JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

CHANGES IN STREAMBED COMPOSITION IN SALMONID SPAWNING HABITAT OF THE ELWHA RIVER DURING DAM REMOVAL[1]

Roger J. Peters, Martin Liermann, Michael L. McHenry, Paul Bakke, and George R. Pess[2]

ABSTRACT: One uncertainty associated with large dam removal is the level of downstream sediment deposition and associated short-term biological effects, particularly on salmonid spawning habitat. Recent studies report downstream sediment deposition following dam removal is influenced by proximity to the source and river transport capacity. The impacts of dam removal sediment releases are difficult to generalize due to the relatively small number of dam removals completed, the variation in release strategies, and the physical nature of systems. Changes to sediment deposition and associated streambed composition in the Elwha River, Washington State, were monitored prior to (2010-2011) and during (2012-2014) the simultaneous removal of two large dams (32 and 64 m). Changes in the surface layer substrate composition during dam removal varied by year and channel type. Riffles in floodplain channels downstream of the dams fined and remained sand dominated throughout the study period, and exceeded levels known to be detrimental to incubating salmonids. Mainstem riffles tended to fine to gravel, but appear to be trending toward cobble after the majority of the sediment was released and transported through system. Thus, salmonid spawning habitats in the mainstem appear to have been minimally impacted while those in floodplain channels appear to have been severely impacted during dam removal.

(KEY TERMS: sediment; sediment transport; sediment composition; restoration; environmental impacts.)

Peters, Roger J., Martin Liermann, Michael L. McHenry, Paul Bakke, and George R. Pess, 2017. Changes in Streambed Composition in Salmonid Spawning Habitat of the Elwha River during Dam Removal. *Journal of the American Water Resources Association* (JAWRA) 1-15. https://doi.org/10.1111/1752-1688.12536

INTRODUCTION

Large dam removal (>10 m in height) has become a viable option over the last two decades to achieve numerous objectives including the decommissioning of unnecessary or unsafe structures (Doyle *et al.*, 2008; Warrick *et al.*, 2015) and aquatic ecosystems recovery (Heinz Center, 2002; Stanley and Doyle, 2003; Service, 2011). The release of large volumes of sediment stored in the reservoir during and following dam removal is a primary concern for large dam removal projects (Minear and Kondolf, 2009; Sawaske and Freyberg, 2012; Merritts *et al.*, 2013). Dam removal typically results in a significant increase in sediment supply downstream (*i.e.*, 3-20 times the

[1]Paper No. JAWRA-16-0130-P of the *Journal of the American Water Resources Association* (JAWRA). Received May 17, 2016; accepted April 10, 2017. **Discussions are open until six months from issue publication**.

[2]Supervisory Fish and Wildlife Biologist (Peters) and Geomorphologist (Bakke), Western Washington Fish and Wildlife Conservation Office, U.S. Fish and Wildlife Service, 510 Desmond Drive, SE, Suite 102, Lacey, Washington 98503; Statistician (Liermann) and Supervisory Research Fishery Biologist (Pess), Northwest Fisheries Science Center, NOAA Fisheries, Seattle, Washington 98112; and Habitat Biologist (McHenry), Natural Resources Department, Lower Elwha Klallam Tribe, Port Angeles, Washington 98363 (E-Mail/Peters: roger_peters@fws.gov).

average annual sediment transport), regardless of how long it takes to remove the dam (Major *et al.*, 2012; Wilcox *et al.*, 2014; Warrick *et al.*, 2015). The composition of released sediment from dam removal varies, but is generally much finer grained than most of the pre-dam removal riverbed (Kibler *et al.*, 2011; Tullos *et al.*, 2014; East *et al.*, 2015). How this increased sediment supply affects aquatic ecosystems remains unclear (Tullos *et al.*, 2014). This study examines the impacts of removing two large mainstem dams on the Elwha River on fine sediment concentrations in salmonid spawning habitat during the three-year dam removal period.

Streambed and associated aquatic habitat responses to sediment pulses associated with dam removal can vary considerably in both temporal and spatial extent, with responses ranging from minimal and temporary, to large and persistent (Kibler *et al.*, 2011; Tullos *et al.*, 2014; East *et al.*, 2015). Change to downstream aquatic habitats in the mainstem, associated floodplains, and delta areas typically can vary as a function of stream channel slope, sediment supply, and peak flow history (Stanley and Doyle, 2003; Riggsbee *et al.*, 2007; East *et al.*, 2015).

Streambed response and aquatic habitat changes have been evaluated for several large dam removals. Immediately after the Condit Dam (38 m) removal on the White Salmon River, Washington, bed material transport increased and subsequent deposition filled pools and channel margins, aggrading the channel between 1 and 2 m over 2 km downstream (Wilcox *et al.*, 2014). However, the channel incised five days later because of the diminished sediment supply exiting the reservoir and small size of the transported sediment, which was too small to armor the bed (Wilcox *et al.*, 2014). Over the course of three years, pool area below the dam decreased over 50%, while salmonid spawning habitat increased by approximately the same amount (Hatten *et al.*, 2016). The Marmot Dam (14 m) removal on the Sandy River, Oregon, resulted in deposition immediately downstream of the dam which persisted four years after removal; however, there was no apparent change in streambed composition 7-12 km downstream (Cui *et al.*, 2014). After the Milltown Dam (~10 m) removal in the Clark Fork River, Montana, deposition of fine sediment (<2 mm) and intrusion of fines into the streambed pore space were minimal in reaches that were dominated by complex channel features, high sediment supply, and mobile streambeds (Evans and Wilcox, 2013). These dam removal projects differ from Elwha dam removals in that they were rapid, occurring within several days or months, while the dam removals on the Elwha were staged over the course of a three-year period (Warrick *et al.*, 2015). In addition, these dam removal projects were smaller than the removals on the Elwha River (32 and 64 m) and resulted in much smaller releases of sediment. The slower rate of dam removal was selected to reduce turbidity levels downstream to protect water supplies for human consumption and fisheries resources (Randle *et al.*, 2015). These pulsed releases along with the steep gradient were expected to result in a majority of fine sediment being transported through the river system. If this assumption was correct, fine sediment deposition within salmonid spawning habitat should be minimal. However, given the large quantities of material to be released, it is hypothesized that some fine sediment deposition will occur.

Newly deposited sediment from dam removal in the Elwha River, Washington, resulted in 2- to 10-fold changes in bed elevation relative to the previous four years (East *et al.*, 2015). Significant channel changes occurred, including increased gravel bar area, channel avulsions, floodplain channel aggradation, and reduced streambed particle size over the entire river area below the dams (East *et al.*, 2015). The altered geomorphic conditions and streambed sediment composition along the Elwha River may have important ecological implications, potentially affecting aquatic habitat structure, benthic fauna, and salmonid spawning and rearing habitat (East *et al.*, 2015).

Although the impacts of increased sediment supply resulting from dam removal on aquatic ecosystems remain unclear (Tullos *et al.*, 2014), the impacts of fine sediment on biological communities including periphyton, invertebrates, and fish have been extensively reported (Wood and Armitage, 1997). Fine sediment deposition can affect salmonids during all life stages; however, impacts during the incubation period have been the most widely reported (Jensen *et al.*, 2009). The impact of fine sediment on incubation survival varies by species and fine substrate size, but survival decreases substantially at fine sediment concentrations >25-30% (Jensen *et al.*, 2009). An improved understanding of fine sediment impacts to salmonid spawning habitat resulting from dam removal is important to understand given the large volumes of fine sediment generally released through dam removal and the sensitivity of salmonids to fine sediment impacts in spawning habitat.

This study examines the influence of a long-term dam removal project and the associated release of large volumes of sediment on riffle substrate composition downstream of the dams during dam removal (three-year period). In addition, we examine the influence of two factors that may influence changes in riffle substrate composition, time (year) and channel type. Specifically, our study addresses two questions related to quantifying streambed composition changes following sediment releases during dam removal in the Elwha River (Table 1). First, does streambed composition differ among years? Second, do changes in streambed composition vary between mainstem and floodplain channels? Changes in streambed composition, especially fine sediment, are discussed relative to salmonid spawning habitat. This study summarizes data collected prior to (2010 — mainstem; 2011 — floodplain channels) and during dam removal (2012-2014 — mainstem and floodplain channels) to address the questions above and to examine the relative importance of these factors (*i.e.*, time, channel type) on short-term sediment composition downstream of a large-scale and longer-duration (three years) dam removal project.

Study Area

The Elwha River's 833 km^2 watershed begins at an elevation of 2,120 m in the Olympic Mountains of Washington State's Olympic Peninsula (Figure 1). The Elwha flows north for 72 km before emptying into the Strait of Juan de Fuca. The mountains, composed of metasedimentary rock, are subject to frequent landslides supplying relatively large volumes of sediment and are situated in a maritime climate with dry summers and cool, wet winters (Acker *et al.*, 2008). The average annual precipitation is 550 cm in the headwaters and 100 cm near the river mouth with peak flow events driven by both winter rain-on-snow precipitation events and late spring/early summer snowmelt (Duda *et al.*, 2008). Average annual discharge and the median (two years) peak discharge are 42 and 400 cm, respectively (Curran *et al.*, 2009).

