EVALUATION OF CONSTRUCTED WOOD JAMS IN A FOREST, GRAVELBED STREAM

by

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ABSTRACT

Evaluation of constructed wood jams
in a forest, gravelbed stream

Joél Benegar

Whole tree materials that include trees with attached rootwads, logs, and branches are recognized as important components of streams flowing through coastal redwood forests of Northern California. As the understanding of the importance of large wood materials has emerged, they have been recognized as key physical elements missing from many streams due to the historic and systematic removal associated with timber harvest and stream cleaning practices. The recognition of the ecological importance of wood materials within stream and floodplain ecosystems has led scientists and managers to advocate for the re-introduction of large wood directly into these environments. However, common applications of instream wood restoration can fall short of producing features capable of inducing the physical changes necessary to achieve desired restoration objectives, such as the formation of deep pools and cover. Current research shows that natural wood jams, with increased wood piece counts and volumes, are more effective at producing the hydraulic and geomorphic conditions necessary for creating and sustaining complex habitat. This study hypothesized that wood jams constructed with whole tree materials, increased wood piece counts, and greater wood volumes would be more effective than simple structures at creating the hydraulic conditions necessary for increasing instream complexity, geomorphic function, and aquatic habitat quality. Results were based on an evaluation of changes to surface sediment textures and channel morphology at ten constructed wood features built with varying complexity and wood volumes. Eight of these features were complex wood jams constructed with whole tree materials including large diameter trees with attached rootwad, logs, and branches. Each complex jam was individually designed to interact with seasonal variations in stream flow, floodplain morphology, and the dominant sediment transport regime. Two of the studied features were "simple structures" constructed in 1995 and comprised of one or two logs anchored to imported boulders with cable. The simple structures were designed following a standard California restoration protocol. Results indicate that complex wood jams were more effective than simple fish habitat structures in achieving common restoration objectives that include: (1) increasing percentage pool cover; (2) increasing scour pool habitat; (3) metering and sorting salmon spawning gravels; and (4) improving habitat heterogeneity. In addition, the effectiveness of an individual constructed jam improved as the overall wood piece count and volume within the jam increased. The increase in pool depths demonstrate that complex wood jams were effective at improving over summering and overwintering pool habitats for steelhead trout, coho salmon, and Chinook salmon.

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INTRODUCTION

Whole tree materials that include trees with attached rootwads, logs, and branches are recognized as important components of streams flowing through coastal redwood forests of Northern California (Lassettre and Harris 2001). As the understanding of the importance of large wood materials has emerged, they have been recognized as key physical elements missing from many streams due to the historic and systematic removal associated with timber harvest and stream cleaning practices (Maser and Sedell 1994, Reich et al. 2003). The recognition of the ecological importance of wood materials within stream and floodplain ecosystems has led scientists and managers to advocate for the re-introduction of large wood directly into these environments (Abbe et al. 2003), Reich et al. 2003). However, common applications of instream wood restoration can fall short of producing features capable of inducing changes needed to achieve the desired restoration objectives, such as the formation of deep pools and cover. In order for wood restoration to become more effective at improving instream habitat for salmonid populations, hydrogeomorphic conditions, wood size, and wood quality must become a primary focus of design (Nagayama and Nakamura 2010).

Previous research has established a solid understanding of the impact of instream wood on changes to channel morphology, sediment routing and storage, and channel dynamics and processes. Large wood has been shown to influence channel morphology (Keller and Swanson 1979, Bilby 1984, Montgomery et al. 1996), Piegay and Gurnell 1997, Montgomery and Buffington 1997); pool formation, size and spacing (Bilby and

Ward 1989, Montgomery et al. 1995), Abbe and Montgomery 1996, Gurnell and Sweet 1998); channel width and variability (Trotter 1990, Smith et al. 1993b); channel roughness (Buffington and Montgomery 1999b, Manga and Kirchner 2000); bed-surface grain size (Lisle 1995, Buffington and Montgomery 1999a); and the stabilization of gravel bars and other depositional sites (Lisle 1986, Fetherston et al. 1995). In addition to wood within the channel, wood outside or above the bankfull channel influences pool formation by directing patterns of scour at or above bankfull flows (Dolloff and Warren 2003) and forces flows onto floodplain surfaces, creating and sustaining secondary channels and wetlands (Triska 1984, Sedell and Froggart 1984, Collins and Montgomery 2002, Abbe et al. 2003).

By altering the spatial distribution of shear stress, lateral bed slope, and sediment supply, large wood impacts channel sediment storage, mobility, and bed surface textures (Dietrich et al. 1993, Smith et al. 1993a, Rice 1994, Buffington and Montgomery 1999b). Channels containing large wood jams have been shown to exhibit highly variable sediment surfaces and reflect localized sorting of sediment by grain-size, often into relatively homogeneous facies textural patches (Hogan 1989, Rice 1994). Such facies patches result from size-selective deposition or entrainment caused by spatial variations in shear stress, sediment supply, and lateral bed slope (Pettijohn 1975, Dietrich et al. 1993, Kondolf and Piégay 2003). Roughness caused by wood can significantly reduce bed shear stress and channel competence, diminishing reach-average grain sizes (MacDonald and Keller 1987, Assani and Petit 1995, Lisle 1995, Buffington and Montgomery 1999b, Manga and Kirchner 2000, Haschenburger and Rice 2004). Large wood jams can additionally force the formation of upstream bars by creating organic dams that physically block sediment transport or by forcing local flow divergence and consequent sediment deposition (Montgomery et al. 2003). Downstream of jams, scoured sediment can create complimentary bars, partially defining the boundaries of the pool (Montgomery et al. 2003). Sediment deposition and storage from instream large wood can control the formation and function of riparian forests by providing surfaces for vegetation colonization, forest island growth, coalescence, and forest floodplain development (Bisson et al. 1987), Bilby and Ward 1989, Fetherston et al. 1995). Removal or displacement of wood decreases streambed roughness and has been shown to increase sediment transport out of low order stream reaches, reducing sediment storage and increasing the overall sediment bed grain size (Beschta 1979, Bilby 1981, Megahan 1982, Smith et al. 1993a, Diez et al. 2000, Lassettre and Harris 2001).

Large wood jams are a principal mechanism for controlling reach-level habitat diversity and are critical for creating and maintaining the area and complexity of fish habitat (Bisson et al. 1987), Abbe and Montgomery 1996). Wood jams increase habitat complexity and heterogeneity by creating areas of local sediment deposition and scouring pools (Maser and Sedell 1994, Abbe and Montgomery 1996). Fish populations have been found to be typically larger in streams with high levels of large wood (Fausch and Northcote 1992, Maser and Sedell 1994) and complex wood structures have been shown to attract more fish than single logs (Sedell et al. 1984, Roni and Quinn 2001). Conversely, wood removal is associated with the loss of physical complexity in fluvial systems (Shields and Smith 1992, Beechie et al. 2001, Collins et al. 2003) and decreases in fish abundance (Bryant 1983, Dolloff 1986, Elliott 1986). In addition, large wood jams are considered “hot spots” for invertebrate activity because they provide both substrate and nutritional resources for macroinvertebrates (Anderson et al. 1978), Wallace et al. 1995), Hershey and Lamberti 1998, Lemly and Hilderbrand 2000, Naiman et al. 2002).

Old-growth redwood forests of Northern California exhibit the highest levels of instream wood loading along the Pacific Coast and contribute large amounts of biomass to streams (Harmon et al. 1986, Bilby and Bisson 1998, Lassettre and Harris 2001, Wooster and Hilton 2004). However, a variety of management practices employed in the Pacific Northwest over the last century, including timber harvesting and stream wood cleaning for fish passage, have altered the amount and characteristics of large wood in streams (Sedell et al. 1984, Bilby and Bisson 1998, Reich et al. 2003, Wooster and Hilton 2004). Before the importance of instream wood was understood, it was considered deleterious to anadromous fish because some jams were considered migration barriers and erosion inducing (Wooster and Hilton 2004). The State of California’s Energy Resources Fund of 1980 and the 1981 Bosco-Keene Assembly Bill 951 allocated one million dollars per year for salmon restoration that included stream cleaning at the rate of at least 100 miles per year (Wooster and Hilton 2004). Such stream cleaning efforts often removed all wood below a stream’s high water mark (Wooster and Hilton 2004). Consequences from riparian timber harvest and instream wood removal included alteration of riparian habitat, reduction of wood inputs into channels by removing the future sources of wood, simplification of stream channels, changes in nutrient cycles, and the subsequent loss of fish habitat (Likens and Bilby 1982, Bilby and Bisson 1998, Reich et al. 2003). By 1987, the stream restoration paradigm began to shift away from complete stream cleaning and towards selective removal of debris dams and the installation of wood structures (Wooster and Hilton 2004).

Over the past three decades, the recognition of large wood as a necessary element in streams has led scientists and managers to advocate for the manual re-introduction of large wood directly into channels and for increasing the width of riparian timber buffer zones as future sources of instream wood recruitment (Harmon et al. 1986, Gregory and Davis 1992, Abbe et al. 2003, Dolloff and Warren 2003, Reich et al. 2003). The re-introduction of large wood into fluvial ecosystems is intended to re-establish natural processes and conditions that create and sustain physical complexity, such as restoring instream structure and cover (Abbe et al. 2003). However, the current application of instream wood loading often falls short of constructing jams that can affect the channel hydraulics to the degree necessary to produce desired restoration objectives (Abbe et al. 2003). Few guidelines exist on appropriate methods for emulating natural wood jams, where and how to construct jams, or how to manage systems where wood is reintroduced (Abbe et al. 2003).

In order for wood loading efforts to become more effective at meeting salmonid recovery objectives, project designs should be guided by natural wood jam structure, hydrogeomorphic conditions, wood size and quality, and an understanding of the magnitude to which the system may change (Abbe and Montgomery 1996, Abbe et al. 2003, Nagayama and Nakamura 2010). Natural wood jams are often accumulations of combinations of woody pieces from nearby banks and those pieces transported fluvially from upstream sources (Abbe and Montgomery 2003). These jams often begin with a single key member and then evolve over time into a jam composed of accumulations of woody and organic debris that range in size from leaves and twigs to entire tree trunks (Manners et al. 2007). The number of wood pieces in an individual jam influences the porosity, which has control on velocities upstream, adjacent, and downstream of the jam, shear stress distribution, and the drag force (Manners et al. 2007). The interaction of both the hydraulic and geomorphic complexity enhances the habitat value (Zalewski et al. 2003, Lepori et al. 2005).

Current research shows that natural wood jams, with increased wood piece counts and volumes, are more effective at producing the hydraulic and geomorphic conditions necessary for creating and sustaining complex habitat (Manners et al. 2007). This study hypothesized that wood jams constructed with whole tree materials, increased wood piece counts, and greater wood volumes would be more effective than simple structures at creating the hydraulic conditions necessary for increasing instream complexity, geomorphic function, and aquatic habitat quality. Results were based on an evaluation of changes to surface sediment textures and channel morphology at ten constructed wood features built with varying complexity and wood volumes. The total volume of wood used in each constructed jam was used as a proxy to evaluate the jam's effect as a channel obstruction. Eight of these features were complex wood jams constructed with whole tree materials including large diameter trees with attached rootwad, logs, and branches. Each complex jam was individually designed to interact with seasonal variations in stream flow, floodplain morphology, and the dominant sediment transport regime. Two of the studied features were “simple” fish habitat structures constructed in 1995 and comprised of one or two logs anchored to imported boulders with cable and designed following a standard protocol (Flosi and Reynolds 1994). The two 1995 “simple” structures were re-configured in 2008 with the addition of whole tree materials.

The purpose of this study was to evaluate whether complex wood jams were more effective than simple structures at restoring instream geomorphic processes and habitat needed to support the recovery of salmonid populations. The two “simple” structures were considered representative of existing stream restoration practices in California. The complex wood jams were examples of a strategy to restore the instream processes needed to recover declining salmonid populations in California. Specifically, this study evaluated whether there was a significant relationship between increased wood loading (total site wood volume, total wood volume per channel width, and wood piece count) and changes to: (1) percentage pool cover; (2) residual pool depth (Lisle 1987); (3) upstream sediment aggradation; (4) number of facies patches; (5) habitat heterogeneity; and (6) reach average D50 (i.e. the median reach sediment size).

STUDY SITES

The study was conducted on East Fork Mill Creek, a third-order tributary to Mill Creek, located in northwest coastal California near the Oregon border (Figure 1). The Mill Creek watershed (99.7 km^2) drains into the Smith River at Jedediah Smith Redwoods State Park, near Crescent City, Del Norte County. Mill Creek has two main tributaries, East Fork Mill Creek (37 km^2) and West Branch Mill Creek (24 km^2). The study site is within the Mill Creek Addition to Del Norte Coast Redwoods State Park that was acquired from Stimson Lumber Company in 2002.

Geology of the Mill Creek watershed is dominated by the “Broken Formation” of the Franciscan Assemblage (Madej et al. 1986). The Broken Formation comprises tectonically fragmented interbedded greywacke, shale, and conglomerate (Madej et al. 1986). The predominant soil types in the Mill Creek basin are the Melbourne and Josephine associations. These soil series have a moderately high-to-high erosion potential (Madej et al. 1986).

The Mill Creek watershed is located within the portion of the California Coast Range Province known as the coastal fog belt. Precipitation primarily occurs between November and March, with a mean annual precipitation of 152 to 381 cm (60-150 inches). Average monthly maximum and minimum air temperatures in Crescent City vary from 8 to 19° C (41- 67° F) (Stillwater Sciences 2002).

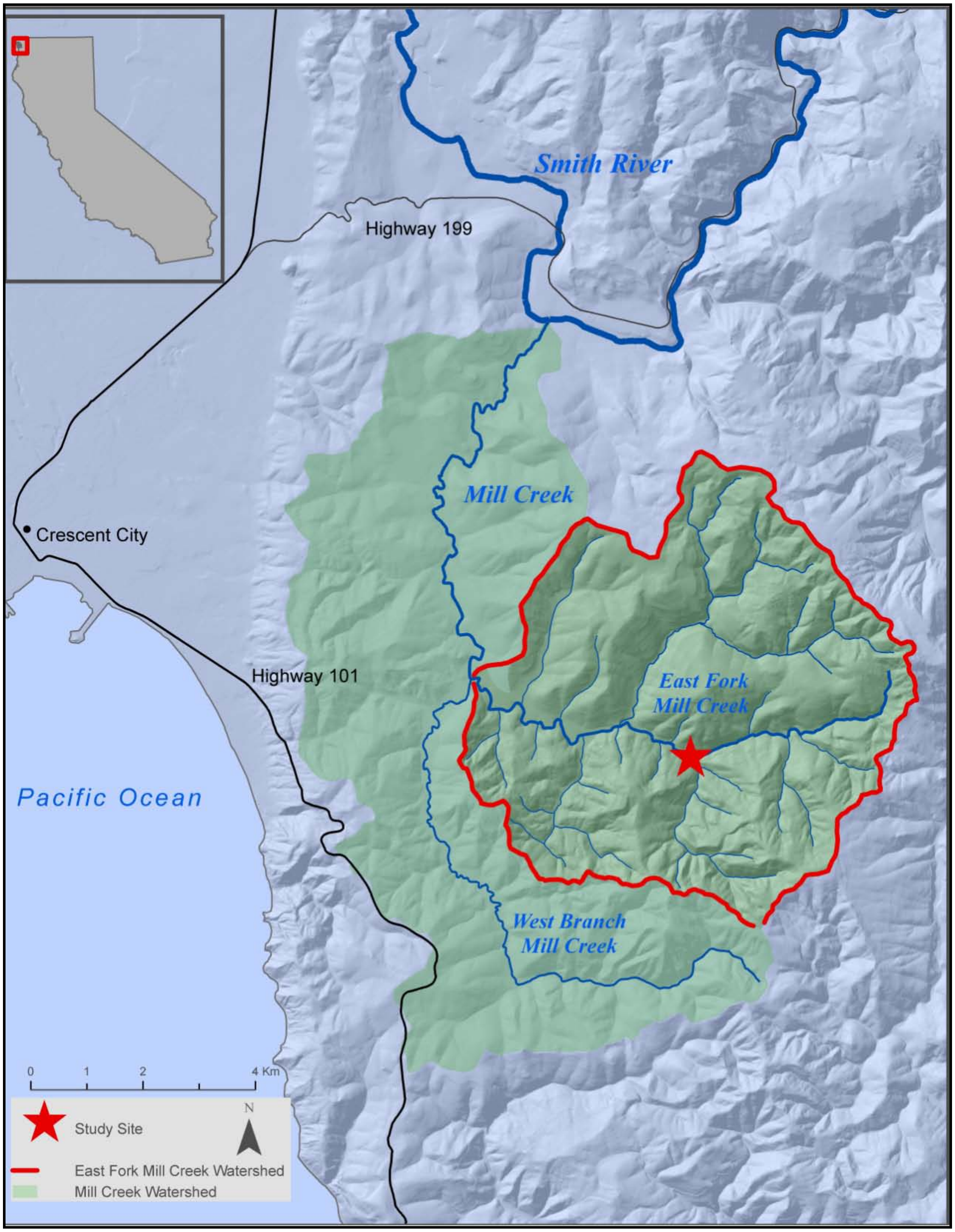

Figure 1. Study site location, East Fork of Mill Creek within the Mill Creek watershed, Del Norte County, California.

The Mill Creek watershed is characterized by steep, mountainous terrain typical of Northern California coast ranges. Elevations range from 21-710 m above mean sea level and average hillslope gradients range from 18 to 20 degrees (Madej et al. 1986). The watershed shape is nearly circular, with a slight elongation in the northerly direction and the channel pattern mostly dendritic (Madej et al. 1986).

The Mill Creek hydrograph mimics that of the Smith River, although the Smith River has higher runoff-per-unit-area than Mill Creek (Madej et al. 1986). Mill Creek stream flow was monitored by United States Geological Society (USGS) from 1974 to 1981 at a site 1 km below the confluence of the East Fork and West Branch (Stillwater Sciences 2002). During this time, the mean annual discharge of Mill Creek was three cubic meters per second (cms). The lowest and highest mean daily flows were 0.07 cms and 84 cms, respectively. The peak recorded flow was 126 cms on 18 March 1975 (Madej et al. 1986). For this study, Smith River daily discharge and peak flow measurements at the USGS Jedediah Smith Redwoods State Park gauging station and rainfall data from the Gasquet Ranger Station were used as surrogates for flow and precipitation conditions in the Mill Creek watershed. Peak flow and daily discharge estimates for the East Fork Mill Creek were based on the Jedediah Smith gauging station measurements and weighted by drainage area, where the East Fork Mill Creek watershed is approximately 2% of the Smith River watershed area at the Jedediah Smith gauging station. These weighted estimates are likely overestimates of actual East Fork Mill Creek flow as the Smith River watershed includes areas of higher elevations than the Mill Creek watershed and peak runoff would include snowmelt from rain on snow events.

Fish populations in East Fork Mill Creek include natural runs of Chinook salmon (*Oncorhynchus tshawytscha*), Southern Oregon and Northern California coast "threatened" coho salmon (*O. kisutch*), chum salmon (*O. keta*), steelhead trout (*O. mykiss irideus*) and coastal cutthroat trout (*O. clarki clarki*). Other fish species that have been reported from streams on the Mill Creek property include, western brook lamprey (*Lampetra richardsoni*), river lamprey (*Lampetra ayresi*), Pacific lamprey (*Lampetra tridentata*), prickly sculpin (*Cottus asper*), riffle sculpin (*Cottus gulosus*), threespine stickleback (*Gasterosteus aculeatus*), Klamath smallscale sucker (*Catostomus rimiculus*), and American shad (*Alosa sapidissima*) (Albro and Gray 2002, Justice 2007, McLeod and Howard 2010).

The Mill Creek watershed has a long history of timber harvest dating back to the 1850's but the vast majority of logging occurred after the property was purchased by Miller Timber Company in 1941(Stillwater Sciences 2002) . Harvest peaked between 1964 and 2000 (Stillwater Sciences 2002). An aerial photograph from 1980 (Figure 2) shows the clear-cut land adjacent to the 2006 and 2008 instream wood restoration sites. Today only 200 acres of old-growth forest remain in five separate stands within the Mill Creek watershed. Most of the East Fork Mill Creek watershed has been harvested at least once (Justice 2007, Carroll and Robison 2007). Today, the riparian overstory vegetation along East Fork Mill Creek is dominated by red alder (*Alnus rubra*) and big-leaf maple

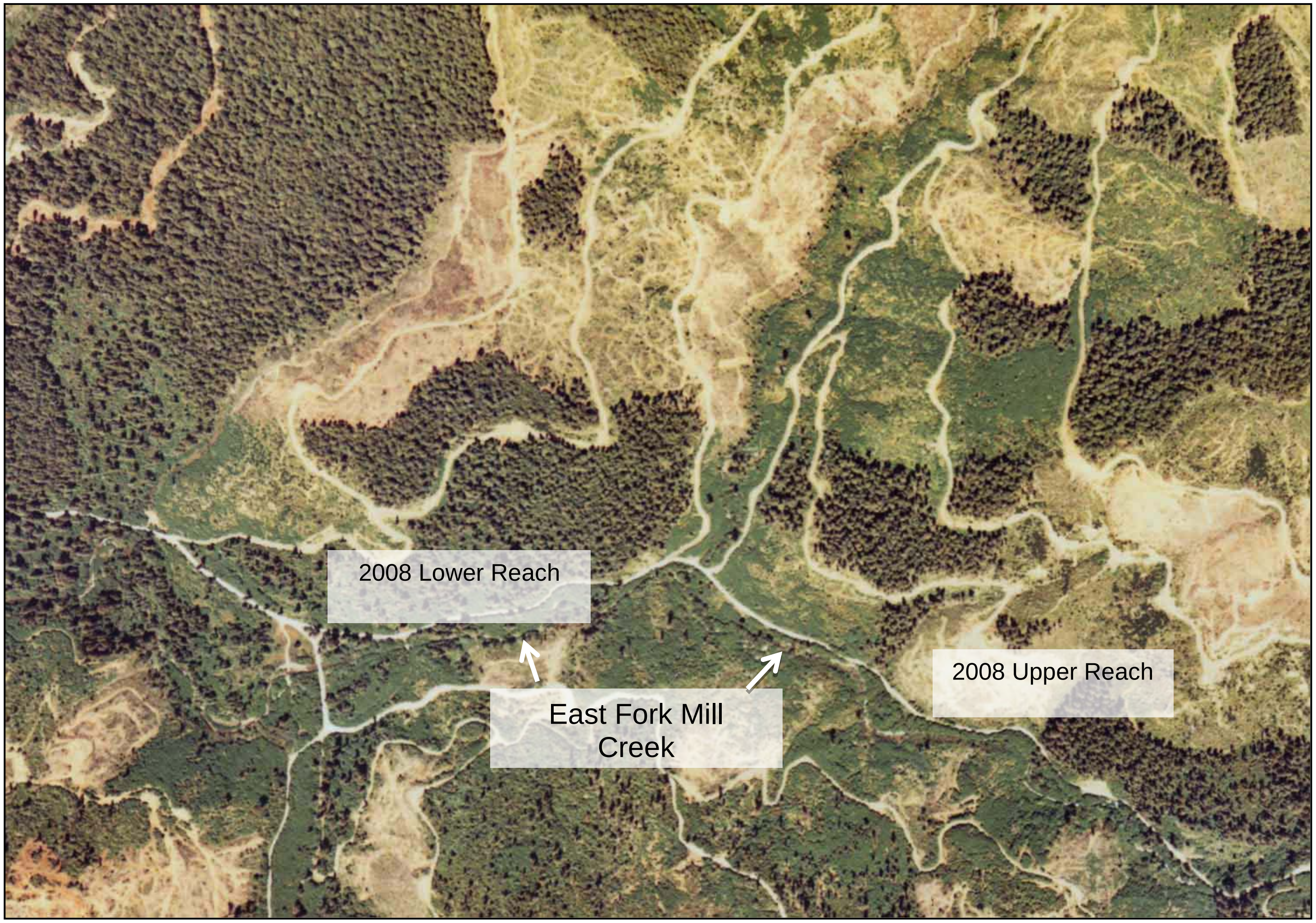

Figure 2. 1980 aerial photo of clearcut logging timber harvest units surrounding 2008 wood loading study sites, East Fork Mill Creek, Del Norte County, California.

(*Acer macrophyllum*) with smaller populations of coastal redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), tan oak (*Lithocarpus densiflorus*) and western hemlock (*Tsuga heterophylla*) (Justice 2007). Evidence of past higher wood loading within the riparian corridor and channel includes multiple old-growth redwood stumps adjacent to the channel. Historically, these trees would have provided significant volumes of wood to stream corridors.

