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Quantifying Channel Responses to the Removal of the Glines Canyon Dam in the Middle Reach of the Elwha River, Washington

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QUANTIFYING CHANNEL RESPONSES TO THE REMOVAL OF THE GLINES CANYON DAM IN THE MIDDLE REACH OF THE ELWHA RIVER, WASHINGTON

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by

Bryon James Free

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Graduate Studies

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ABSTRACT

QUANTIFYING CHANNEL RESPONSES TO THE REMOVAL OF THE GLINES CANYON DAM IN THE MIDDLE REACH OF THE ELWHA RIVER, WASHINGTON

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Four different study sites throughout the middle reach of the Elwha River were monitored before, during, and after the dam removal process over a period of two years from 2012-2014. The complexity of the river geometry was a major factor in the ability of the river to trap and accumulate the new influx of woody debris and sediment from the dam removal, which influenced the response of the river channel. The change that occurred was quantified by using repeat Terrestrial LiDAR (TLS), sediment distribution surveys, and large woody debris mapping techniques. The morphologic changes that occurred during this time were caused by multiple different geomorphic influences. The most notable was the initial sediment pulse that that inundated the downstream river channel in the first few months of the reservoir sediment release. In turn, it filled the riffles and pools throughout the entire middle reach of the river, and the subsequent deposition was channel geometry dependent. As the initial sediment wave dissipated and the river continued transport sediment from the Glines Canyon Dam, the channel geometry was still the major factor in woody debris collection and sediment deposition followed by river discharge. Woody debris anchored and accumulated on sediment bars

throughout the entire middle reach; it became apparent that the more complex the channel system (i.e. multiple channels, vegetated islands, riffles and pools, or a sharp channel bend), the more likely the woody debris was to collect. Furthermore, as the woody debris deposited coalesced into log jams, it influenced the sediment deposition by armoring the banks of channels and creating areas of slow moving water. The combined deposition of sediment and woody debris caused areas of the channel to migrate, increasing the complexity of the river geometry. This study has provided some much-needed empirical data necessary to model future dam removal projects. It demonstrated that the use of TLS combined with surveys of large woody debris and sediment distribution can provide detailed information about the effects of the dam removal in different geomorphic settings.

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

Currently, there are more than 85,000 dams in the United States, most of which are in need of relicensing and repair (Heinz, 2002; Burroughs et al., 2009; Graf et al., 2010). Relicensing regulations require the entities that manage the dams to adhere to new fishery regulations and hazard assessments for safety purposes. Due to the nation-wide push to restore watersheds and ecosystems to their natural state and the cost of relicensing, in many cases it has become more economically viable to remove a dam rather than to relicense it (Doyle, 2002; Heinz, 2002; Graf et al., 2010). To date, there have been approximately 1,000 dam removal projects completed in the United Sates (O'Connor et al., 2015).

A primary concern of removing a dam is how to handle the sediment that is impounded behind the dam, which can range in volume from 10^1 to 10^{10} m^3; over ten orders of magnitude (Heinz, 2002; Graf et al., 2010; Magirl et al., 2010; Draut et al., 2011). The potential downstream effects that can be created by a large sediment release could impact the downstream ecosystem, infrastructure, and human population within the watershed. By quantifying the morphological changes to the river channel, it will be possible to provide predictive tools to assess the downstream effects of a sediment release for future dam removals. (Doyle, 2002; Draut et al., 2011; Johnsen, 2011).

