream and Floodplain Habitat Improvement Project in Del Norte Coast Redwood State Park. This project utilized several constructed wood jams to restore the natural large wood in-stream processes such as the pool formation, trapping and sorting sediment, and provide essential salmonid habitat. In 2008, Flannery et al. (2011 and 2017) conducted a study evaluating the relationship between increased wood loading (i.e. total site wood volume, total wood volume per channel width, and wood piece count) and the changes to the following variables: 1) percentage pool cover; 2) residual pool depth; 3) upstream sediment aggradation; 4) number of facies patches; 5) habitat heterogeneity; and 6) reach average D50 (i.e. median reach sediment size). Her results found increased percentage pool cover with increased wood loading in the active channel in areas surrounding the installed wood jam. In addition to a decrease of the reach average D50 was found to be correlated with wood jam volume (Flannery et al. 2011 and 2017).

Long-term research is necessary to monitor the recovery of watersheds. Short-term goals (2-3 years) for stream habitat restoration projects are often intended to increase the quantity and quality of juvenile salmonids (Lacy and Thom 2000). Long-term goals (10-100+ years) can be intended to restore the physical and biological processes that create and maintain salmon habitat (Lacy and Thom 2000). Bryant (1995) describes an approach to long-term monitoring for tracking the outcome of restoration efforts by using a pulse monitoring strategy. Pulse monitoring consists of low-density data collected every 3-5 years and high-intensity studies every 10-15 years. This strategy may provide an effective means of implementing long-term monitoring with a reasonable degree of accuracy and cost. California State Parks is considering permanent monitoring of in-stream large wood effects in the Mill Creek watershed (CDPR 2013). Therefore, this study will evaluate the long-term effects of in-stream large wood placement eight years after the completion of the East Fork Mill Creek In-stream and Floodplain Habitat Improvement Project and provide an effective means of implementing long-term monitoring. Data collection and analysis will reevaluate the relationship between increased wood loading (total site wood volume, wood volume within active channel, and wood piece count) and changes to the following variables: 1) percentage pool cover; 2) residual pool depth; 3) upstream sediment aggradation; and 4) bed sediment size above and below constructed wood jams; utilizing data collected in 2008 and 2009 by Joèl Flannery (2011) as comparison data. I expect to find an increase, compared to 2008 and 2009, in variable factors (floodplain connectivity, percentage pool cover, residual pool depth, and upstream sediment aggradation) with total site wood volume.

The objective of this study is to understand and identify the long-term effects of constructed large wood jams placed in a forested gravel-bed stream utilizing the pulse monitoring strategy. This study identifies the distribution of depositional and erosional environments; and the relationship between these environments and placed large wood jams. Furthermore, the implications for fish habitat quality and long-term restoration success is examined.

STUDY SITE DESCRIPTION

Location

The Mill Creek watershed is located on the northwestern coast of California near the northern border of coastal redwoods (*Sequoia sempervirens*) geographic range. The 99.7 km^2 Mill Creek watershed drains north to the Smith River approximately 10 km (6 mi.) southeast of Crescent City, Del Norte County. The 37 km^2 subwatershed area of East Fork Mill Creek (East Fork) and 24 km^2 subwatershed area of West Branch Mill Creek (West Branch) are tributaries to Mill Creek watershed (Madej et al., 1986; Carroll and Robison 2007; CDPR 2013). This project's study site is located in East Fork Mill Creek (Figure 1).

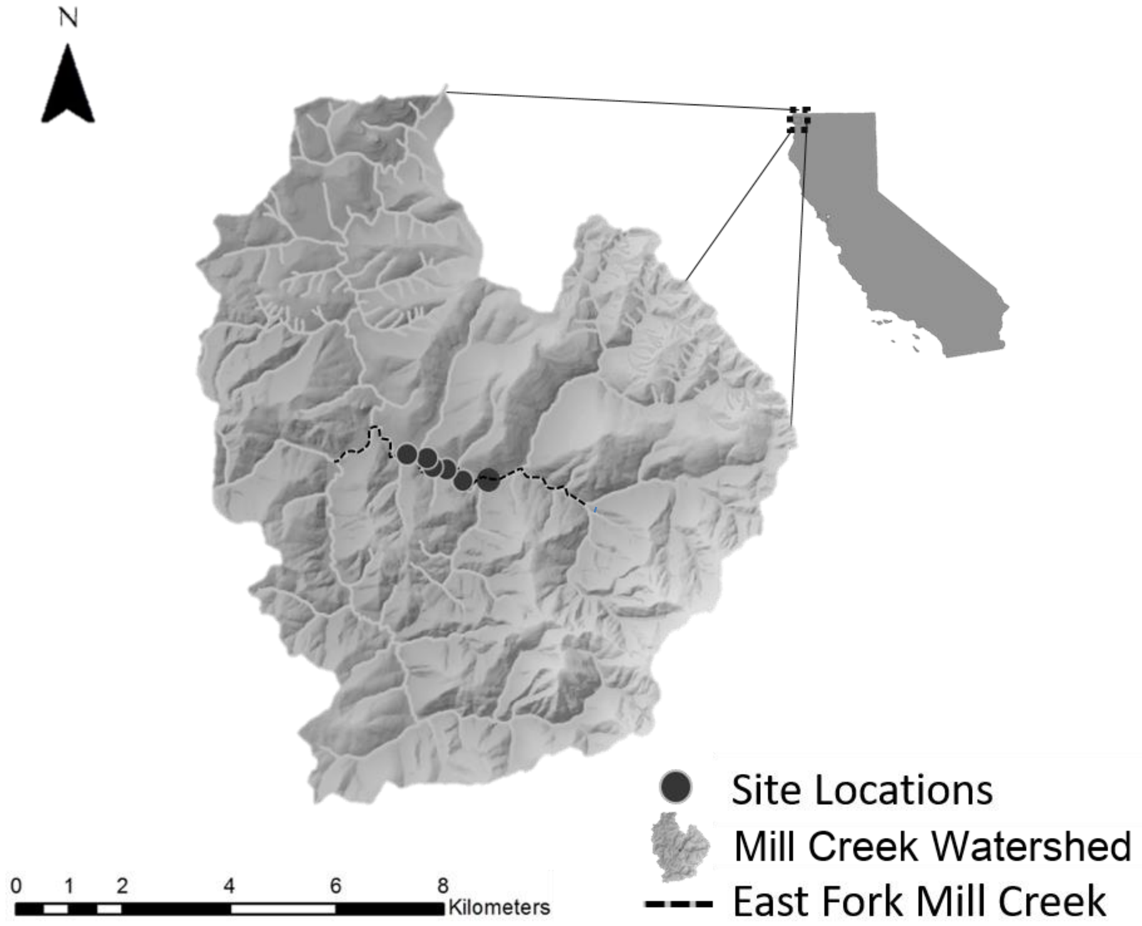


Figure 1. Study site location within the Mill Creek watershed, Del Norte County, California.

Climate and Hydrology

The climate of the Mill Creek watershed is coastal Mediterranean, defined by cool rainy winters and dry summers with frequent coastal fog (CDPR 2013). The range annual precipitation varies between 152 cm and 381 cm (Stillwater Sciences, 2002). Most precipitation falls as rain during the winter months with a small accumulation of snow at higher elevations (CDPR 2013). Mean annual air temperature ranges from a minimum of

8°C to a maximum of 19°C (Stillwater Science 2002). From 2012-2015, California was in a severe extended drought that likely affected the hydrology of the site (Asner et al. 2016).

The Mill Creek watershed is located in the northern limits of the California Coast Range and western Klamath Mountains forming a series of northwestern valleys and ridges. Ridges are commonly broad and mild sloping with ridge crest elevations increasing from east to west. The West Branch and East Fork are broad with flat-bottom valleys (CDPR 2013). Elevations within the watershed range from 16 m to 685 m (CDPR 2010).

The geology of the Mill Creek watershed is dominated by the Broken Formation of Franciscan Assemblage (Madej et al. 1986). The broken formation is composed of tectonically fragmented graywacke, shale, and conglomerate (Blake and Jones 1974). The north-northwest portion of the Coast Range thrust fault intersects the northeastern corner of the watershed and separates the Franciscan Assemblage sedimentary rock from the highly sheared serpentinite and peridotite of the Klamath Mountain (Madej et al. 1986). Franciscan Assemblage sedimentary rock units are primarily composed of sandstone and mudstone with slight amounts of conglomerate, chert, and volcanic rock (Madej et al. 1986). The Mill Creek watershed is dominated by coherent sandstone defined by high sandstone content, massive bedding, and moderate shearing and fracturing arising in steep, straight hillslopes (Harden et al. 1981). The dominant soil type in the watershed is physically stable Melbourne-Josefine with moderate erosion potential (Madej et al. 1986).

Current vegetation has been influenced by timber harvest. Douglas-fir (*Pseudotsuga menziesii*), knobcone pine (*Pinus attenuata*), and redwood (*Sequoia sempervirens*) were planted following timber harvest and continue to be the most common tree species on most of the study site. Other tree species present in the study site include sugar pine (*Pinus lambertiana*), western hemlock (*Tsuga heterophylla*), Port-Orford-cedar (*Chamaecyparis lawsoniana*), western redcedar (*Thuja plicata*), red alder (*Alnus rubra*), and grand fir (*Abies grandis*) (CDPR 2013).

Fish Community

The Mill Creek watershed is one of the most productive tributaries of the Smith River for resident and anadromous salmonid populations (CDPR 2013). Anadromous salmonid species found in the Mill Creek watershed are Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*O. kisutch*), steelhead trout (*O. mykis irideus*), Chum salmon (*O. keta*) and coastal rainbow trout (*O. mykiss* ssp. *irideus*). These anadromous salmonids extend 8.9 km (5.5 mi) up the West Branch and 9.6 km (6 mi) up the East Fork Mill Creek (CDPR 2013). Coho salmon were federally listed as threatened in 1997 (62 Federal Register 62:24588- 24609, May 6, 1997) and reaffirmed in 2005 (70 Federal Register 70:37160-37204, June 28, 2005). Additionally, Coho salmon were listed as threatened under the California Endangered Species Act in 2002 and in 2004 (CDFG 2004; CDPR 2013).

Non-salmonid populations found in the Mill Creek watershed include western brook lamprey (*Lampetra richardsoni*), Pacific lamprey (*Lampetra tridentate*), prickly sculpin (*Cottus asper*), Coastrange sculpin (*Cottus aleuticus*), threespine stickleback (*Gasterosteus aculeatus*), and Klamath smallscale sucker (*Catostomus rimiculus*) (McLeod and Howard 2010).

History and Land Use

Historically, wildfire and prescribed fire were part of the Mill Creek watershed's ecology, shaping vegetation patterns and creating or maintaining desired conditions (Norman 2007; CDPR 2013). Wildfire was ignited in the area by lightning and more commonly by prescribed fires by the native Tolowa tribe (Norman 2007). Between 1700 and 1850, mean fire intervals ranged from 11 to 26 years (Norman 2007). Norman (2007) and CDPR (2013) recorded fire scar heights below 30 cm (12 in) indicating low fire intensity. The Tolowa's use of prescribed fire was intended to reduce understory vegetation cover, induce acorn drop, and increase grass seed production (Driver 1939; Anderson 2005). During the early 20th century, the Tolowa collected acorns on the east-west-trending ridgeline between the East Fork and West Branch (Drucker 1937).

Timber harvest in the mill creek watershed began in the 1850's and continued to a larger extent in the 1920's through 1930's when Hobbs and Wall Company harvested most of the West Branch. Timber harvest discontinued for a short period until the purchase in 1954 by the Miller Redwood Company, afterward known as Rellim Redwood Company, then as Miller-Rellim Redwood Company, and finally Stimson Lumber Company (Stillwater Science 2002; CDPR 2013). Harvesting of the upper West Branch Mill Creek and East Fork Mill Creek watersheds occurred by 1958. By the 1980's much of the Mill Creek watershed had been fragmented by timber harvest units. Continuous timber harvesting on the property ceased in 2003 when California State Parks procured the Mill Creek watershed (CDPR 2013). Stream cleaning that removed large wood from waterways was routinely conducted in the mid- and upper- portion of the watershed until 1992 (Verhey and Schwabe 1993).

Restoration Treatments

The East Fork Mill Creek In-stream and Floodplain Habitat Improvement Project consisted of the strategic design and placement of log jams throughout East Fork Mill Creek. The project's restoration goals are: increasing hydraulic complexity by (1) creating pools, (2) increasing floodplain connectivity, (3) installing key log jams to rack mobile wood thus creating self-sustaining log jams; (4) improve rearing habitat for salmonids by trapping and sorting sediments exposing spawning gravel and creating cover and resting habitats such as side channels and floodplains for adult and juvenile salmonids (CDPR 2013).