Logging practices and instream wood cleaning have reduced wood jam frequency in the East fork of Mill Creek. Stream cleaning, or removal or large woody materials from stream channels, was routinely conducted in the middle and upper watershed until as recently as 1992 (Verhey and Schwabe 1993). This practice severely depleted Mill Creek and its tributaries of instream wood necessary for habitat form and function. Carroll and Robison (2007) showed that wood loading was substantially lower in the East Fork Mill Creek compared to the West Branch Mill Creek and Prairie Creek. Prairie Creek is a 3rd order tributary that flows through an old-growth redwood forest in Prairie Creek State Park and has similar a stream gradient and bankfull width as the study reaches in East Fork Mill Creek. The West Branch Mill Creek has similar gradient and bankfull width as East Fork Mill Creek and Prairie Creek, with a land management history very similar to the East Fork Mill Creek (Carroll and Robison 2007, Stillwater Sciences 2002). In 2004, Carroll and Robison (2007) examined pool-forming mechanisms by evaluating the characteristics of channel morphology and the role of large wood in similar reaches of Prairie Creek, West Branch Mill Creek, and East Fork Mill Creek. Wood loading and wood piececounts in East Fork Mill Creek were significantly lower than in Prairie Creek and West Branch Mill Creek (Table 1). East Fork Mill Creek total wood loading were only 5%-12% of estimates for Prairie Creek and West Branch Mill Creek and ranged from 21-27% for wood piececounts and wood pieces per 100 m stream length (Carroll and Robison 2007).

Three instream wood loading projects have occurred in the East Fork Mill Creek in 1995, 2006, and 2008 (Figure 3). In 1995, the California Department of Fish and Game (CDFG) installed several large wood and boulder structures throughout the Mill Creek watershed to improve rearing habitat for juvenile salmonids, including 15-20 structures on East Fork Mill Creek (Schwabe 1998, Justice 2007). To further this restoration effort and to begin to increase wood loading levels towards background conditions in East Fork Mill Creek, California State Parks began implementation of a large-scale instream habitat improvement project in 2006 (Fiori 2010). During the summer 2006, 12 wood jams were constructed as hybrid designs between the CDFG protocols (Flosi and Reynolds 1994) and a more complex, biogeomorphic design (Fiori 2010). Two years later, in 2008, 13 complex wood jams and one mobile wood loading site were constructed (Fiori 2010). As will be discussed in the next section, two of the 1995 CDFG simple structures and eight of the 2008 California State Parks' complex wood jams were included in this study.

Although it was not analyzed for this study, the mobile wood loading site influenced three of the complex wood jam sites. The mobile wood loading site involved the placement of nine large wood elements of varies sizes that were placed directly into the

Table 1. Channel reach, large wood, and pool characteristics for Prairie Creek, West Branch Mill, and East Fork Mill Creek, Del Norte County, California, 2003 (Carroll and Robison 2007).

Variable	Prairie Creek	West Branch Mill Creek	East Fork Mill Creek
Reach length (m)	1098	1051	1408
Large Wood loading (m^3/ha)	759	329	39
Number of pieces	263	244	66
Pieces/100 m	24	23	5
Mean piece diameter (m)	0.6	0.4	0.4
Mean piece length (m)	7.3	6.3	7.3
Mean piece volume (m^3)	5.2	1.9	1.5
Percent channel in pools (%)	64	64	50
Number of pools	32	27	24
Pool spacing (active channel widths)	2	1.8	3.2

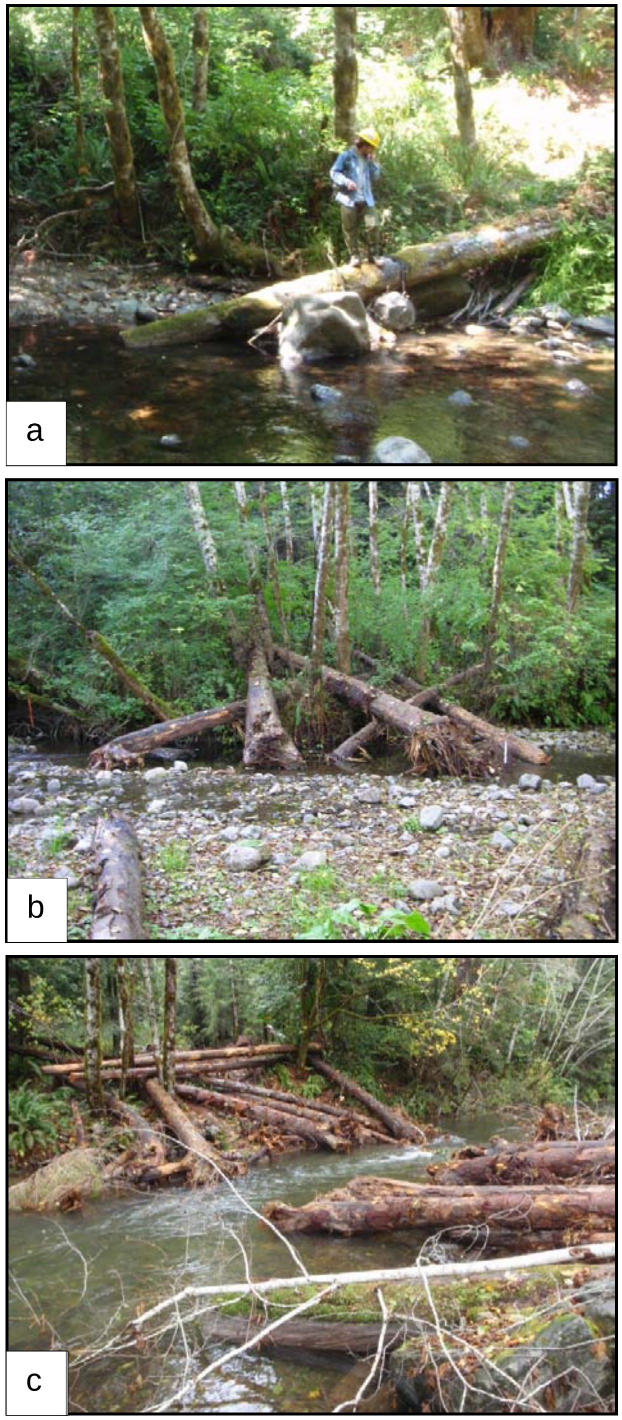

Figure 3. Instream wood loading projects in East Fork Mill Creek, Del Norte County, California: (a) 1995 simple fish habitat structure; (b) 2006 hybrid constructed wood jam; and (c) biogeomorphic constructed complex wood jam (Fiori 2010).

creek and parallel to flow. The purpose of the mobile wood experiment was to monitor the mobility of varies-sized wood elements and the racking potential of complex wood jams constructed downstream of the input site. During the peak flow of water year 2009, all nine mobile wood elements were transported approximately 900 m downstream. They passed through two constructed complex jams and racked at a channel spanning complex jam located at the downstream end of the study site.

MATERIALS AND METHODS

Study sites on East Fork Mill Creek include eight 2008 complex wood jam sites and two 1995 simple fish habitat structure sites (Figure 4). The 2008 complex jams were constructed with an excavator using a combination of large diameter trees with an attached rootwad, logs, and branches. Each jam was geomorphically designed to mimic natural wood jam form and function and to interact with seasonal variations in stream flow, hydraulic forces, floodplain morphology, and the dominant sediment transport regime. Riparian trees were key components of jam design and were utilized as living piling for support during high flows. Other consideration in selecting jam locations included spacing for fish utilization, excavator access, and an assessment of effects to the streambed, floodplain, and downstream infrastructure, such as bridges and roads. Specific restoration objectives included increasing hydraulic complexity; creating pool, foraging, resting and cover habitat for salmon; trapping and sorting sediments; increasing floodplain connectivity; and creating key jams to rack mobile wood.

The majority of wood for construction was reused from local road removal projects in 2006 and 2008 and was primarily whole Douglas-fir and redwood trees with average bole diameters of 0.41 m and 0.47 m, respectively. Most large stems with attached rootwads were installed with the rootwad and lower bole of the tree within the active channel and the stem of the tree set into the riparian forest and wedged between standing riparian trees to limit movement of jams during high flows (Figure 3c).

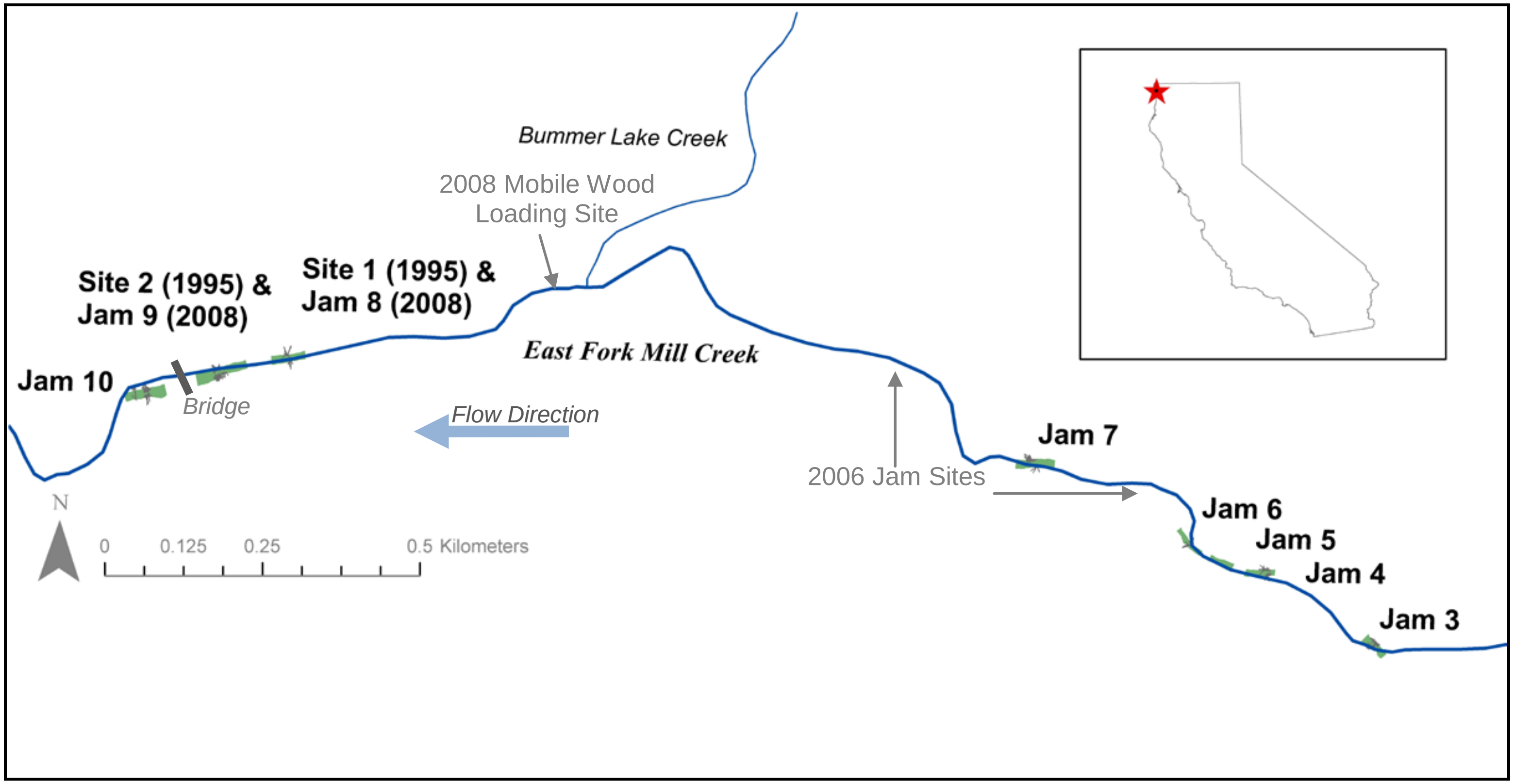

Figure 4. Study site map showing location of: (1) 1995 simple habitat structures; (2) 2006 complex wood jams; (3) 2008 complex wood jams; and (4) 2008 mobile wood loading site (Jams 3-10) in East Fork Mill Creek, Del Norte County, California.

Additional wood elements included rootwads (with short stems attached), old-growth wood salvaged from stream crossings and landings, smaller diameter logs without rootwads, and branches.

Following jam typology of Wallerstein and Thorne (2004), the eight constructed complex jams were categorized as deflector, opposing, and underflow jams. Deflecting jams deflect flows from one bank towards the opposite bank. Opposing jams constrict flows towards the center of the channel. Underflow jams span the entire active channel width, creating high flow obstruction and local flow acceleration. Individual wood elements were installed vertically, pitched, or horizontal (Montgomery et al. 2003). Specific wood elements used for construction included: (1) large wood stem with attached rootwad (diameter >10 cm with rootwad attached); (2) large wood stem without rootwad (diameter >10 cm with no rootwad); (3) rootwad (diameter of any size); (4) medium wood stem without rootwad (1 cm< diameter <10 cm); and (5) small woody debris (diameter < 1 cm) (adapted from Manners et al. 2007).

In addition to the eight complex jams constructed in 2008, two simple wood structures built by CDFG and the California Conservation Corps in 1995 were included in this study. These two simple habitat enhancement structures were considered representative of current CDFG design protocol. They were included to compare impacts to channel morphology and habitat complexity brought about by simple structures and complex jams (Figure 3a). The two simple structures were constructed using CDFG protocol (Flosi and Reynolds 1994) to improve stream salmonid habitat

(Schwabe 1998). These log and boulder structures were constructed with large rock used to ballast one end of the log on the bank and the other within the active channel. Large rock was also placed along the banks upstream and under the structures for bank protection. At Site 1, additional large boulders were placed within the channel to increase hydraulic complexity (Figure 4). Because the two 1995 CDFG structures were constructed 13 years prior to this monitoring effort, it was assumed that the adjacent 2008 channel morphology and facies textures resulted from the placement of the 1995 structures. Therefore, “before” channel conditions for the two CDFG structures were estimated based on past project documentation (Verhey and Schwabe 1993) and local channel characteristics upstream of and at the project sites. Two of the 2008 complex jams (jams 8 and 9) were constructed to incorporate the two 1995 CDFG structures (e.g. one on top of the other, Figure 4). Because the complex jams were built at the same location as the two simple sites, the “after” condition for simple sites 1 and 2 are also the “before” conditions for complex jams 8 and 9.

For this study, a reach was defined as the length of the constructed wood jam plus 1-3 active channel widths upstream and downstream of the jam. The reach upstream and downstream endpoints were set at riffle crests. These endpoints were set as far from the jams as possible (three active channel widths). However, due to channel conditions such as the presence of side channels, islands, and other jams, some endpoints were set to within 1-2 channel widths.

Pre-construction and "as-built" data were collected concurrent with the construction phase of the 2008 complex jam project (July-August 2008). Post-construction data were collected from August 2008 through October 2009. Results were based on physical changes that occurred at the study sites during water year 2009 (1 Oct 2008 - 30 Sept 2009). Primary field methods included: (1) scaling of jam wood materials; (2) total station surveys of wood position and channel and floodplain topography; and (3) facies mapping of distinct textural sediment patches within the active channel.

Wood Scaling and Volume Measurements

In order to calculate wood volume at each jam, all wood was measured before being placed in the jams. Large wood with rootwad, large wood without rootwad, and medium wood without rootwad were placed by an excavator on a road or landing to measure lengths and diameters of the stems and rootwads (Figure 5). Large wood with rootwad elements were measured with the most detail. For each large wood with rootwad, the length measurement of the stem was measured from the basal swell to the top end (L1). Diameter measurements were taken at the top (Dt), midpoint (Dm), and at the basal swell (Db) (Figure 6). The rootwad length was measured from the top of the basal swell to the base of the dominant rootwad branches (L2). Two diameters were taken of the rootwad (D1, D2). For large wood without rootwad and medium wood without rootwad, only the length and the top and bottom diameters were measured. Small wood was measured while gripped between the bucket and thumb of the excavator (Figure 7). The objective was to obtain a measurement of the compacted volume of the small woody debris bundles as it would occur within the jam. The

Figure 5. Wood construction materials for constructed wood jams. Wood materials were measured prior to jam construction. East Fork Mill Creek, Humboldt County, California. 29 July 2008.

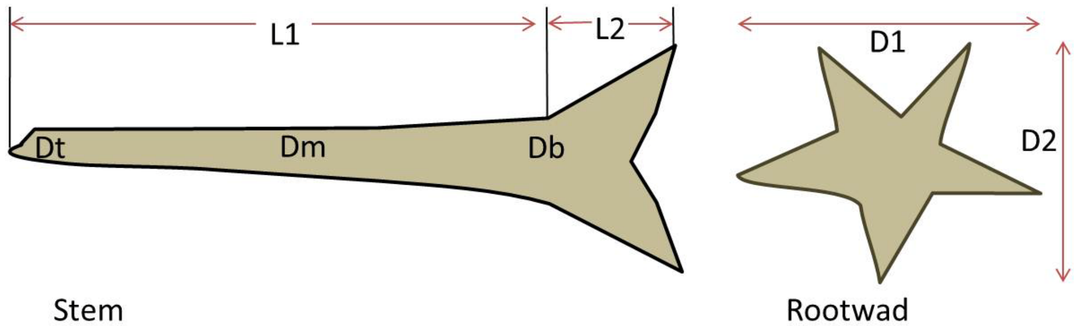

Figure 6. Large wood stem with rootwad measured dimensions.

Figure 7. Small woody debris bundle compressed by the excavator for measurement prior to installation into a constructed wood jam in East Fork Mill Creek, Del Norte County, California. 2 August 2008.

length, width, and height of each small wood bundle were measured.

During site construction, individual wood elements were mapped and assigned a unique number relative to stream bank location and its longitudinal and vertical position within the jam. These wood identification numbers were marked on hand-drawn maps and then used to identify key jam elements during total station surveying and facies mapping. Jam elements were additionally classified into four stream influence zones based on protocol in the Timber-Fish-Wildlife Monitoring Program Manual for the Large Woody Debris Survey (Figure 8) (Robison and Beschta 1990, Schuett-Hames et al. 1999). Note that due to localized aggradation and scour, this study has defined the active channel as the area of channel below the tops of banks. In Figure 8, active channel and bankfull channel are synonymous.

Facies Mapping and Habitat Heterogeneity

Before and after facies maps were drawn for each project site. Facies patches are surface sedimentary deposits distinct in grain size and/or sedimentary structure, representing distinct local depositional environments (Pettijohn 1975). A facies map captures reach-wide variations in surface sediment size and is a useful tool for describing stream flow conditions and a baseline for comparing future change (Kondolf and Piégay. 2003). Textural patches result from size-selective deposition or entrainment caused by spatial variations in shear stress, sediment supply, and lateral bed slope (Dietrich et al. 1993). Facies maps can additionally show changes in aquatic habitat heterogeneity by visually representing changes to patchy bed surfaces that have

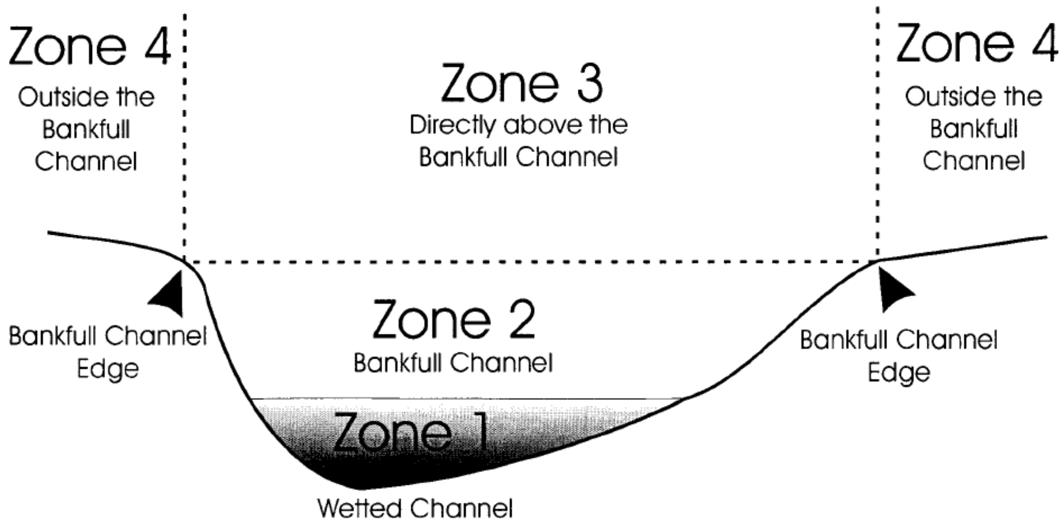

Figure 8. Zone criteria used to define the location of placed wood at study sites (from Schuett-Hames et al. 1999).

direct biological implications (Townsend 1989, Kondolf and Wolman 1993).

For this study, a facies was defined as a distinct surface sediment patch 1 m^2 or larger and 240 facies units were mapped during the two-year study period. Because there were not facies maps available for the two 1995 simple structures (sites 1 and 2) the “before” facies maps were drawn based on adjacent channel conditions not affected by wood loading efforts. For these structures, the “after” facies map were drawn in 2008, 13 years after construction. For the 2008 complex wood jam sites, the “before” sediment texture patches were mapped with corresponding pebblecounts (Wolman 1954). Bed materials were measured with a gravelometer, a template cut in the sizes of the grain size classes (Figure 9). Template measurements are considered more comparable to sieve measurements and less prone to observer error in identifying the b-axis to measure (Kondolf and Peigay 2003). Grain size was recorded by the lower end of the size range, by analogy to sediments collected on sieves, where grains are not allowed to pass through the template diagonally.

For the 2009 “after” conditions, there were 222 facies patches. Because it was not feasible to conduct pebble-counts on the 222 facies patches (22,200 sediment measurements), a field-based “quick estimate” was used to estimate the D50s, or median patch grain size. For this method, three field technicians would first visually calibrate their D50 estimates by conducting 3-5 pebblecounts on several facies patches. After calibration, D50s for remaining patches were estimated. The particle representing the median particle (D50) grain size was selected from a facies patch and placed through the gravelometer to determine the size class D50.

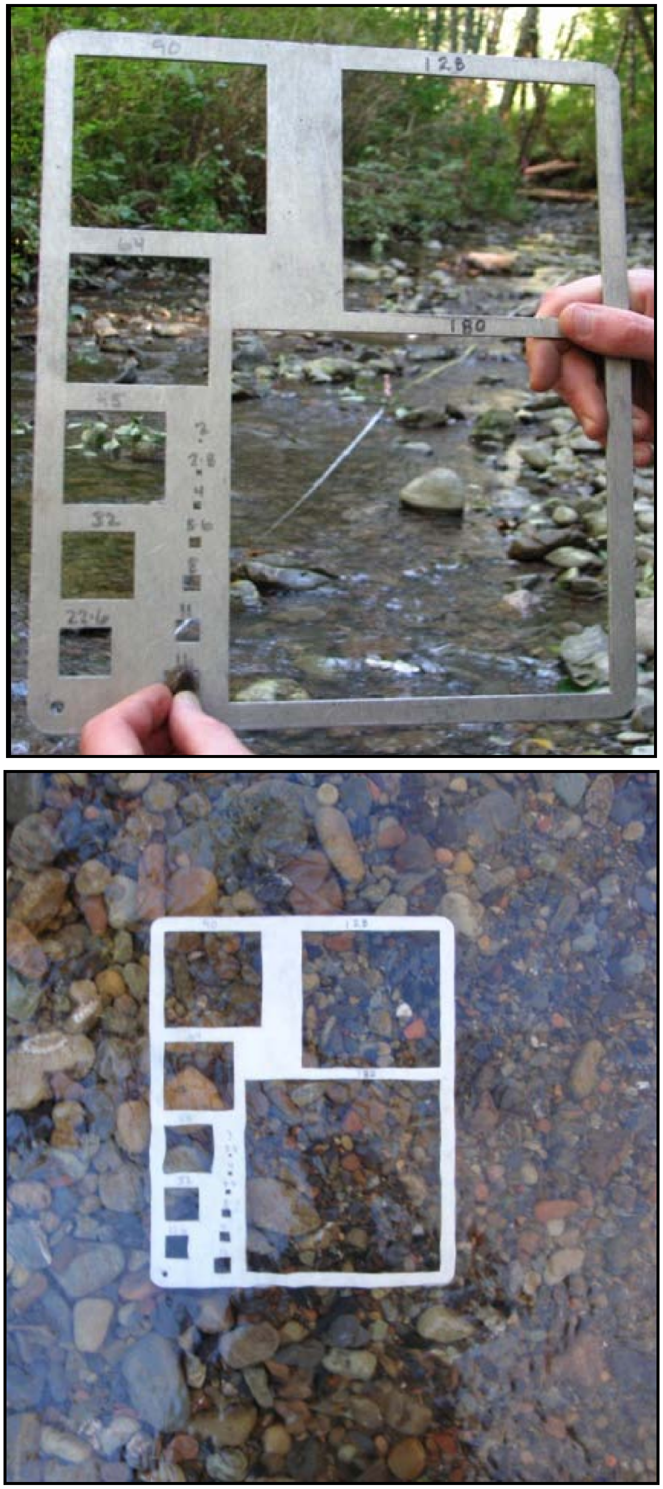

Figure 9. Gravelometer used to measure gravel and cobble sediment for pebble-counts and field based D50 quick estimate.