The construction of Elwha Dam (7.9 Rkm) and Glines Canyon Dam (21.6 Rkm) completed in the early 1900s, prevented anadromous fish from accessing about 90% of the watershed (Pess *et al.*, 2008). Elwha and Glines Canyon dams, which impounded Lake Aldwell and Lake Mills, respectively, impounded approximately 21 Mm^3 ($\pm$3 Mm^3) of sediment (Warrick *et al.*, 2015). Most of this sediment was trapped behind Glines Canyon Dam (16 $\pm$ 1.2 Mm^3), with the remaining sediment (5 $\pm$ 1.4 Mm^3) impounded by Elwha Dam. Just over half of the sediment trapped behind the dams was coarse material (Glines — 56%; Elwha — 53%) and the rest was composed of silt and clay (<0.063 mm) (Warrick *et al.*, 2015).

The Elwha River consists of several alternating bedrock canyons and alluvial floodplain reaches (Pess *et al.*, 2008). The alluvial Lower Elwha River, below former Elwha Dam, has an average slope of 0.4%. The Middle Elwha River, between the former Elwha and Glines Canyon dams, has a slope of 0.7-0.8% (East *et al.*, 2015). Before dam removal, the streambed in the Lower and Middle Elwha was armored with predominately cobble-sized material due to incision and reduced sediment loads in response to the dams (64-256 mm) (Childers *et al.*, 2000; Pohl, 2004; Draut *et al.*, 2011).

The removal of both dams, initiated in the fall of 2011, released an estimated approximately 7.1 Mm^3 (~9.2 Mt) of sediment during the first two years, 6 Mm^3 (~7.8 Mt) from Glines Canyon Dam (~37% of stored sediments) and 1.1 Mm^3 (~1.4 Mt) from Elwha Dam (~23% of stored sediment) (Warrick *et al.*, 2015). The release represents a decade's worth of sediment based on the estimated normal sediment transport of approximately 147,000-500,000 m^3/yr (2.17×10^8-5.13×10^8 Mt) (Curran *et al.*, 2009; Czuba *et al.*, 2011).

Sand and gravel began flowing over Glines Canyon Dam in October of 2012 (Randle *et al.*, 2015). Bedload transport during the second year after dam removal was about an order of magnitude greater than the first year (Magirl *et al.*, 2015). Approximately 23% of the sediments stored in the former Lake Aldwell (formed by Aldwell Dam) had been transported past the former dam site, with 85% of the erosion occurring in the first year (Randle *et al.*,

TABLE 1. Summary of the Hypotheses Tested in This Study for Four Different Response Variables; Proportion <0.85 mm in the <75 mm Fraction, Proportion <3.35 mm in the <75 mm Fraction, Proportion Gravel (>2 and <75 mm), and Proportion >75 mm in the Total Sample. The independent variables assessed, their definition, and test are also included in the table.

Independent Variables	Definition	Hypothesis	Conclusions
Year	Yearly samples were collected with 2010 and 2011 representing pre-dam removal and designated as "Pre" and data collected after 2012 representing initiation and completion of dam removal	The response variables will vary by year	Response variables varied by year as well as with substrate size and channel type
Channel	Channel type sampled: main channel or floodplain channel	All four response variables will vary with channel type	Response variables varied by channel type

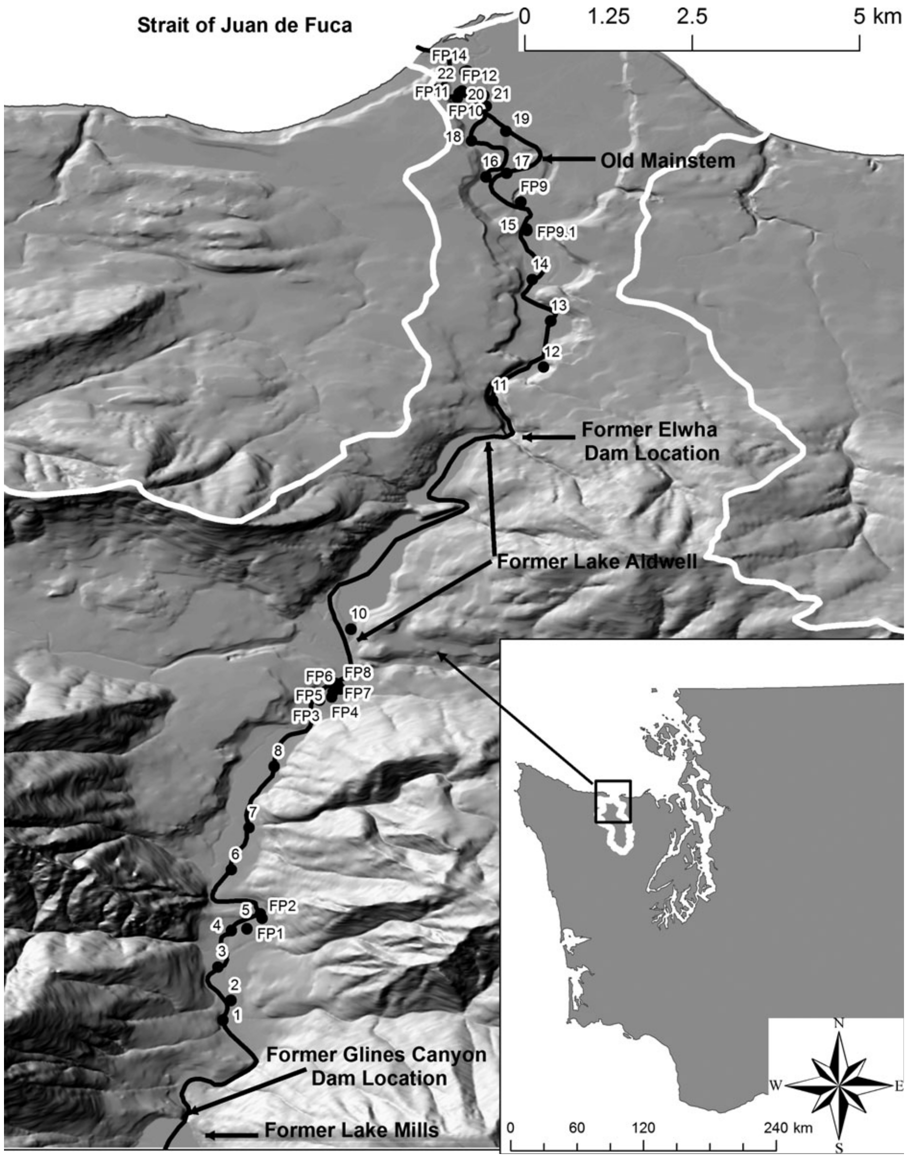

FIGURE 1. Elwha Study Area and Sites Sampled during Late Summer 2010-2014, Showing the Former Dam Locations and the Old Mainstem. The base layer is USDA/NRCS 10 m national elevation data. The white line on the insert map and the main map show the watershed boundary.

2015). As of September 2013, new sediment storage in the lower 18 km of the Elwha River was estimated at 580,000 m^3 (East *et al.*, 2015).

METHODS

Field Methods

The proportion of fine sediment ($\leq$3.35 mm) and salmonid spawning gravel (3.35-75 mm) in the Elwha River below the former dams (Glines Canyon and Elwha dams, respectively) was quantified by sampling 20 of 46 selected riffle crest sites in the mainstem, and 18 floodplain channel sites during August and September 2010-2014. The 20-mainstem sampling sites were randomly selected from the population of riffle crests available in 2010 from 21.6 Rkm to the river mouth (Figure 1). Floodplain channels, defined as channels in the 100-year floodplain that can be inundated by water either during low- or high-flow periods (Peters *et al.*, 2014), were selected using a randomly stratified sampling scheme in order to coincide with ongoing biological sampling efforts and were generally sampled at the upstream and downstream end of each channel (*e.g.*, Morley *et al.*, 2008). Three subsamples were collected at each mainstem site and large floodplain channels, whereas two sub-samples were collected at narrower (<5 m wetted width) floodplain channels. When possible, subsamples encompassed the entire riffle crest. One subsample was collected in the center of the riffle crest and two closer to each bank at mainstem locations. In smaller floodplain channels, the two subsamples were situated closer to each bank. Where this was not possible due to water depth and/or velocity, we sampled along one bank, at the upstream, downstream, and mid riffle crest portion of the site. Subsamples were combined to calculate an average streambed composition at the site for use in comparisons.