Log jam placement in East Fork Mill Creek occurred in 1995, 2006, 2008, 2011 and 2012. In 1995, according to California Department of Fish and Wildlife (CDFW) protocol several large wood and boulder structures (simple log jams) were placed throughout the Mill Creek watershed including 15-20 simple log jams on the East Fork by CDFW (Flosi et al., 1998). The simple log jams were designed using two large boulders and one log; one boulder acted as a ballast against the end of the log on bankside and the other was placed within the active channel (Figure 2) (Schwabe 1998; Flannery 2011).

Figure 2. Simple log jam structure in 1995 by California Department of Fish and Wildlife in East Fork Mill Creek, Del Norte County, California (Flannery 2011).

Supplementary restoration continued in East Fork Mill Creek with California State Parks implementation of large-scale in-stream habitat improvements that consisted of the installation of twelve complex log jams in 2006 and thirteen complex log jams and one mobile wood loading site in 2008 (Flannery 2011). Complex log jams were constructed by combining large diameter trees with attached rootwads, logs, and branches (Figure 3). The majority of stems with large rootwads were installed with the bole and rootwad within the active channel and the stem wedged between standing riparian trees to control the movement of the jam during high flows (Flannery 2011). The mobile wood loading site consisted of nine pieces of LWD varying in size and these pieces were placed in the active channel parallel to the flow to monitor mobility and racking potential of complex log jams downstream (Flannery 2011). Additional log jams, placed in 2011 and 2012, were positioned by helicopter and excavator along the East Fork Mill Creek channel.

Figure 3. Complex log jam structure installed in 2008 by National and California State Parks in East Fork Mill Creek, Del Norte County, California (Flannery 2011).

Study Site Restoration Treatment

The study reach contains six 2008 complex log jam study sites (Figure 4). Site 6 contained a 1995 simple log jam structure which later was incorporated into 2008 complex log jams. The six complex log jams were categorized as deflecting, opposing, or underflow jams (Wallerstein and Thorne 2004) (Table 1). Deflecting log jams deflect the water flow from one bank towards the opposite bank. Opposing log jams constrict water flow towards the center of the channel. Underflow log jams span the entire active channel width generating high water flow obstruction and local water flow acceleration (Wallerstein and Thorne 2004). Sites 1 and 4 contain complex channel-spanning underflow log jams. Sites 2 and 5 contain complex deflecting log jams and sites 3 and 6 contain complex opposing log jams (Table 1).

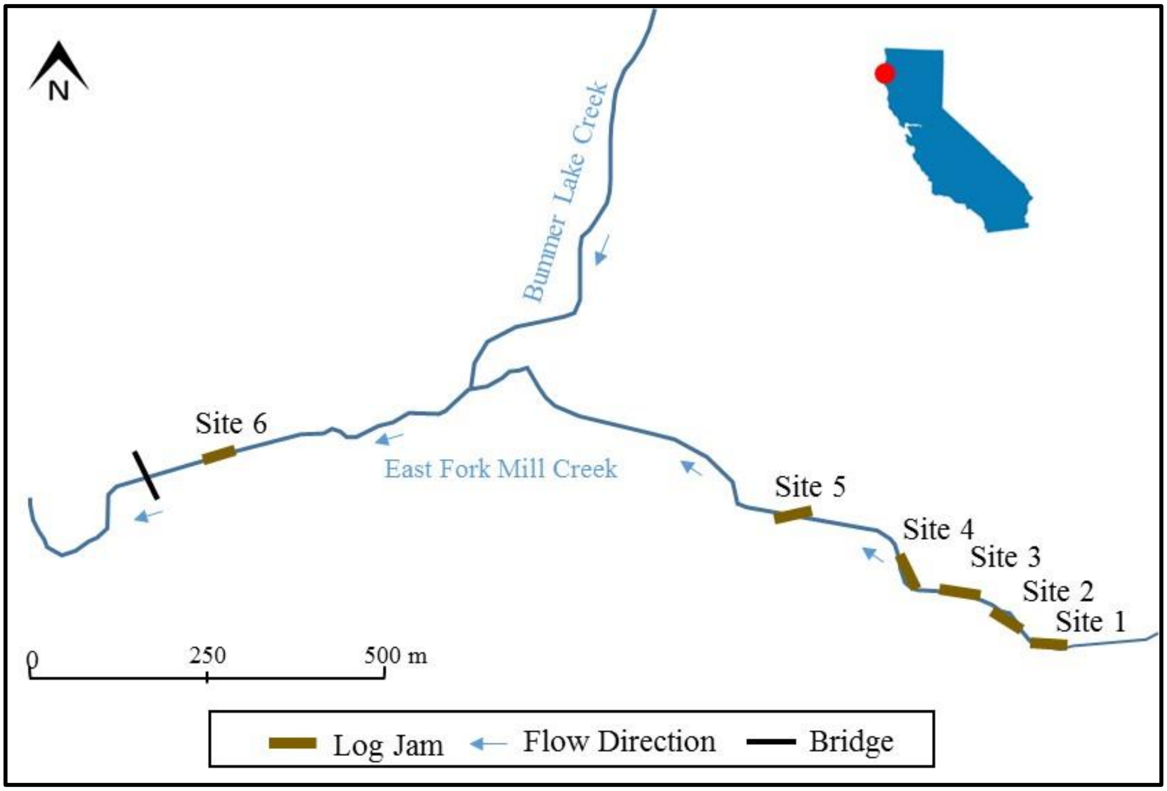


Figure 4. Site locations within study reach in East Fork Mill Creek, Del Norte County, California.

Table 1. Complex log jam type location within study reach in East Fork Mill Creek, Del Norte County, California.

Site	***Complex Log Jam Type***		
	Deflecting	**Opposing**	**Underflow**
1			✓
2	✓		
3		✓	
4			✓
5	✓		
6		✓	

MATERIALS AND METHODS

Study Site Mapping

Log jam type was taken into consideration when the six study sites were chosen. Two of each log jam types were selected from the study reach (Table 1). The specific log jam components in these six log jam sites were: (1) large wood stems with and (2) without an attached rootwad, stem diameter greater then 10cm; (3) rootwad of any size diameter; (4) medium wood stem (1-10 cm diameter) without an attached rootwad; and (5) small woody debris, less than 1cm in diameter.

Each study site was mapped using a Nikon DTM-350 total station and compass. The total station was spatially referenced utilizing benchmarks established by a real time kinematic (RTK) Trimble GeoExplorer. Study site maps include: (1) complex log jam and/or in-stream large wood location; (2) stream features such as pools, side channels; (3) facies patches immediately above and below log jam; (4) floodplains; and (5) active channel (summer low flow channel). The floodplain, active channel, and pool areas were calculated through ArcMap 10. 2008 and 2009 maps were adapted from Flannery (2011). and compared to 2016 maps.

Cross-sections and Longitudinal Profiles

Cross-sections and longitudinal profiles allow for identification of the location of depositional and erosional environments. Cross-sections used in the prior study were reevaluated at each study site and extended onto the floodplain. Data point collection for longitudinal profiles were collected along the thalweg. A Nikon DTM-350 total station, compass, and stadia rod were used to produce cross-sections and longitudinal profiles. Cross-sections established in 2008 were reassessed and compared to 2016 cross-sections to illustrate the progression of the streambed morphology and the development of floodplains. Longitudinal profiles provided necessary data to analyze channel gradient and create a comparison between 2016 and 2008 data.

Wood Volume Measurements

Wood volume measurements aided in determining the relationships between the amount and volume of wood effect on stream features such as pools, side channels and floodplains; features linked to quality fish habitat. Wood volume measurements from 2008 and 2009 were compared to 2016 to allow a comparison of stream condition over time. Total large wood includes large wood on the floodplain and in the active channel was counted and measured in addition to constructed log jams at each site. The volume of large wood in the active channel, in-stream large wood, was extracted in Table 3 for comparison. Counted and measured large wood was greater than 20cm in diameter and 1.5m in length (Wooster and Hilton 2004).

The volume of stems and rootwads were measured separately. The diameter of a stem was measured using a Spencer logger’s diameter tape. The length of the stem was measured by a meter tape from end to end or furthest most visible end provided that one end of the stem was buried. Two diameters were recorded from each end of the log (Figure 5A). If one end of the stem was broken or damaged, the diameter measurement was recorded at the end's closest undamaged portion of stem. In the case that one end of the stem was buried, one diameter was measured at the largest measurable diameter (Figure 5B). Furthermore, a Biltmore stick was utilized to measure diameter in cases that the stem was partially buried along its length and to have one diameter measurement at the average diameter point (Figure 5C). Rootwad volume was measured using a meter tape determining the length, height, and width (Figure 6A). An estimated percentage of pore space was visually determined in cases when the rootwad had an open frame (Figure 6 B).

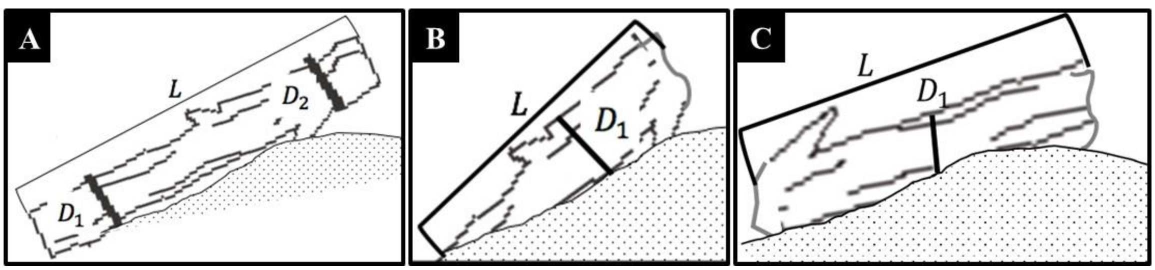


Figure 5. Stem volume measurement methods: (A) two diameters (D1 and D2) measured at each end and length (L) from end to end; (B) if one end of the stem was buried, one diameter (D1) was measured at the largest measureable point; (C) if stem was buried along its length, one diameter (D1) was recorded at average diameter point.

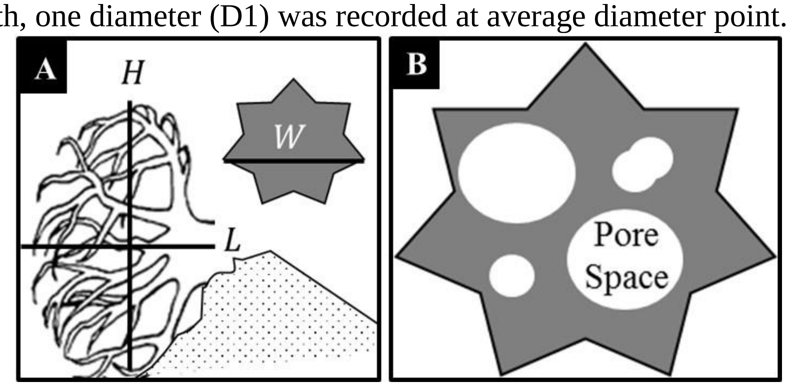


Figure 6. Rootwad volume measurement methods: (A) measured length (L), height (H), and width (W) with meter tape, and (B) estimated pore space when the rootwad had an open frame.

The Smalian's formula was used for calculating stem volume (Equations 1 and 2) (Wooster and Hilton 2004). Rootwad volume was determined by using Equation 3. If the rootwad had an open frame, the estimated pore space was subtracted from the volume determined by Equation 3 (Equation 4) (Wooster and Hilton 2004). Wood surface area in the active channel was measured using a Spencer's logger diameter tape and meter tape. The wood surface area was utilized to calculate percentage pool cover.