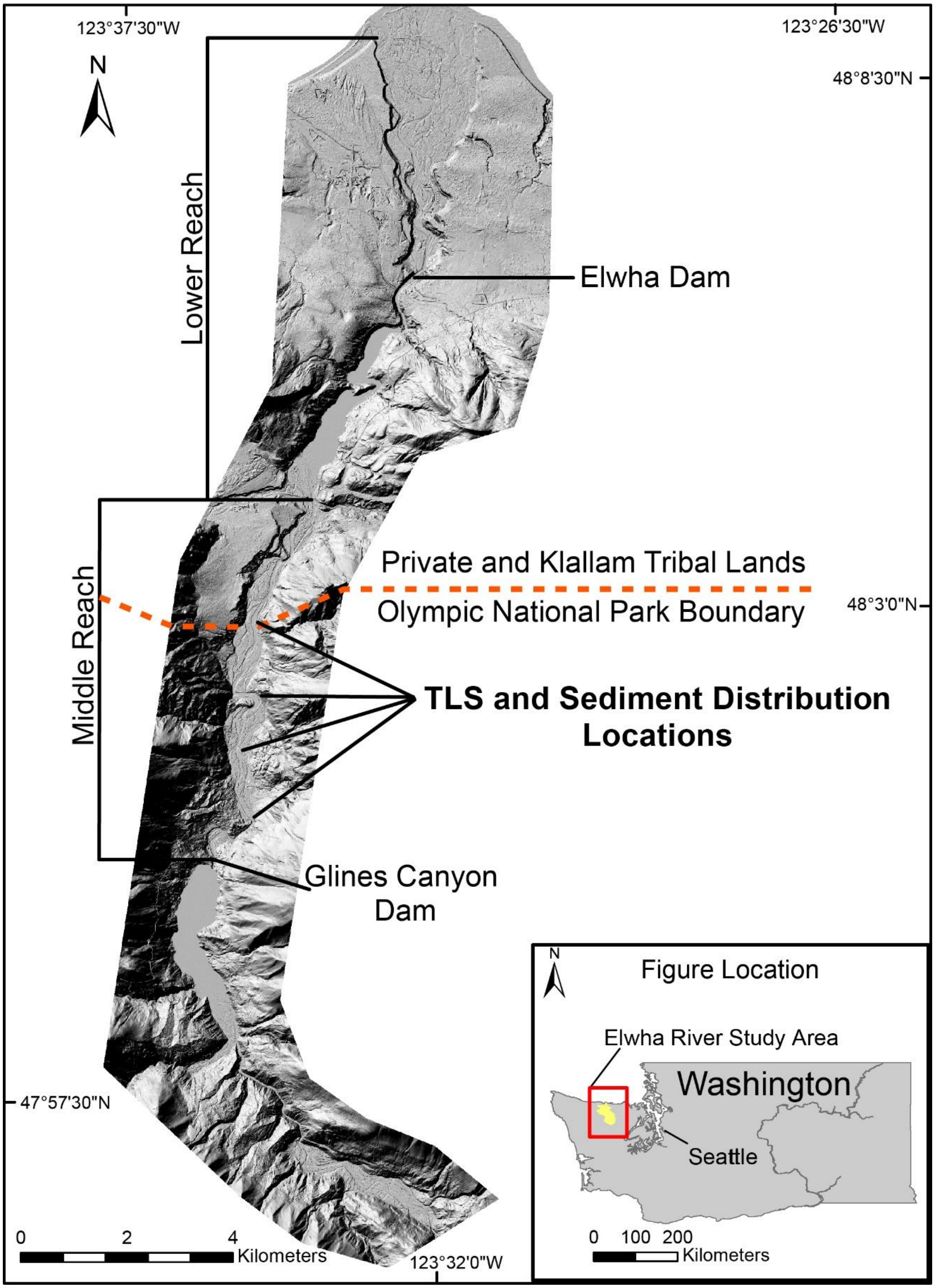

Figure 1: Elwha Restoration Project Map, Located in northwestern Washington State on the Olympic Peninsula. Base map is the 2012 aerial LiDAR provided by the USGS.

The removal of the two dams on the Elwha River within the Olympic Peninsula of Washington (Fig. 1) by the National Park Service and the Bureau of Reclamation was the largest dam removal project in history. The dam removal process consisted of simultaneously removing the upstream Glines Canyon Dam and downstream Elwha Dam starting June, 2011. In September 2012, the downstream Elwha dam was fully removed and the Glines Canyon Dam was finished in August 2014 (Figs. 1-3). The two dam removals were undertaken to restore natural fish passage and habitat to much of the mainstream river.