Hand-drawn facies maps were scanned and then digitized in ArcMap Version 9.3.1. To improve accuracy, digitized facies maps were georeferenced and aligned with total station survey control points. Each facies patch was assigned the corresponding D50 based on the calculated lower-limit pebble-count or field-based quick estimate. The D50, or median particle size, was selected to represent each facies as an ecology-based indicator of patch habitat as the D50 has been linked to salmon spawning gravel preferences (Kondolf and Wolman 1993). Reach average D50s were calculated based on the lower limit D50 estimates for each patch and weighted by patch area. Habitat heterogeneity of the study reaches was quantified using metrics in Patch Analysis, an extension to ArcView GIS (Elkie et al. 1999). Patch Analysis calculates the Shannon's Diversity Index, an ecologically meaningful index of habitat heterogeneity (McGarigal and Marks 1995). The Shannon's Diversity Index will equal zero when there is only one patch in the landscape and increases as the number of patch types or proportional distribution of patch types increases (McGarigal and Marks 1995).

Total Station Surveying

High-density total station surveys (on average 920 total points per site, equivalent to 16,750 points per km) were conducted at the 2008 complex wood jam sites before and after the WY2009 using a Leica Robotic total station (model TCRA1105) following standard topographic survey methods (Harrelson et al. 1994). Rebar and wooden staked control points were established in 2008 and reoccupied in 2009. The following survey data was collected at each site: (1) ground surface cross-sections; (2) topographic points along the thalweg, low flow wetted edges, active channel margins, bedrock outcrops and bar crests; (3) top and bottom position of key wood members; and (4) observed high water levels from the WY2009 that were recorded with nails hammered into riparian trees at the water edge during the 28 December 2008 and 16 March 2009 storm events.

Cross-sections were positioned to characterize wood jams and adjacent channel reaches using 2 to 3 meter spacing. Two additional hydraulic reference cross-sections were located 1-4 channel widths upstream and downstream of wood jams. The hydraulic reference cross-sections were located as far from the jams as possible, were positioned at riffle crests in a section of channel representative of the project site and were assumed to be out of the influence of the associated complex wood jam. In certain situations, channel morphology such as side channels, islands, and wood jams forced the hydraulic cross-sections to be located closer to the wood jams. With this methodology, each reach had 7-11 cross-sections, depending on the length of the wood jam. Cross-section survey points were taken at all breaks in slope, including active channel margin, low flow edge of water, and thalweg. Bankfull stage was considered the stage at which stream water just begins to exit the active channel and overtop the floodplain. For this study and due to possible incision and aggradation that would alter the true geomorphic bankfull stage, bankfull channel is synonymous with the active channel. During the surveys, active channel indicators coincided with the break in slope between the active channel and floodplain, which generally was coincident with the alder tree line. Active channel margins were surveyed as longitudinal profiles and for all cross-sections.

Survey data and facies maps were used to quantify changes to channel morphology and percentage pool cover. Specifically, survey results include longitudinal profile and cross-sectional graphs, channel gradient, high water profile, residual pool depths (Lisle 1987), and upstream aggradation depth. The average active channel width was determined based on the average of multiple cross-sections through the study reach. Reach gradient, residual pool depths, and aggradation depths were determined based on changes in survey data elevations. Percentage pool cover was calculated as the ratio of wood structure or jam surface area to pool area. The surface area of wood was calculated in ArcView GIS from digitized field maps where wood position and dimensions were based on combined measurements of total station surveys, field mapping, and scaling of individual wood elements. Pool surface area was calculated in ArcView GIS from digitized polygons based on total station data marking the extent of pools and riffle crests.

Case Studies and Linear Correlations

Ten case studies were developed to illustrate structure or jam design and changes to jam configuration, percentage pool cover, channel morphology, bed textures, and habitat heterogeneity. Of the ten case studies, eight were complex jams and include results from total station surveying and facies mapping. Two case studies include the 1995 simple structures. These case studies include facies mapping results but do not include survey results, as these sites were not surveyed in 1995.

Linear correlations between wood loading input variables (wood piece count, total wood volume, and total wood volume per active channel width) and response variables (percentage pool cover, residual pool depth, upstream sediment aggradation, number of facies patches, habitat heterogeneity, and reach average D50) were determined based on Pearson's correlation (for alpha = 0.05 and n=10, r^2 must be greater than 0.399 to be significant).

RESULTS

Results provide detailed descriptions of the changes to percentage pool cover, residual pool depth, upstream sediment aggradation, number of facies patches, habitat heterogeneity, and reach average D50 at eight complex jams and two simple wood structures on a 3rd order stream in coastal Northern California.

Storm conditions for the first twelve months post-treatment period were characterized by two flood events that exceeded channel capacity (28 Dec 2008 and 16 March 2009) inundating the floodplains at Jams 3, 6, 9, and 10 (Figure 10). Although floodplains were inundated at these sites during both events, only the 28 Dec 2008 storm flows exceeded the 1.5-year recurrence interval, as estimated based on 78 years of peak storm data for the USGS Jedediah Smith Redwoods State Park gauging station. The 28 Dec 2008 peak flow event was the fourth largest peak flow since the simple structures were constructed in 1995 (Figure 11) and 19th largest since 1932. Both WY09 storms events were responsible for the majority of sediment routing, storage, sorting, and pool formation during the study period. The third highest runoff event occurred on 1 May 2009. Because there was no field data collected during this storm, it is unknown whether runoff exceeded channel capacity.

A tabulated summary of structure and jam design and wood elements are given in Table 2. In total, 333 wood elements or 292 m^3 of wood was used to construct eight complex wood jams and two simple structures. By influence zone, 16 m^3 (5%) of wood was placed within the wetted channel (Zone 1); 121 m^3 (42%) was placed within the

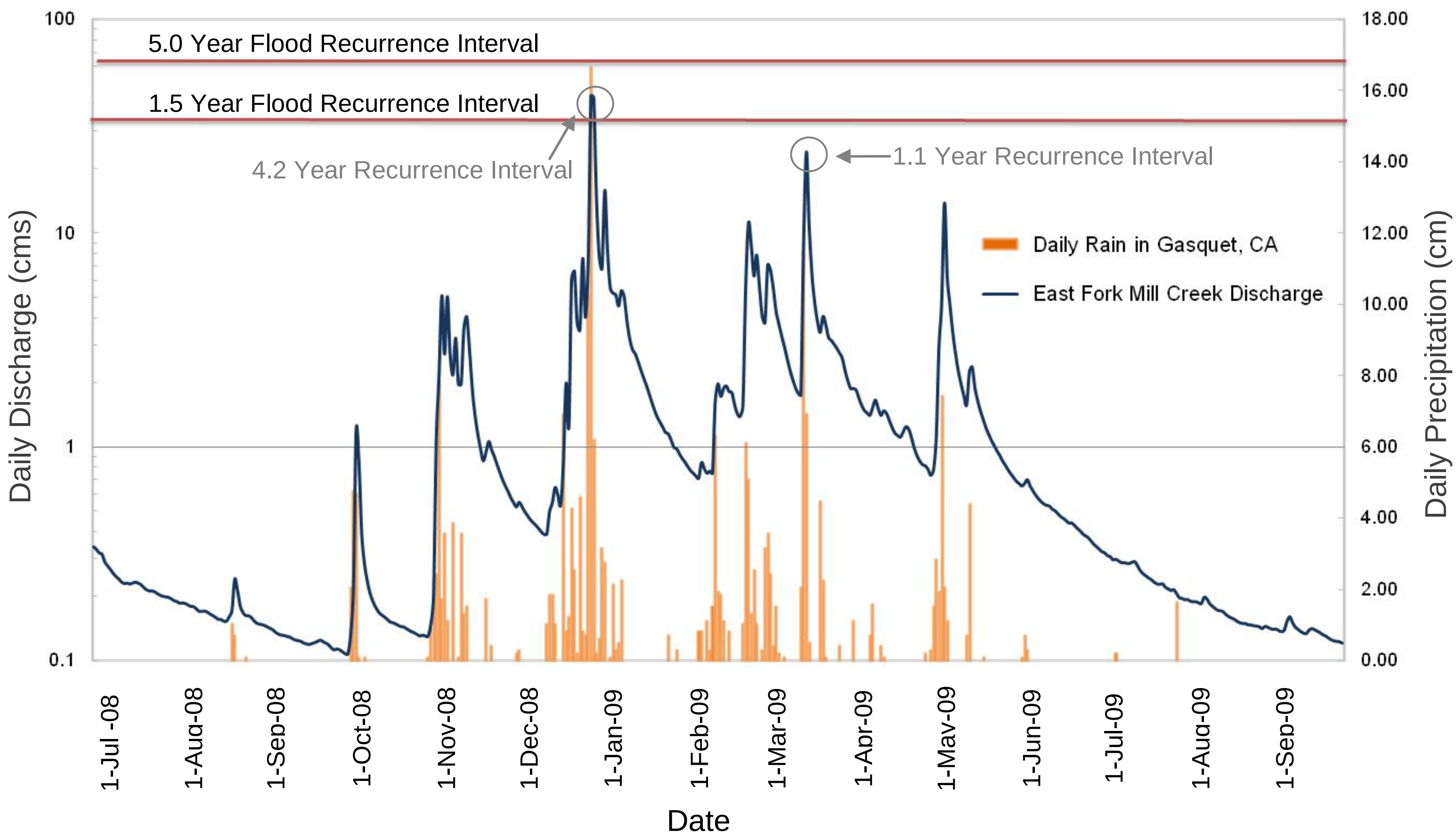

Figure 10. Daily discharge for East Fork Mill Creek, estimated as 2% of measured discharge at the Smith River's USGS Jedediah Smith Redwoods State Park gauging station and daily precipitation in Gasquet, Del Norte County, California during the study period (1 July 2008 to 30 September 2009).

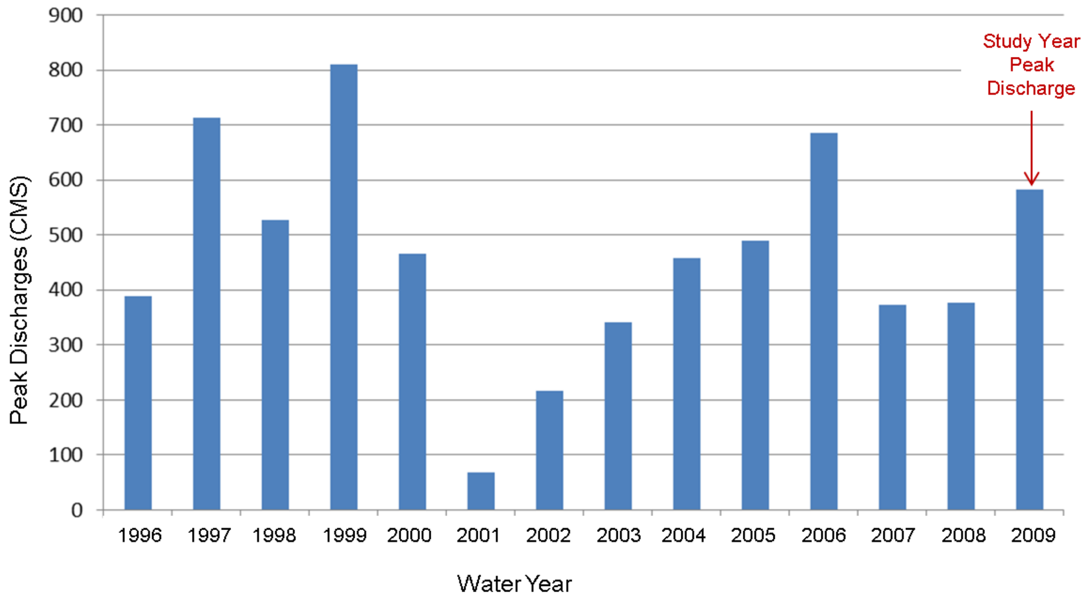

Figure 11. Peak annual discharges for East Fork Mill Creek, Del Norte County, California, estimated based on peak annual discharge at the Smith River Jedediah Smith gauging station (1996-2009). Note that the simple structures were constructed in the summer of 1995.

Table 2. Summary of feature design and wood construction material element type for ten large wood restoration sites (two simple wood structures and eight complex wood jams) within the East Fork Mill Creek, Del Norte County, California.

Site	Feature Design	Constrictor	Backwater Inducing	Floodplain Connectivity	Feature Length (m)	Wood Piece Counts						Volume Wood (m^3)	Volume Wood per Active Channel Width
						Large Wood with Root-wad	Large Wood without Root-wad	Medium Wood without Root-wad	Root-wad	Small Woody Debris	Total		
1[a]	Simple Deflector[b]				7.0		1				1	1.7	0.14
2[a]	Simple Opposing	X			7.8		2				2	6.8	0.49
3	Complex Underflow	X	X	X	18.7	12	81			4	97	37.5	3.11
4	Complex Constrictor	X	X		19.9	14	3		2		19	22.5	2.03
5	Complex Opposing	X			6.5	7	3				10	13.4	1.21
6	Complex Underflow	X	X	X	11.7		9		1		10	27.1	3.04
7	Complex Deflector	X			23.4	24	2				26	31.0	2.39
8	Complex Opposing	X	X		16.9	11	8			1	20	33.0	2.64
9	Complex Opposing	X	X	X	23.2	33	22				55	58.1	4.15
10	Complex Underflow	X	X	X	31.2	17	69	3		4	93	60.9	4.16

[a] Sites 1 and 2 are simple structures constructed by California Department of Fish and Game in 1995. In 2008, Structure 1 was incorporated into the construction of Complex Wood Jam 8; Structure 2 was incorporated into Complex Jam 9.
[b] Deflecting jams deflect flows from one bank towards the opposite bank. Opposing jams constrict flows towards the center of the channel. Underflow jams span the entire active channel width, creating high flow obstruction and local flow acceleration.

active channel (Zone 2); 32 m^3 (11%) was placed directly above the active channel (Zone 3); and 123 m^3 (42%) was placed on the floodplain (Zone 4) (Table 3).

Project Case Studies

Case Study 1

Structure 1 was constructed in 1995 by CDFG as a pitched log and boulder structure with large rock used to ballast one end to the bank and the other to large boulders installed within the active channel (Figure 3a). Large rock was additionally placed along the right-bank upstream and under the installed log for bank protection and boulders were placed within the channel to increase hydraulic complexity. Study results show an increase in facies patches from 6 to 19, resulting in an increase in habitat heterogeneity from 0.20 to 0.29. The maximum pool depth at the project site was only 4 cm. The increase in patches and the habitat heterogeneity appear to be due to the placement of large bank protection rock and the hydraulic influence of instream boulders. There appeared to be no change in facies due to the hydraulic influence of the placed wood (Figure 12).

Case Study 2

Structure 2 was constructed in 1995 by CDFG to improve stream habitat and is a double pitched log and boulder structure. Each pitched log was cabled to large instream boulders and to large rock on each bank. Large rock was additionally installed along the bank upstream and under the installed logs for bank protection. The number of

Table 3. Volume of wood placed at ten large wood restoration study sites by influence zone in East Fork Mill Creek, Del Norte County, California.

Study Site	Zone[a]	Large Wood with Rootwads (m^3)	Large Wood without Rootwad	Medium Wood without Rootwad	Rootwad	Small Woody Debris	Total Wood
1	1		0.5				0.5
	2		0.8				0.8
	3		0.2				0.2
	4		0.1				0.1
	Total		1.7				1.7
2	1		1.1				1.1
	2		2.7				2.7
	3		0.0				0.0
	4		3.0				3.0
	Total		6.8				6.8
3	1	0.5	0.2			0.0	0.7
	2	4.9	16.8			5.0	26.6
	3	3.1	0.3			0.0	3.4
	4	4.6	2.3			0.0	6.9
	Total	13.1	19.5			5.0	37.5
4	1	0.7	0.0		0.0		0.7
	2	7.3	1.0		0.7		8.9
	3	2.2	0.0		0.0		2.2
	4	9.5	1.1		0.0		10.6
	Total	19.7	2.1		0.7		22.5
5	1	0.7	0.0				0.7
	2	2.5	0.0				2.5
	3	0.6	0.2				0.8
	4	6.5	3.0				9.4
	Total	10.2	3.2				13.4

[a] Zone 1 is within low flow wetted channel; Zone 2 is within the active, or bankfull, channel; Zone 3 is above the active channel; Zone 4 is outside of the active channel, on the floodplain.

Table 3. Volume of wood placed at ten large wood restoration study sites by influence zone in East Fork Mill Creek, Del Norte County, California (continued).

Study Site	Zone[a]	Large Wood with Rootwads (m^3)	Large Wood without Rootwad	Medium Wood without Rootwad	Rootwad	Small Woody Debris	Total Wood
6	1		0.3		2.4		2.7
	2		4.2		4.6		8.8
	3		3.7		0.0		3.7
	4		11.9		0.0		11.9
	Total		20.2		7.0		27.1
7	1	3.2	0.0				3.2
	2	9.3	0.6				9.9
	3	2.9	0.0				2.9
	4	15.0	0.0				15.0
	Total	30.4	0.6				31.0
8	1	0.4	0.6			0.0	1.0
	2	1.9	2.2			5.2	9.4
	3	3.9	1.3			0.0	5.2
	4	9.4	8.1			0.0	17.5
	Total	15.6	12.2			5.2	33.0
9	1	2.8	1.1				3.9
	2	10.1	6.0				16.1
	3	5.6	0.9				6.5
	4	16.6	15.0				31.6
	Total	35.0	23.0				58.1
10	1	0.8	0.4	0.0		0.0	1.2
	2	5.2	18.0	0.1		12.3	35.6
	3	6.1	0.7	0.0		0.0	6.9
	4	15.0	2.2	0.0		0.0	17.2
	Total	27.1	21.4	0.1		12.3	60.9

[a] Zone 1 is within low flow wetted channel; Zone 2 is within the active, or bankfull, channel; Zone 3 is above the active channel; Zone 4 is outside of the active channel, on the floodplain. Table 3 (continued).

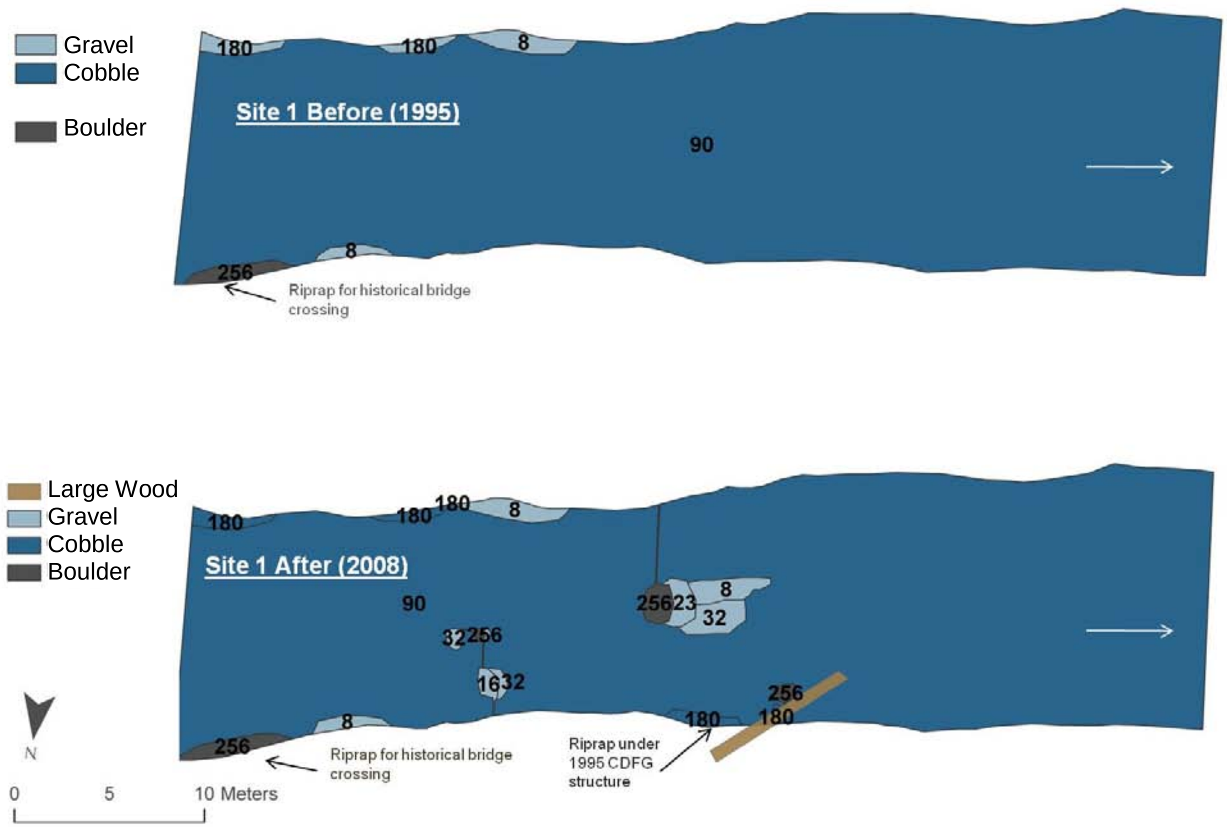

Figure 12. Structure 1 is a simple deflector structure constructed in 1995 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood structure maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.20 to 0.29 and residual pool depth increased from 0.13 to 0.17 m.

facies patches increased from 6 to 8, resulting in an increase in the habitat heterogeneity from 0.20 to 0.45. Increases in number of patches and the habitat heterogeneity appear to be due to the placement of large rock for bank protection and the right-bank structure that created a right-bank eddy, forming a gravel bar with a D50 of 23 mm (Figure 13). The right-bank structure created a 0.64 m deep pool.

Case Study 3

Jam 3 is a complex channel-spanning underflow jam constructed during the summer of 2008 to increase hydraulic complexity, create pool, foraging, resting, and cover habitat for salmon, to trap and sort sediments, and to increase floodplain connectivity (Figures 14-15). Of the ten restoration features, Jam 3 ranks first for number of wood elements used during construction and volume of wood per channel area. It ranks third overall for total volume of wood and volume of wood per active channel width. Jam 3 accumulated additional wood elements during WY09 and remained stable through winter storm flows (Figure 15).

The jam's horizontal and vertical obstruction forced flow downwards towards the bed, creating a powerful hydraulic jet that created the second deepest pool of the study (1.54 m) (Figure 16, longitudinal profile and cross-section 12). The jam's 10 pitched large wood with rootwad elements interacted with flows to create complex hydraulics with multiple flow strands. The resulting scour and eddy current formed a complex topography with small pools and depositional features along the channel margin. Scoured material was transported downstream, to form a complementary

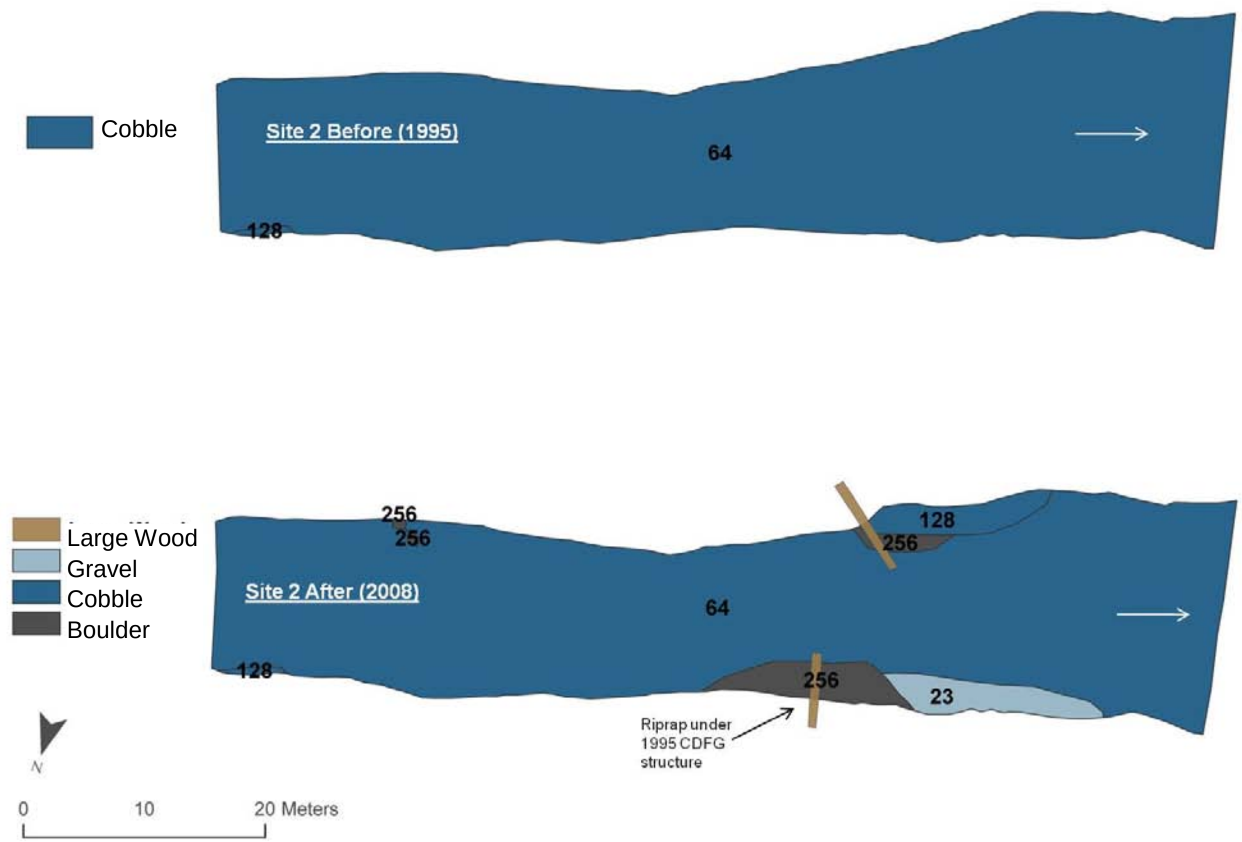

Figure 13. Structure 2 is a simple deflector structure constructed in 1995 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood structure maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.20 to 0.45. Residual pool depth increased from 0.13 to 0.64 m.