Equation 1. Smalian's formula for two measureable stem diameters

$$\boldsymbol{Stem\ Wood\ Volume = \frac{\pi\left(D_1^2 + D_2^2\right)L}{8}}$$

L: Length
D: Diameter

Equation 2. Smalian's formula for one measureable stem diameter

$$\boldsymbol{Stem\ Wood\ Volume = \frac{\pi\left(D_1^2 + D_1^2\right)L}{8}}$$

L: Length
D: Diameter

Equation 3. Rootwad Volume

$$\boldsymbol{Rootwad\ Volume = L \times W \times H}$$

L: Length
W: Width
H: Height

Equation 4. Rootwad with open frames

$$\boldsymbol{Rootwad\ Volume = (L \times W \times H) - (estimated\ percent\ pore\ space)}$$

L: Length
W: Width
H: Height

Sediment and Residual Pool Depth Measurements

Sediment and pool measurements describe the connection between constructed log jam placement and/or in-stream large wood effects on quality of fish habitat. Longitudinal profiles were utilized to gather residual pool depth and percentage pool cover (Figure 7). Residual pool depth was necessary to note the depth of pools at low flows. Moreover, residual pool depth is independent of discharge and recommended to only be measured once before and once after restoration treatment in order to detect changes (Lisle 1987). Residual pool depth was measured by subtracting bed elevation between pool depth and downstream riffle crest (Equation 5) (Lisle 1987). The 2016 residual pool depth measurements were compared to 2008 and 2009 measurements (Flannery et al. 2011 and 2017). Percentage of the pool covered by in-stream large wood or constructed log jam is the area in which fish are provided shelter. The percentage pool cover was calculated by dividing in-stream large wood or constructed log jam surface area by pool surface area (Equation 6). Pool surface area was determined by using the length, depth, and volume from the longitudinal profile (Equation 7).

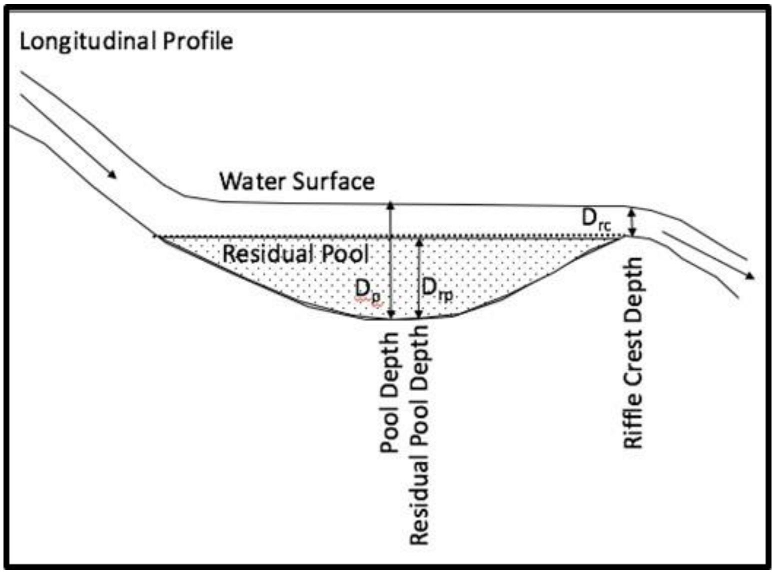


Figure 7. Example of a longitudinal profile and areas that were measured to gather residual pool depth data.

Equation 5. Residual Pool Depth

$$\boldsymbol{Drp = Dp - Drc}$$

D_{rc}: $Depth\ at\ Riffle\ Crest$
D_p: $Pool\ Depth$
D_{rp}: $Residual\ Pool\ Depth$

Equation 6. Percent Pool Cover

$$\boldsymbol{Percent\ Pool\ Cover = \frac{LWD\ or\ Log\ Jam\ Surface\ Area}{Pool\ Area} \times 100}$$

Equation 7. Pool Surface Area

$$\boldsymbol{Pool\ width = \frac{volume}{(length)\ (depth)}}$$

Longitudinal profiles served to illustrate areas of sediment aggradation in relation to in-stream large wood and/or constructed log jam. Sediment aggradation measurements gathered by 2008 and 2009 longitudinal profiles were compared to 2016 profiles to measure the amount of aggradation over time. Pebble counts were conducted immediately above and below constructed log jam using the Wolman's pebble count method (Wolman 1954). The median sediment size (D_{50}) extracted by the pebble counts was compared to 2008 and 2009 D_{50}. D_{50} size provides insight to suitable spawning gravel.

Evaluation of Long-term Restoration Success

Success was measured by the degree to which the project achieved the restoration goals and self-sustaining large wood structures (Table 2). An accumulation or mobile in-stream large wood racking rate was determined to note the sustainability of the log jam placement restoration technique (Equation 8).

Equation 8. Accumulation Rate

$$Accumulation\ Rate\ (m^3/ha/yr) = \frac{(V_{'16} - V_{'09}\,(m^3))}{(site\ area\ (ha))(8yrs)}$$

$V_{'09}$: 2009 total site wood volume

$V_{'16}$: 2016 total site wood volume

Table 2. Restoration Evaluation of Success

Restoration Goals	***Evaluation Questions***	***Yes***	***No***
Increase hydraulic complexity:	**An increase of:**		
1. Creating pools	• Number of pools		
2. Increasing floodplain connectivity	• Floodplain Connectivity		
3. Self-sustaining wood jams	• In-stream large wood volume		
Improve rearing habitat for salmonids:	**Quality of salmon habitat improved by:**		
1. Trapping and sorting sediment	• Presence of spawning gravel		
Creating cover and resting habitat for adult and juvenile salmonids:	**Increased amount of resting areas:**		
1. Side channels	• Side channels		
2. Floodplains	• Floodplain area		
3. In-stream large wood pool cover	• Pool cover percentage		

RESULTS

Since the introduction of complex wood jams in 2008, bankfull widths have increased (Figure 8). Initial bankfull width conditions (2008) contained a narrow range of 10 – 32m (Figure 8). Bankfull width conditions in 2016 varies over a larger range of 15-80 m (Figure 8). Specific cross-sections were not available to compare with past cross-sectional data, as permanent markers were lost due to bank erosion from flows. Moreover, channel gradients decreased and at bankfull flows all channels have access to a floodplain. Furthermore, signs of winter refugia (i.e. wet bed material and lower elevation) were found in several sites. Salmonids benefit from available winter refugia for resting and food catchment during high flows. The majority of the placed log jams persisted throughout the 8 years. Several sites were found to have increased pool numbers and pool cover; pool locations within years 2008 and 2009 were not available due to lack of past data. Median particle sizes in 2016 were smaller than in 2008. The following is a description of the results found in each site.

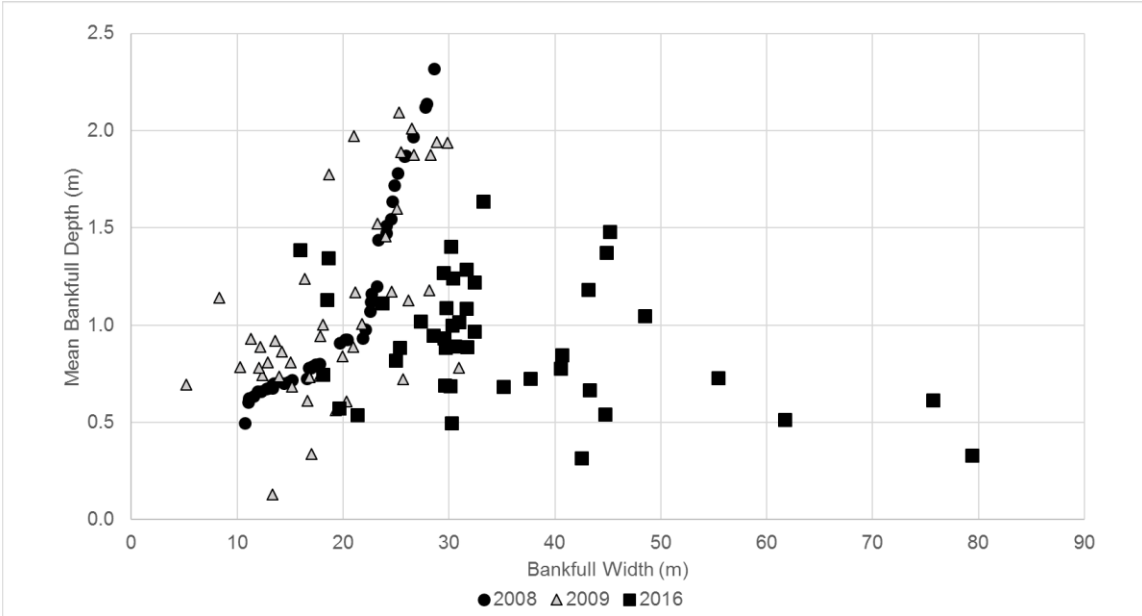


Figure 8. Bankfull widths and depths among years 2008, 2009, and 2016.

Site 1

Site 1 contained an underflow log jam meant to span the entire channel width; generating high water flow obstruction and accelerated local water flow (Figure 5 and Table 3). This study site did not accumulate large wood but the in-stream large wood volume increased (Table 3). The majority of the large wood stayed in the active channel and some migrated onto the floodplain and downstream (Figure 9, Table 3). The in-stream large wood aided the development of pools and pool coverage, increasing the number of pools, in site 1, from 1 in 2009 to 4 in 2016 and retaining 15% pool coverage from 2009 (Table 3 and 4). The median residual pool depth was greater in 2016 than in 2008, however median residual pool depth was greater in 2009 (Table 4). Furthermore, the underflow jam increased the bankfull width an additional 18m by backing up flow, causing the channel to widen from increased bank erosion (Figure 9, Table 5). Signs of winter refuge, lowered elevation and wet sandy material were found on the northern floodplain (Figure 9). Additionally, the channel gradient decreased and floodplain area was accessible at bankfull flows (Figure 9, Table 6).

Table 3. Geomorphic description of large wood jams in sites 1-6 in East Fork Mill Creek, CA for years 2008, 2009 and 2016.

Site	Wood Jam Design	Year	Total Large Wood (n)	Large Wood with Rootwad (n)*	Total Large Wood Volume (m^3)	Instream Large Wood Volume (m^3)	Pool Coverage (%)	Accumulation Rate (m^3/ha/yr)
1	Underflow	2009	93	12	37.5	3.1	18%	-5.7
		2016	26	5	25.8	7.1	15%	
2	Deflecting	2009	17	14	22.5	2.0	7%	-6.8
		2016	15	5	16.4	5.0	39%	
3	Opposing	2009	10	7	13.4	1.2	5%	66.2
		2016	28	10	67.0	1.8	79%	
4	Underflow	2009	9	0	27.1	28.7	11%	236.9
		2016	310	27	541.1	3.0	18%	
5	Deflecting	2009	26	24	31.0	2.4	7%	93.1
		2016	17	11	107.5	67.6	57%	
6	Simple	2008	1	0	1.7	0.1	-	82.6
	Opposing	2009	19	11	33.0	2.6	10%	
		2016	14	4	107.5	50.67	36%	

*Total large wood includes large wood on the floodplain and in the active channel (in-stream large wood). Total large wood and large wood with rootwads were counted (n = number of pieces) was counted and measured in addition to constructed log jams at each site.