A modified plywood shield (Bunte and Abt, 2001) was used to define a sampling area of approximately 0.10 m^2. We modified the shield from a three-sided box, to a shield with four sides to provide a "V" configuration into the current, which provided better deflection of the fast and deep water of the Elwha River. The shield was placed on the streambed with the open-end downstream to provide a protected area for sampling. A depth-integrated water sample was collected from the sampling location to estimate the proportion of suspended sediments in the water column prior to sampling. The average depth within the sample area was estimated by measuring five water depths with a ruler near the largest rocks (*i.e.*, representing D_{84}) within the sampling area, but were spaced out as much as possible. Three to five of the largest surface layer rocks, estimated to represent the 84th percentile particle size (D_{84}), were removed, measured, and weighed on-site. Water depths were measured in the voids left by the removed particles to determine an average excavation depth. The surface layer was defined as the material lying between the original channel bottom and the average depth of the voids left by the rocks removed (Bunte and Abt, 2001). The surface layer was then uniformly excavated and placed into a canvas bag using cupped hands to avoid losing the fine sediment fraction. Each sample was marked with the date, study site, and within-site location (*i.e.*, left bank, right bank, and middle). Once the sample was completely removed, a second depth-integrated water sample was collected while the water was still turbid from the removal of the surface layer to assess the weight of fines dislodged into suspension during sampling (see below).

The length, width, original depths, and final depths of the excavated area were recorded and used to calculate the volume of water within the sampling area, which were used to estimate the weight of fines suspended in the water column (see below). In some cases, the site had large particles that were difficult to transport back to the laboratory (generally, 90 mm or larger). The intermediate- or *b*-axis of these large particles was measured (Bunte and Abt, 2001) and the particle weighed in the field. Smaller rocks (<6 kg) were weighed with a platform scale accurate to 0.001 kg (Acculab VI-6 kg, Acculab USA, Edgewood, New York), while larger rocks were placed in a sample bag and weighed using a spring scale accurate to 0.1 kg (Intercomp CS200, Intercomp, Medina, Minnesota).

Bulk samples were taken to a laboratory, dried, and sieved following standard procedures (Bunte and Abt, 2001). Samples were shaken through sieves having openings of 75, 26.5, 13.2, 9.5, 3.35, 2.0, 0.85, and 0.106 mm on an electric-powered shaker for 5-10 min. Particles in each sieve were weighed using a platform scale accurate to the nearest 0.001 kg (Ohaus Valor 2000w, Ohaus, Parsippany, New Jersey).

Water samples collected prior to and following the bulk sample collection were used to determine the weight of fine sediments dislodged during sample collection, but too small to be transferred to the bulk sample bag. This sampling assumes only fines within the surface layer were suspended and that the suspended sediment concentrations are uniform within the shield, thereby allowing the calculation of total weight from the volume of water within the shielded sampling area. The concentration of suspended sediments (mg/l) in the water samples associated with each bulk sample collected was determined by laboratory filtration using a modified standard methods approach (Franson, 1985). Fiberglass filters (90 mm diameter) were washed (using 30 ml distilled water) and dried (103-105°C for 4 h) two separate times to remove dust and loose fibers. Filters were weighed to 0.0001 mg at the beginning and end of each wash/dry cycle (Denver Instruments SI-234, Denver Instrument, Bohemia, New York). Suspended sediment samples were shaken for 5 min using an electric sediment shaker fitted with a bottle holder. Once shaken, 200-300 ml of the sample was quickly poured into a graduate cylinder and the volume noted. This subsample was slowly poured onto the glass filter to allow the water to be sucked through the filter by a vacuum pump. Once the entire subsample was processed, the graduated cylinder was washed three times using 20 ml of distilled water, which was also poured onto the filter. The funnel supporting the glass filter was washed three consecutive times and allowed to drain completely. The filter was then removed and dried in an oven overnight at 103-105°C, weighed, and placed in a muffle furnace at 550°C for 15 min to burn off any organic matter. The filter was weighed again after cooling.

The suspended sediment concentration following sample collection was calculated by subtracting the original, clean, washed, and dried filter weight from the final filter weight, and then dividing this difference by the volume of water filtered. The background concentrations obtained from the water sample collected before the substrate sample was collected were subtracted to calculate the suspended sediment concentration generated by sample collection. The total weight of nonorganic solids suspended during sampling was then computed by multiplying this concentration by the estimated volume of water within the shield based on sample area dimensions and water depth. The estimated fine sediment weight determined from this procedure was included in the <0.106 mm size fraction in the sample analysis.

Data were stratified by mainstem channel and floodplain channels, and summarized for percent <0.85 mm, percent <3.35 mm, percent gravel (>3.35 mm, <75 mm), and percent cobble (>75 mm). Percent <0.85 mm was used as a threshold because this substrate size has the greatest impact on salmonid egg survival (Jensen *et al.*, 2009). Percent <3.35 mm was selected as a size category for correspondence to the sizes reviewed by Jensen *et al.* (2009). Percent <0.85 and 3.35 mm were calculated based only on that portion of the sample <75 mm, for statistical comparisons of fine sediments among years and channel types, to reduce the potential for bias which can result when a few extremely large particles make up a large proportion of the overall sample weight, and a practice that is consistent with methods reported elsewhere (Evans and Wilcox, 2013).

Statistical Analysis

We used a Bayesian multilevel beta regression model (Gelman *et al.*, 2014) to estimate the mean proportions for each substrate class (<0.85, <3.35 mm, gravel, and cobble) and channel type (mainstem or floodplain). The mean proportion was modeled as an intercept plus factors accounting for site, year, river section (middle, lower), and section by year (to account for dam removal), with a logit link, $logit(\mu_{\text{site,year,section}}) = a + b_{\text{site}} + c_{\text{year}} + d_{\text{section}} + e_{\text{year,section}}$. The values for the site effect (b_{site}) were assumed to come from a common distribution (*i.e.*, site was modeled as a random effect). All statistical inference was based on graphical display of 95% credible intervals for group medians (comparable to confidence intervals, Gelman *et al.*, 2014). For cases where two intervals are compared, nonoverlapping intervals provide strong evidence for a difference (*i.e.*, the test is conservative). We highlighted general patterns and avoided emphasis of isolated results. Details on implementation of the analysis are provided in Appendix.

RESULTS

Substrate composition varied by year, channel type, and section (Lower Elwha River and Middle Elwha River) (Figures 2-4; note that nonoverlapping CIs in Figure 4 indicate a statistically significant difference where $p < 0.05$). Small substrate classes (<0.85 and <3.35 mm) increased the most during dam removal in the floodplain channels (Figures 2-4). The estimated median percent <0.85 and <3.35 mm combined in the floodplain channels increased from close to zero prior to dam removal to over 50% in the Lower Elwha River in 2014 and >99% in the Middle Elwha River in 2013 (Figures 3 and 4). Increases in fine sediment (<0.85 mm) from pre-dam to 2013 and 2014 were most pronounced in the Middle Elwha River floodplain channels with fines representing <3% at all sites pre-dam removal and >99% at all except one site in 2013 (Figures 3 and 4). Trends in percent fines in the Lower Elwha River floodplain channels were on average positive, but inconsistent, with a combination of increases and decreases (Figure 4). There was a larger increase between 2012 and 2013 in the Middle Elwha River floodplain channels and a smaller and more gradual increase in the Lower Elwha River floodplain channels during that same time span. These increases coincided with the respective removal of each dam. The percentage of smaller substrate (<0.85) at the mainstem sites was negligible both pre- and during dam removal.

The proportion of gravel pre- and during dam removal was also different in the floodplain and mainstem channels (Figures 2-4). There was a decrease in amount of gravel in the Middle Elwha River floodplain channels from 2012 to 2013, which coincided with an increase in the proportion of substrate <0.85 and 3.5 mm. In the mainstem channel, gravel increased in both the Middle Elwha and Lower Elwha River in 2013, followed by a slight decrease in 2014 (Figure 4).

DISCUSSION

The accumulation of fine- and gravel-sized sediments in the Elwha River during dam removal varied as a function of channel type (mainstem or floodplain) and the amount and size of sediment transported in a given year. The results suggest an interaction between channel type and substrate size (Figure 4). In floodplain channels, the proportion of fine sediments in the surface layer increased and remained high during the study period, while gravel and cobble decreased and remained low during the study period (Figure 3). In contrast, the mainstem had relatively little change in fine sediments in the surface layer but a large increase in the proportion of gravel starting in 2013 (Figure 2). Sediment composition at mainstem sites trended toward their pre-dam