Summer low flow 1 August 2008

Spring high flow event 16 March 2009

Figure 14. Post construction photos of complex wood jam 2 during low flow and storm conditions in East Fork Mill Creek, Del Norte County, California. Flow is from left to right. White arrows are pointing towards common reference alder tree. Photos by Thomas Dunklin, Thomas B. Dunklin Photography, and Videography.

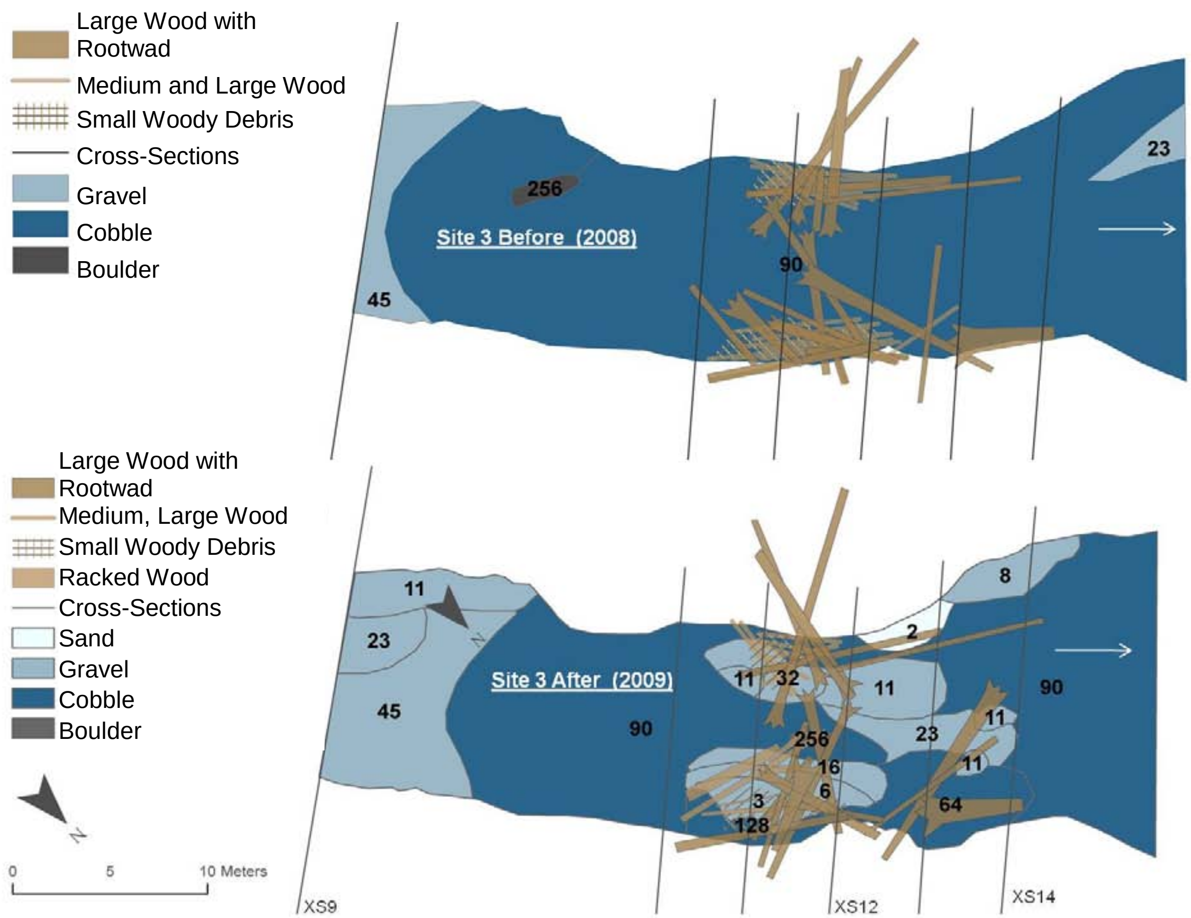

Figure 15. Jam 3 is a complex channel-spanning underflow jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. The habitat heterogeneity (Shannon's Diversity Index) increased from 0.31 to 1.61. Residual pool depth increased from 0.10 to 1.54 m.

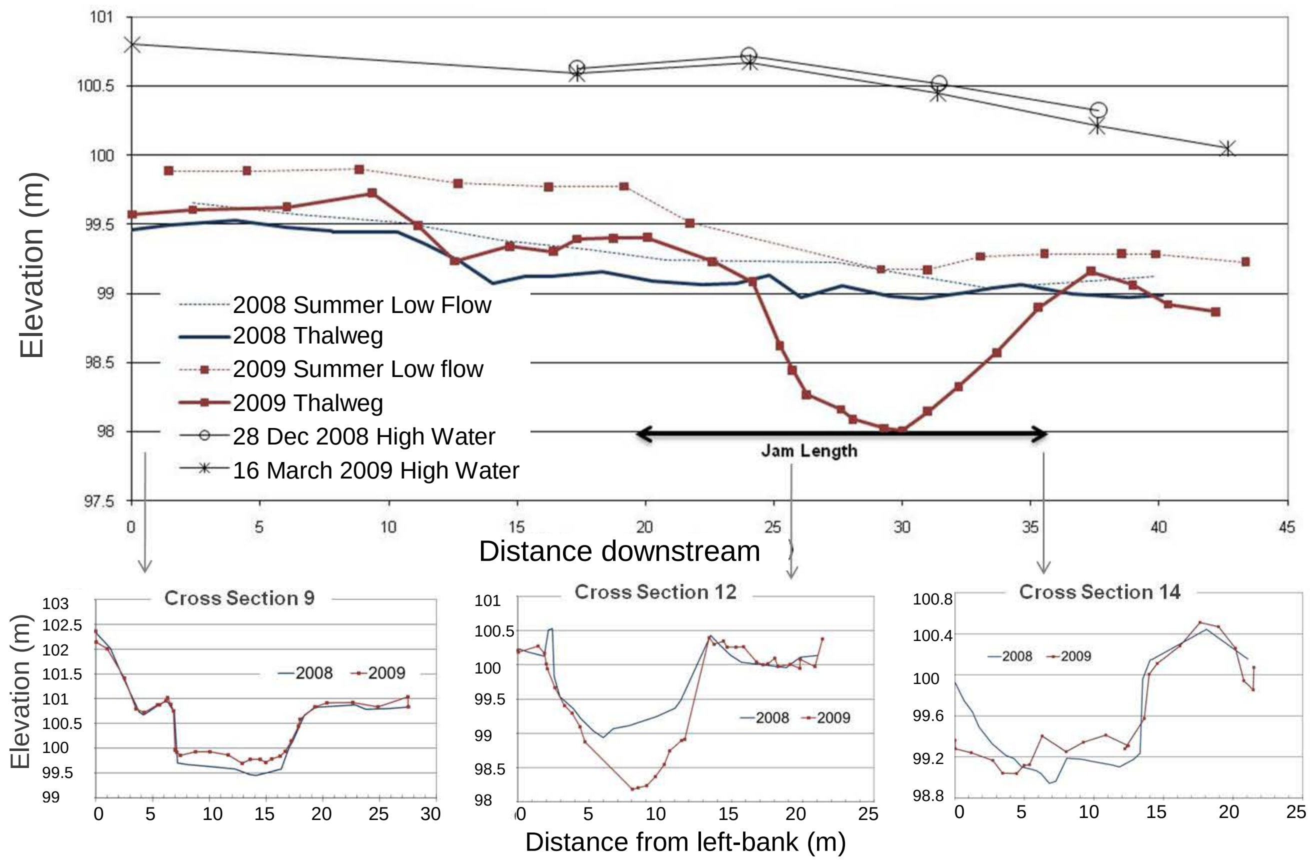

Figure 16. Jam 3 is a complex channel-spanning underflow jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation, and bar formation, bank erosion, floodplain side channel development, high water slopes, and low water levels and slopes.

gravel bar.

The upstream backwater caused by the jam induced channel aggradation (Figure 16, longitudinal profile and cross-section 9). Flows upstream of the jam were forced towards the left and right-banks. Flows directed towards the right-bank inundated the floodplain and scoured side-channels that that reconnected to the primary channel downstream of the jam (Figure 14). Downstream of the jam, flows directed towards the left-bank resulted in localized channel bank erosion and an overall channel width increase (Figure 16, cross-section 14). The number of sediment facies patches increased from 4 to 19 and habitat heterogeneity increased from 0.31 to 1.61 (Figure 14). Reach average D50 decreased from 88 to 65 mm.

<u>Case Study 4</u>

Jam 4 is a complex deflecting jam constructed to increase hydraulic complexity, create pool, foraging, resting, and cover habitat for salmon, and to trap and sort sediments. During the 28 December 2008 storm, the right-bank portion of the jam shifted downstream as there were few supporting riparian alders to resist the increased hydraulic forces. The resulting configuration remained stable for the remaining study season and accumulated additional medium and small woody debris (Figure 17).

The resulting configuration created an upstream backwater, resulting in the third greatest gravel aggradation and the formation of a large bar within the footprint of the jam (Figure 18, longitudinal profile, cross-sections 21 and 24). The reach average D50 decreased from 65 to 42 mm and the decrease in reach average D50 changed the overall

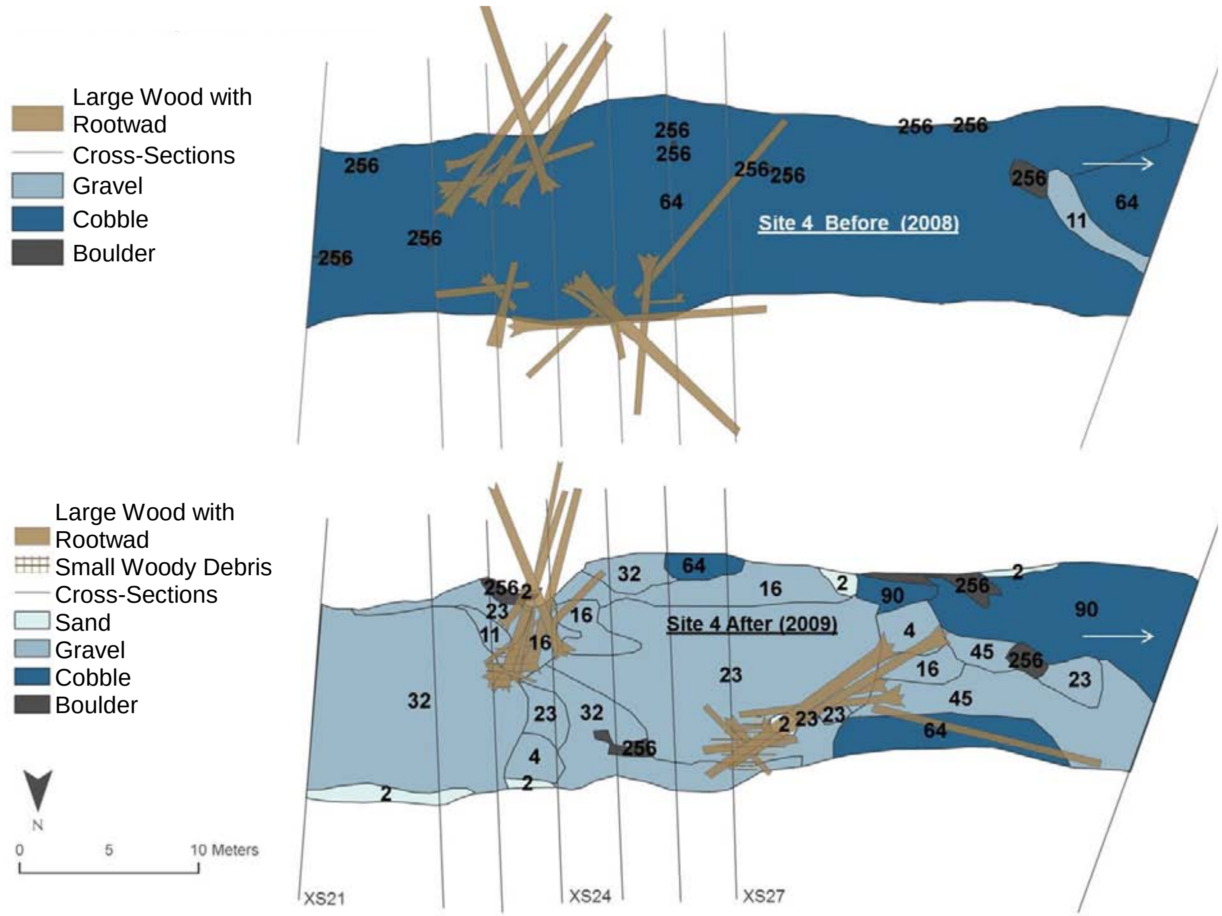

Figure 17. Jam 4 is a complex deflecting jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.15 to 1.89 and residual pool depth increased from 0.09 to 0.45m.

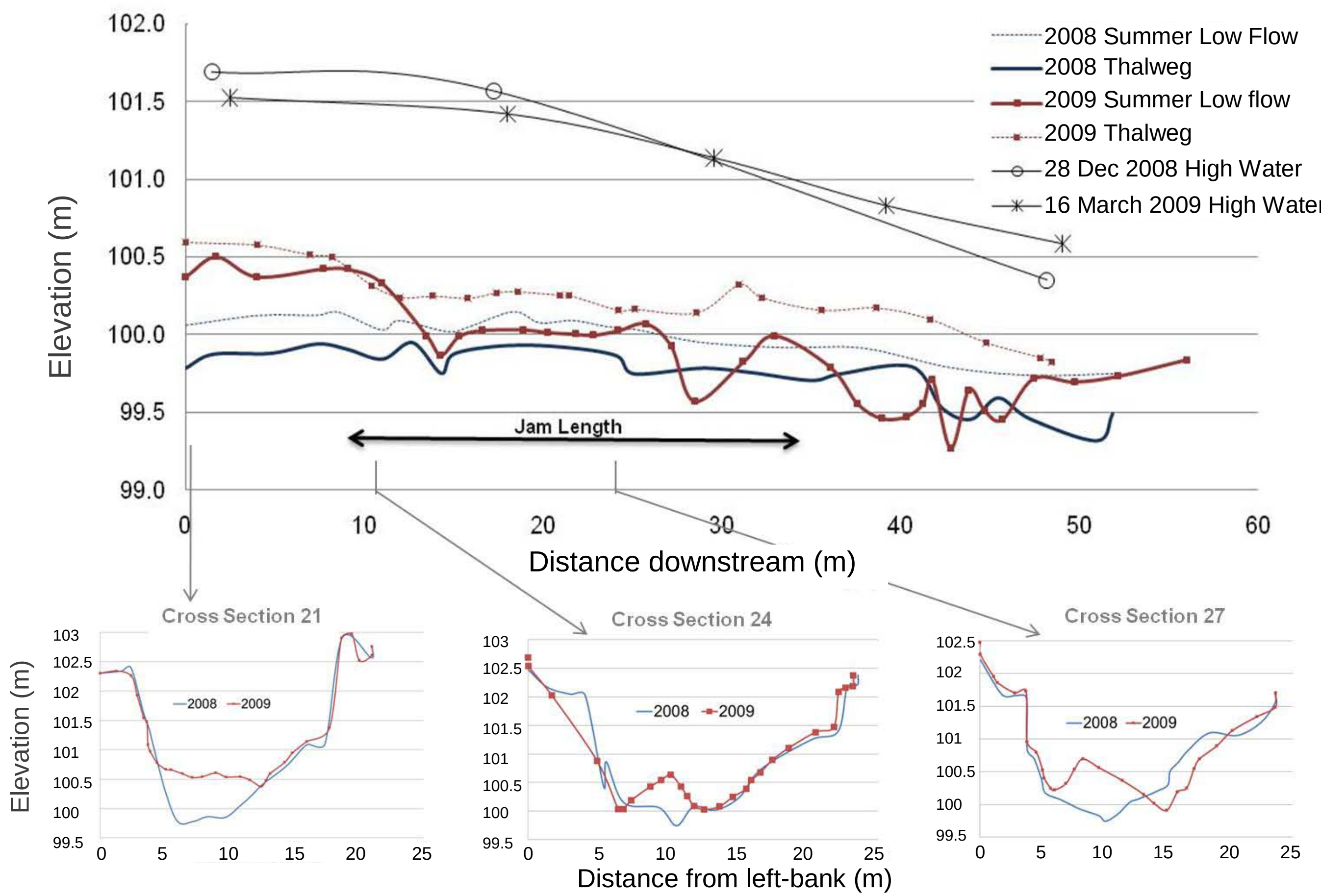

Figure 18. Jam 4 is a complex deflector jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating aggradation and bar formation, pool formation, bank erosion, high water slopes, and low water levels and slopes.

reach sediment makeup from cobble to gravel (Figure 17). Habitat heterogeneity increased from 0.15 to 1.89 and the number of sediment facies patches increased from 11 to 32). The bed was scoured to form a 0.45 m deep pool.

Case Study 5

Jam 5 was constructed as a complex opposing jam. During the 28 December 2008 storm, flows flanked the right-bank of the jam, toppling support alders, converting the right-bank jam to a midchannel island and bar apex jam. The resulting formation, split flows around the jam (Figure 19). The resulting jam moved slightly downstream and increased in length to become a 12.2 m channel-spanning underflow jam. At higher flows, the logs on the right-bank created an underflow jam across a portion of the flows. This horizontal obstruction forced higher flows downwards towards the bed, creating a hydraulic jet that resulted in the formation of a 0.48 m deep residual pool (Figure 20, cross-section 34). The scoured material formed a complementary downstream gravel bar (Figure 20, longitudinal profile and cross-section 34). Jam 5 also forced flows towards the right and left-banks, creating the greatest amount of bank erosion of the study (Figure 20, cross-sections 32).

The reduction in flow velocity upstream of jam caused a local reduction in velocity and shear stress resulting in gravel aggradation of 0.18 m (Figure 20, cross-section 30 for upstream aggradation and cross-section 34 for bar formation). Habitat heterogeneity increased from 0.36 to 1.50 and the number of sediment facies patches increased from 5 to 15. Reach average D50 decreased from 58 to 45 mm.

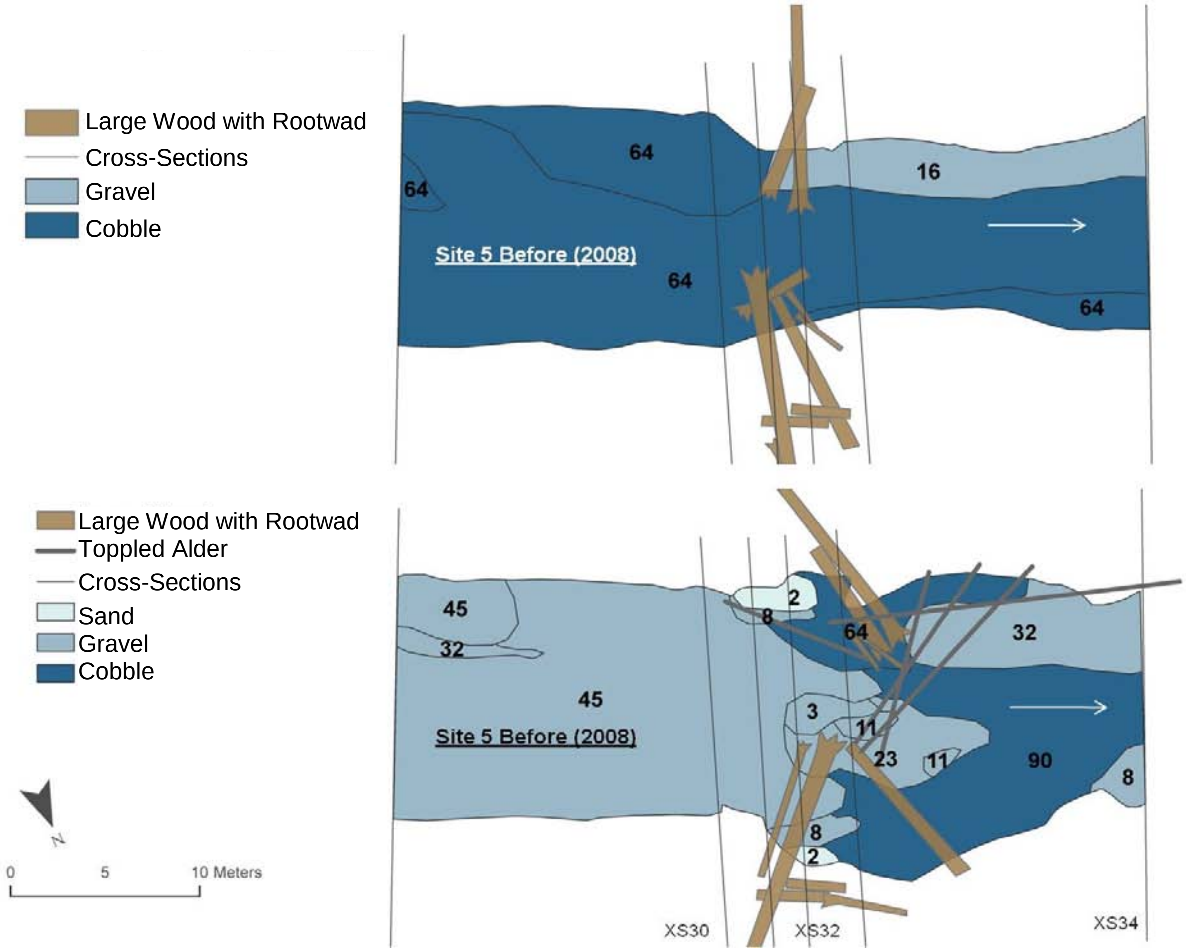

Figure 19. Jam 5 was constructed as a complex opposing jam in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.36 to 0.1.5 and residual pool depth increased from 0.07 to 0.48 m.