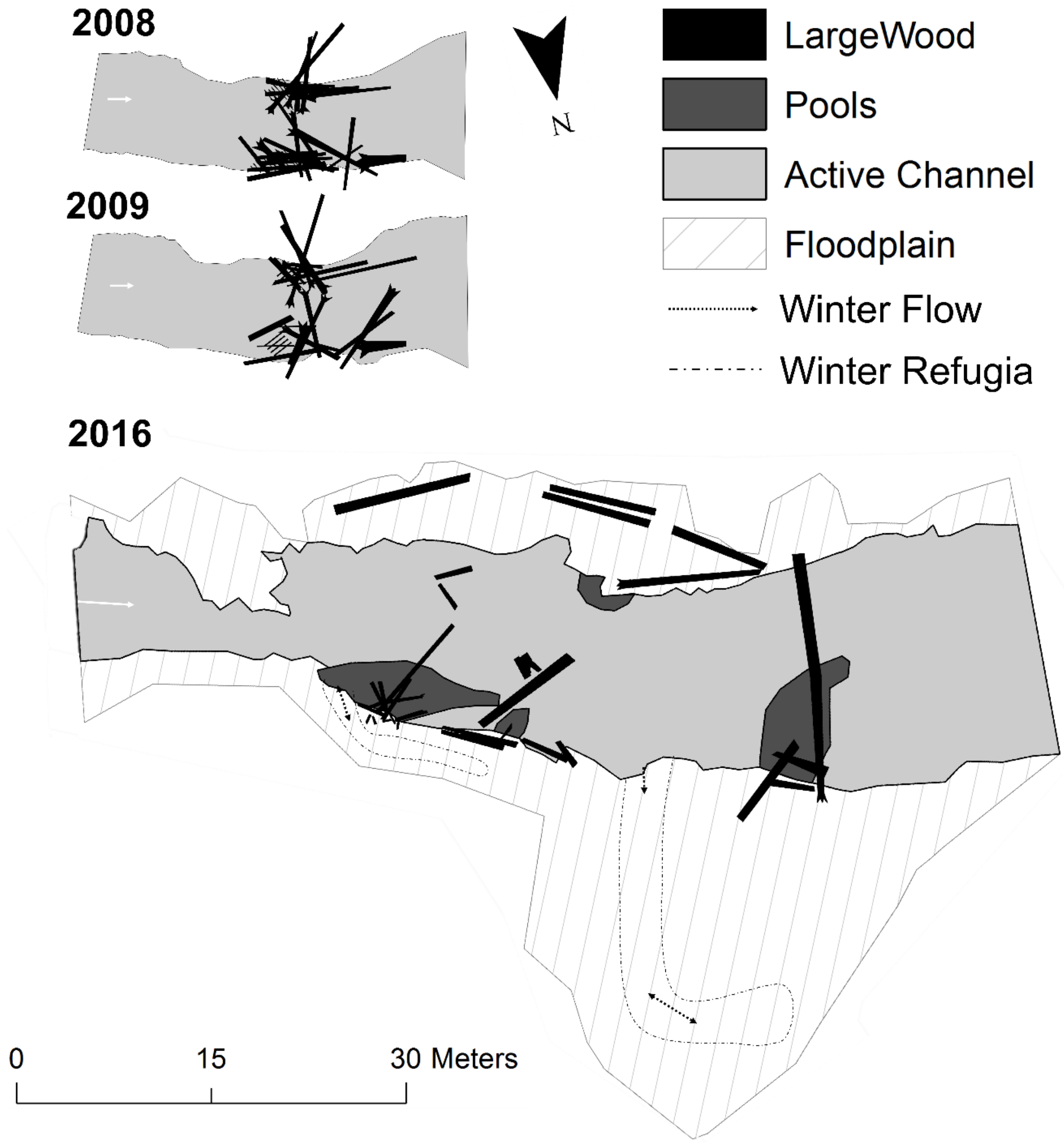


Figure 9. Site 1 pool location, underflow log jam placement, large wood migration and dispersal in East Fork Mill Creek, CA.

Table 4. Pool numbers and median residual pool depths, years 2008-2009 and 2016, in sites 1-6, East Fork Mill Creek, CA.

Site	**Year**	**Number of Pools (n)**	**Median Residual Pool Depth (m)**
1	2008	1	0.1
	2009	1	1.5
	2016	4	0.3
2	2008	1	0.1
	2009	1	0.5
	2016	4	0.1
3	2008	1	0.1
	2009	2	0.5
	2016	1	0.1
4	2008	2	0.3
	2009	2	0.7
	2016	3	0.7
5	2008	1	0.2
	2009	1	0.3
	2016	2	0.6
6	2008	2	0.2
	2009	1	0.3
	2016	3	0.3

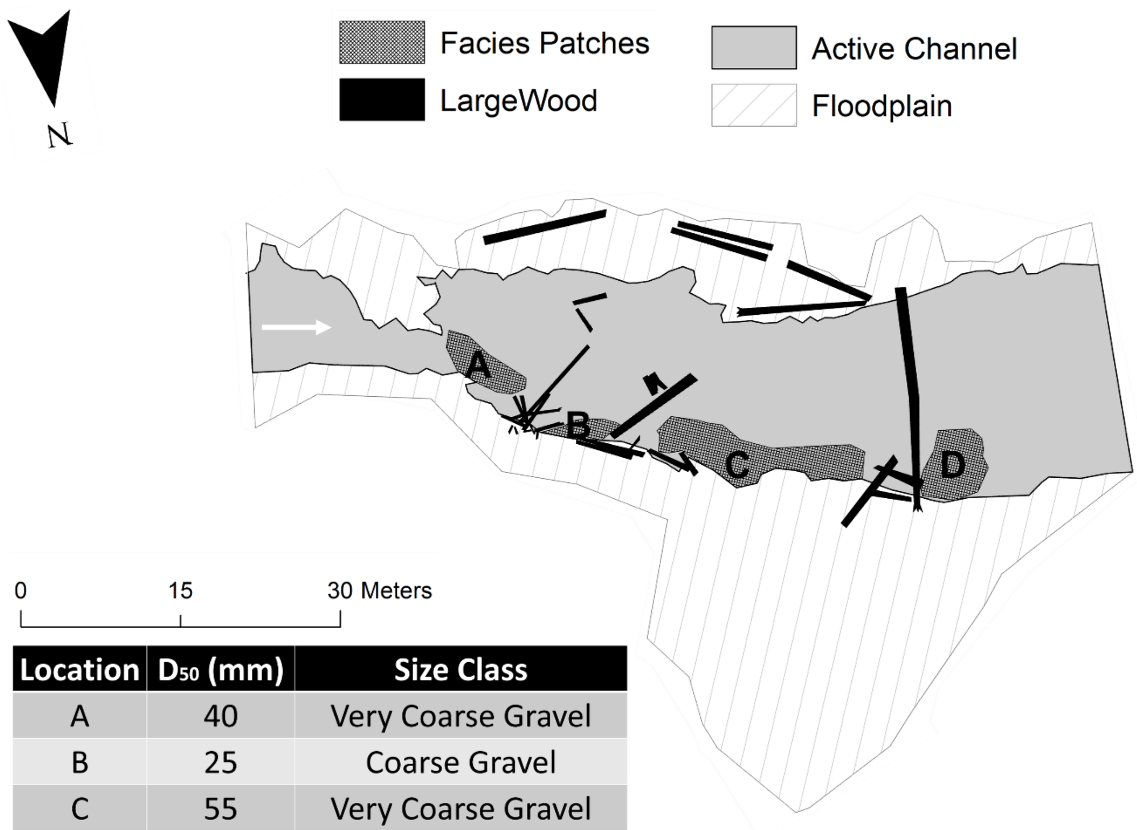
Table 5. Bankfull widths (years 2008, 2009, and 2016) and 2016 floodplain area in sites 1-6 in East Fork Mill Creek, CA.

Site	**Year**	**Bankfull Widths (m)**	**2016 Floodplain Area (m^2)**
1	2008	12.2	1,361
	2009	12.5	
	2016	30.2	
2	2008	14.8	610
	2009	16.2	
	2016	31.9	
3	2008	13.7	684
	2009	15	
	2016	29.7	
4	2008	12.5	2,283
	2009	14.3	
	2016	22.3	
5	2008	18	745
	2009	17.2	
	2016	34.9	
6	2008	24.3	425
	2009	24.4	
	2016	33.3	

Table 6. Channel gradient for years 2008, 2009, and 2016 in sites 1-6 in East Fork Mill Creek, CA.

Site	Year	Channel Gradient (%)	Channel Gradient Difference (%)
1	2008	1.5	0.8
	2016	0.7	
2	2008	1.1	0.4
	2016	0.7	
3	2008	1.9	1.2
	2016	0.7	
4	2008	1.0	0.6
	2016	0.4	
5	2008	0.8	0.4
	2016	0.4	
6	2008	0.7	0.3
	2016	0.4	

The underflow log jam constructed in site 1 served to trap and sort sediment. There were pronounced median particle size differences between years and locations (i.e. above and below log jams) (Figure 10, Table 7). The median particle size increased between 2009 and 2016 but remained smaller than in 2008 (Table 7). The median particle size distribution among the locations of the facies patches showed a larger diameter size above the log jams (Figure 10).



Location	D_{50} (mm)	Size Class
A	40	Very Coarse Gravel
B	25	Coarse Gravel
C	55	Very Coarse Gravel
D	35	Very Coarse Gravel

Figure 10. Median particle size (D_{50}) distribution in site 1, East Fork Mill Creek, CA.
*Large wood not to scale

Table 7. Changes in median particle size (D_{50}) 2008-2016 in East Fork Mill Creek, CA.

Site	Year	D_{50} Location (mm)		D_{50} Difference (mm)				D_{50} Difference between locations within same Year (mm)
		Above Log Jam	Below Log Jam	2008 - 2009 Above	2008 - 2009 Below	2009 - 2016 Above	2009 - 2016 Below	
1	2008	90	90	-74	-74	24	19	0
	2009	16	16					0
	2016	40	35					-5
2	2008	256	256	-233	-192	27	-9	0
	2009	23	64					41
	2016	50	55					5
3	2008	64	64	0	26	1	-20	0
	2009	64	90					26
	2016	65	70					5
4	2008	91	256	-46	-166	35	-45	165
	2009	45	90					45
	2016	80	45					35
5	2008	45	45	0	19	5	-53	0
	2009	45	64					19
	2016	50	11					-39
6	2008	90	90	-26	-85	-29	10	0
	2009	64	5					-59
	2016	35	15					-20

Site 2

A deflecting log jam, meant to deflect water flow from one bank towards the opposite bank, was placed in 2008 on site 2. Similar to site 1, site 2 did not accumulate large wood but the majority of the large wood within the site was located in the active channel (Table 3). The majority of the large wood migrated downstream towards the northeastern portion of the active channel and onto the floodplain (Table 3, Figure 11). Furthermore, the deflecting log jam forced eddying in the active channel upstream from the main portion of the log jam leading to erosion of the southwestern bank. This erosion caused recruitment of red alder (*Alnus ruba*) (Figure 11). The sole portion of the red alder in the active channel was located in the pool area (Figure 11). The in-stream large wood assisted in continued pool development, increasing pool numbers from 1 to 4, and increasing pool coverage by 32% (Figure 11, Table 3 and 4). However, median residual pool depth decreased to 2008 depth (Table 3). Average bankfull widths increased by 16.9m, channel gradient lowered and at bankfull the active channel could access the 610m^2 of floodplain (Figure 11, Table 5).

Sediment trapping and sorting by the deflecting log jam decreased median particle size from 90mm, in 2008, to 35-40 mm in 2016 (Table 7). The median particle size distribution was similar to site 1, with larger diameter sizes found above the log jams (Table 7, Figure 12).