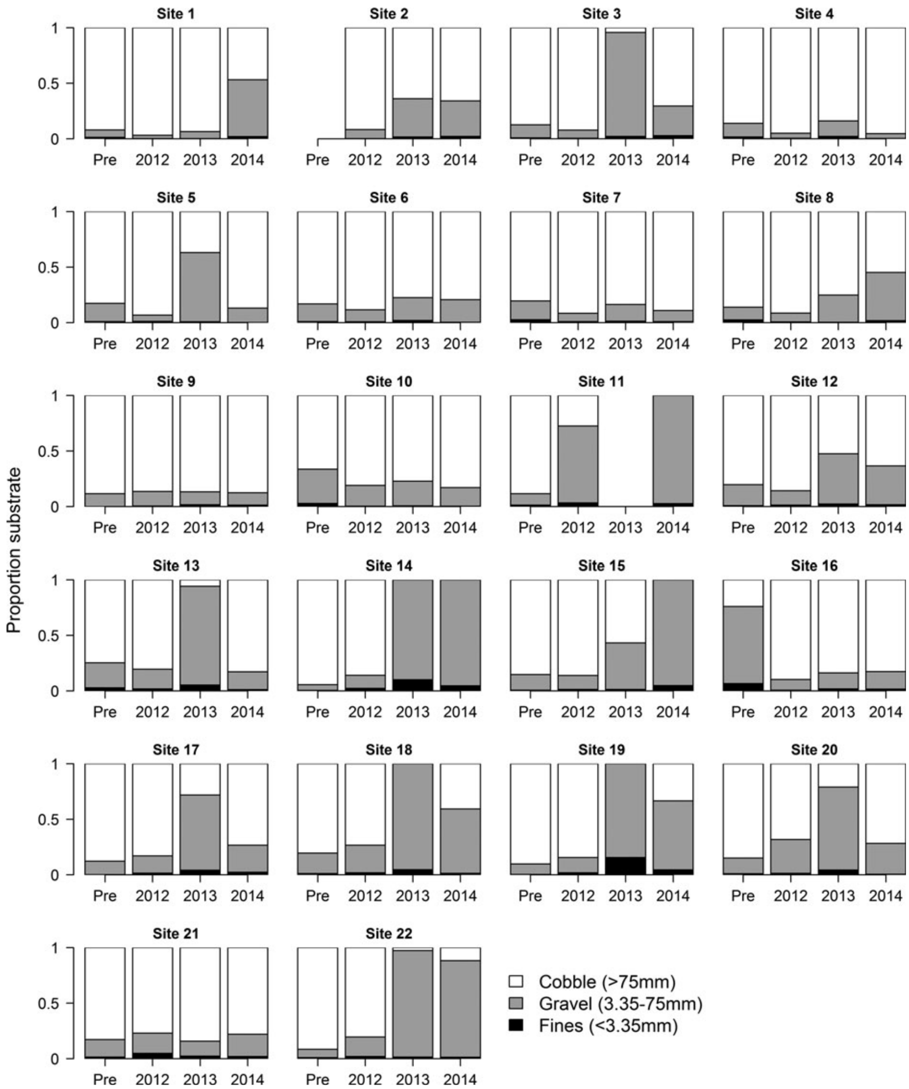

FIGURE 2. Bar Charts Showing the Proportion of Fines (<3.35 mm), Gravel, and Cobble at Mainstem Sample Sites in the Elwha River from Pre-Dam Removal (2010) and during Dam Removal (2012-2014). Sites are organized from upstream to downstream (1-22) and coincide with the numbers on Figure 1. Sites 1-10 are in the middle river and sites 11-22 in the lower river. Site names listed above each bar chart are consistent with those in Figure 1.

removal distribution in 2014, while no such trend was observed in floodplain channels (Figures 2-4). These changes were consistent with the timing and composition of sediment released from the two dams. Specifically, initial stages of dam removal resulted in the release of fine sediment, followed by coarser sediment near the completion of dam removal, particularly from the former Mills reservoir (impounded by Glines Canyon Dam) (East *et al.*, 2015; Randle *et al.*, 2015; Warrick *et al.*, 2015).

This difference in fine sediment accumulation in the floodplain channels and rapid reduction in fine sediment in the mainstem (Figure 4) is, in part, due to the somewhat anomalous river hydrology during the period of study (East *et al.*, 2015). Peak flows were lower than normal during the phased dam removal (Figure 5). This muted flood regime (no flows approaching the two-year flood as of September 2013) restricted the spatial extent and potentially the magnitude of channel changes that might have occurred given bankfull or greater flooding (East *et al.*, 2015). Specifically, while hydrology in the mainstem was sufficient to transport fine sediment in the mainstem channel, it was insufficient in floodplain channels, resulting in them becoming a sink for finer material (East *et al.*, 2015). Floodplain channels were expected to serve either as a sink for sediment deposition (*i.e.*, sediment plugs) or as refugia for fish during the sediment pulses (Pess *et al.*, 2008; Konrad, 2009; Peters *et al.*, 2014). Based on our results and other results with respect to channel form (East *et al.*, 2015), it is clear floodplain channels have become a sink for fine

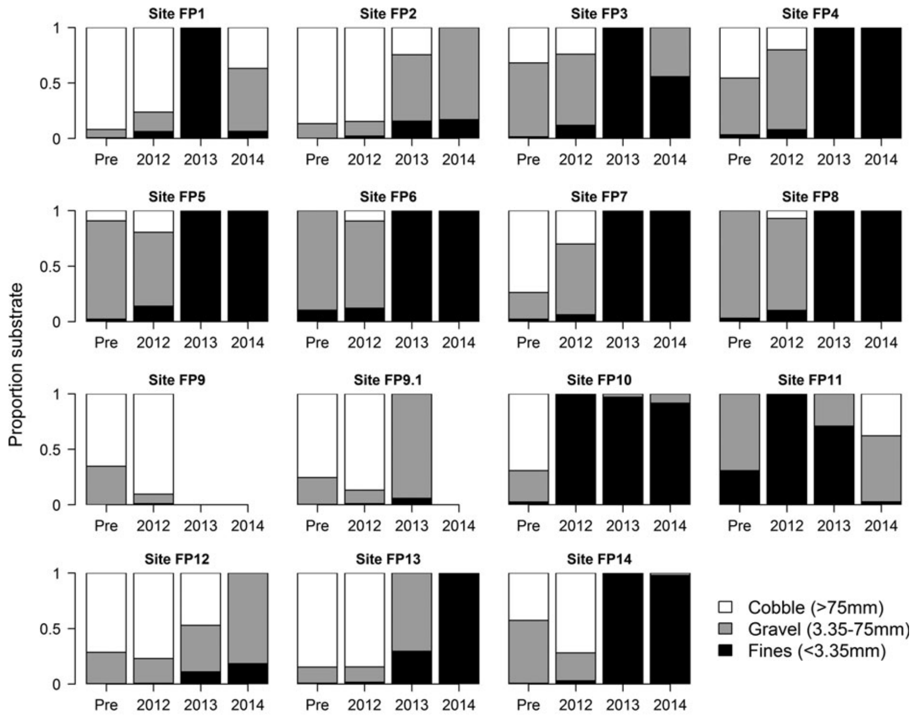

FIGURE 3. Bar Charts Showing the Proportion of Fines (<3.35 mm), Gravel, and Cobble at Floodplain Sample Sites in the Elwha River. Sites are organized from upstream to downstream (FP1-FP14, except FP9.1 is upstream of FP9) and the names listed above each chart coincide with the numbers on Figure 1. Sites FP1-FP8 are in the middle river and sites FP9-FP14 in the lower river.

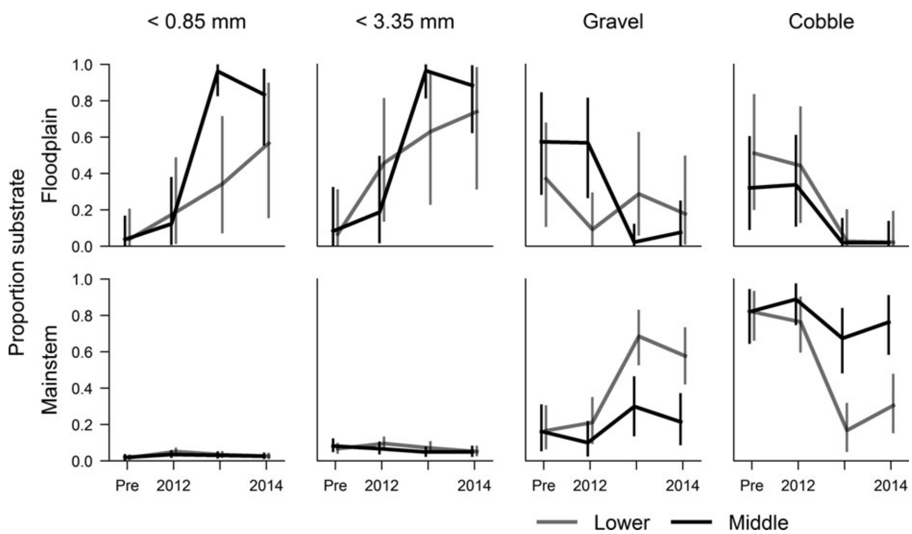

FIGURE 4. Estimated Median Proportion of Substrate Composed of <0.85, <3.35 mm, Gravel, and Cobble over Time for Floodplain and Mainstem Sites in the Lower Elwha River and Middle Elwha River. Pre includes data collected in 2010 and 2011 prior to dam removal. Error bars represent 95% credible intervals (CIs). The substrate class' proportion <0.85 mm and proportion <3.35 mm are calculated as a proportion of substrate <75 mm. Note that nonoverlapping CIs indicate a statistically significant difference where $p < 0.05$.

sediments in the near term and have stored a considerable portion of the fine sediments released during dam removal that was not transported to the Strait of Juan de Fuca and Elwha River delta (Warrick *et al.*, 2015). It remains unclear if floodplain channels will be permanent sediment sinks or will become a source of fine sediment in the future (*i.e.*, Madej and Ozaki, 1996). We hypothesize that sediment stored in floodplain channels will evacuate more slowly than that in the mainstem and this evacuation will be quite variable. Our future long-term monitoring will address this hypothesis.