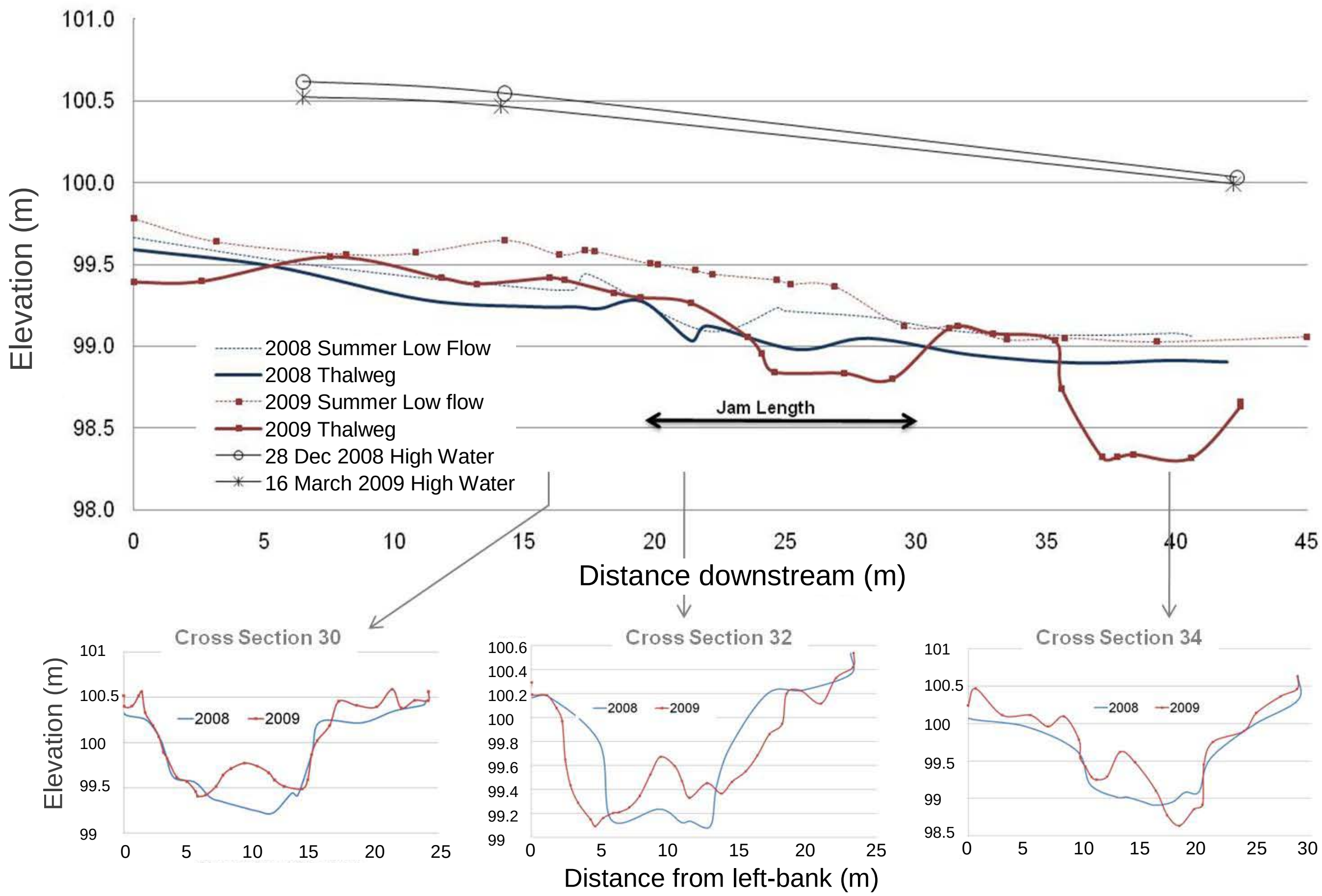

Figure 20. Jam 5 was constructed as a complex opposing jam in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation, bank erosion, bar formation, and high and low water levels and slopes.

Case Study 6

Jam 6 is a complex channel-spanning underflow jam, constructed to increase hydraulic complexity, create pool, foraging, resting, and cover habitat for salmon, to trap and sort sediments, and increase floodplain connectivity (Figures 21-22). Of the 10 features, Jam 6 was the only jam constructed with old-growth redwood. It was constructed with nine large old-growth stems without rootwads and one very large rootwad. These elements were found on a historical logging access road near the site. Jam 6 remained stable throughout the study period (Figure 22).

The jam's horizontal obstruction directed flow downwards towards the bed, creating a powerful hydraulic jet that created a 0.66 m deep pool (Figure 23, longitudinal profile, cross-sections 37 and 38). The jam's pitched logs adverted flows in a multitude of directions, creating scour and eddy pools adjacent to the underscour pool and forcing flows downstream of the jam towards the right-bank, resulting in localized erosion and an overall channel width increase (Figure 23, cross-sections 37 and 38).

The reduction in flow velocity upstream of the jam created an upstream mid-channel gravel bar with aggradation depth of 0.18 m (Figure 23, longitudinal profile and cross-section 35). This backwater forced water onto the right-bank floodplain scouring out significant side-channels that reconnected to the primary channel downstream of the jam (Figure 23, cross-section 37). Habitat heterogeneity increased from 0.04 to 1.11 and the number of sediment facies patches increased from 10 to 16. Reach average D50 decreased from 91 to 71 mm.

Figure 21. Post construction photos of Complex Wood Jam 6 during low flow condition and during storm flows in East Fork Mill Creek, Del Norte County, California. Photos are taken looking upstream and white arrows are pointing towards large rootwad as a common reference point.

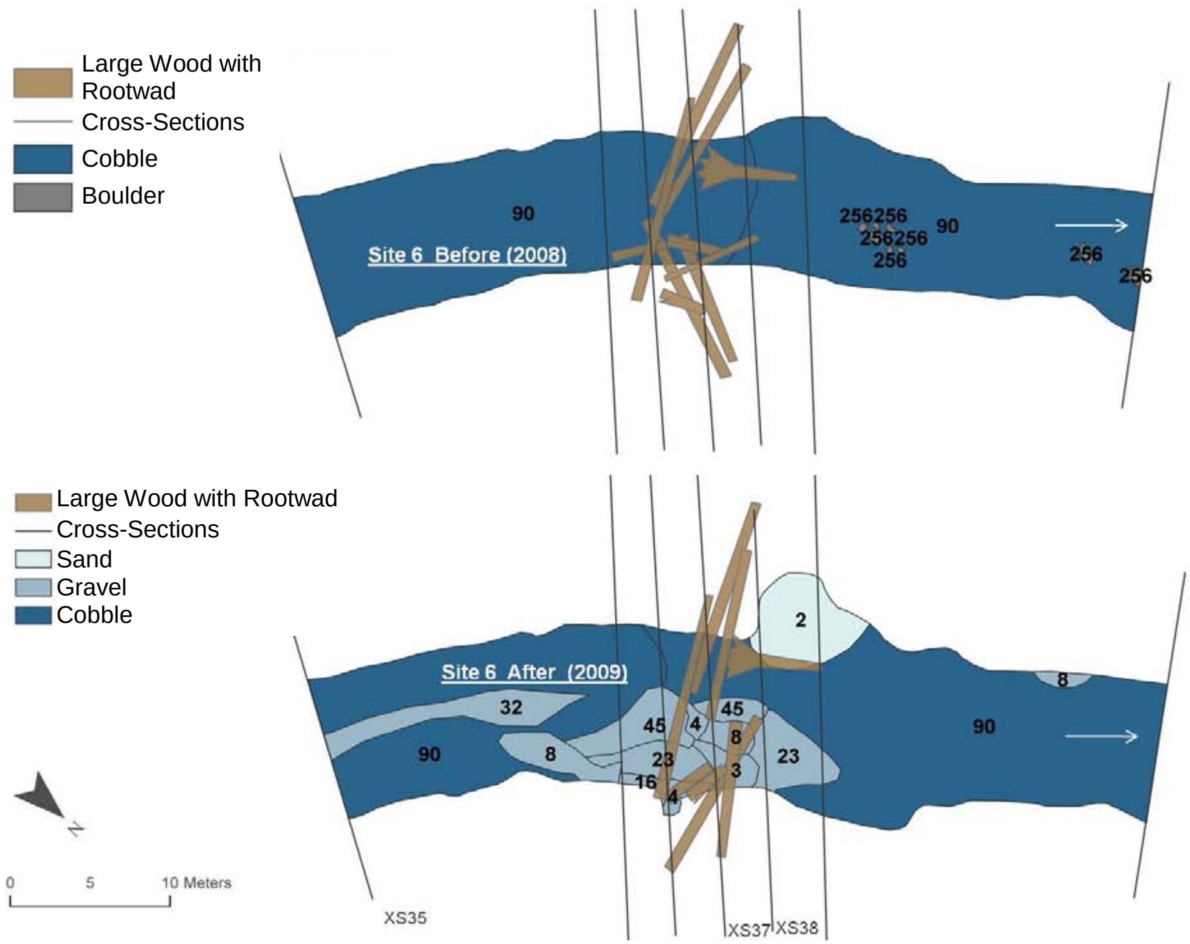

Figure 22. Jam 6 is a complex channel-spanning underflow jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.04 to 1.11 and residual pool depth increased from 0.29 to 0.66 m.

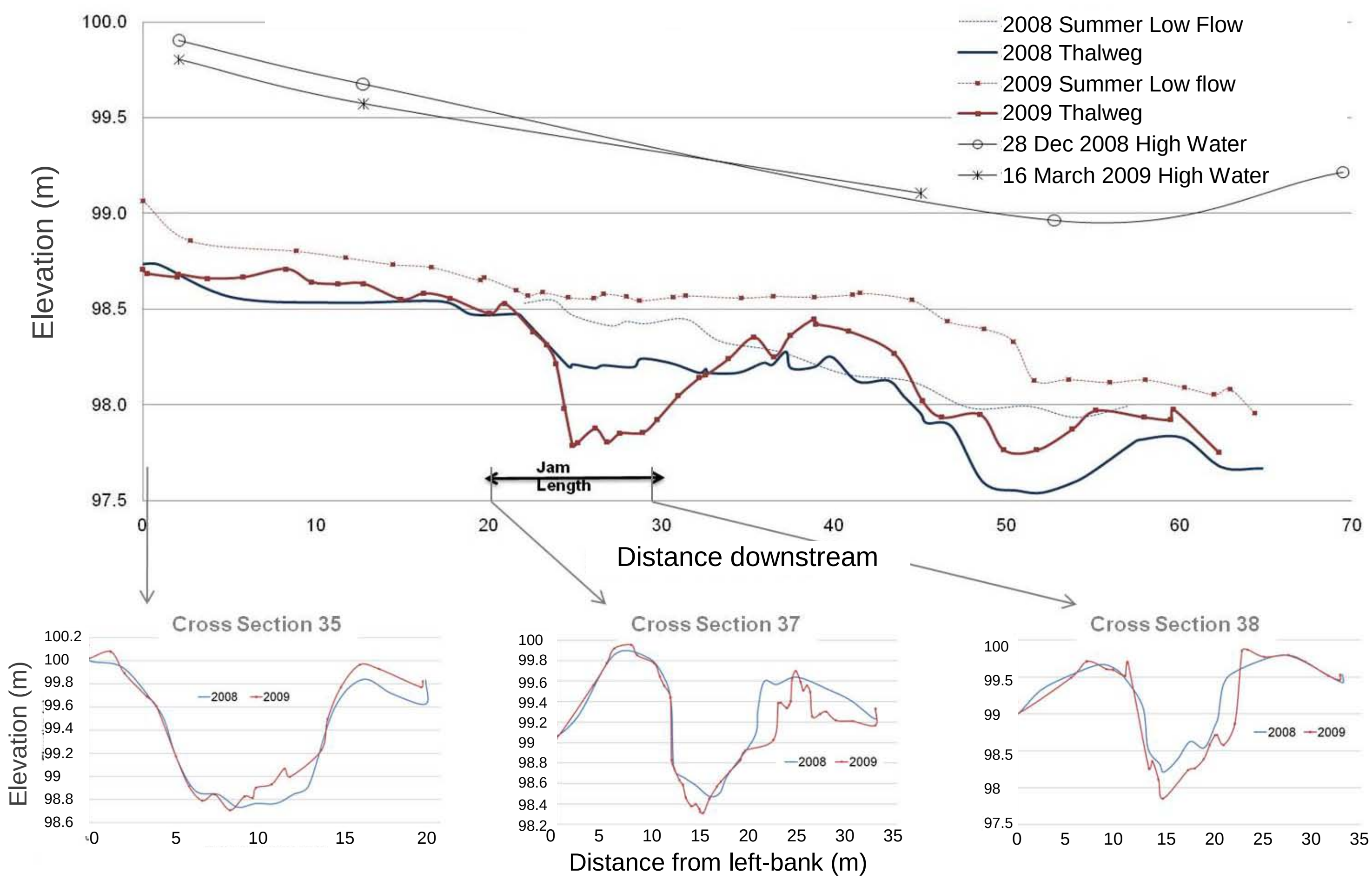

Figure 23. Jam 6 is a complex channel-spanning underflow jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation and bar formation, bank erosion, floodplain side channel development, high water slopes, and low water levels and slopes.

Case Study 7

Jam 7 is a complex deflector jam constructed during summer of 2008 to increase hydraulic complexity and to create pool, foraging, resting, and cover habitat for salmon. Jam 7 remained stable through winter storm flows (Figure 24). The jam's configuration forced flows from the left-bank towards the center-right of the channel and along the right-bank row of pitched large wood with rootwad, creating a long and adjacent pool (Figure 25, longitudinal profile, cross-sections 95, 97, and 98). Jam 7 ranked third for residual pool depth as the channel scoured through coarse cobble to form a 0.94 m deep pool (Figure 25, longitudinal profile, cross-sections 95, 97, and 98).

Habitat heterogeneity increased from 0.12 to 2.05 and the number of sediment facies patches increased from 2 to 24. Jam 7 was the only jam that resulted in an increased (coarsened) reach average D50. The reach average D50 increased from 44 to 56 mm as in-situ material was exposed by channel scour.

Case Study 8

Jam 8 was constructed in 2008 to incorporate the CDFG 1995 wood and boulder structure in order to increase hydraulic complexity and to create pool, foraging, resting, and cover habitat for salmon. During 28 December 2008 flows, mobile wood that was placed approximately 0.5 km upstream of Jam 8, as part of a wood experiment to test the mobility of instream unanchored wood, mobilized and became suspended in the high flows. Storm surges and the suspended wood elements moved through Jams 8 and 9 and all mobile wood accumulated on the upstream face of Jam 10. Although the movement

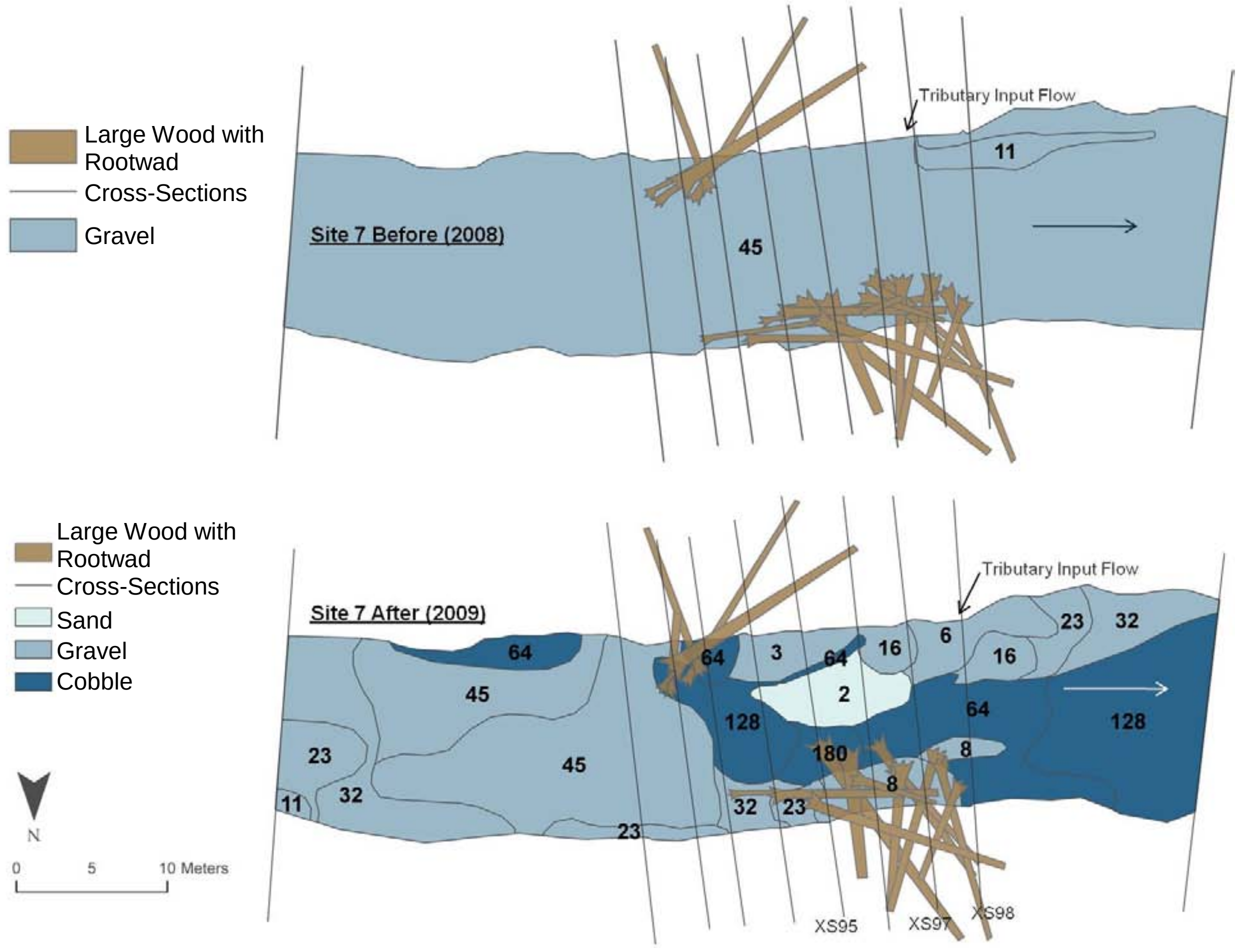

Figure 24. Jam 7 is a complex deflecting jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.12 to 2.05 and residual pool depth increased from 0.12 to 0.94m.

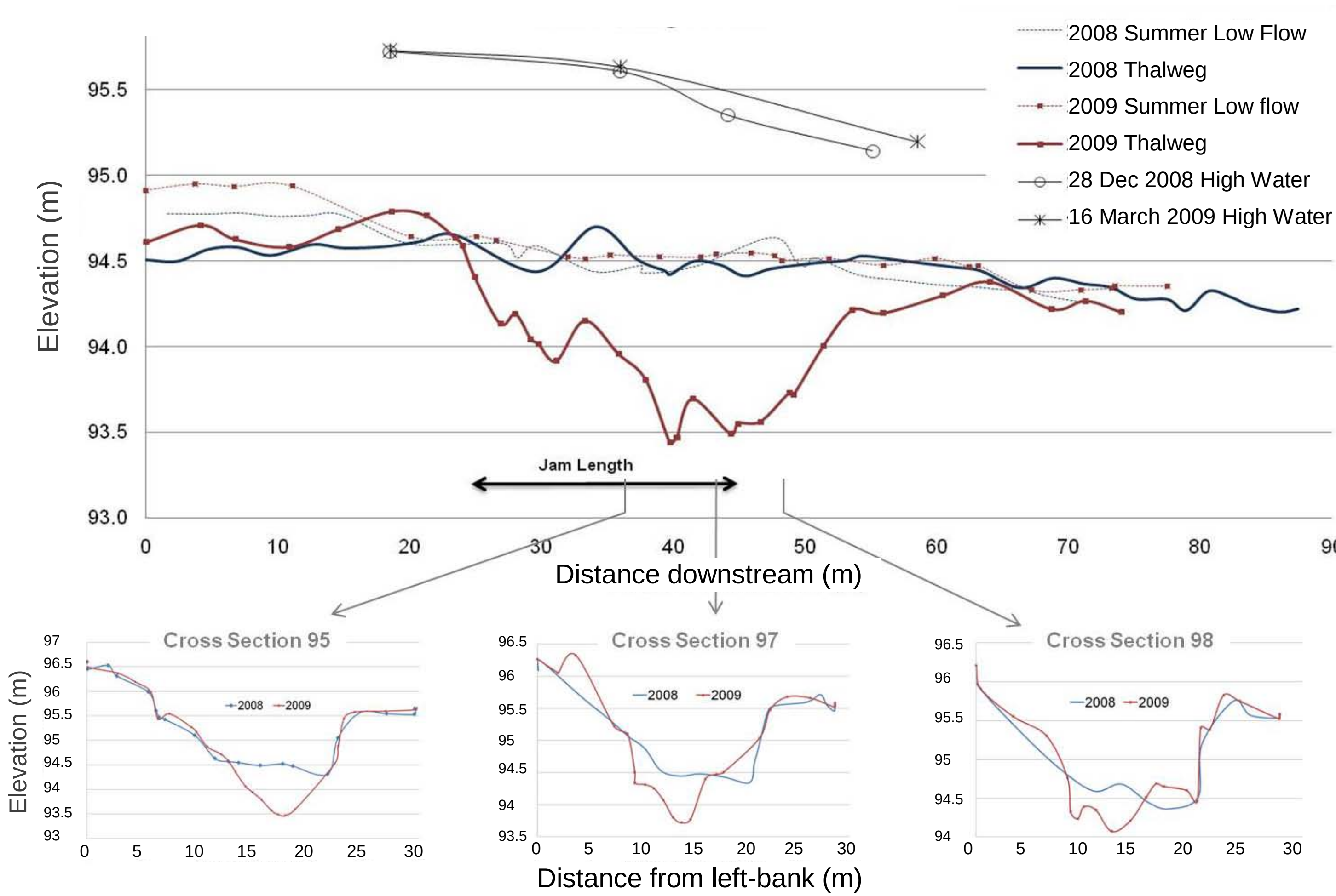

Figure 25. Jam 7 is a complex deflector jam constructed in 2008 on East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation and bar formation, and low and high water levels and slopes.

of the mobile wood was not monitored as a part of this study, the strong flows coupled with the mobile wood broke through the jam and changed the configuration of the jam from being pitched upstream to a configuration with logs pitched downstream (rootwads pointing downstream) (Figure 26). Another consideration for the change in configuration at Site 8 is that it is the only project site with no floodplain hydraulic connectivity to ease the in channel hydraulic forces. Historical channel straightening and realignment from its original location to pass through a downstream bridge are responsible for the lack of floodplain connectivity.

The resulting jam configuration eased the constriction of flow from the original configuration. The jam’s pitched logs channeled flows to the center of channel resulting in a 0.29 m deep pool (Figure 27, longitudinal profile). A downstream gravel bar was formed (Figure 27, cross-section 56). Note that the 1995 structure included the placement of a very large boulder (0.75 m in diameter) in the center of the channel. The dramatic changes to cross-section 53 are due to the downstream movement of this boulder (Figure 27, cross-section 53). It appears that there was a reduction in flow velocity upstream of the jam as there was 0.50 m deep of gravel aggradation upstream, forming a midchannel bar (Figure 27, longitudinal profile and cross-section 52). Jam 8 ranked second for the increase in number of sediment facies patches (19 to 49) and habitat heterogeneity increased from 0.29 to 2.05. The reach average D50 decreased from 91 to 79 mm.

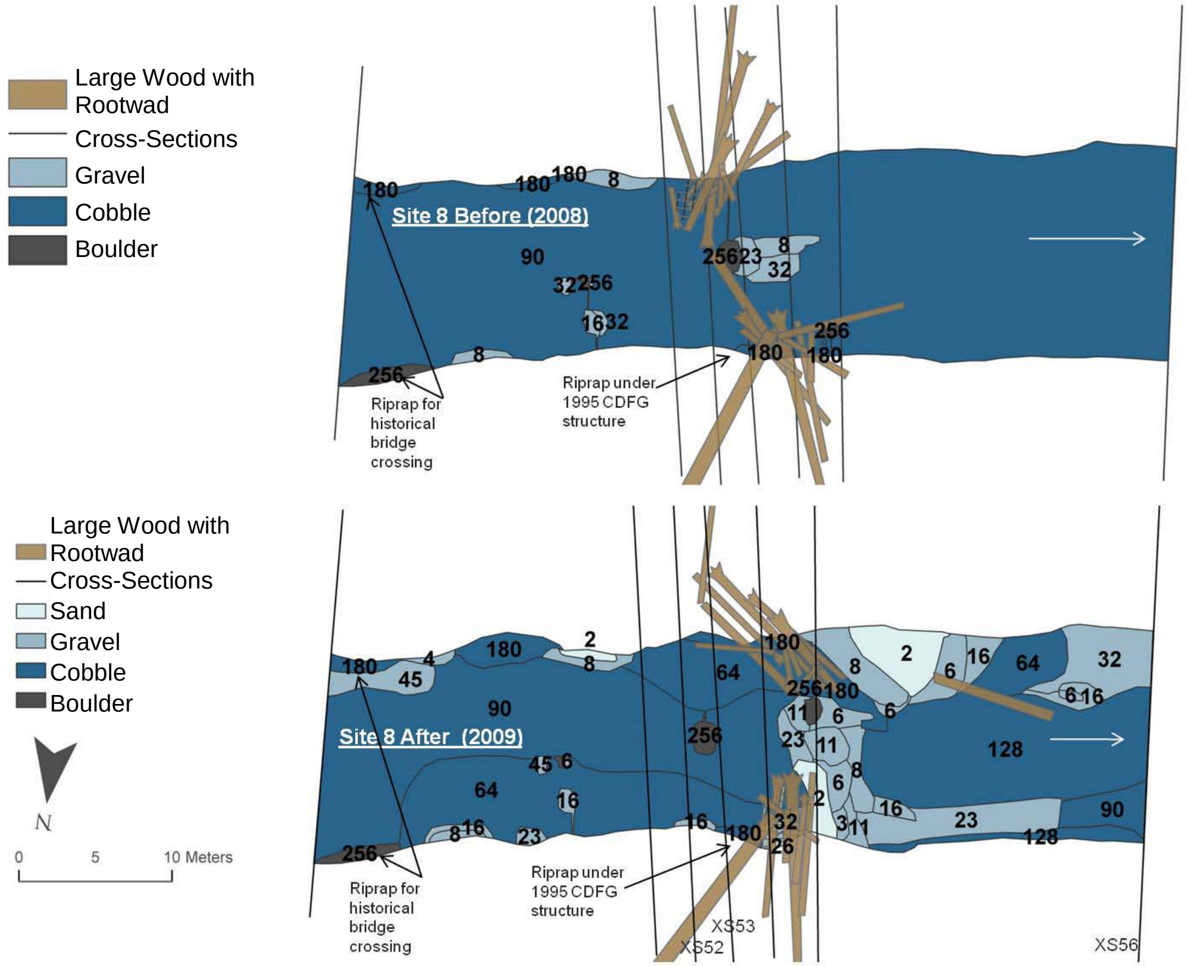

Figure 26. Jam 8 is a complex opposing jam constructed in 2008 on East Fork Mill Creek, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.29 to 2.05 and residual pool depth increased from 0.17 to 0.29 m.