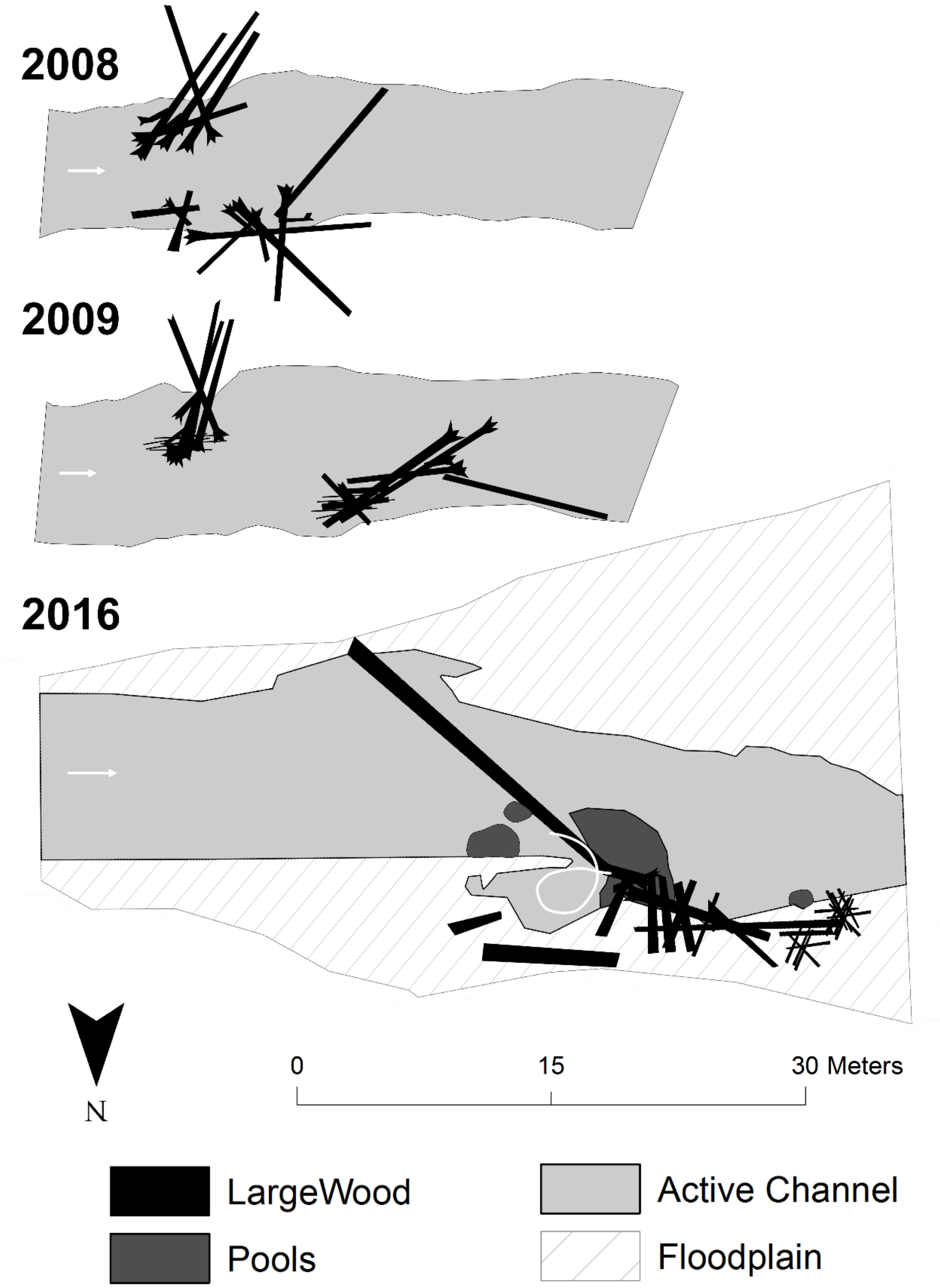
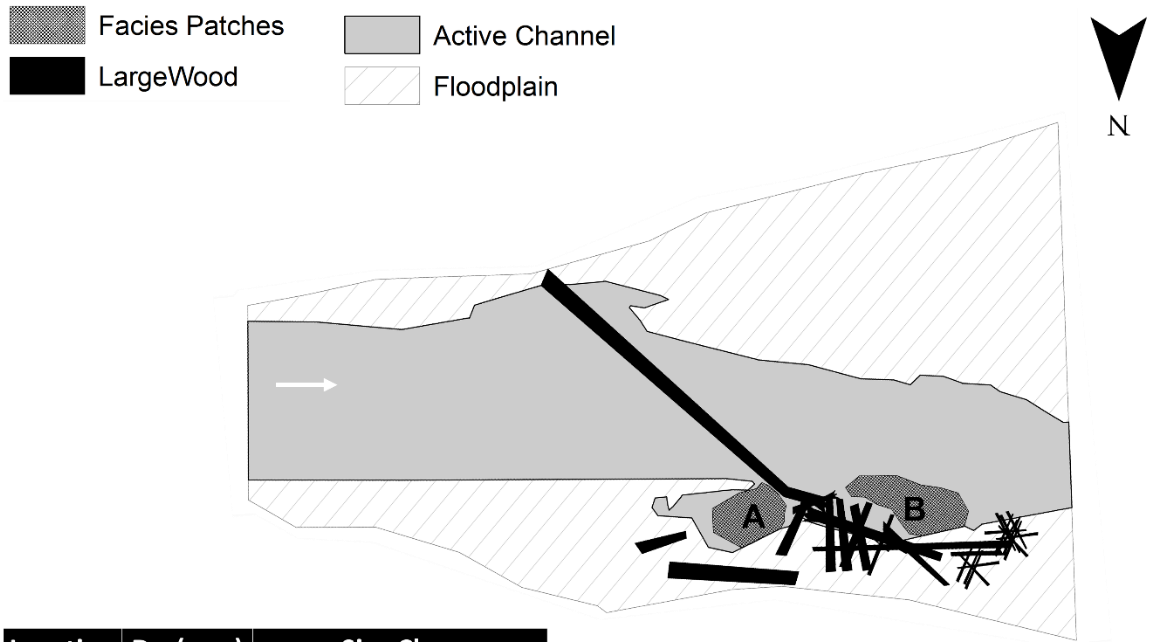


Figure 11. Site 2 pool location, deflecting log jam placement, large wood migration and dispersal in East Fork Mill Creek, CA in 2008, 2009, and 2016. *Large wood not to scale. The white arrow near the northern floodplain indicates the flow above the log jam.



Location	D_{50} (mm)	Size Class
A	50	Very Coarse Gravel
B	55	Very Coarse Gravel

Figure 12. Median particle size (D_{50}) distribution in site 2, East Fork Mill Creek, CA in 2016. *Large wood not to scale

Site 3

An opposing log jam was constructed in site 3 and accumulated large wood at a rate of 62.2m^3/ha/yr (Table 3). An opposing log jam constricts water flow towards the center of the channel. It appears that the opposing design resulted in a backwater with enough power during high flows to lift the jam and place the majority of the wood on the floodplain with 1.8m^3 in-stream large wood, 0.6m^3 more than in 2009 (Figure 13). The large log furthest upstream was suspended above the active channel and had no interaction with the active channel (Figure 13). Pool numbers and residual pool depth returned to 2008 levels in 2016 (Table 4). However, the increased volume of in-stream large wood provided more pool coverage than in the past (Table 3). Furthermore, since 2008, bankfull widths expanded, the channel gradient lowered and the active channel can access 684m^2 of floodplain at bankfull (Table 5 and 6). Additionally, signs of winter refugium were found on the northern floodplain, upstream of the log jam (Figure 13).

Trapped and sorted sediment above and below the log jam were similar in size. Slightly coarser particle sizes were found below the log jam (Figure 14). The median particle size above the log jam did not change much between years, however, particle sizes below the log jam decreased since 2009 (Table 7).

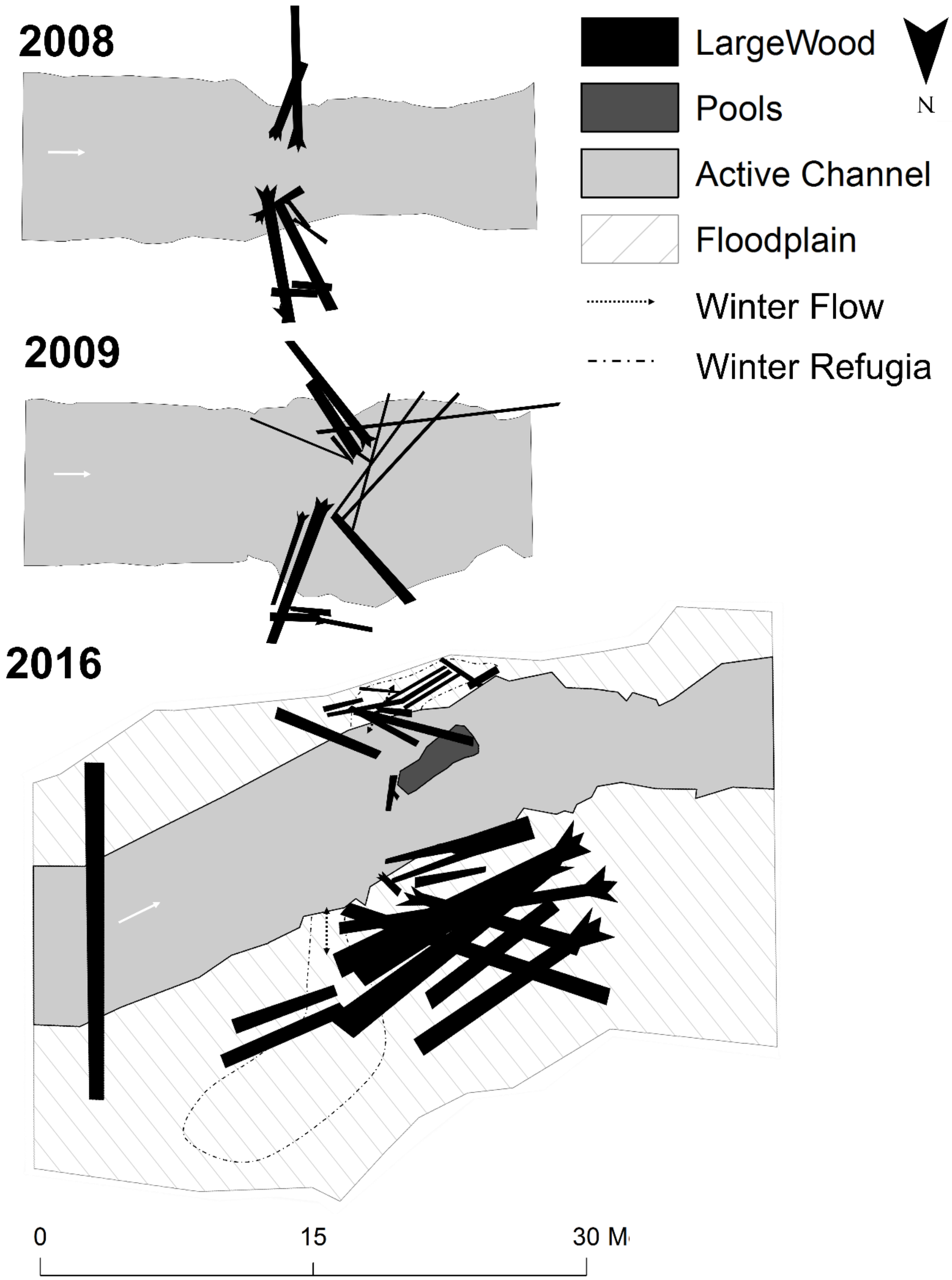


Figure 13. Site 3 pool location, opposing log jam placement, large wood migration and dispersal in East Fork Mill Creek, CA in 2008, 2009, and 2016. *Large wood not to scale

Location	D_{50} (mm)	Size Class
A	65	Small Cobble
B	70	Small Cobble

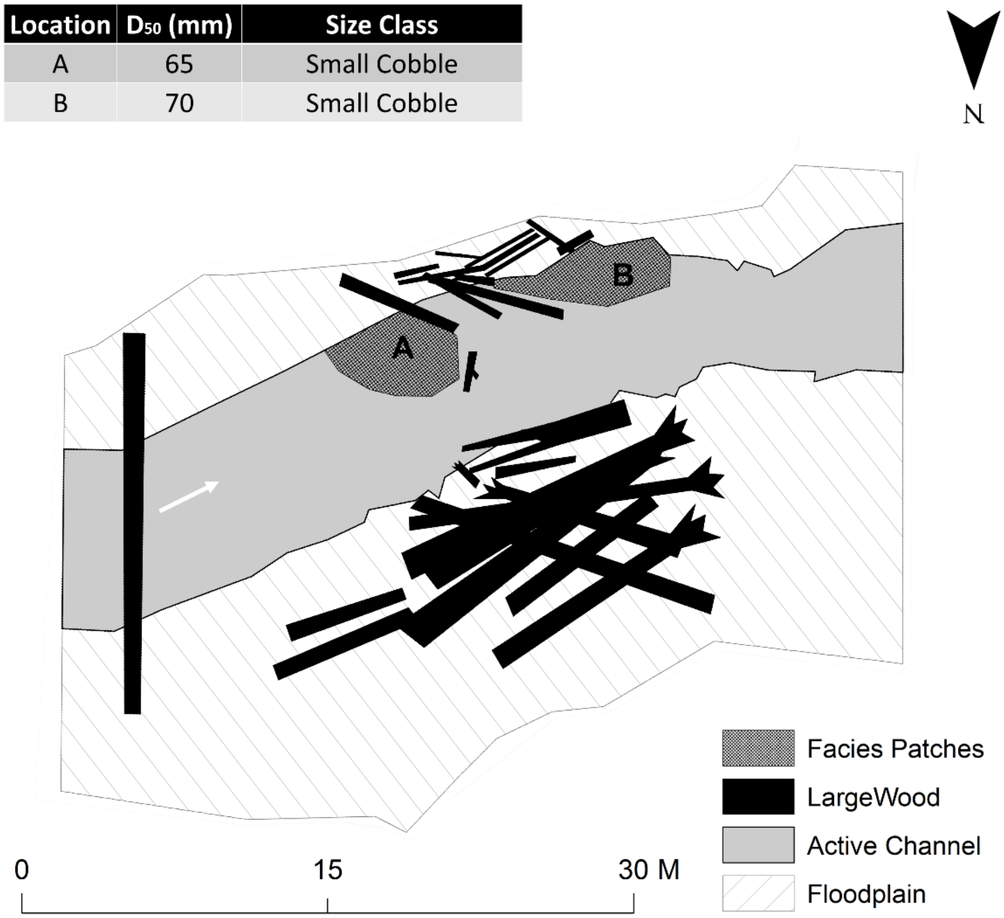


Figure 14. Median particle size (D50) distribution in site 3, East Fork Mill Creek, CA in 2016. *Large wood not to scale

Site 4

Site 4 contained the same type of log jam as site 1, underflow log jam. The large wood accumulation rate at this site was 236.9m^3/ha/yr, the largest rate observed rate in this study and two to four times as much as other sites that saw an increase. (Table 3). This log jam spanned the active channel width generating high water flow obstruction. Furthermore, in 2012, Redwood National and State Parks' added large wood upstream of the study reach and may have created an obstruction assisting in racking large wood. Additionally, the original underflow log jam accelerated local water flow, eroding banks, leading to the creation of winter refugia and winter side channel flow (Figure 15). During high winter flows the channel may run around an island with well-developed red alders and reconnects downstream based on the wet sandy soil that surrounds the area (Figure 15). The total large wood volume increased by 514m^3, but only 3m^3 of large wood remains in the active channel during summer low flows. However, the 3m^3 of in-stream large wood provided more pool coverage than before, gaining 7% more pool coverage (Table 3). The number of pools increased while the median residual pool depth stayed the same (Table 4). Active channel bankfull widths followed the same trend as the rest of the six sites, gaining 9.8m, and at bankfull the channel has access to 2,283m^2 of floodplain (Table 6).