Figure 2: Glines Canyon Dam from the Lake Mills Reservoir taken August, 2012 prior to the coarse sediment release. Dam removal had already begun in June 2011 however, only suspended sediment was flowing at this point. (Photo taken by Bryon Free)

A number of methods have been previously used for the physical management of sediment during the dam removal process. The most basic method is the excavation of the impounded sediments from the reservoir. This is primarily done where it is more economical to remove the sediment beforehand, such as where the sediment volume is small or the site is contaminated (Doyle, 2002; Magirl et al., 2010). The benefit of this method is that there are no adverse effects on the aquatic ecosystem and/or the need for potential hazard mitigation due to mass wasting of the sediment inundating the downstream infrastructure. As dams grow larger, however, the expense of this type of sediment management grows as well (Doyle, 2002; Downs et al., 2009).

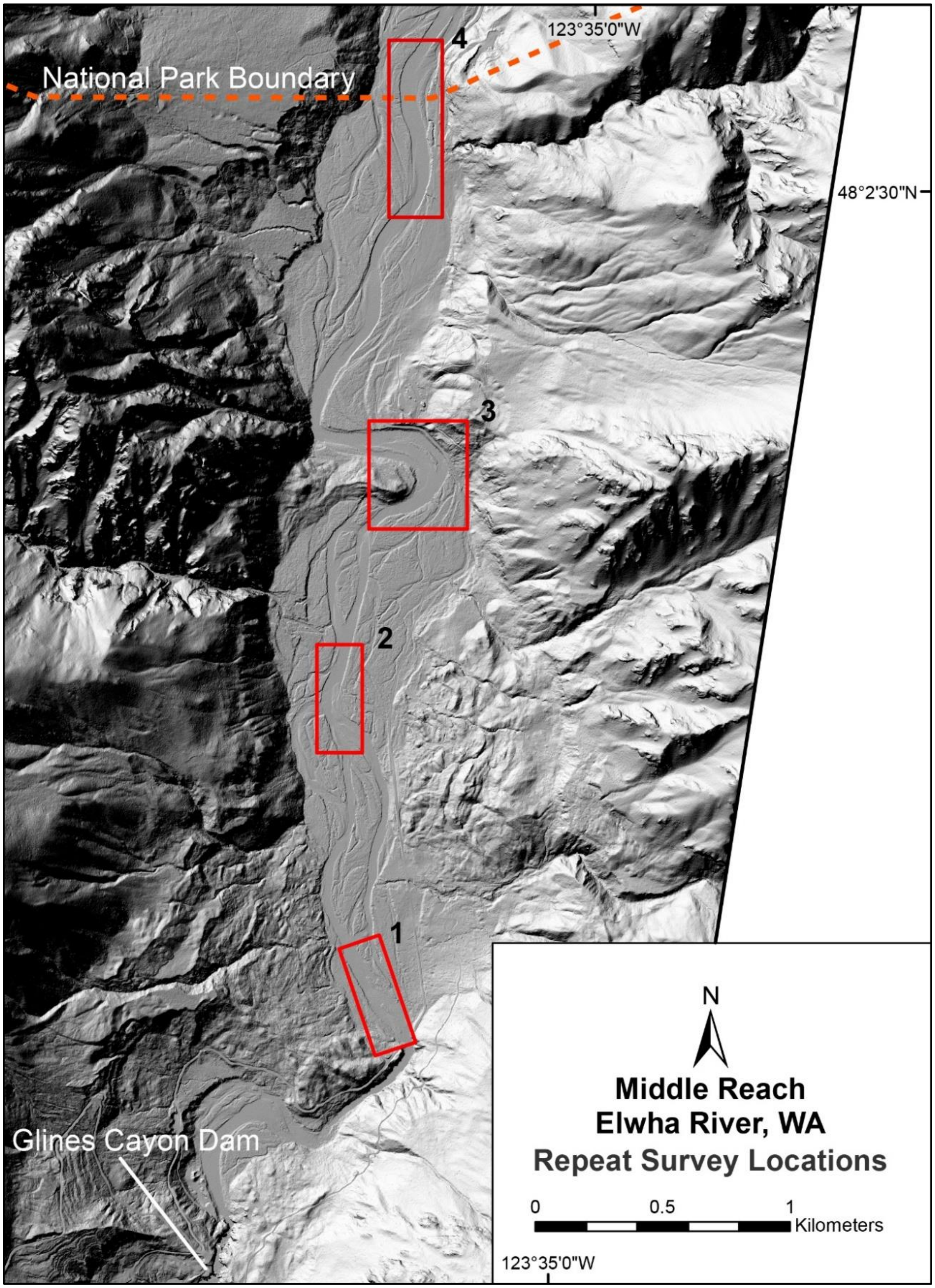

Figure 3: Middle Reach of the Elwha River study site map. Red boxes denote each of the study sites and are the footprints of the TLS surveys. The base map is the 2012 LiDAR coverage was provided by the USGS.