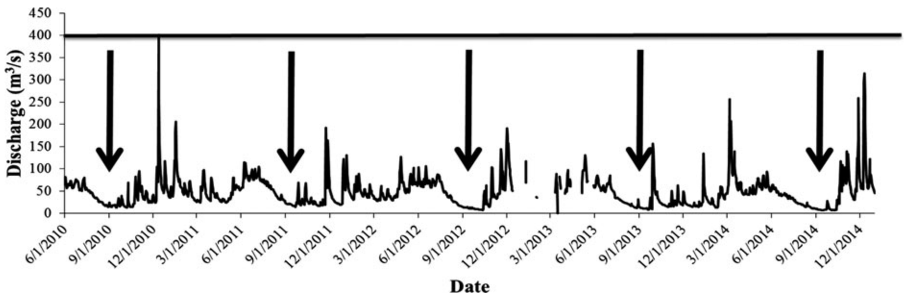

FIGURE 5. Elwha River Daily Mean Discharge Measured at USGS Station 12045500; Elwha River at McDonald Bridge. The arrows show when bulk gravel samples were collected each year (August-September). The solid horizontal line represents the two-year recurrence interval flood calculated for this station. Data retrieved from http://waterdata.usgs.gov/wa/nwis/uv?station=12045500.

The difference in sediment accumulation between the mainstem and floodplain channel substrates (Figure 4) has potential implications to salmonids. Potential spawning habitat in floodplain channels (Figure 3) has been almost completely covered with fine sediment (90%), while mainstem spawning habitat (Figure 2) has relatively low percentages of fine sediment present (~6%) (during summer low flow). In addition, nearly half of the main channel sites have transitioned from cobble dominated to having similar proportions of gravel and cobble, making them more suitable for spawning salmonids. The remaining main channel sites are currently composed of cobble, which is at the upper size range for spawning salmonids. The difference among floodplain and mainstem channels has several potential effects on all life-history stages of salmonids. First, many of these floodplain channels have completely filled in and contain very little flow during the winter and no flow during the summer. Floodplain channels provide important spawning (*i.e.*, Morley *et al.*, 2005; Hatten *et al.*, 2014) and rearing habitats (*i.e.*, Bustard and Narver, 1975; Murphy *et al.*, 1989; Sommer *et al.*, 2001) for some salmonid species. The reduced or eliminated seasonal flow resulting from sediment deposition significantly reduces or eliminates this habitat. This should not appreciably affect Chinook salmon or steelhead, as few of these fish spawn in Elwha floodplain habitats (McHenry *et al.*, 2016). However, the distribution of other salmonids (*i.e.*, coho, pinks, chum) among floodplain and mainstem habitats has not been evaluated extensively in the Elwha River. Second, even if spawning salmonids could get into floodplain channels they may not spawn there, or their progeny would be unsuccessful due to the high proportion of finer sediment. In contrast, spawning salmonids will likely utilize the mainstem sites due to more suitable depths, velocities, and substrate. Salmonids that spawn in floodplain channels conversely also have a higher likelihood of deleterious effects at other life stages such as the egg to fry life stage due to elevated fine levels (Jensen *et al.*, 2009) assuming low-flow samples collected during this study reflects conditions likely to occur during incubation. Mainstem sites will have a higher likelihood of being utilized at the spawning life stage and a lower likelihood of deleterious effects at the egg to fry life stage resulting from fine sediment impacts because of the lower levels of fine sediment (Jensen *et al.*, 2009), again assuming low-flow samples collected during this study reflect those likely to occur during incubation. The loss of spawning habitat in floodplain channels may appreciably affect salmonids that prefer to spawn in those habitat types to the mainstem.

Our result that fine sediment concentrations were low in the mainstem includes several caveats. Our sampling method resulted in a relatively small sample being collected from individual large riffle crests of the mainstem Elwha and the samples represent conditions during a single point in time; summer low-flow conditions. When combined, the three subsamples from each riffle represented an average area of about 1.25 m^2. Diplas and Fripp (1991) recommend that areal samples should be a minimum of 100 times the area of the largest particle, while Fripp and Diplas (1993) recommend 400 times the largest particle to obtain precise estimates of all particle sizes. Individual particles with surface areas of 0.15 m^2 were common during sediment sampling in the Elwha River from 2010 to 2013 (Roger J. Peters, unpublished data). Given this, sampling areas of 15-60 m^2 would be required to obtain an unbiased sample based on these areal methods. Sampling this area is logistically impractical and environmentally undesirable. Thus, the total area sampled during our sampling efforts was small relative to that required to obtain unbiased samples. To counteract this potential bias, the percent fine sediment (both <0.85 and 3.35 mm) was calculated based on the overall sample weight of only those particles <75 mm — the largest sieve used to characterize particle size in this study. Eliminating the extremely large particles from the calculation reduces the overall area recommended for sampling, which reduces the potential bias associated with very large particles and is consistent (other than the specific maximum size class used) with methods reported elsewhere (Evans and Wilcox, 2013).

The potential bias described above is also possible for floodplain channels; however, to a lesser extent due to the generally smaller substrate size in floodplain channels prior to (Pess *et al.*, 2008) and during dam removal (*i.e.*, data collected during this study). Two subsamples were collected in most floodplain channels, so the area sampled was about 0.8 m^2. However, particles up to 190 mm (~0.04 m^2) were present, requiring a sample area of approximately 4 m^2 to obtain unbiased estimates. This potential bias existed for only five of the thirteen floodplain sites sampled. However, with the exception of two of these sites, concentrations of the <0.85 mm particles were >10%, a level reported to result in increased incubation mortality (Jensen *et al.*, 2009). Thus, even with this potential bias against fine sediment concentrations, the concentration of 0.85 mm particles was sufficient to affect incubation survival of salmonids, assuming any salmonids spawned in these channels. In addition, our results are similar to those reported by Pess *et al.* (2015), who reported significant fine sediment (<2 mm) accumulations in floodplain channels from the Lower and Middle Elwha River. Finally, by calculating percent fine sediment based on the total weight of sediment <75 mm the potential for this bias was reduced.

Fine sediments (*i.e.*, <0.85 and <3.35 mm) have been declining since 2012 in main channel sites (Figure 2) and levels are still below levels reported to reduce incubation survival. In addition, the bed appears to be degrading back to its original elevation and re-exposing previous cobble substrates, an observation supported by East *et al.* (2015). The somewhat reduced deposition in floodplain channels between 2013 and 2014 (Pess *et al.*, 2015) has also resulted in increased substrate size in several of the floodplain sites sampled, although at a much slower rate (Figure 3).

The minor accumulation of fine sediments in the mainstem was unexpected given the pre-dam removal estimated sediment releases (Randle *et al.*, 2015). However, this is less surprising given observations since dam removal. First, sediment released during the removal of the two Elwha dams was transported through dispersion processes (East *et al.*, 2015), a process where the sediment accumulation decays in place. Sediment is eroded from the crest of the accumulation and deposited downstream of the crest, while sediment upstream of the crest is trapped upstream (Pizzuto, 2002). Dispersive transport is expected to have less severe impacts than sediments transported through translation processes, where a sediment accumulation is transported in a wave with no decrease in amplitude (Pizzuto, 2002). Second, no flood magnitude greater than the two-year recurrence interval (400 m^3/s) occurred during the study. This likely resulted in reservoir sediments being transported over the surface of the unaltered armored layer that existed prior to dam removal (*i.e.*, Phase I transport, Jackson and Beschta, 1982). Third, the Elwha River is a relatively steep, high-energy system and apparently has sufficient power to transport significant increases in sediment above background levels in relatively short time periods (Warrick *et al.*, 2015). This resulted in approximately 90% of the sediment passing through the riverine system to the coast during the first two years of dam removal, with a greater proportion of fines transported relative to coarse sediments (Warrick *et al.*, 2015). Finally, former Lake Mills sediment releases during the first two years of dam removal were primarily coarse sediment due to the progradation of the coarse delta sediments over the finer sediments deposited on the lake bottom (Warrick *et al.*, 2015). This likely resulted in the coarse sediments in the delta moving downstream and covering the fine sediments, thereby preventing their release until the overlying coarse materials were eroded. The fine sediment layers were not likely released in large volumes until the river began to incise into the fine surface layer of the former Lake Mills sediment delta during winter 2012-2013, with the fine sediment layer not being intercepted by the river for the entire length of the former lakebed until the early part of 2014 (Jennifer Bountry, Technical Service Center, Bureau of Reclamation, December 18, 2015, personal communication). These combined factors apparently limited fine sediment deposition in the mainstem downstream of the two dams.