Trapped and sorted sediment by the underflow log jam decreased median particle size from 256 - 91mm, in 2008, to 80 – 45mm in 2016 (Table 7). The median particle size distribution among locations of the facies patches found courser sediment above the log jams (Table 7, Figure 16).

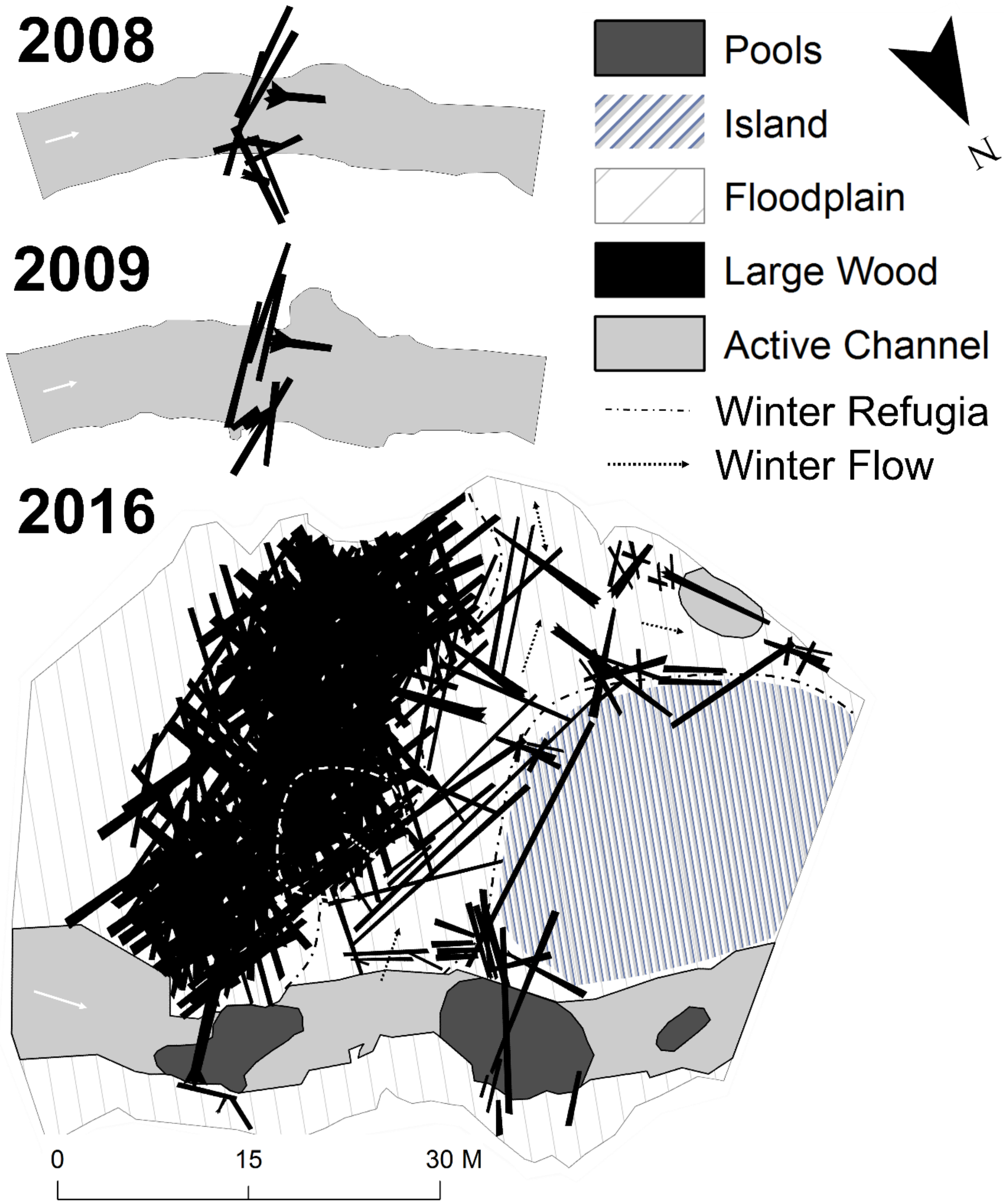
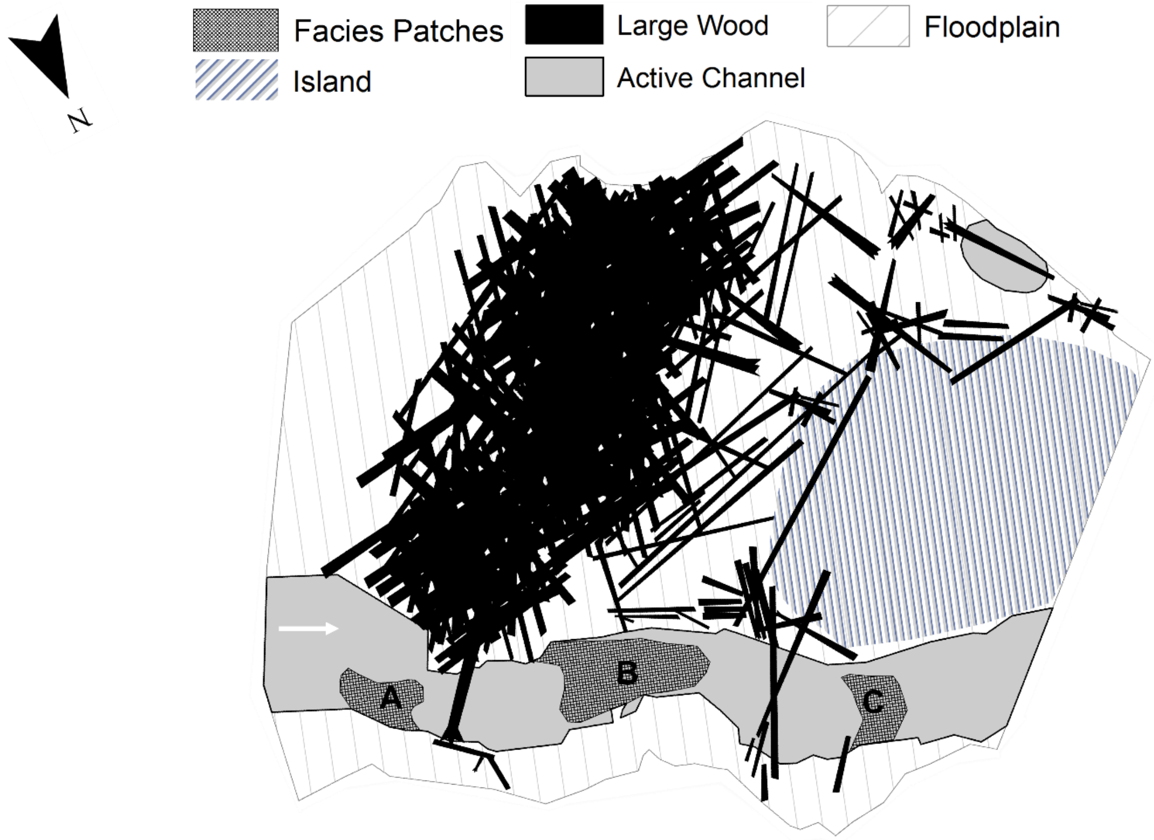


Figure 15. Site 4 pool location, and large wood migration and dispersal in East Fork Mill Creek, CA. *Large wood not to scale



Location	D_{50} (mm)	Size Class
A	80	Small Cobble
B	90	Small Cobble
C	45	Very Coarse Gravel

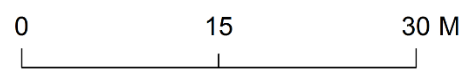


Figure 16. Median particle size (D50) distribution in site 4, East Fork Mill Creek, CA In 2016. *Large wood not to scale

Site 5

A deflecting log jam was constructed in site 5, similar to site 2. Large wood accumulation rate in site 5 was the second highest among the sites examined in this study, 93.1m^3/ha/yr. (Table 3). The in-stream large wood increased by 65.2m^3 resulting in 50% more pool coverage than in 2009 (Table 3). The deflecting log jam continued to grow with minimal migration (Figure 17). Large pools developed around the log jams increasing the number of pools and residual pool depth (Table 4). Bankfull width increased by 16.9m creating a connection with a small tributary southwest to the second large wood jam and signs of winter refugia were found on the northern floodplain (Table 6, Figure 17). Since 2008, the channel gradient has lowered and the active channel has access to 745m^2 of floodplain (Table 5 and 6).

Since 2008, median particle size has minimally increased above the log jam and decreased below the log jam (Table 7). Furthermore, the median particle size distribution of the facies patches shows larger diameter sizes above the log jams and decreasing sizes heading downstream (Figure 18).