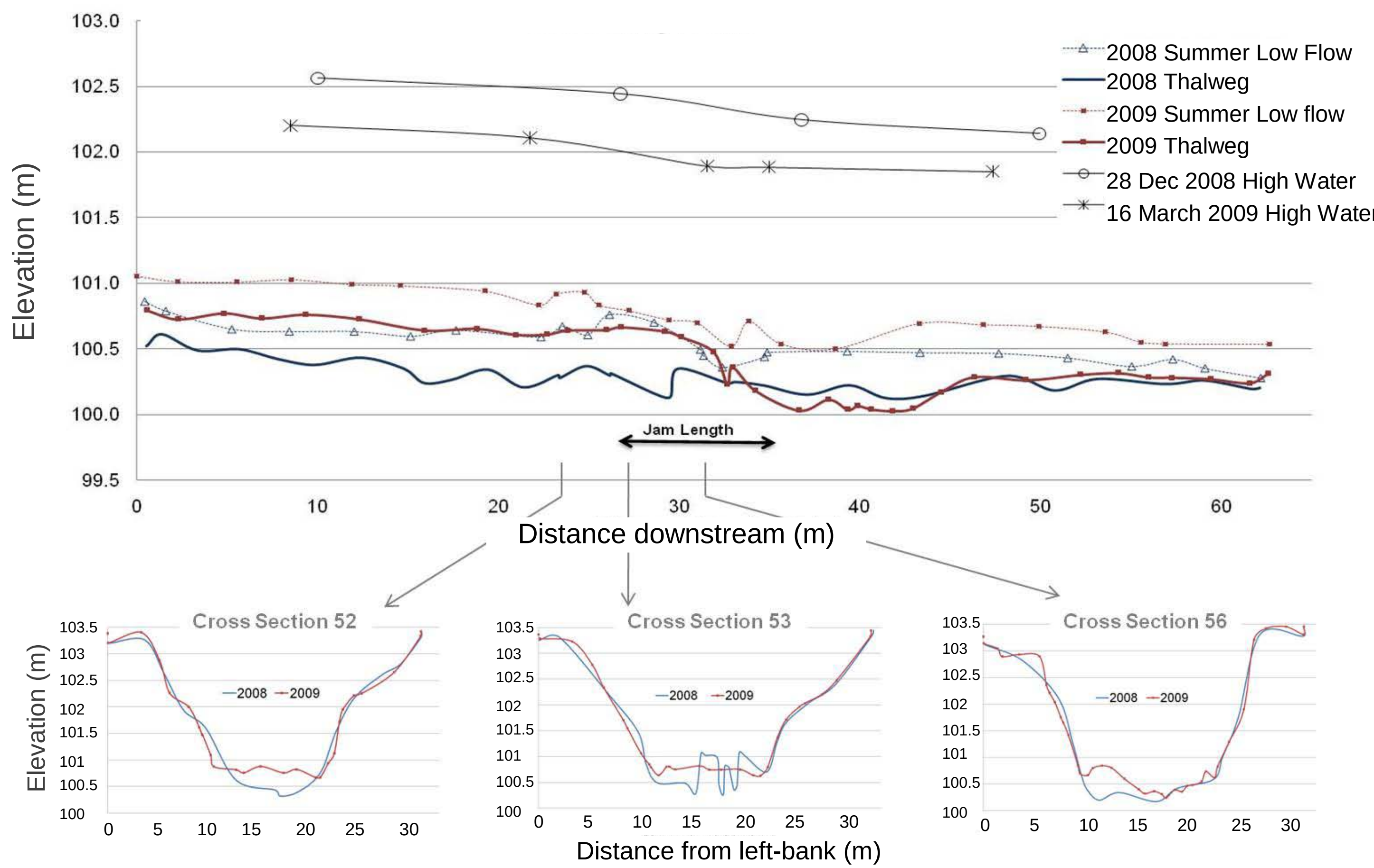

Figure 27. Jam 8 is a complex opposing jam constructed in within East Fork Mill Creek. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation and bar formation, and low and high water levels and slopes.

Case Study 9

Jam 9 is a complex opposing wood jam built to incorporate a 1995 CDFG wood and boulder structure in order to increase hydraulic complexity, create pool, foraging, resting, and cover salmon habitat, to trap and sort sediments, and increase floodplain connectivity. Jam 9 ranked second of all jams for the volume of wood per active channel width. Construction included the use of anchoring hardware to increase jam stability and decrease the likelihood that jam elements would move downstream towards the bridge crossing. Hardware was specifically used on a portion of the right-bank jam to tie individual large wood with rootwad elements together. During an early storm, a large alder that was not part of the upstream mobile wood experiment, racked at the center of the jam altering the geometry of the jam and creating a channel-spanning underflow jam (Figures 28-29). This formation remained stable throughout the study period.

The jam's horizontal and vertical obstruction forced flow downwards towards the bed, creating a turbulent hydraulic jet that formed the deepest pool of all the jams (1.82 m) (Figure 30, longitudinal profile and cross-section 69). The scoured material was moved downstream, to form a large downstream gravel bar (Figure 30, longitudinal profile and cross-section 70). The horizontal obstruction created an upstream backwater that resulted in the second most significant upstream aggradation of the study (0.59 m) and the formation of an upstream gravel bar (Figure 30, longitudinal profile and cross-section 60). The backwater flow forced water onto the left-bank floodplain scouring significant side-channels that reconnected to the primary channel downstream of the jam (Figure 30, cross-section 69). In addition, the significant aggradation upstream and.

Figure 28. Photos of Jam 9 during low flow and high flow storm events in East Fork Mill Creek, Del Norte County, California. Photo taken from right-bank looking towards left-bank and flow is from left to right. White arrows are pointing towards a large wood element on the floodplain as a common reference point. Note extensive left-bank floodplain inundation in 16 March 2009 photo. Photos by Thomas Dunklin, Thomas B. Dunklin Photography and Videography.

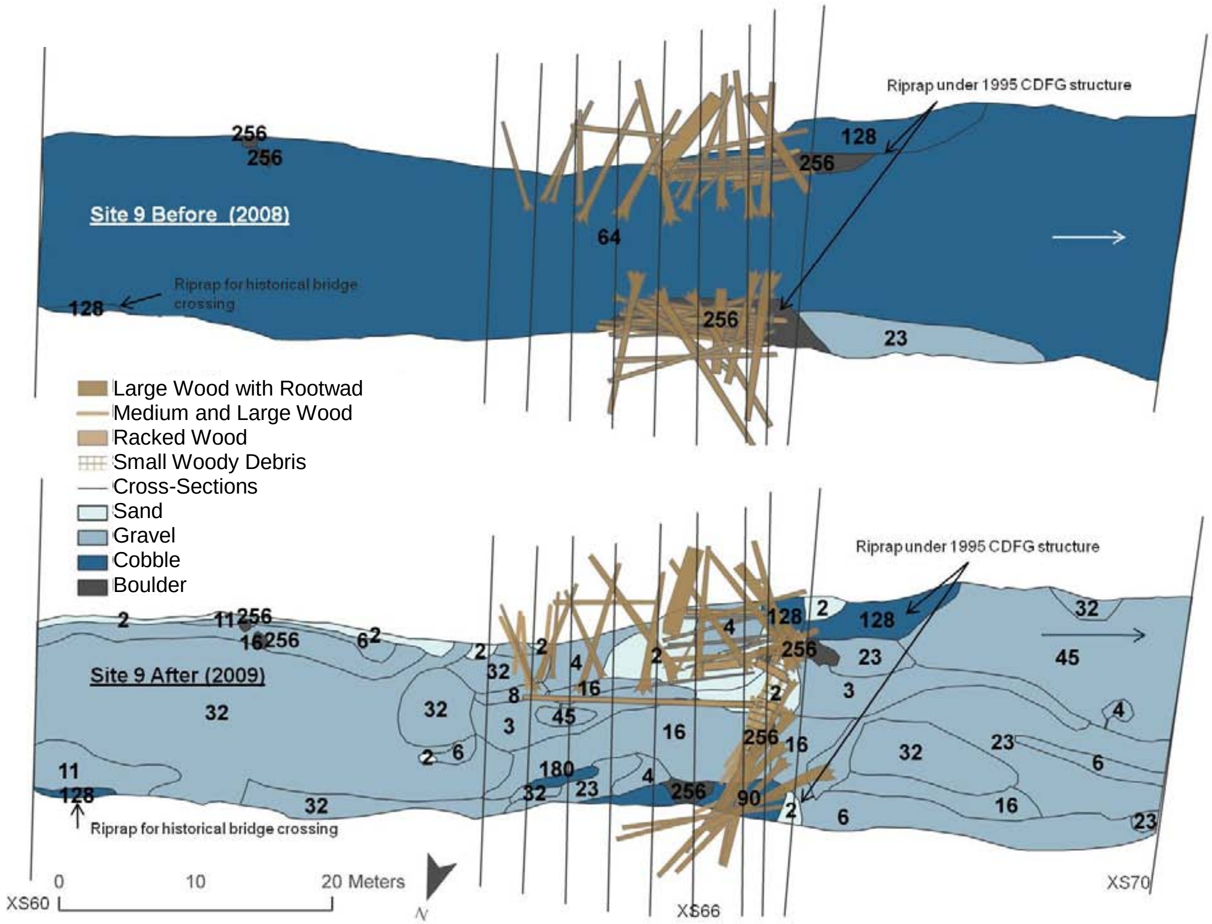

Figure 29. Jam 9 is a complex opposing jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. The D50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 0.45 to 2.12 and residual pool depth increased from 0.64 to 1.82m.

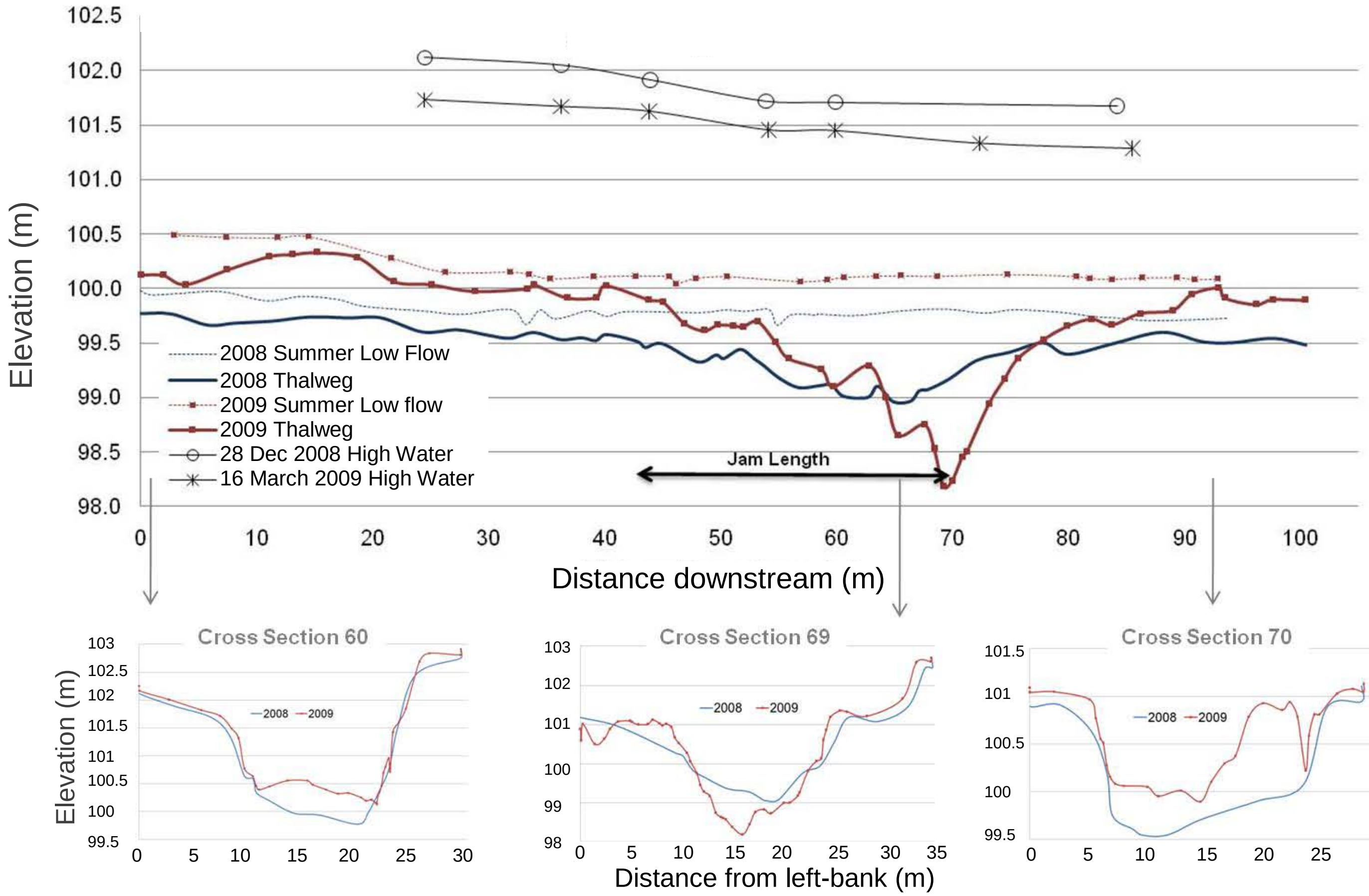

Figure 30. Jam 9 is a complex opposing jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation and bar formation, low and high water levels and slopes and floodplain channel development.

downstream at Jam 9 is in response to both the backwater created by Jam 9 and downstream at Jam 10 (Figure 4). Note that Jam 9 is located 45 m upstream of a bridge that constricts water flows to the active channel. Jam 10 is located 52 m downstream of the bridge and is a channel-spanning underflow jam that blocked an estimated 80-90% of the active channel and created a significant backwater. Jam 10 created an upstream backwater that forced flows onto both floodplains and the effects extended upstream, under the bridge and to Jam 9, potentially creating the conditions necessary for the extensive aggradation.

Jam 9 ranked highest for the number of facies patches (52) and second overall for habitat heterogeneity (increased from 0.45 to 2.12) due to the strong spatial variation in flows throughout the reach (Figure 29). The reach average D50 decreased from 73 to 31 mm, which is the lowest reach average D50 of all the study sites. The only portions of the reach that did not have a decrease in D50 were the large rock patches associated with the CDFG simple log structures. This significant reduction to grain size is likely due to the impact from hydraulic backwater influence of Jam 10 and the bridge located between Jams 9 and 10.

Case Study 10

Jam 10 is a complex channel-spanning underflow jam that was constructed to increase hydraulic complexity, create pool, foraging, resting, and cover salmon habitat, to trap and sort sediments, and increase floodplain connectivity. Jam 10 ranked first for total wood volume and volume of wood per active channel width and ranked second overall for total wood piece count. Throughout the study period, the jam remained stable and accumulated hundreds of large, medium, and small logs, rootwads, and branches within the constructed jam skeleton. With the accumulation of wood, the jam evolved into a much larger jam and blocked an estimated 80-95% of the active channel while allowing for salmon passage beneath the jam (Figures 31-32). Jam 10 is presumed to have racked every significant wood element that came loose from Jams 8 and 9 as well as mobile instream wood that was placed 0.5 km upstream of Jam 8.

Jam 10's complete horizontal obstruction created the most significant upstream backwater of all the study sites, forming a large upstream gravel bar (0.63 m) (Figure 33, longitudinal profile, cross-section 80). The upstream flows were forced onto both the right and the left-bank floodplains, scouring out large channels that reconnected to the primary channel downstream of the jam (Figure 33, cross-sections 80, 83, 86).

The underflow jam forced water towards the bed, creating a powerful hydraulic jet that resulted in the third deepest pool (0.94 m) of all the jams (Figure 33, longitudinal profile, cross-section 83). In addition to the horizontal influence, the jam's pitched logs diverted flows , creating scour and eddy pools adjacent to the underscour pool formed by the strong hydraulic jet (Figure 33, longitudinal profile and cross-sections 83 and 86). The coarse cobbles that were scoured from under the jam formed a very coarse cobble bar downstream of the jam (Figure 33, longitudinal profile and cross-section 86). Jam 10 ranked highest for habitat heterogeneity (increased from 1.06 to 2.18) and ranked third overall for the number of facies patches (increased from 4 to 35) (Figure 32). Reach

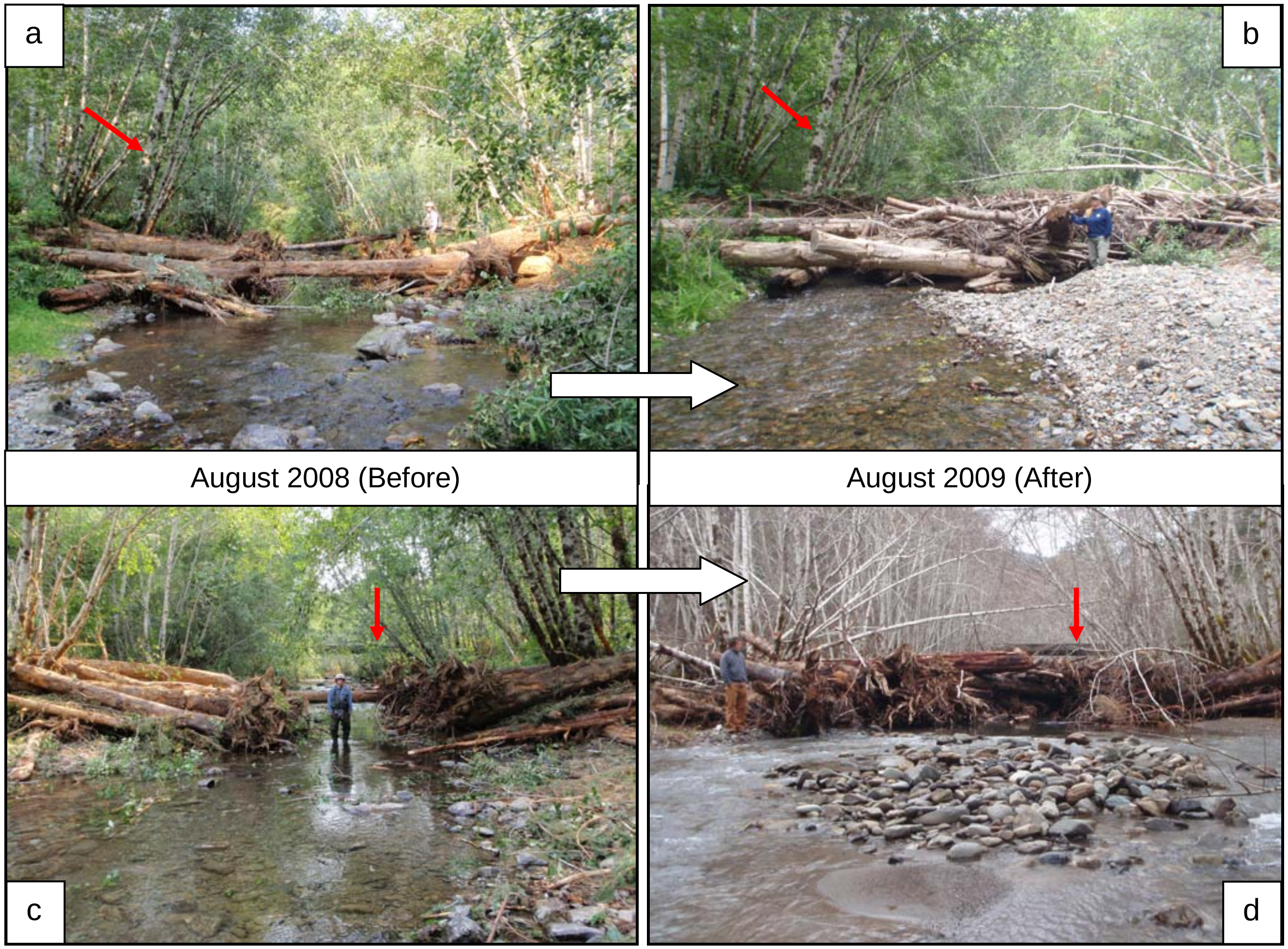

Figure 31. Jam 10: (a, b) photos looking downstream at post-construction jam and after high-flow events; (c, d) photo looking upstream at post construction jam and after high-flow event. Smaller red arrows point to reference points. East Fork Mill Creek, Del Norte County, California. 4 August 2008 and 4 August 2009.

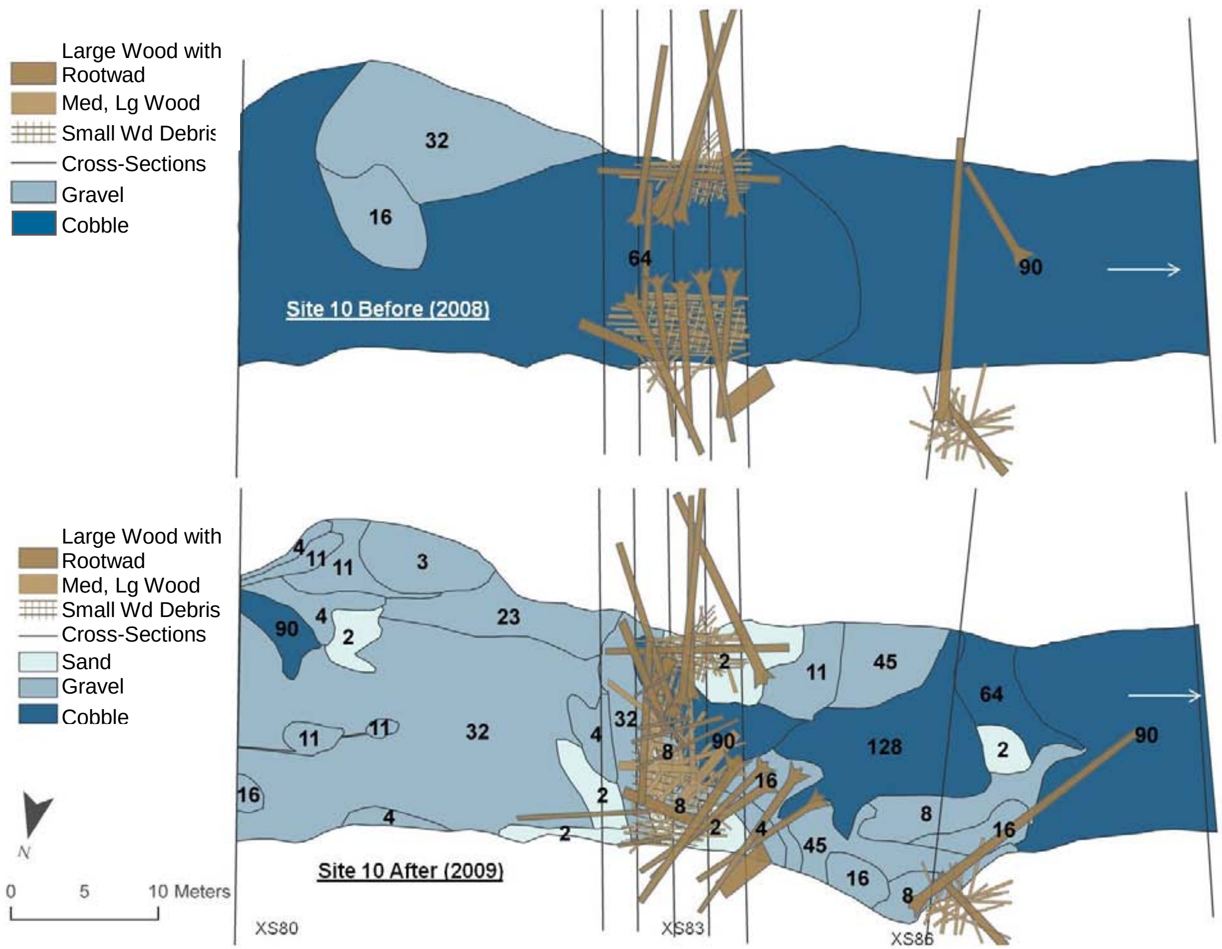

Figure 32. Jam 10 is a complex deflecting jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are before and after facies and wood jam maps. TheD50 for each facies patch is given in black text. Habitat heterogeneity (Shannon's Diversity Index) increased from 1.06 to 2.18 and residual pool depth increased from 0.24 to 0.94m.