Our observations of relatively low proportion of small fine sediment composition in Elwha mainstem riffles (Figure 2) are consistent with observations from other dam removal projects. The work of Evans and Wilcox (2013) provides the best comparison for our work, as both studies assessed fine sediment using bulk sampling techniques. Evans and Wilcox (2013) reported no significant fine sediment deposition in a morphologically complex reach that included multiple channels and gravel bars. In contrast to our observation, Evans and Wilcox (2013) did not report greater fine sediment deposition in side channels. No significant fine sediment deposits were observed in the Sandy River following removal of Marmot Dam (Cui *et al.*, 2014), where fine sediments increased only about 10% 13 and 30 km downstream of the Marmot Dam removal project (Major *et al.*, 2012). Gravel and fine sediment filled pools and created bars in the White Salmon River following the removal of Condit Dam; however, fine sediments decreased by

34% overall and spawning habitat increased as a result of habitat transition from pools to glides and riffles (Hatten *et al.*, 2016). Thus, it appears that fine sediment releases during and shortly after dam removal (less than three years) have little impact on the proportion of fine sediment in the gravels of mainstem salmonid spawning habitat. Evans and Wilcox (2013) suggest that scour during winter flows as a potential explanation for this observation. Aggradation was observed in all of the studies described above and for the Elwha (East *et al.*, 2015). The hypothesis that scour helped reduce fine sediment levels in the substrate is consistent with hypotheses that scour increases in systems with sediment transport imbalances (Tripp and Poulin, 1986; DeVries, 2000), a common occurrence for dam removal projects. Thus, it may be important for future dam removal projects to assess scour as both a source of mortality for spawning salmonids and as a sediment transport mechanism resulting in efficient fine sediment transport that limits fine sediment intrusion into spawning habitat.

The question now turns to what extent fine sediments pose a long-term threat to biological communities now that dam removal is complete? The answer to this question depends on the volume and type of sediment eroded from the reservoirs in the future, which will depend on future hydrology and soil stabilization resulting from revegetation, and the channel type. Estimates of total sediment erosion from the two reservoirs vary drastically. Predictions range from 10-25% (Randle *et al.*, 1996) to 97% (Konrad, 2009) for the former Aldwell reservoir, and 50-60% (Randle *et al.*, 1996) and 70-90% (Konrad, 2009) for the former Mills reservoir. Approximately 46% and 26-34% of the sediment had eroded from the former Aldwell and Mills reservoirs, respectively, during the first two years following dam removal (Randle *et al.*, 2015). Although erosion is expected to continue (East *et al.*, 2015), the rate of erosion has slowed and appreciable (no quantitative estimate provided) portions of the sediment are expected to remain in the two reservoirs (Randle *et al.*, 2015). Apparently, the majority of the sediment release has occurred and future releases should be much smaller and more similar to normal background levels, while also being more episodic based on flood levels. The observations of reduced sediment export from the reservoirs over time are consistent with other dam removal projects (*e.g.*, Pearson *et al.*, 2011; Major *et al.*, 2012), as reservoir sediments transition from process-driven to event-driven transport (Pizzuto, 2002).

Although overall sediment releases are expected to decline, fine sediment releases may represent a greater proportion of the transported sediment as the river begins to erode the finer-grained lakebeds (Warrick *et al.*, 2015). As of September 2013, there were approximately 8 Mt of fine-grained sediment in the two reservoirs (~2 Mt from Lake Aldwell and ~6 Mt from Lake Mills) (Warrick *et al.*, 2015). However, these remaining sediments are more cohesive than the coarser sediments transported from the former reservoir during delta progradation due to the abundance of wood materials, leaves, proportion of clays (10-20%), and increased bulk densities that contributed to greater cohesiveness (Randle *et al.*, 2015). These cohesive sediments are expected to be less prone to erosion than the less cohesive sediments eroded during and shortly after removal was complete (Sawaske and Freyberg, 2012). Thus, fine sediment erosion from the former reservoirs is expected to be less than that documented during the first two years following dam removal.

Sediment stored in upstream reaches of the main channel, floodplain channels, and the floodplain also may become a sediment source for downstream reaches in the future. Madej and Ozaki (1996) reported upstream reaches retained sediment, thereby reducing transport to downstream reaches initially but noted those stored sediments became important sources in the future. Warrick *et al.* (2015) estimated that approximately 1.2 Mt of sediment was captured in the riverine system, with a majority (75%) captured in the main channel. However, only a small fraction of this stored sediment (~4%) is fine-grained material and therefore unlikely to negatively affect spawning habitats in the future. Transport of these stored materials may greatly benefit floodplain channels, as fine sediment that filled these channels would then be transported, presumably leaving substrate conditions more similar to those prior to dam removal.

Although total sediment transport in the future is expected to decline to near background levels as sediment transport from the former reservoirs becomes event driven (Pizzuto, 2002; Randle *et al.*, 2015), fine-grained sediments will likely be a greater proportion of the sediment transported in the future. The efficiency of sediment transported through the mainstem may be because dispersion transport processes dominated the transport of released materials from the reservoirs (East *et al.*, 2015), which is consistent with conceptual models (*e.g.*, Pizzuto, 2002). In addition, Phase I transport, the movement of sediments over the top of a stable substrate matrix (Beschta and Jackson, 2008), likely dominated transport through the mainstem due to small flood magnitudes observed since dam removal was initiated. This may have resulted in the limited fine sediment deposition observed in the mainstem to date and the large accumulations of fines in the floodplain channels. It is unlikely that these processes will continue to dominate in the future. East *et al.* (2015) suggest that the Elwha River may require decades or more to adjust to sediment pulses resulting from dam removal. Future hydrology will obviously have a major influence on the volume of sediment exported from the two former reservoirs in the future due to the observation that sediment transport has moved from process-driven to event-driven processes (*e.g.*, Randle *et al.*, 2015). Although larger events, which have been limited since dam removal, have the potential to transport larger volumes of sediment, they are also more likely to deposit those sediments in the floodplains, where limited deposition occurred during the first two years following dam removal (East *et al.*, 2015). Our observations to date suggest the initial pulse of sediment resulting from dam removal had limited impacts on fine sediment levels in downstream main channel riffle crests, but have covered existing sediments in floodplain channels with a layer of fine sediment. Fine sediment deposition in floodplain channels was due to mainstem bed aggradation that resulted in floodplain channels receiving flow and sediment accumulation even during low flows (East *et al.*, 2015). Due to the initiation of mainstem incision (East *et al.*, 2015), greater discharges will be necessary to activate and transport sediments from these floodplain channels. We predict that future sediment releases resulting from the final stages of sediment transport from the reservoirs also will have limited impact on spawning habitat in the mainstem channel. We expect larger discharges (event-driven processes) will result in flushing fine sediments out of some floodplain channels, while others will likely be abandoned and become part of the exiting floodplain, and new ones likely formed through avulsions resulting from the increased sediment supplies.

During the three-year dam removal process, impacts from fine sediments on salmonid spawning habitat have been severe for floodplain dependent species, but mild for species preferring mainstem habitats. It has been suggested (Evans and Wilcox, 2013) that bed scour during winter flows may help reduce fine sediment concentrations in sediments following dam removal. Scour can significantly affect salmonids (*e.g.*, Tripp and Poulin, 1986; DeVries, 2000) and has been shown to increase in systems with sediment imbalances, like those occurring following dam removal. Spawning ground surveys and outmigration sampling suggest spawning has not been overly successful during dam removal (Mike McHenry, Lower Elwha Tribe, unpublished data). Overall, long-term impacts of fine sediments released during dam removal on salmonid spawning habitat will likely be minimal if larger discharges in fact flush fine sediments from floodplain channels and this sediment is transported quickly out of the system. The long-term impacts may be severe if future flood events continue to be too small to flush and transport this material or develop new floodplain channels. These long-term impacts will be addressed by future long-term monitoring in the Elwha River. Future dam removals with similar fine sediments stored behind the dams and released over a relatively long period (1-3 years) may need to take precautionary measures to protect floodplain-dependent spawners.

APPENDIX
BETA REGRESSION MODEL DETAILS

For each substrate and channel type (mainstem or floodplain), the following model was applied:

$$p_{\text{site,year,section}} \sim beta(a_{\text{site,year,section}}, b_{\text{site,year,section}}) \quad (A1)$$

$$a_{\text{site,year,section}} = \phi\mu_{\text{site,year,section}} \quad (A2)$$

$$b_{\text{site,year,section}} = \phi(1-\mu_{\text{site,year,section}}) \quad (A3)$$

$$\begin{aligned} logit(\mu_{\text{site,year,section}}) = {} & intercept + siteEff_{\text{site}} \\ & + yearEff_{\text{year}} + sectionEff_{\text{section}} \\ & + yearBySectionEff_{\text{year,section}} \end{aligned} \quad (A4)$$

Here, $p_{\text{site,year,section}}$ is the proportion of the substrate type for a given site, year, and river section (lower or middle) and is assumed to follow a beta distribution. The beta distribution is parameterized in terms of the mean, $\mu_{\text{site,year,section}}$, and dispersion, φ with a logit link. The a and b parameters are the standard beta distribution parameters (defined here in terms of the mean and dispersion parameter).