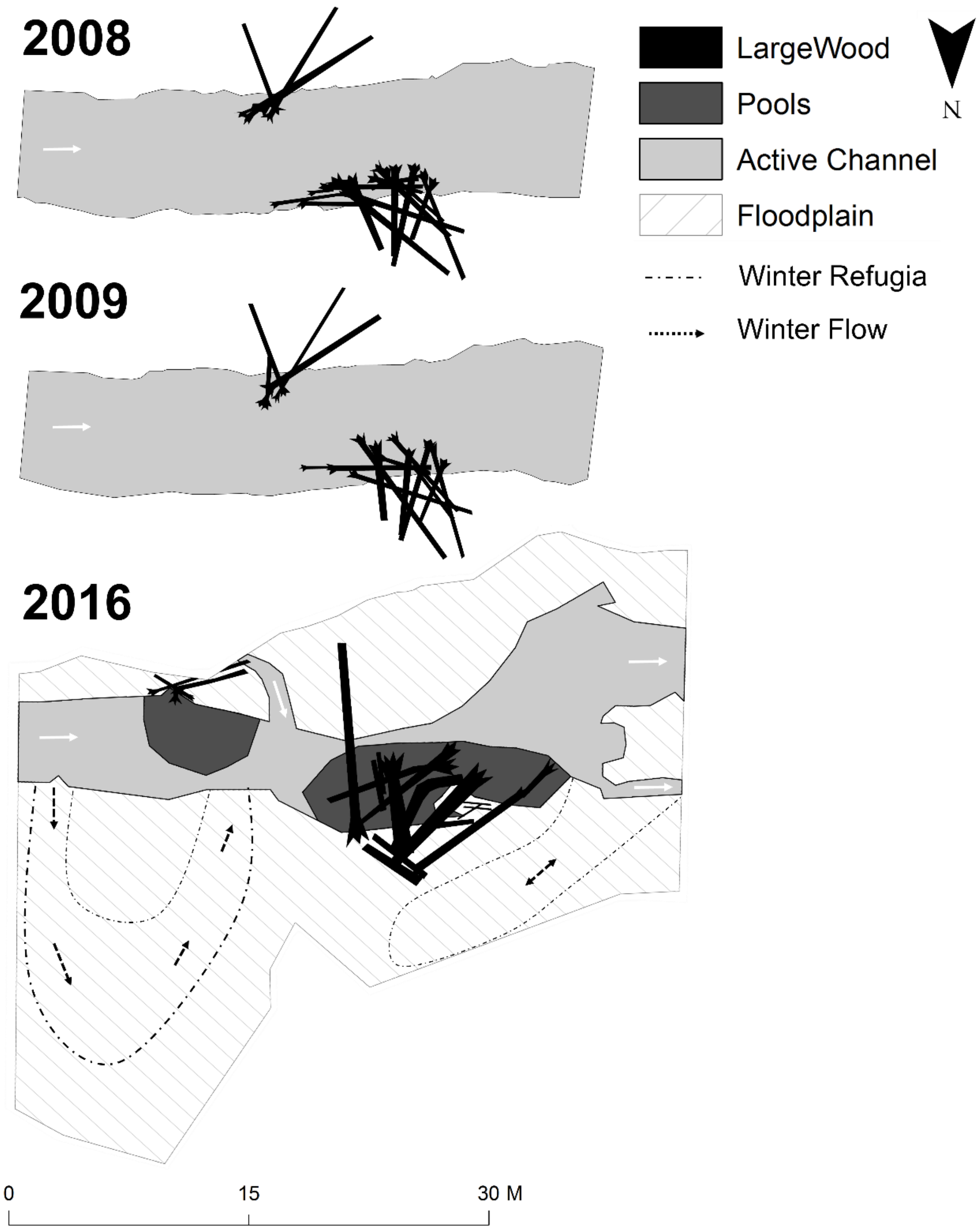
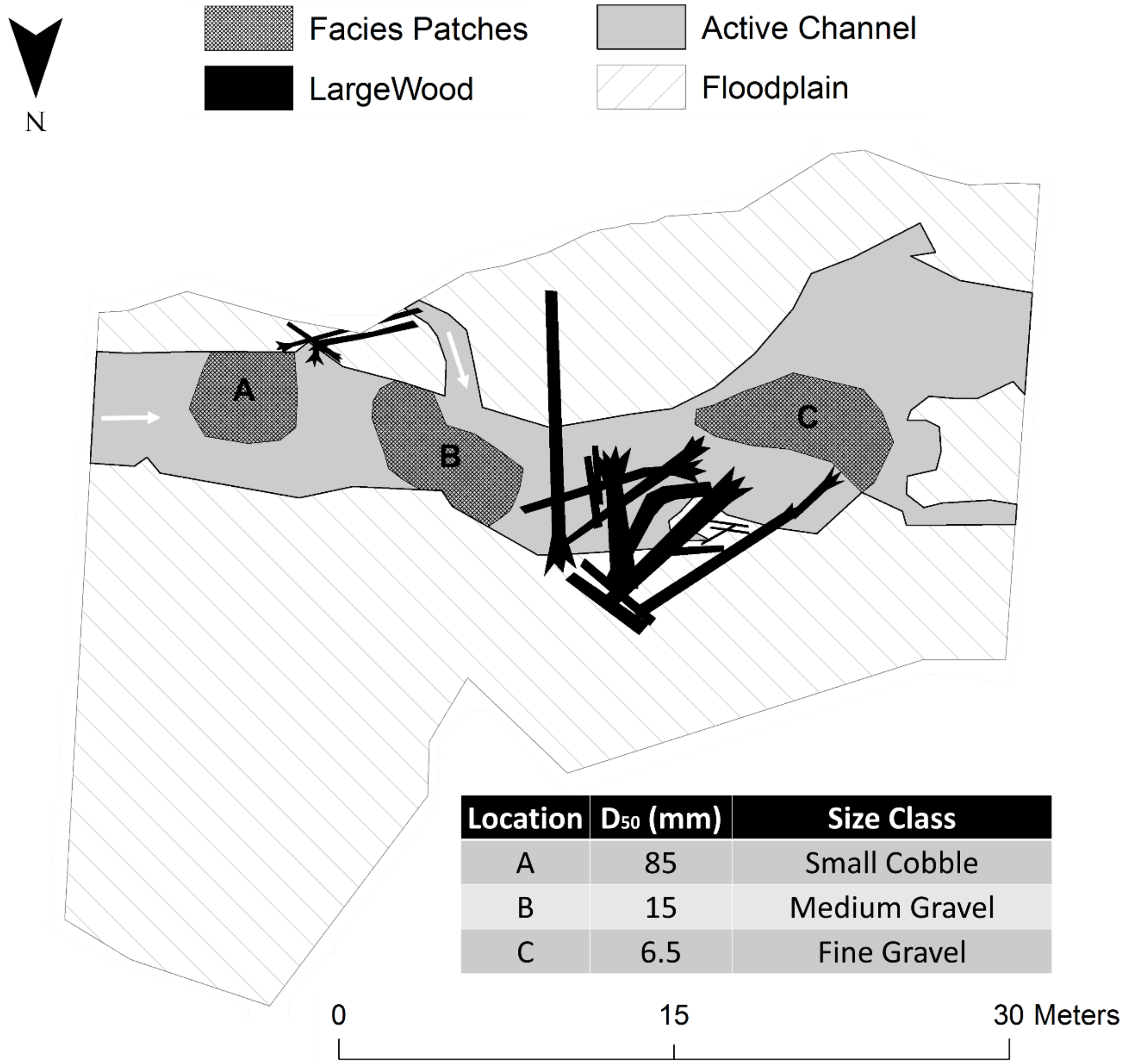


Figure 17. Site 5 pool location, deflecting log jam placement, large wood migration and dispersal in East Fork Mill Creek, CA in 2008, 2009, and 2016. *Large wood not to scale



Location	D_{50} (mm)	Size Class
A	85	Small Cobble
B	15	Medium Gravel
C	6.5	Fine Gravel

Figure 18. Median particle size (D50) distribution in site 5, East Fork Mill Creek, CA in 2016. *Large wood not to scale

Site 6

Site 6 contained an opposing log jam, similar to site 3, and an incorporated 1995 simple log jam (Figure 19). An opposing log jam constricts water flow towards the center of the channel thus the strong flow towards the center moved the large wood onto the floodplain and large wood accumulation rate of $82.6m^3$/ha/yr. (Table 3, Figure 19). The large wood remaining in the active channel aided in further pool development and pool cover increasing pool numbers and overall pool cover from 10% to 36% (Table 3 and 4). Furthermore, signs of winter refugia were found on both floodplains, downstream of the log jams (Figure 19). Site 6 followed the same trend in all six sites of lower channel gradient, an expansion of bankfull width and increased access to the floodplain at bankfull (Table 5 and 6).

Since 2008, the opposing log jam placement has resulted in a decrease in median particle size from 90mm to 15 - 35mm in 2016 (Table 7). Comparison of median particle size distribution among the locations of the facies patches shows a larger diameter size above the log jams, similar to site 5 (Table 7, Figure 20).

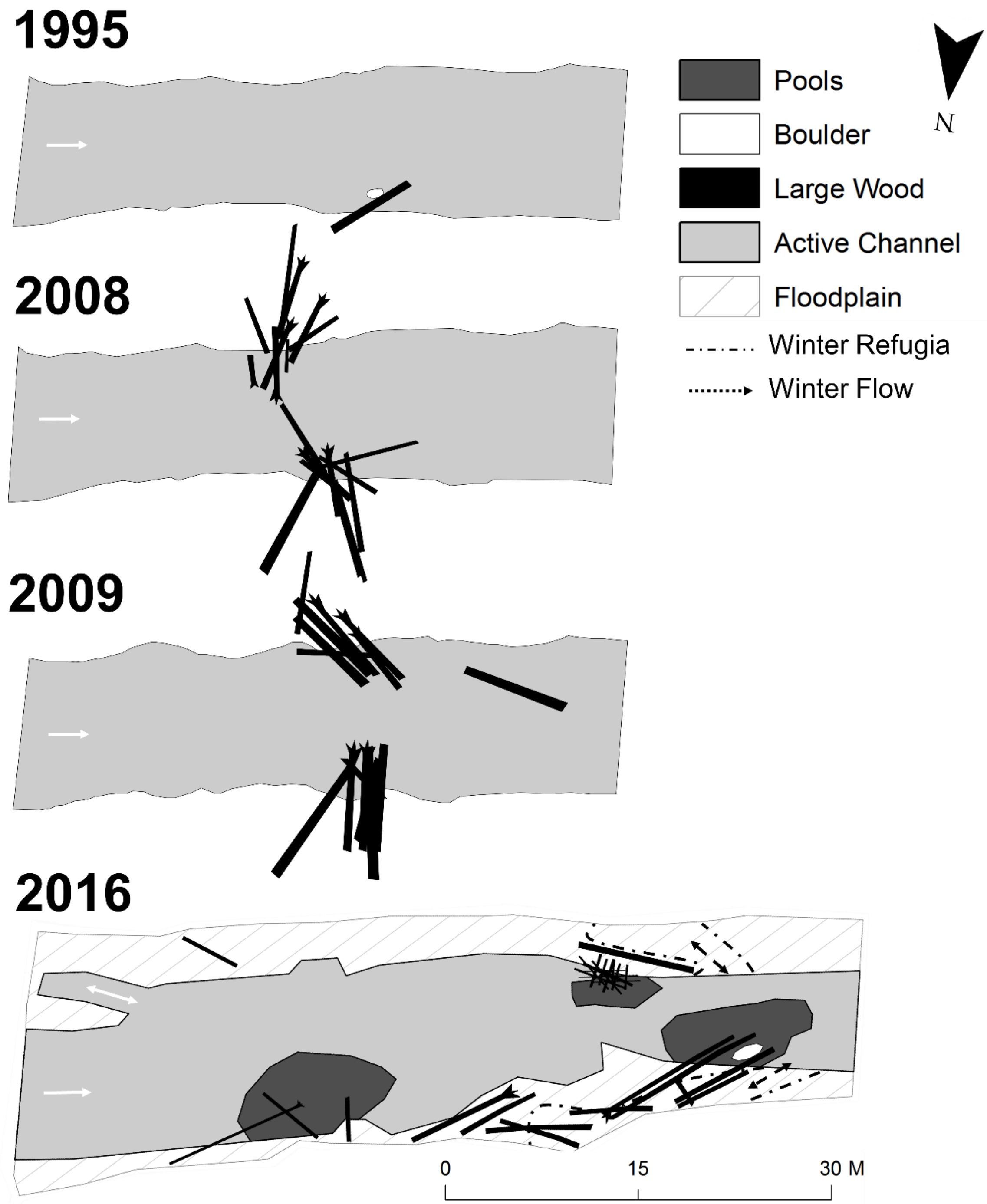
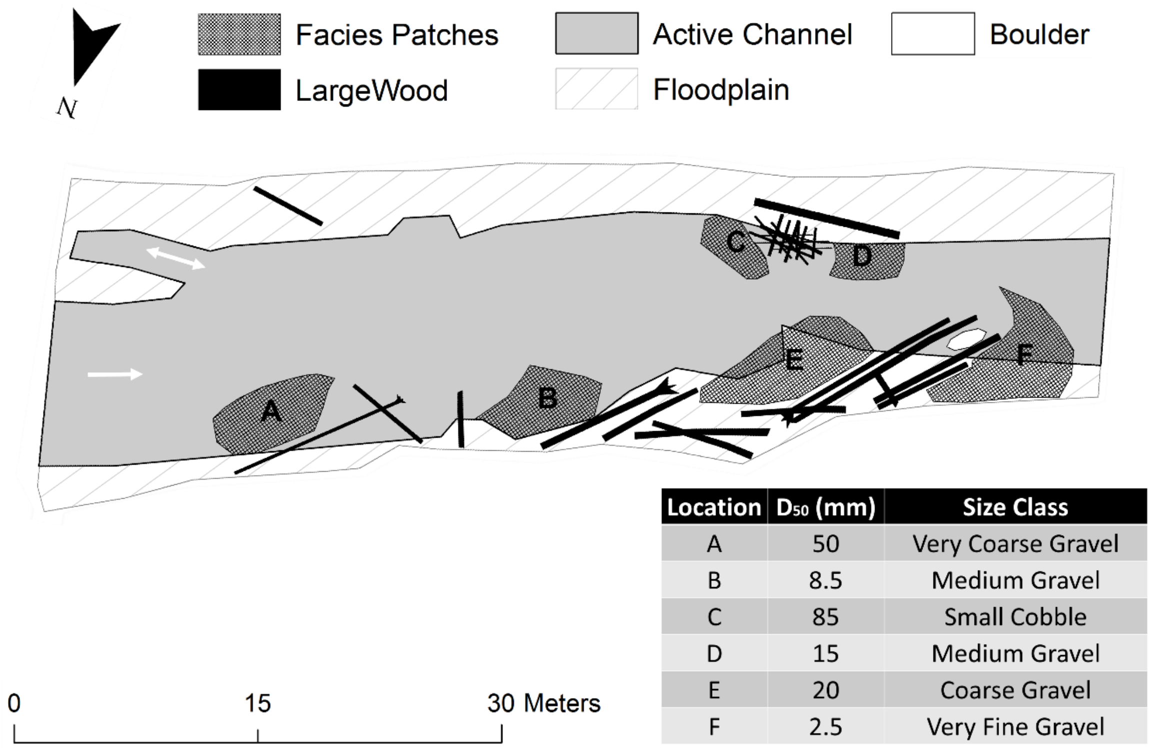


Figure 19. Site 6 pool location, opposing log jam placement, large wood migration and dispersal in East Fork Mill Creek, CA in 1995, 2008, 2009, and 2016. *Large wood not to scale



Location	D_{50} (mm)	Size Class
A	50	Very Coarse Gravel
B	8.5	Medium Gravel
C	85	Small Cobble
D	15	Medium Gravel
E	20	Coarse Gravel
F	2.5	Very Fine Gravel

Figure 20. Median particle size (D50) distribution in site 5, East Fork Mill Creek, CA in 2016. *Large wood not to scale

DISCUSSION

This study examined the long-term effects and persistence of complex wood jams and their effectiveness in achieving long-term restoration goals (Table 2). Results indicate that since the introduction of complex wood jams in 2008, bankfull widths increased and channel gradient decreased (Figure 8, Table 5 and 6). Moreover, the channel now accesses the floodplain at bankfull flows and has more refugia sites for salmonid overwintering. Channel bank widths widened and the sediment lowered channel gradient. This increase of width and decrease in steepness may have aided the channel's current access to the floodplain.