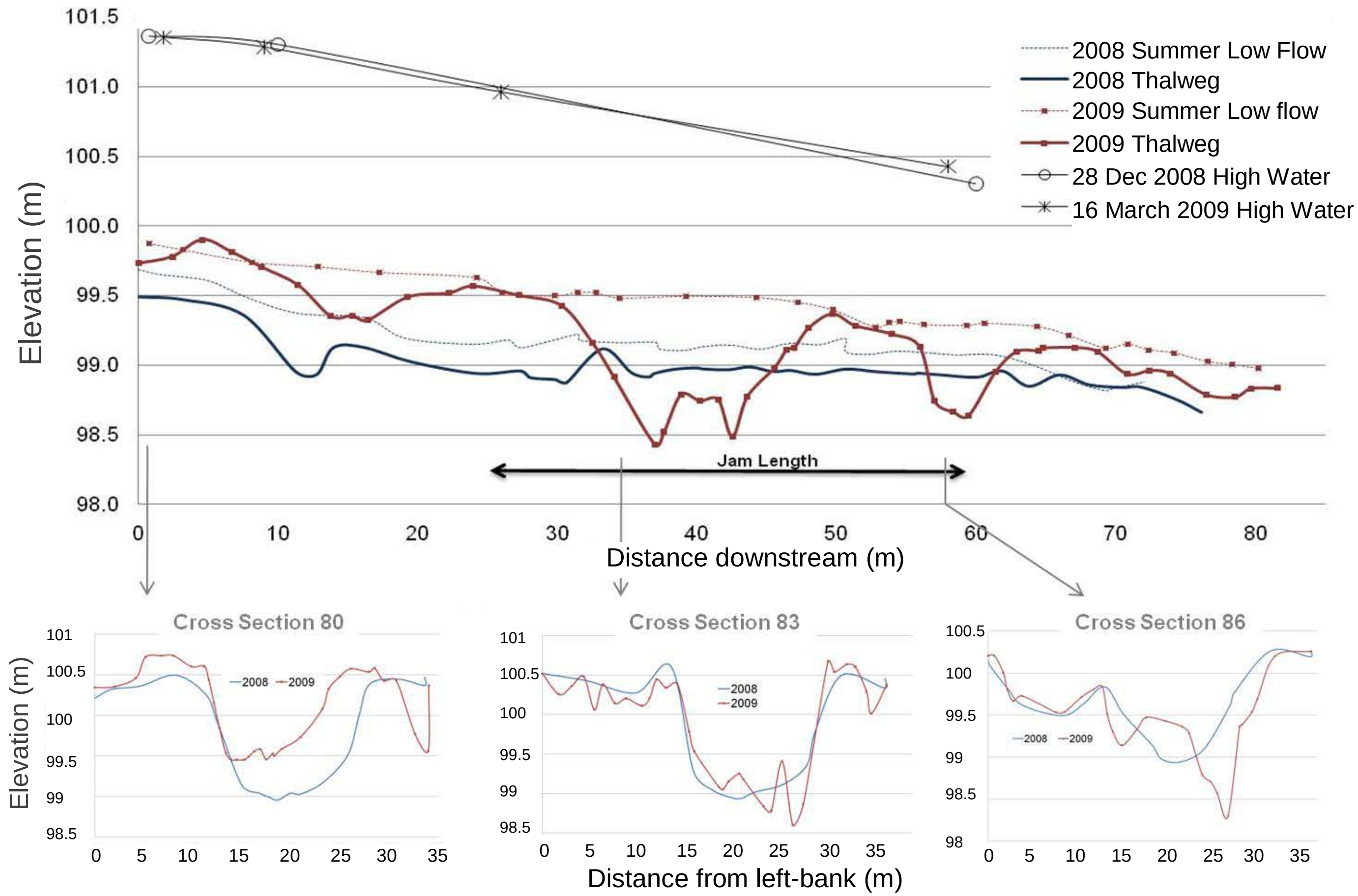

Figure 33. Jam 10 is a complex deflector jam constructed in 2008 within East Fork Mill Creek, Del Norte County, California. Shown are longitudinal profiles and cross-sections of the study site, illustrating pool scour, aggradation and bar formation, low and high water levels and slopes and floodplain channel development.

average decreased from 68 to 45 mm.

Percentage Pool Cover

Increased percent pool cover is positively correlated with increased wood loading in the active channel. Wood cover and pool size statistics are summarized by site in Table 4. Linear correlations between wood loading input variables (surface area of wood within active channel and volume wood per active channel) and response variable (percentage pool cover) are summarized in Table 5 and illustrated in Figures 34-35.

Channel Morphological Changes

Overall, greater jam wood volume was positively correlated with greater residual pool depth and upstream aggradation. Baseline geomorphic characteristics of study reaches are given and changes in residual pool depth and reach upstream aggradation are summarized in Table 6. Prior to construction, average residual pool depth was 0.20 m (range 0.07-0.64) and after construction, residual pool depths increased to 0.79 m (range: 0.17-1.82). Upstream aggradation at the study sites averaged 0.31 m (range 0.00 to 0.63 m). Linear correlations between wood loading input variables (total site wood volume, wood volume per active channel width, and wood piece count) and response variables (residual pool depth and upstream aggradation) are summarized in Table 5. Primary linear relationships for this study are illustrated in figures 36-38. Graphs clearly show increases in both residual pool depths and upstream aggradation with increasing wood piece count and wood volume.

Table 4. Percentage pool cover and pool size statistics for 10 large wood instream restoration study sites in East Fork Mill Creek, Del Norte County, California.

Site	Area Wood Cover (m^2)	Volume Wood within Active Channel (m^3)	Pool Length[a] (m)	Pool Area (m^2)	Percent Pool Cover (%)	Volume of Wood per Pool Area (m)	Volume of Wood per Pool Length (m^2)
			Simple Wood Structures				
1	3.3	1.5	57.0	676	0	0.0	0.03
2	6.6	3.8	76.0	1111	1	0.0	0.05
			Complex Wood Jams				
3	60.4	30.7	28.5	327	18	0.09	1.08
4	35.7	11.9	46.0	498	7	0.02	0.26
5	12.9	4.0	23.5	248	5	0.02	0.17
6	23.5	15.2	18.0	223	11	0.07	0.84
7	38.6	16.0	44.0	541	7	0.03	0.36
8	27.0	15.6	20.0	279	10	0.06	0.78
9	73.7	26.5	73.0	991	7	0.03	0.36
10	86.1	43.7	26.0	330	26	0.13	1.68

[a] Pool length and area based on extent of pool formed in response to jam construction and one year of winter flows.

Table 5. Pearson's correlations coefficient of linear correlation and associated r^2 values for relationships between project wood loading independent variables and response variables in East Fork Mill Creek, Del Norte County, California.

Response Variable	Independent Variable	Linear Equation	r^2
Percentage Pool Cover (%)	Surface Area of Wood within Active Channel	y = 0.0022x + 0.02	**0.65**
	Volume Wood per Active Channel	y = 0.0054x + 0.001	**0.86**
Habitat Heterogeneity (SHDI)	Volume Wood	y = 0.0283x + 0.6987	**0.64**
	Volume Wood per Active Channel Width	y = 0.3935x + 0.6062	**0.62**
	Volume Wood per Channel Area	y = 21.49x + 0.5139	**0.51**
	Wood Piece Count	y = 0.0108x + 1.1661	0.31
Number Facies Patches	Volume Wood	y = 5203x +11.706	**0.48**
	Volume Wood per Active Channel Width	y = 6.7204x + 11.213	**0.40**
	Volume Wood per Channel Area	y = 254.37x + 16.31	0.16
	Wood Piece Count	y = 0.1338x + 22.443	0.11
Decreased Reach Average D50 (mm)	Volume Wood	y = -0.6038x + 77.781	**0.41**
	Volume Wood per Active Channel Width	y = -7.9654x + 78.743	0.35
	Volume Wood per Channel Area	y = -343.63x + 74.456	0.18
	Wood Piece Count	y = -0.2253x + 67.651	0.19
Residual Pool Depth (m)	Volume Wood	y = 0.0192x + 0.2315	**0.50**
	Volume Wood per Active Channel Width	y = 0.2628x + 0.1794	**0.47**
	Volume Wood per Channel Area	y = 12.651x + 0.2662	0.30
	Wood Piece Count	y = 0.0107x + 0.4369	**0.52**
Maximum Reach Aggradation (m)	Volume Wood	y = 0.0101x + 0.0173	**0.72**
	Volume Wood per Active Channel Width	y = 0.1372x - 0.008	**0.66**
	Volume Wood per Channel Area	y = 6.9299x + 0.0238	**0.47**
	Wood Piece Count	y = 0.004x + 0.1796	0.37

[a] For alpha = 0.05 with n=10, significant r^2 relationships are bolded (r^2>0.399).

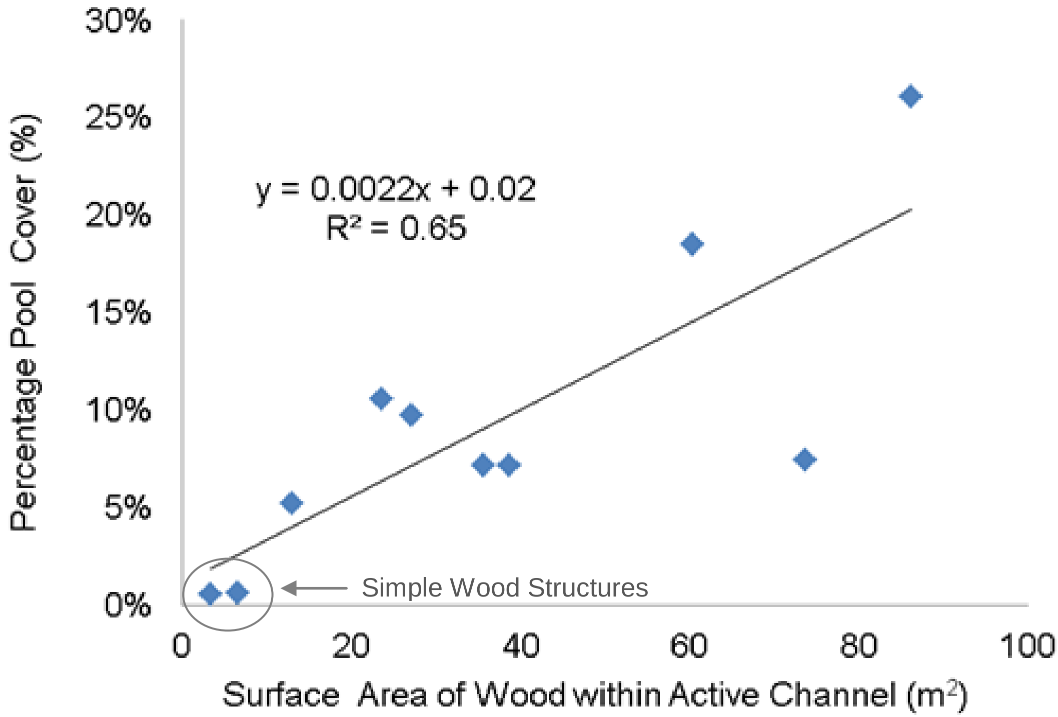

Figure 34. Relationship between surface area of wood within active channel and percent pool cover for two simple wood structures and eight complex wood jams in East Fork Mill Creek, Del Norte County, California.

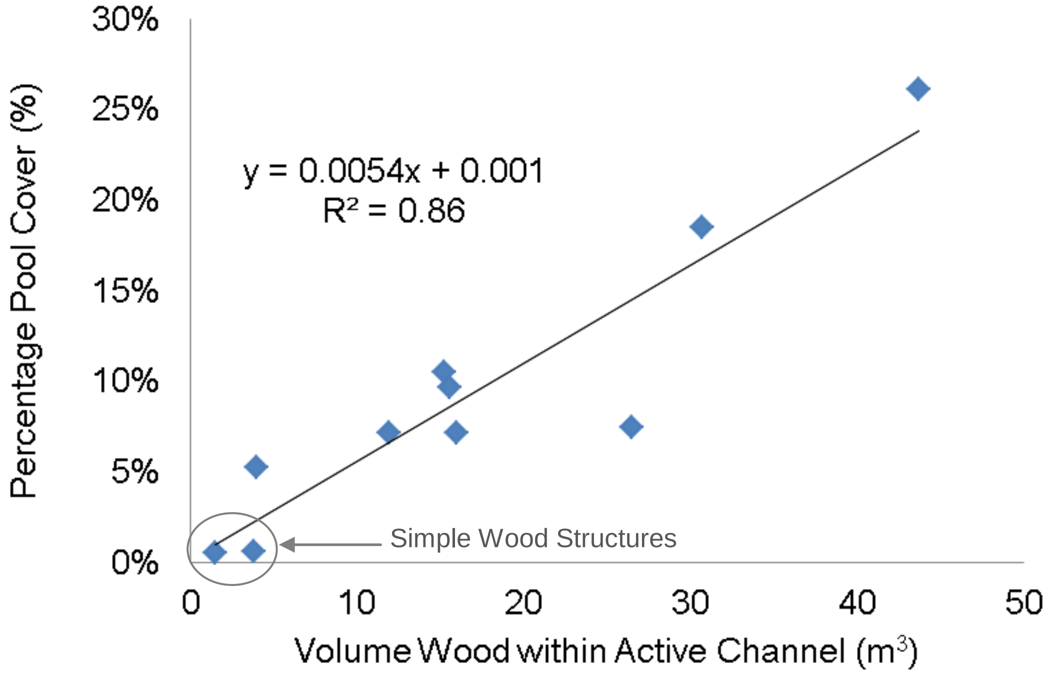

Figure 35. Relationship between volume wood within active channel and percent pool cover for two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California.

Table 6. Channel morphological characteristics and changes to residual pool depths and upstream aggradation for 10 study sites (two simple wood structures and eight complex wood jams) in East Fork Mill Creek, Del Norte County, California.

Site	Active Channel Width (m)	Reach Length (m)	Before Channel Gradient (%)	Before Residual Pool Depth (m)	After Residual Pool Depth (m)*	Maximum Upstream Aggradation (m)
			Simple Wood Structures			
1	12.5	54	0.7	0.1	0.2	0.0
2	13.0	82	0.2	0.1	0.6	0.0
			Complex Wood Jams			
3	11.1	43	1.6	0.1	1.5	0.3
4	11.1	46	0.9	0.1	0.5	0.5
5	11.1	40	1.5	0.1	0.5	0.2
6	8.9	50	1.7	0.3	0.7	0.2
7	13.0	61	0.7	0.1	0.9	0.2
8	12.5	54	0.7	0.2	0.3	0.5
9	13.0	82	0.2	0.6	1.8	0.6
10	14.3	67	0.9	0.2	0.9	0.6

[a] Structures 1 and 2 are simple structures constructed by California Department of Fish and Game in Circa 1995. Structure 1 was incorporated into Jam 8 and Structure 2 was incorporated into Jam 9.

[b] For sites 1 and 2, the before residual pool depth are assumed same as the average value for sites 3-7 (Site 10 was excluded due to the natural complexity at that site due to the island upstream of the site.

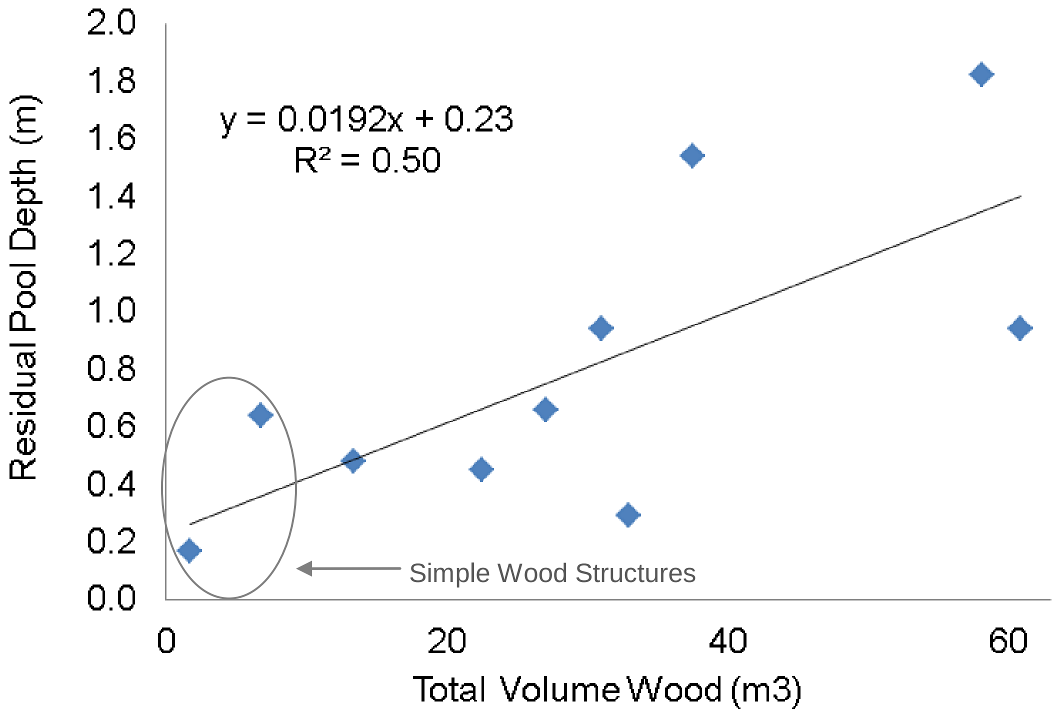

Figure 36. Relationship between total wood volume and residual pool depth at two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California.

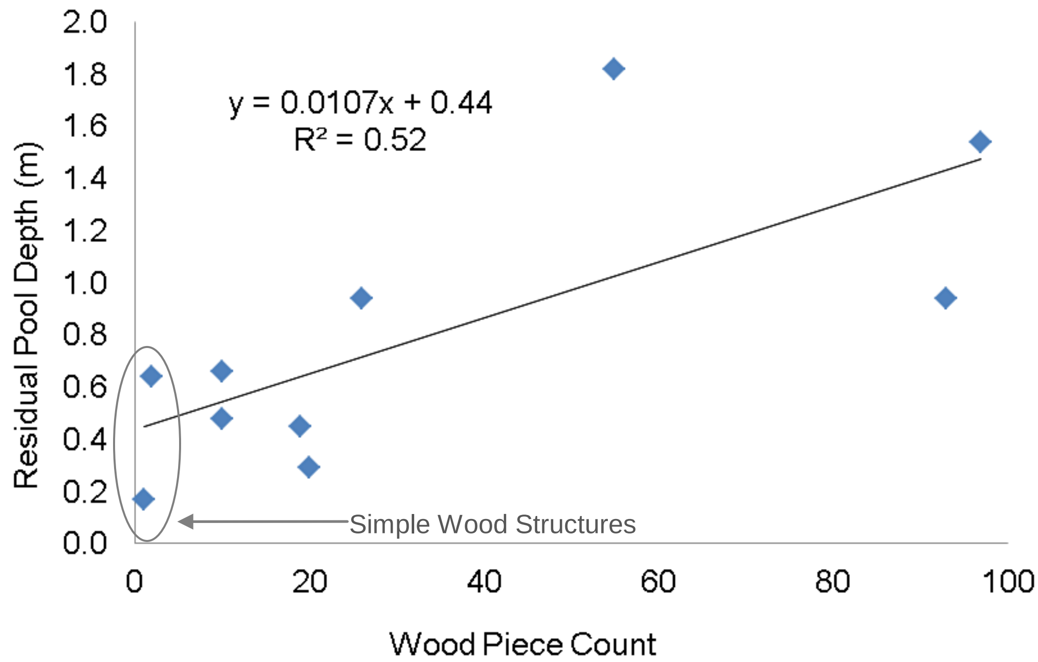

Figure 37. Relationship between wood piece count and residual pool depth at two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California.

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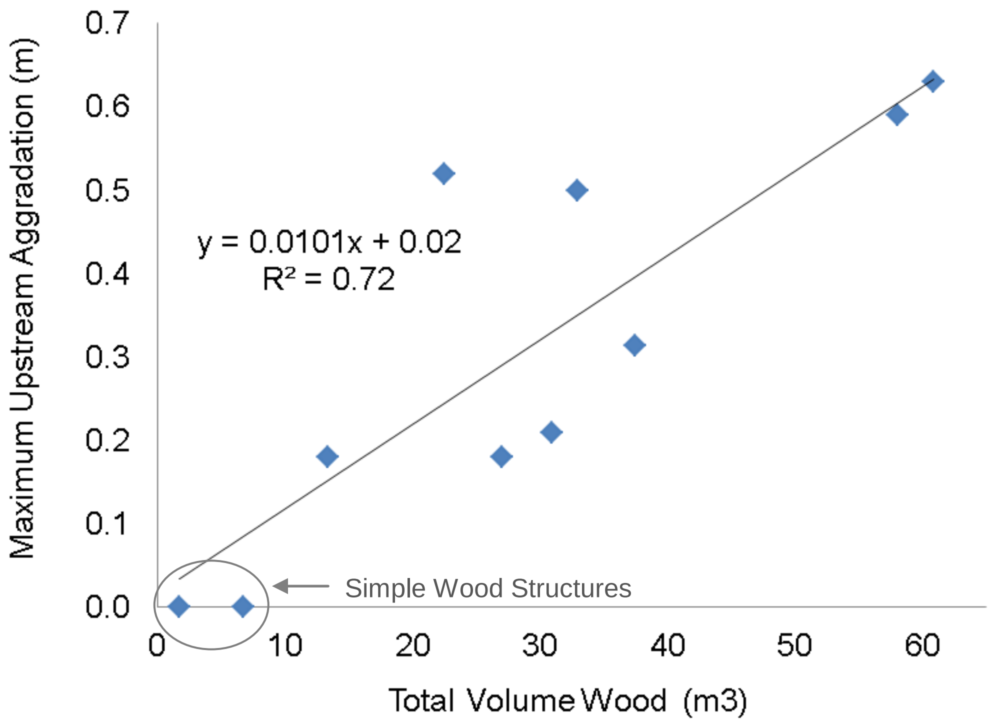

Figure 38. Relationship between total wood volume and upstream aggradation at two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California.

Surface Bed Texture and Habitat Heterogeneity

The change in surface bed material textures at the eight complex jams and two simple wood structures are given in Table 7. Greater jam wood volume was positively correlated with: (1) increased number of facies patches; (2) greater habitat heterogeneity and (3) decreased reach average D50. Prior to the construction of the 8 jams, the average habitat heterogeneity at the eight stream reaches was 0.32 (range: 0.12-1.06) and after construction heterogeneity averaged 1.53 (range: 0.29-2.18). The average number of facies patches increased from 8 (range: 2-19) to 27 patches (range: 8-52). The overall average D50 decreased from 73 mm to 60 mm (Table 7).

Linear correlations between wood loading input variables (total site wood volume, wood volume per active channel width, total wood volume per channel area, and wood piece count) and response variables (habitat heterogeneity, number of facies patches, and reach average D50) are summarized in Table 5. Primary relationships for this study are plotted in figures 39-40. The strongest correlations were with total wood volume and wood volume per channel width. Figures 39 and 40 illustrate that increased site wood volume is correlated with increased habitat heterogeneity and decreased reach average D50.

Table 7. Wood volume and bed texture variables (reach average D50, number facies patches, and habitat heterogeneity (Shannon's Diversity Index)) for 10 large wood instream restoration study sites in East Fork Mill Creek, Del Norte County, California.

Site	Wood Piece Count	Volume Wood (m^3)	Volume Wood per Active Channel Width	Reach Average D50 Before (mm)	Reach Average D50 After (mm)	Number Patches Before	Number Patches After	Habitat heterogeneity (Shannon's Diversity Index) Before	Habitat heterogeneity (Shannon's Diversity Index) After
				Simple Wood Structures					
1[a]	1	1.7	0.1	91	91	6 [b]	19	0.20[b]	0.29
2[a]	2	6.8	0.5	64	73	6 [b]	8	0.20[b]	0.45
				Complex Wood Jams					
3	97	37.5	3.1	88	65	4	19	0.31	1.61
4	19	22.5	2.0	65	42	11	32	0.15	1.89
5	10	13.4	1.2	58	51	5	15	0.36	1.5
6	10	27.1	3.0	91	71	10	16	0.04	1.11
7	26	31.0	2.4	44	56	2	24	0.12	2.05
8	20	33.0	2.6	91	79	19	49	0.29	2.05
9	55	58.1	4.2	73	31	8	52	0.45	2.12
10	93	60.9	4.2	68	45	4	35	1.06	2.18

[a] Sites 1 and 2 are simple structures constructed by California Department of Fish and Game in 1995. Structure 1 was incorporated into Jam 8 and Structure 2 was incorporated into Jam 9.
[b] For Sites 1 and 2, the number of facies patches and the habitat heterogeneity (Shannon's Diversity Index) is assumed to be the same as the average value for Sites 3-7 (Site 10 was excluded due to the natural channel complexity).