The intercept, year effect ($yearEff_{\text{year}}$), section effect ($sectionEff_{\text{section}}$), and year-by-section effect ($yearBySectionEff_{\text{year,section}}$) were assigned normal priors with mean 0 and standard deviation 100. The site effect values are assumed to come from a common normal distribution with mean 0 and standard deviation, site_{SD}, where site_{SD} is assumed to follow a uniform distribution (Gelman *et al.*, 2014):

$$\text{site}_{SD} \sim \text{uniform}(0, 100) \quad (A5)$$

The dispersion parameter, φ, is assumed to follow a *gamma* (0.1, 0.1) distribution.

Because there were a number of zeros and ones and the beta distribution does not accommodate these values (support = (0, 1) not [0, 1]), the following transformation of the proportions was applied prior to analysis (*e.g.*, Fox and Weisberg, 2010):

$$p_{\text{new}} = \frac{p \cdot 99 + 0.5}{100} \tag{A6}$$

This draws the p values slightly toward 0.5 so that the new range of possible values is from 0.005 to 0.995. When reporting year, river section and year-by-river section affects the sum to zero constraint was enforced. That is the sum of the year effects and the sum of the section effects summed to zero. The margins of the interaction were zero.

The Bayesian model was implemented in JAGS (Plummer, 2003), with all data preparation and plotting in R (R Core Team, 2015). Trace plots were used to assess convergence of the Markov Chain Monte Carlo, effective sample size, and the Heidelberger and Welch statistic was calculated as additional diagnostics. Simulations were run until the chains appeared to converge.

Model fit was assessed by superimposing the estimated medians and credible intervals on the data. The posterior predictive coverage of the 80% prediction interval was also examined to investigate problems with the beta distribution (with constant φ) assumption. Any substantial lack of fit was noted in the results.

ACKNOWLEDGMENTS

This manuscript was improved by reviews from Denise Hawkins (FWS), Michael Pollock (NOAA), Pat Crain (ONP), Andy Ritchie (USGS/ONP), two anonymous reviewers, and the editor (JAWRA). Mel Elofoson and Sonny Sampson (LEKT) provided substantial assistance by handling field logistics, organizing crews, and assisting with field sampling. Kim Williams (LEKT), Sam Barcklow, and Shane Taylor (both WCC) also assisted with field work. Sonny Sampson processed the bulk gravel samples. Alex Bell, Rachel Brooks, Meimie Li, Zach Moore, Teal Waterstrat (USFWS), Sarah Gabel (Saint Martin's University), and Jason Holmes (Volunteer) completed the suspended sediment processing. Funding for this project was provided by Olympic National Park through the Lower Elwha Klallam Tribe (Agreement# PC00296 and PC00364). The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the U.S. Fish and Wildlife Service or NOAA Fisheries. Mention of trade names does not imply endorsement by the Federal Government.

LITERATURE CITED

Acker, S.A., T.J. Beechie, and P.B. Shafroth, 2008. Effects of a Natural Dam-Break Flood on Geomorphology and Vegetation on the Elwha River, Washington, U.S.A. Northwest Science 82(Special Issue):210-223.

Beschta, R.L. and W.L. Jackson, 2008. Sediment Studies Following the Alsea Watershed Study. *In*: Hydrological and Biological Responses to Forest Practices, J.D. Stednick (Editor). Springer, Berlin, pp. 183-210.

Bunte, K. and S.R. Abt, 2001. Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analysis in Sediment Transport, Hydraulics, and Streambed Monitoring. General Technical Report RMRS-GTR-74. USDA, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.

Bustard, D.R. and D.W. Narver, 1975. Preferences of Juvenile Coho Salmon (*Oncorhynchus kisutch*) and Cutthroat Trout (*Salmo clarki*) Relative to Simulated Alteration of Winter Habitat. Journal of the Fisheries Board of Canada 32:681-687.

Childers, D., D.L. Kresch, S.A. Gustafson, T.J. Randle, J.T. Melena, and B. Cluer, 2000. Hydrologic Data Collected during the 1994 Lake Mills Drawdown Experiment, Elwha River, Washington. U.S. Geological Survey Water-Resources Investigation Report 99-4215, 115 pp.

Cui, Y., J.K. Wooster, C.A. Braudrick, and B.K. Orr, 2014. Lessons Learned from Sediment Transport Model Predictions and Long-Term Post Removal Monitoring: Marmot Dam Removal Project on the Sandy River in Oregon. Journal of Hydraulic Engineering 140(9):04014044(1-16), https://doi.org/10.1061/(asce)hy.1943-7900.0000894,04014044.

Curran, C.A., C.P. Konrad, J.L. Higgins, and M.K. Bryant, 2009. Estimates of Sediment Load Prior to Dam Removal in the Elwha River, Clallam County, Washington. U.S. Geological Survey Scientific Investigation Report 2009–5221, 18 pp. http://pubs.er.usgs.gov/publication/sir20095221.

Czuba, C.R., T.J. Randle, J.A. Bountry, C.S. Magirl, J.A. Czuba, C.A. Curran, and C.P. Konrad, 2011. Anticipated Sediment Delivery to the Lower Elwha River during and Following Dam Removal. *In*: Coastal Habitats of the Elwha River, Washington—Biological and Physical Patterns and Processes Prior to Dam Removal, J.J. Duda, J.A. Warrick, and C.S. Magirl (Editors). U.S. Geological Survey Scientific Investigations Report 2011-5120, pp. 27-46. http://pubs.er.usgs.gov/publication/sir201151202.

DeVries, P.E., 2000. Scour in Low Gradient Gravel Bed Rivers: Patterns, Processes, and Implications for the Survival of Salmonid Embryos. Water Resources Series Technical Report No. 160, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington.

Diplas, P. and J. Fripp, 1991. Bed Material Sampling: Issues and Answers. *In*: Proceedings of the Fifth Federal Interagency Sedimentation Conference, Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data, Las Vegas, Nevada, pp. 281-288.

Doyle, M.W., E.H. Stanley, D.G. Havlick, M.J. Kaiser, G. Steinbeck, W.L. Graf, G.E. Galloway, and J.A. Riggsbee, 2008. Aging Infrastructure and Ecosystem Restoration. Science 319:286-287.

Draut, A.E., J.B. Logan, and M.C. Mastin, 2011. Channel Evolution on the Dammed Elwha River, Washington, USA. Geomorphology 127:71-87.

Duda, J.J., J.E. Freilich, and E.G. Schreiner, 2008. Baseline Studies in the Elwha River Ecosystem Prior to Dam Removal. Northwest Science 82(Special Issue):1-12.

East, A.E., G.R. Pess, J.A. Bountry, C.S. Magirl, A.C. Ritchie, J.B. Logan, T.J. Randle, M.C. Mastin, J.J. Duda, M.C. Liermann, M.L. McHenry, T.J. Beechie, and P.B. Shafroth, 2015. Large-Scale Dam Removal on the Elwha River, Washington, USA: River Channel and Floodplain Geomorphic Change. Geomorphology 228:765-786, https://doi.org/10.1016/jgeomorph.2014.08.028.

Evans, E. and A.C. Wilcox, 2013. Fine Sediment Infiltration Dynamics in a Gravel-Bed River Following a Sediment Pulse. River Research and Application 30:372-384.

Fox, J. and S. Weisberg, 2010. An R Companion to Applied Regression (Second Edition). Sage Publications, Thousands Oaks, California. ISBN-13: 978-1412975148.

Franson, M.A., 1985. Standard Methods for the Examination of Water and Wastewater (Sixteenth Edition). American Public Health Association, Washington, D.C. ISBN-13: 978-0875531311.

Fripp, J.B. and P. Diplas, 1993. Surface Sampling in Gravel Streams. Journal of Hydraulic Engineering 119(4):473-490.

Gelman, A., J.B. Carlin, H.S. Stern, and D.B. Rubin, 2014. Bayesian Data Analysis (Vol. 2). Chapman & Hall/CRC, London. ISBN-13: 978-1439840955.

Hatten, J.R., T.R. Batt, P.J. Connolly, and A.G. Maule, 2014. Modeling Effects of Climate Change on Yakima River Salmonid Habitats. Climatic Change 124(1–2):427-439.

Hatten, J.R., T.R. Batt, J.J. Skalicky, R. Engle, G.J. Barton, R.L. Fosness, and J. Warren, 2016. Effects of Dam Removal on Tule Fall Chinook Salmon Spawning Habitat in the White Salmon River, Washington. River Research and Applications 32:1481-1492, https://doi.org/10.1002/rra.2982.

Heinz Center, 2002. Dam Removal: Science and Decision Making. H. John Heinz III Center for Science Economics and the Environment, Washington, D.C., 221 pp.

Jackson, W.L. and R.L. Beschta, 1982. A Model of Two-Phase Bedload Transport in an Oregon Coast Range Stream. Earth Surface Processes and Landformes 7:517-527.