Residual pool depths increased (sites 1, 4-6) or remained the same (sites 1-2) compared to pre-project depths measured in 2008 (Table 4). However, residual pool depths became shallower (sites 1-3) or unchanged (sites 4 and 6) when compared to 1 year post-project depths measured in 2016. It is likely that with the dispersal of the complex wood jams, the flow dynamics were no longer in place to create and maintain deep pools. Sites 1 – 4 and 6 experienced log jam dispersal from their original placement and residual pool depths decreased (Table 4 and Figures 9, 11, 13, 15, 19). While Site 5 contained minimal dispersal of its original log jam and may have led to an increase in residual pool depths (Table 4 and Figure 17). Although, residual pool depths did not increase throughout the eight years in most sites, four of six sites showed an increase in pool numbers. At sites 1 and 2 there was less in-stream wood than the original placement, but it was more widely distributed at other sites (3 - 6). At other sites (3 - 6) large wood racking led to an increase in-stream large wood volumes.

The complex log jams were designed to rack mobile wood leading to self-sustaining log jams (Table 2). Sites 3-6 exhibited an increase in large wood volumes. The two upstream sites, 1 and 2, may have supplied downstream sites, 3 through 6, with large wood from originally placed log jams (Table 3). In 2012 a large heliwood project was conducted in upstream tributaries of the East Fork Mill Creek watershed. Heliwood is a term for large wood placed in river channels by helicopter. This large wood can be recognized by cut stems with whole root wads attached. The huge log jam at site 4 is likely to be heliwood that was flushed downstream in subsequent flood events (Figure 15).

An additional long-term objective of the restoration was to create cover and resting habitat for adult and juvenile salmonids (Table 2). Sites 1-3 and 5-6 resulted in greater percentage pool cover caused by increased in-stream large wood (Table 3). Placed log jams assisted in creating resting habitat in all six sites. All six sites featured access to floodplains at bankfull and sites 1 and 4 demonstrate side channel access (Figures 9, 11, 13, 15, 17, and 19). Overwintering refugia was found in sites 1, and 3 – 6 (Figures 9, 11, 13, 15, 17, and 19).

This study demonstrated the improved rearing habitat for juvenile salmonids by trapping and sorting spawning gravel (Table 2). The study consistently found coarser particle sizes upstream of log jams and finer particles downstream. It is likely that velocities increase at the top of the jams as water speeds up to flow through the constriction. Higher velocities result in greater sediment transport, winnowing away smaller particle sizes and leaving larger ones. In the lee of the jams, in the flow eddies created by the jams, flow is slower and more conducive to deposition of finer materials (Figures 10, 16, 18, and 20). In some cases where larger particle sizes were found downstream of the log jam, this may be caused by the morphology of the channel. For example, sites 2 and 3 were found to contain slightly finer sediment sizes above the log jam, a difference of 5mm (Figure 12 and 14). Site 2 contained an eddy, created by the current log jam structure, above the log jam slowing down the velocity of the flow before hitting the log jam leading to higher deposition of finer sediment above the log jam. Site 3's main stream flow was directed towards the southern portion of the channel away from the main portion of the log jam. Therefore, the water in this area was slower allowing the mobilized fine sediment to settle (Figure 14).

Lack of available spawning gravel can be a limitation for spawning salmonids (Buffington and Montgomery 1997). Anadromous fish found in East Fork Mill Creek such as the Chinook salmon spawn in gravels and fine cobbles ranging in size from 30.0 to 69.3 mm (Kondolf and Wolman 1993). Coastal Rainbow trout spawn in gravels, ranging from 10.0 to 40.0 mm and Coho salmon spawn in gravels, ranging from 5.4 to 35.0 mm (Kondolf and Wolman 1993). This information, combined with the particle size data, indicates that 8 years after the installation of complex wood jams all of the sites had trapped and sorted finer particle sizes and in 2016 contained particle sizes suitable for spawning salmonids such as Chinook salmon, Coastal Rainbow trout and Coho salmon (Table 7, Figure 10, 12, 14, 16, 18, and 20).

Several studies agree that many processes that create habitat operate on a long-term scale (e.g., channel migration and the formation of off-channel habitats) and long-term monitoring is necessary to capture the results of long-term restoration goals (Reeves et al. 1995; Beechie and Bolton 1999; Roni et al. 2002). The complex jams studied were constructed to mimic natural wood accumulation and designed to support the recovery of stream ecosystem processes and function (Flannery et al. 2017). Even after 8 years, large conifers with attached rootwads were still present in the channel. While log jams moved from the initial placement in many of the sites, they were still actively creating pools and cover, trapping fine sediments, and pushing flow out onto the floodplain. The results observed in this study provide evidence that the long-term goals of the restoration project, focused on restoring processes that form, connect, and sustain habitats, were met.

Similar studies found relatively similar results as in this study such as Thom (1997) and Roni et al. (2001). Thom (1997) examined physical responses of streams to in-stream large wood 1 year after treatment and found a significant increase in number and volume of in-stream large wood and number of habitats and deep pools but not in pool area. According to Reeves et al. (1997) several high-flow events may be necessary before the channel responds completely to placed in-stream large wood. Therefore, Roni and Quinn (2001) reexamined re-examined the study reach from Thom (1997) and found a much larger response to placed in-stream large wood. Roni and Quinn (2001) compared several reaches in which large wood was utilized to restore salmonid habitat (treated) with unrestored reference reaches. The ages of the restoration projects studied ranged from 1 to 10 years. Roni and Quinn (2001) found treated and reference reaches were similar in slope and bankfull width. However, they differed in physical habitat features expected to respond to large wood placement. The total number of pieces of in-stream large wood, pool area and pool numbers was significantly higher in treated reaches than in reference reaches.

Other similar studies have been conducted to confirm in-stream large wood effectiveness in other areas that may need improvement for different fish species. Pierce et al. (2015) examined in-stream large wood placement in Spring Creek in the Blackfoot Basin, Montana designed to increase trout abundance. During the early phase of habitat recovery, Pierce et al. (2015) a found deep, narrow, revegetated stream with increased shear stress and sediment entrainment, however long term results indicated that low density in-stream large wood significantly improved trout abundance and increased biomass.

The Salmon River Riparian Assessment Project within the Klamath National Forest, Sikiyou County, California evaluated several pilot project sites to restore healthy riparian forest conditions and increase rearing habitat for juvenile salmonids (SRRA. 2012). Coho salmon require slow water refugia and summer cold water temperatures for rearing habitat. In addition to side channel habitat and riparian forest canopy. These requirements benefit the future health and population of Coho salmon. This project found that by increasing the side channel connectivity and duration of floodplain inundation an increase of habitat area and re-growth of a robust riparian forest occurred. Both habitat area and riparian forests provide materials needed to maintain the natural process of a resilient alluvial system and provide complex rearing habitat for juvenile salmonids (SRRA 2012).

River meandering is an important long-term goal in sites that contain a constricted river. Many meander bends are complicated by naturally occurring persistent obstacles, such as in-stream large wood (Daniels and Rhoads 2003). In-stream large wood functions as a resistance element modifying flow and sediment transport, patterns of erosion and deposition, and floodplain development (Keller and Swanson 1979; Fetherston et al. 1995; Richmond and Fausch 1995). Daniels and Rhoads (2003) found that in-stream large wood is an important local influence on bend migration and evolution. In-stream large wood has the potential to profoundly disrupt flow structure and influence river dynamics. In-stream large wood significantly effects fluvial dynamics of meander bends and could be utilized in areas lacking complicated meaning bends (Daniels and Rhoads 2003).

This study demonstrated the long-term effectiveness of complex wood jams in achieving long-term restoration goals. The results showed an increase of hydraulic complexity by increasing the number of pools, floodplain connectivity and in-stream large wood. Furthermore, this study found an improvement of rearing and resting habitat for salmonids by containing spawning gravel, side channels and floodplain area. In addition to creating pool cover though an increase in pool cover percentage.

Long-term monitoring for restoration managers interested in restoring the physical and biological processes that create and maintain salmonid habitat is recommended due to the dynamic processes a streams undergoes over time such as high and low water years. Pulse monitoring of fish populations within the study area before and after restoration is recommended to be able to quantify the biological response to restoration. From the observation that deepest residual pool depths were maintained by restoration techniques that utilized both static and dynamic complex log jams, further investigation of this combined technique is recommended.

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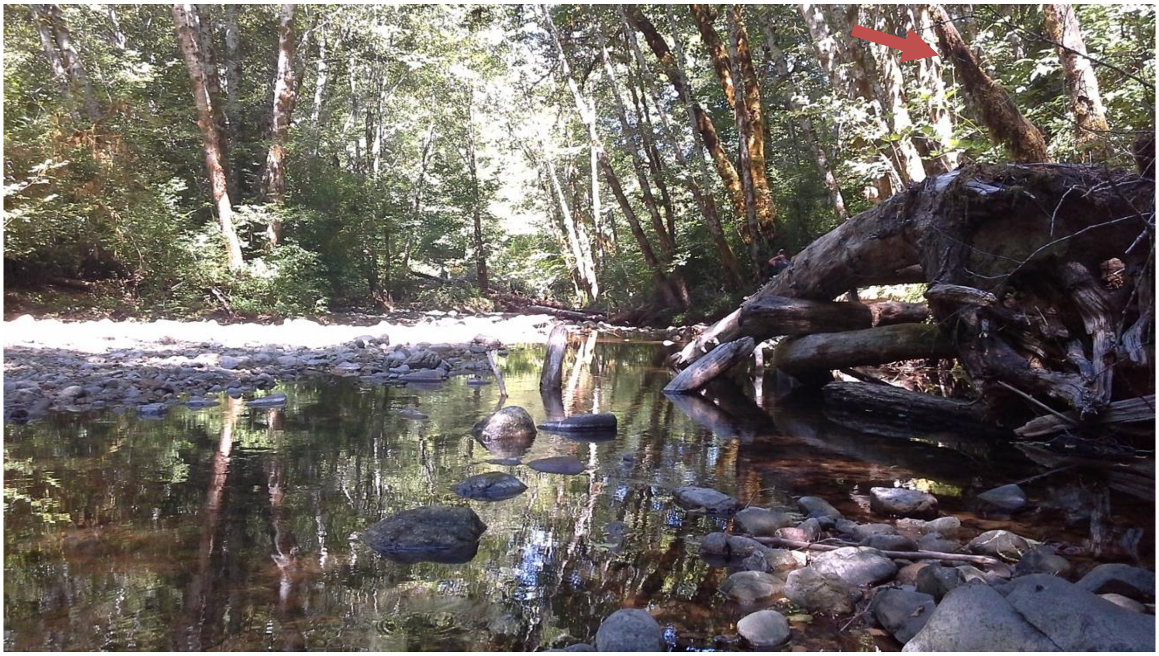
APPENDIX

Appendix A: Site photograph comparisons of years 2008 and 2016.

<u>Site 1 2008 (facing downstream)</u>

Site 1 2016 (facing downstream)



Site 2 2008 (log jam on northern floodplain)

Site 2 2016 (facing upstream)

Site 2 2008 (facing downstream log jam on northern floodplain)

Site 2 2016 (facing downstream log jam on northern floodplain)

Site 3 2008 (facing upstream)

Site 3 2016 (facing upstream)

Site 4 2008 (facing downstream)

Site 4 2016 (facing downstream)

Site 5 2008 (facing downstream)

Site 5 2016 (facing downstream)

Site 5 2008 (facing log jam on southern floodplain)

Site 5 2016 (facing log jam on southern floodplain)

Site 6 2008 (facing downstream)

Site 6 2016 (facing downstream)