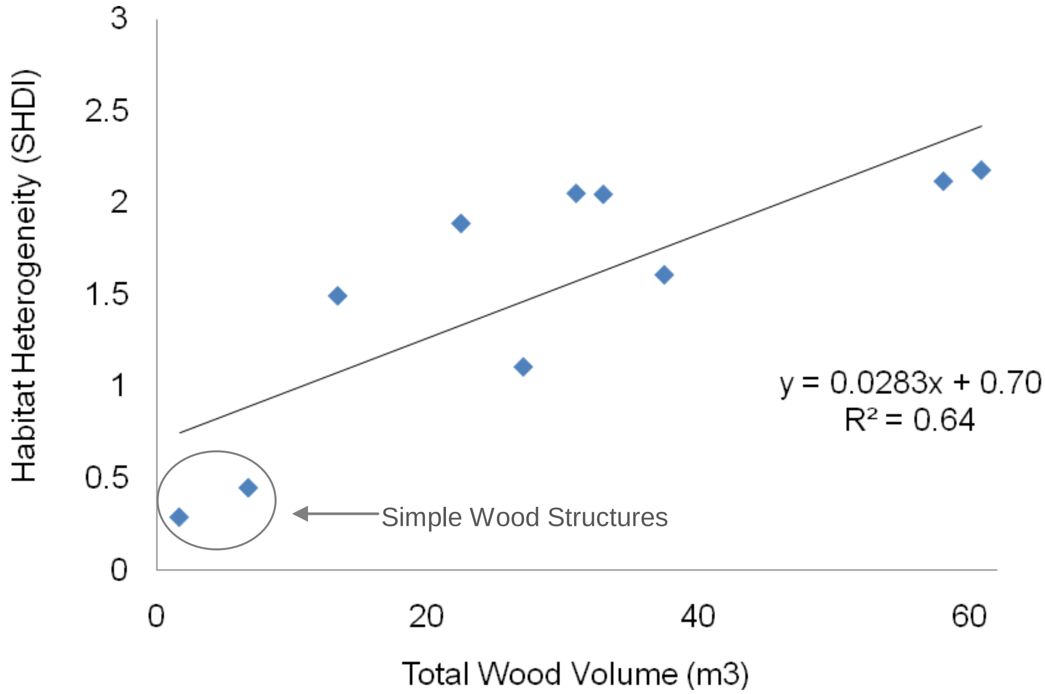

Figure 39. Relationship between habitat heterogeneity (Shannon's Diversity Index) and the total wood volume at two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California

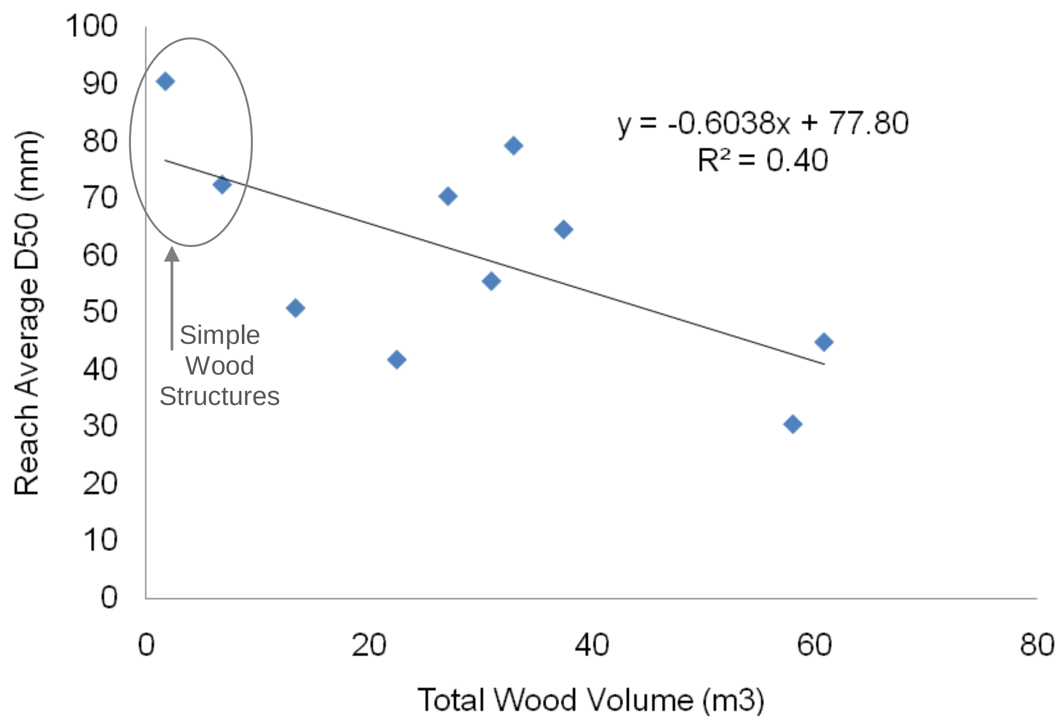

Figure 40. Relationship between reach average D50 and total wood volume at two constructed simple wood structures and eight constructed complex wood jams in East Fork Mill Creek, Del Norte County, California.

DISCUSSION

Results indicate that complex wood jams are more effective than simple fish habitat structures in achieving common restoration objectives that include: (1) increasing percentage pool cover; (2) increasing pool habitat; (3) enhancing salmon spawning gravels; and (4) increasing habitat heterogeneity. In addition, the effectiveness of an individual constructed jam increases as the overall volume of wood within the jam increases.

Percentage Pool Cover

The strongest linear relationship developed from this study was between increased wood volume and percentage pool cover (r^2=0.86). Complex wood jams proved much more effective than simple structures at providing pool cover. Although increasing percentage pool cover is a common restoration objective, it is seldom monitored (Cederholm et al. 1997), Whiteway et al. 2010). Increases in wood placed within the stream channel directly increased the percentage pool cover. In addition, complex jams proved more effective than simple structures at racking additional mobile wood, naturally increasing the percentage pool cover.

Channel Morphological Changes

Complex jams with increased wood volumes proved more effective than simple structures at increasing pool depths. These results are important to consider when trying to achieve restoration objectives such as facilitating the formation and maintenance of deep pools. Deep pools (1) increase the ability of a fish to avoid terrestrial predators, (2) provide fish with low velocity environments that minimize energy expenditures, (3) provide maximum exposure to drift food organisms and (4) provide more available habitat niches and over wintering habitat (Naiman et al. 2002). In addition, the complex wood jams increased summer low flow water depths through the study reaches, as expressed by the increase in residual pool depth and riffle depth at all sites. The increase in low flow water depth demonstrated that complex wood jams were effective at increasing the amount of vitally important summer rearing habitat available for juvenile steelhead trout and coho salmon. Although it was not explicitly studied, the increase in low flow water depths suggested that jams may increase water storage in the channel and floodplains during summer, thus extending beneficial water conditions further into the dry season

Complex wood jams with greater volumes of wood proved more effective at impeding downstream flow and at creating upstream gravel bars (r^2=0.72). Jams that had the highest level of upstream aggradation were Jams 3, 4, 8, 9, and 10. Of these jams, all but Jam 4 were constructed as channel-spanning underflow jams or became underflow jams by racking mobile wood. This suggests that channel spanning jams are very effective designs for impeding flow and creating the backwater conditions that facilitate upstream aggradation. Gravel bars that formed downstream of jams were likely formed by sediment scoured out by pool formation forces.

Although floodplains were not studied in detail, all sites where floodplain channel development occurred were constructed as or became underflow jams (Jams 3, 6, 9, and 10). By spanning the channel width, several complex wood jams reduced upstream water velocities and directed a portion of the stream flow onto adjacent floodplains. In cases where the magnitude and duration of overbank flows were great, new floodplain channels were formed and older features re-occupied.

Surface Bed Texture and Habitat Heterogeneity

Complex wood jams proved significantly more effective than simple structures at increasing the number of facies patches and habitat heterogeneity. Because hydraulic heterogeneity has been shown to enhance instream habitat value (Zalewski et al. 2003, Lepori et al. 2005) and previous research has linked increases in habitat heterogeneity with increased aquatic diversity (Beisel et al. 2000, Brown 2003, Ward and Tockner 2001), it is reasonable to conclude that jams with greater wood volumes would be more effective at improving instream habitat value and aquatic diversity. This finding is important as most instream restoration objectives are focused on increasing habitat complexity in systems that have been simplified due to past anthropogenic actions. Results demonstrate that wood loading projects aimed to increase the quantity and quality of aquatic habitats should use greater volumes of high quality wood and be designed in a manner that is based on the biogeomorphic needs of the system.

All but one complex jam resulted in a decreased reach average D50 and all jam sites had an increase in gravel as a percentage of reach surface sediment. Simple structures did not trap nor alter surface bed material. For the complex jams, such textural fining caused by hydraulic roughness is important as the availability of suitably sized spawning gravels has been shown to be a limitation for spawning salmonids (Allen 1969, Buffington and Montgomery 1999b). Spawning salmonids can move gravels approximately 10% of their body length, suggesting that larger fish can move sediment of larger sizes (Kondolf 2000). In East Fork Mill Creek, the largest anadromous fish is the Chinook salmon, which generally spawn in gravels and fine cobbles ranging in size from 30.0-69.3 mm (Kondolf and Wolman 1993). Steelhead trout are the second largest and spawn in gravels ranging from 10.0-40.0 mm, while coho salmon spawn in gravels ranging from 5.4-35.0 mm (Kondolf and Wolman 1993). Before the installation of the complex wood jams in East Fork Mill Creek, four sites had a dominant surface D50 of 90 mm; three sites had dominant surface D50s of 64 mm, and one site was 45 mm. Thus, only four sites had surface sediment suitable for Chinook salmon spawning and no sites had surface sediments suitable for steelhead trout or coho salmon spawning. After only one storm season, all eight complex jam sites had surface textures within the spawning range estimates for steelhead trout, coho salmon, and Chinook salmon provided by Kondolf and Wolman (1993). The recruitment of spawning sized gravels within these sites suggests that jams facilitated an increase in the amount of spawning habitat available for all three salmonid species in East Fork Mill Creek. These results are consistent with research from Buffington and Montgomery (1999b) that showed textural fining caused by instream wood facilitates trapping and storage of gravels in reaches that are otherwise too coarse for spawning.

Salmonid Response

Justice (2007) conducted a study in East Fork Mill Creek to assess correlations between salmonid population statistics and the presence of the 1995 CDFG wood structures. Results presented by Justice (2007) showed no significant difference between reaches with the simple structures and adjacent reference reaches in terms of fish biomass, length, growth, and survival during summer or fall. Although there were no specific fish data collected as a part of this study, the Mill Creek Fisheries Monitoring Program has collected fisheries data in the watershed since 1994 (McLeod and Howard 2010). The purpose of the program is to monitor the freshwater life history stages of returning salmonids and their varying life histories in the West Branch and East Fork Mill Creek (McLeod and Howard 2010). The program includes annual estimation of adult spawner escapement, smolt emigration, and summertime populations of juvenile salmonids. Recent Mill Creek Fisheries Monitoring Program analysis for the Mill Creek watershed suggested that the jams built in 2006 and 2008 are having a positive effect on juvenile coho salmon populations by increasing the quality and quantity of summer rearing habitat (e.g. deep pools with complex cover) (McLeod and Howard 2010). The jams also provide winter high-flow velocity refuge in East Fork Mill Creek (McLeod and Howard 2010). From 2004 to 2008, estimated densities of juvenile coho salmon in the East Fork during summer were considerably less (e.g. ~50% less) than density estimates generated in the West Branch Mill Creek. However, in 2009, the summer coho salmon population estimate in East Fork surpassed the West Branch estimates for the first time in the six-year record (Figure 41). Mill Creek Fisheries Monitoring Program data also showed that while juvenile coho salmon population estimates for shallow pool habitat has steadily decreased in the West Branch Mill Creek, estimates have been steadily increasing in the East Fork (Figure 42). While there may be other factors involved in increased East Fork Mill Creek fish production, the fact that it coincided with the 2006 and 2008 wood loading projects are encouraging and underscore the need for continued monitoring (Fiori 2010).

Management Implications

The management of wood in salmon streams has undergone a transition from a time when it was removed from streams as a standard practice to the present, when instream wood is recognized as integral to stream and riparian function (Reich et al. 2003). Today, the re-introduction of whole tree materials can be a powerful tool for rehabilitating salmonid populations if geomorphic conditions and the size of wood pieces used and overall jam volume are adequately considered (Nagayama and Nakamura 2010). Management has begun to switch from a paradigm of fixed instream structures towards the use of wood in more naturally constructed jams. These jams are often free to move within the channel and floodplain (Reich et al. 2003, Fiori et al. 2009, Fiori 2010). Such a paradigm transition is based on the understanding that salmonid recovery in the Pacific Northwest, and especially within California, will require wood loading strategies aimed at restoring the hydraulic and geomorphic conditions necessary for creating and sustaining complex habitat (e.g. rearing, holding, and spawning) that salmonids rely on

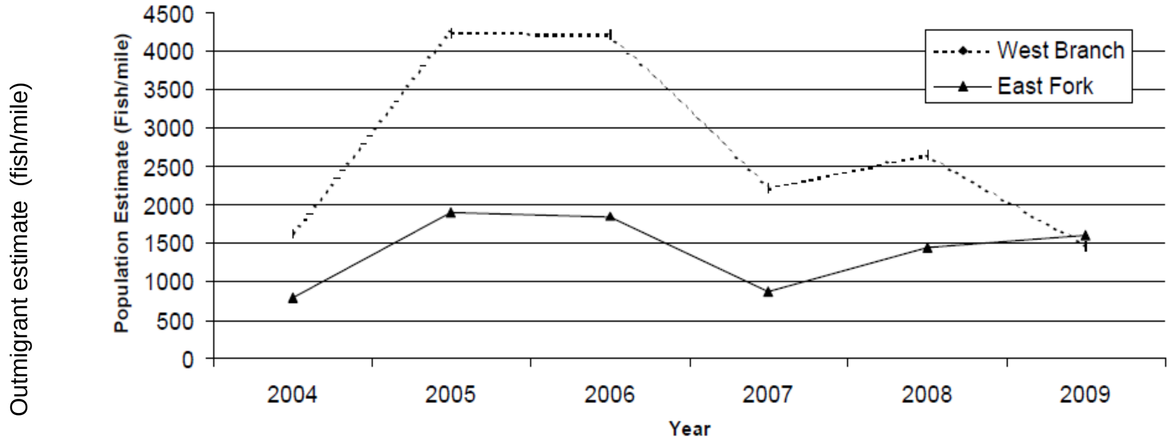

Figure 41. Coho salmon outmigrant estimates (estimate of number of coho salmon smolts migrating divided by miles of anadromy upstream) in East Fork and West Branch Mill Creek, Del Norte County, California, 2004-2009 (McLeod and Howard 2010).

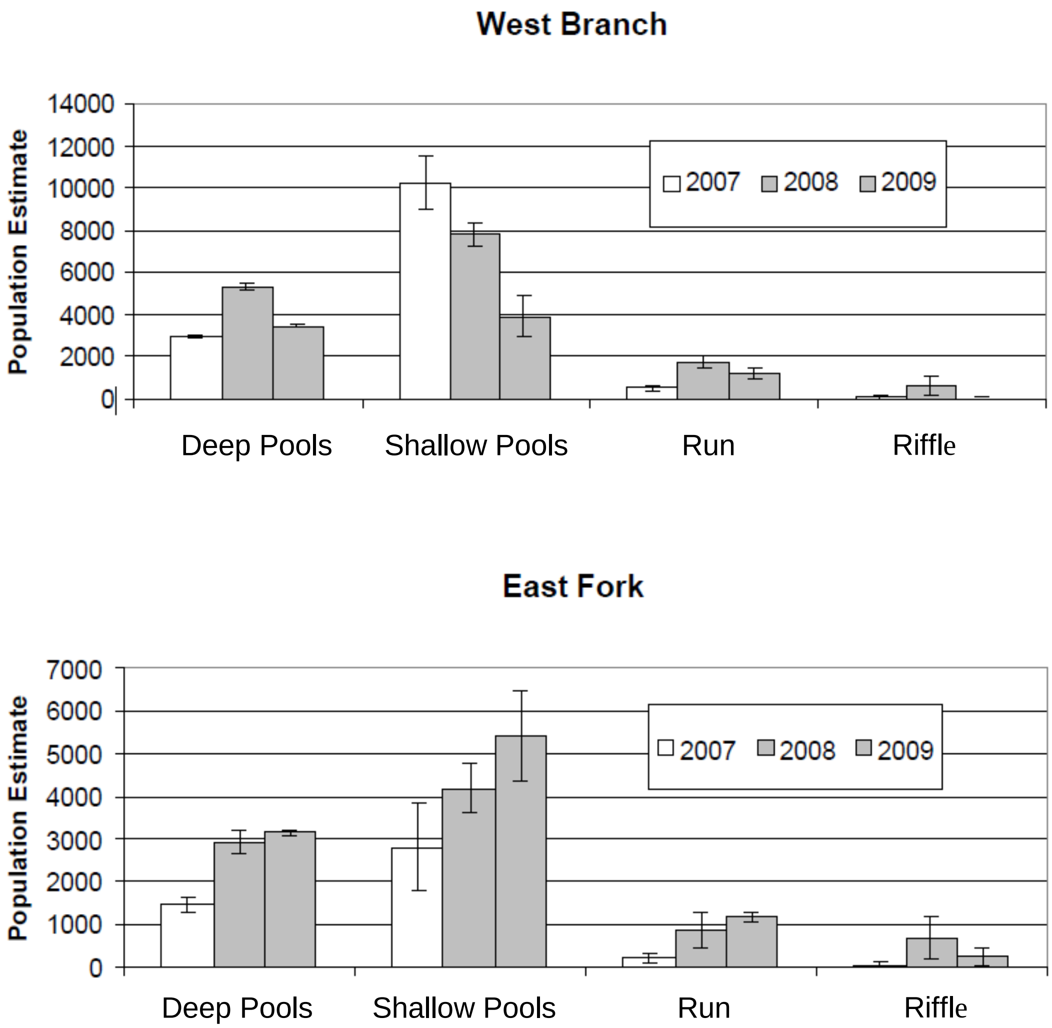

Figure 42. Juvenile coho salmon abundance within specific habitat types for West Branch Mill Creek and East Fork Mill Creek, Del Norte County, California, 2007-2009 (from McLeod and Howard 2010).

for survival.

Determining appropriate targets for instream wood loading has been the subject of research and regulation (Keller and Tally 1979, Klein 1989, Keller et al. 1995, Kramer and Klein 1999, Lisle 2002, Wooster and Hilton 2004, Carroll and Robison 2007, Fox 2007). Table 8 shows reference conditions for natural wood loading in coastal old-growth and 2nd growth redwood forests. A relative comparison of changes in wood loading rates following installation of complex wood jams is possible using data from a study by Carroll and Robison (2007). The 2008 East Fork Mill Creek constructed wood jams added approximately 260 m^3 of large wood with and without rootwads to the project sites. Of this volume, approximately 140 m^3 was placed within the active channel zones. Following complex wood jam installation, wood piece count and volumes within the active channel of the study reaches averaged 72 pieces per 100 m of channel and 31 m^3 per 100 m channel length, respectively (Table 8). Carroll and Robinson (2007) documented that there were on average 5 pieces of wood per 100 meters in East Fork Mill Creek, 23 in West Branch Mill Creek, and 24 in Prairie Creek (Table 8). A simple comparison shows that the 2008 complex jams increased the average number of pieces in East Fork Mill Creek from 5 to 72 wood pieces per 100 m of channel length. This is an increase of over 14 times the number of wood pieces following industrial forest management and stream cleaning conditions.

While complex wood jam installations resulted in a substantial increase in the pieces of wood per 100 m of channel relative to 2004 conditions, the reach averaged

Table 8. Stream and wood loading characteristics for the study reaches and similar streams in old-growth and 2nd growth managed coastal redwood forests.

Data Source	Survey Location	Coastal Redwood Forest Management	Stream/ Forest Condition	Notes	Stream gradient	Bankfull width (m)	Wood Pieces per 100 m channel length	Volume Wood within channel per 100m (m^3/100 m)	Volume Wood within channel or adjacent per 100 m (m^3/100 m)	Wood Volume per cubic meter in channel (m^3/m^2)	Wood loading in channel (m^3/ha)
Carroll and Robison 2007	Prairie Creek	Old-growth	Undisturbed		0.60%	17-21	24				759
Keller and Tally 1979	Coastal old-growth redwood	Old-growth	Undisturbed							0.10	1000 (median)
Keller et al. 1995	Prairie Creek	Old-growth	Undisturbed							0.14	1360
Kramer and Klein 1997	Prairie Creek	Old-growth	Undisturbed	Unpublished data	0.73%	12.6		70			
Kramer and Klein 1999	Prairie Creek	Old-growth	Undisturbed	Unpublished data	0.73%	12.6	10.8	64	103		
Wooster and Hilton 2004	Coastal old-growth redwood	Old-growth	Stream cleaning		2.0-3.0 %	6.7-8.8	13			0.06	589
Klein 1989	Bridge Creek	Old-growth	Stream cleaning	Unpublished data	1.30%	13.9		81	125	0.13	1300
Carroll and Robison 2007	East Fork Mill Creek	2nd growth	Logging, stream cleaning		0.60%	17-21	5				39
Carroll and Robison 2007	West Branch Mill Creek	2nd growth	Logging, stream cleaning		0.60%	17-21	23				329
This study	East Fork Mill Creek	2nd growth	Logging, stream clearing, wood loading	Unpublished data for this study	0.90%	12.16	72	31	59	0.03	265

wood volume per channel area remained relatively low when compared to similar old-growth streams in coastal redwood forests (Table 8). According to Carroll and Robinson (2007), the reach average wood volume in East Fork Mill Creek was 39 m^3/ha in 2004. In 2008, with the installation of the complex wood jams, the volume in the study reaches averaged 265 m^3/ha. This represents an increase of 679% relative to conditions for similar reaches (Table 8). However, the reach average wood volume for East Fork Mill Creek is still much lower than the old-growth Prairie Creek and the managed West Branch Mill Creek reaches, where wood loading was reported to be 759 m^3/ha and 329 m^3/ha, respectively (Carroll and Robison 2007). Relative to the wood loading rates for these streams, the installation of complex wood jams increased the reach average wood volumes to within 35 % of the old-growth forest stream condition and 81 % of the West Branch Mill Creek. The greater piece count relative to the wood volume attained in the East Fork Mill Creek study reaches indicates that individual wood pieces in old-growth systems are much larger than pieces available to construct the jams. For managers to increase wood loading levels in managed streams to old-growth levels, a greater number of smaller diameter stems would be required.

There are few studies from California's north coastal streams that have compared changes to instream wood loading with changes in fish densities. Based on the McCloud and Howard (2010) results, it appears that coho salmon populations responded to increases in wood loading, when levels were increased to within 19.5% of those reported for West Branch and 65.1% of the old-growth reach in Prairie Creek. This suggests that in order to support the winter and oversummering habitat needs of juvenile coho salmon, a lower bound for wood loading of 269 m^3/ha should be considered for similar 3rd to 4th order tributaries. Perhaps more importantly, the spatial scale of these efforts will need to occur at the subwatershed level. It is also important to recognize that the favorable response in fish use and densities occurred where wood jams were very complex, mimicked naturally occurring jams, and were constructed using whole tree materials. The use of simplified stems (wood lacking rootwads) was a component of the total volume of wood used. However, this type and caliber of wood was incorporated into complex jams comprised primarily of large stems with attached rootwads, and used along with branches and small wood fragments to increase overall jam stability and complexity. The simplified stems provided less than 50% of the total volume of wood used.

The complex jams evaluated as part of this study were constructed to mimic natural wood accumulations and designed to support recovery of stream ecosystem processes and function. Such jams restore large-scale roughness to the channel, resetting the direction of stream degradation by creating complex flow fields that slow sediment transport out of stream systems and form vital fish habitat features. Like natural jams, these constructed jams will shift, accumulate wood, and deteriorate overtime (Haschenburger and Rice 2004). While most wood loading efforts should be viewed as a short-term solution, these efforts may need to be supplemented until natural loading levels are reached (Boyer and Berg 2003, Reich et al. 2003, Nagayama and Nakamura 2010). Ultimately, stream restoration for the benefit of salmonid populations depends on riparian forest successional processes that will naturally provide wood to streams.

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