Jensen, D.W., E.A. Steel, A.H. Fullerton, and G.R. Pess, 2009. Impact of Fine Sediment on Egg-to-Fry Survival of Pacific Salmon: A Meta-Analysis of Published Studies. Reviews in Fisheries Science 17(3):348-359, https://doi.org/10.1080/10641260902716954.

Kibler, K., D. Tullos, and M. Kondolf, 2011. Evolving Expectations of Dam Removal Outcomes: Downstream Geomorphic Effects Following Removal of a Small, Gravel-Filled Dam. Journal of the American Water Resources Association 47:408-423.

Konrad, C.P., 2009. Simulating the Recovery of Suspended Sediment Transport and River-Bed Stability in Response to Dam Removal on the Elwha River, Washington. Ecological Engineering 35(7):1104-1115.

Madej, M.A. and V. Ozaki, 1996. Channel Response to Sediment Wave Propagation and Movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21:911-927.

Magirl, C.S., R.C. Hilldale, C.A. Curran, J.J. Duda, T.D. Straub, M. Domanski, and J.R. Foreman, 2015. Large-Scale Dam Removal on the Elwha River, Washington, USA: Fluvial Sediment Load. Geomorphology 246(1):669-686, https://doi.org/10.1016/j.geomorph.2014.12.032.

Major, J.J., J.E. O'Connor, C.J. Podolak, M.K. Keith, G.E. Grant, K.R. Spicer, S. Pittman, H.M. Bragg, J.R. Wallick, D.Q. Tanner, A. Rhode, and P.R. Wilcock, 2012. Geomorphic Response of the Sandy River, Oregon, to Removal of Marmot Dam. U.S. Geological Survey Professional Paper 1792, 64 pp. http://pubs.er.usgs.gov/publication/pp1792.

McHenry, M., G. Pess, R. Moses, S. Brenkman, P. Crain, H. Huginin, and J. Anderson, 2016. Spawning Distribution of Chinook Salmon (*Oncorhynchus tshawaytscha*) in the Elwha River, Washington State during Dam Removal (2012-2015). Lower Elwha Klallam Tribe, Port Angeles, Washington.

Merritts, D., R. Walter, M. Rahnis, S. Cox, J. Hartranft, C. Scheid, N. Potter, M. Jenschke, A. Reed, D. Matuszewski, L. Kratz, L. Manion, A. Shilling, and K. Datin, 2013. The Rise and Fall of Mid-Atlantic Streams: Millpond Sedimentation, Milldam Breaching, Channel Incision, and Stream Bank Erosion. *In*: The Challenges of Dam Removal and River Restoration, J.V. De Graff and J.E. Evans (Editors). Geological Society of America Reviews in Engineering Geology XXI, Geological Society of America, Boulder, Colorado, pp. 183-203.

Minear, J.T. and G.M. Kondolf, 2009. Estimating Reservoir Sedimentation Rates at Large Spatial and Temporal Scales: A Case Study of California. Water Resources Research 45: W12502.

Morley, S.A., J.J. Duda, H.J. Coe, K.K. Kloehn, and M.L. McHenry, 2008. Benthic Invertebrates and Periphyton in the Elwha River Basin: Current Conditions and Predicted Response to Dam Removal. Northwest Science 82(Special Issue):179-196.

Morley, S.A., P.S. Garcia, T.R. Bennett, and P. Roni, 2005. Juvenile Salmonid (*Oncorhynchus* spp.) Use of Constructed and Natural Side Channels in Pacific Northwest Rivers. Canadian Journal of Fisheries and Aquatic Sciences 62:2811-2821.

Murphy, M.L., J. Heifetz, J.F. Thedinga, S.W. Johnson, and K.V. Koski, 1989. Habitat Utilization by Juvenile Pacific Salmon (Onchorynchus) in the Glacial Taku River, Southeast Alaska. Canadian Journal of Fisheries and Aquatic Sciences 46:1677-1685.

Pearson, A.J., N.P. Snyder, and M.J. Collins, 2011. Rates and Processes of Channel Response to Dam Removal with a Sand-Filled Impoundment. Water Resources Research 47:1-15.

Pess, G.R., M.C. Liermann, T.R. Bennett, and T.J. Beechie, 2015. Longitudinal Profiles in Floodplain Channels of the Middle and Lower Elwha River – 2012 and 2014. Northwest Fisheries Science Center (NWFSC), National Oceanic and Atmospheric Administration (NOAA), Seattle, Washington.

Pess, G.R., M.L. McHenry, T.J. Beechie, and J. Davies, 2008. Biological Impacts of the Elwha River Dams and Potential Salmonid Responses to Dam Removal. Northwest Science 82 (Special Issue):72-90.

Peters, R.J., J.J. Duda, G.R. Pess, M. Zimmerman, P. Crain, Z. Hughes, A. Wilson, M.C. Liermann, S.A. Morley, J.R. McMillan, K. Denton, D. Morrill, and K. Warheit, 2014. Guidelines for Monitoring and Adaptively Managing Restoration of Chinook Salmon (*Oncorhynchus tshawytscha*) and Steelhead (*O. mykiss*) on the Elwha River. U.S. Fish and Wildlife Service, Olympia. http://www.fws.gov/wafwo/pdf/Peters%20et%20al%202014%20Elwha%20Mon%20Adapt%20Mng%20Final.pdf, *accessed* March 2017.

Pizzuto, J., 2002. Effects of Dam Removal on River Form and Process. BioScience 52(8):683-691, https://doi.org/10.1641/0006-3568(2002) 052[0683:EODROR]2.0.CO;2.

Plummer, M., 2003. JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling. *In*: Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003), K. Hornik, F. Leisch, and A. Zeileis (Editors), March 20–22, Technische Universitat Wien, Vienna, Austria. ISSN: 1609-395X. http://www.ci.tuwien.ac.at/Conferences/DSC-2003/Drafts/Plummer.pdf, *accessed* March 2017.

Pohl, M., 2004. Channel Bed Mobility Downstream from the Elwha Dams, Washington. Professional Geographer 56:422-431.

Randle, T.J., J.A. Bountry, A. Ritchie, and K. Wille, 2015. Large-Scale Dam Removal on the Elwha River, Washington, USA: Erosion of Reservoir Sediment. Geomorphology 246:669-686, https://doi.org/10.1016/j.geomorph.2014.12.032.

Randle, T.J., C.A. Young, J.T. Melena, and E.M. Ouellette, 1996. Sediment Analysis and Modeling of the River Erosion Alternative. U.S. Department of the Interior, Bureau of Reclamation, Elwha River Ecosystem and Fisheries Restoration Project. Elwha Technical Series PN-95-9, Boise, Idaho, 136 pp.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Riggsbee, J.A., J.P. Julian, M.W. Doyle, and R.G. Wetzel, 2007. Suspended Sediment, Dissolved Organic Carbon, and Dissolved Nitrogen Export during the Dam Removal Process. Water Resources Research 43:W09414.

Sawaske, S.R. and D.L. Freyberg, 2012. A Comparison of Past Small Dam Removals in Highly Sediment-Impacted Systems in the US. Geomorphology 151:50-58.

Service, R.F., 2011. Will Busting Dams Boost Salmon? Science 334 (6058):888-892.

Sommer, T.R., M.L. Nobriga, W.C. Harrell, W. Batham, and W.J. Kimmerer, 2001. Floodplain Rearing of Juvenile Chinook Salmon: Evidence of Enhanced Growth and Survival. Canadian Journal of Fisheries and Aquatic Sciences 58:325-333.

Stanley, E.H. and M.W. Doyle, 2003. Trading Off: The Ecological Effects of Dam Removal. Frontiers in Ecology and the Environment 1:15-22.

Tripp, D.B. and V.A. Poulin, 1986. The Effects of Logging and Mass Wasting on Salmonid Spawning Habitat in Streams on the Queen Charlotte Islands. Ministry of Forests and Lands, Research Branch, Land Management Report 50, Victoria, British Columbia.

Tullos, D.D., D.S. Finn, and C. Walter, 2014. Geomorphic and Ecological Disturbance and Recovery from Two Small Dams and Their Removal. PLoS ONE 9(9):e108091.

Warrick, J.A., J.A. Bountry, A.E. East, C.S. Magirl, T.J. Randle, G.R. Gelfenbaum, A.C. Ritchie, G.R. Pess, V. Leung, and J.J. Duda, 2015. Large-Scale Dam Removal on the Elwha River, Washington, USA: Source-to-Sink Sediment Budget and Synthesis. Geomorphology 246:729-750, https://doi.org/10.1016/j.geomorph.2015.01.010.

Wilcox, A.C., J.E. O'Connor, and J.J. Major, 2014. Rapid Reservoir Erosion, Hyper Concentrated Flow, and Downstream Deposition Triggered by Breaching of 38 m Tall Condit Dam, White Salmon River, Washington. Journal of Geophysical Research-Earth Surfaces 119(6):1376-1394, https://doi.org/10.1002/2013JF003073.

Wood, P.J. and P.D. Armitage, 1997. Biological Effects of Fine Sediment in the Lotic Environment. Environmental Management 21 (2):203-217.