A different method is the sudden removal of the dam in an effort to evacuate as much sediment as possible at one time, allowing the river to remobilize the reservoir sediment on its own (Doyle, 2002; Magirl et al., 2010). Mobilizing all of the sediment at a single moment can potentially lead to fewer long-term adverse effects to the downstream aquatic ecosystem. However, the potential hazards to the downstream infrastructure and population could be catastrophic due to the mass wasting of the channel banks from the reservoir creating a debris flow (PacifiCorp, 2009; Magirl et al., 2010).

Another method is the slow incremental removal of the dam, allowing the river to rework the sediment within the channel and transport it downstream. This method is used for large amounts of reservoir sediment that would be impractical to excavate and/or could be too hazardous for a single, sudden removal that could potentially endanger the downstream population and infrastructure (Doyle, 2002; Magirl et al., 2010). This type of removal mitigates the potential hazard of mass wasting to the downstream end of the river by creating slope stabilizing terraces in the reservoir (Doyle, 2002; Czuba et al., 2011). One problem with this type of removal is the longer potential adverse impacts on the aquatic ecosystem downstream due to the continued sediment dispersal over a much longer period. However, the timing of the stage lowering can be adjusted to minimize the suspended-sediment that affect the downstream biota, such as spawning salmon (Magirl et al., 2010).

The decision of which method to use for the Elwha was based on several factors, including economic benefit, aquatic ecosystem and hazard mitigation. On the Elwha River, the incremental removal of the Elwha and Glines Canyon Dams was incorporated into the dam removal strategy. By doing so, the hazards associated with dam removal were minimized and the cost of the sediment removal was greatly reduced (Doyle, 2002; Magirl et al., 2010; Czuba et al., 2011). By lowering the dam in stages it was also possible to time the release of the suspended-sediment to mitigate the downstream hazards to the downstream biota during spawning season as well (Magirl et al., 2010).

The objective of my research was to quantify the transport and deposition of sediment and large woody debris as it flows through the middle reach of the Elwha River between the two dams (Figs. 1 and 3). This will provide the data necessary to understand the geomorphic changes to the main channel following the two-year removal of the upstream Glines Canyon Dam (Fig. 2). By performing this study in the middle reach of the Elwha River there is an opportunity to collect empirical data in the river channel that has only been influenced by the removal of a single dam and does not have the complication of multiple sediment sources influencing the channel morphodynamics.

The implementation of an incremental dam removal strategy on the Elwha River was used to mitigate the potential downstream hazards that are inherent with a rapid sediment dispersal following an instantaneous dam removal. The results of this study will provide data on how the geomorphology of a gravel-bedded river responds to the influx of new sediment and large woody debris during the process of the incremental dam removal. Based on previous studies involving dam removal, woody debris, and river geometry, I hypothesize that a sediment pulse will propagate downstream through the study reach, and the channel aggradation will result in filling of riffles and pools throughout. In conjunction with the sediment deposition, the large woody debris will influence the lateral channel migration causing new bar formation and the formation or loss of entire branches of the river channel. Furthermore, I hypothesize that the geomorphic change that occurs will be largely dependent on the preexisting geometry of the river channel at each specific study site.

Background

Previous Dam Removal Studies

Several channel evolution models (CEMs) have been designed to help understand the effects of the sediment transported downstream during the dam removal process (Doyle et al., 2002; Doyle et al., 2003; Heinz, 2002; Pizzuto, 2002b; Draut et al., 2011; Johnsen, 2011; East et al., 2015). The addition of empirical data helps build a good statistical representation of the effects of a large sediment perturbation, characterizing the range of variability in the sediment release from large dam removals (Doyle, 2002; Heinz, 2002; Burroughs et al., 2009; Pizzuto, 2002b; Draut et al., 2011; Johnsen, 2011; Matzek, 2013; Major et al., 2012; East et al., 2015). In addition, the data also increase our ability to model the physical process governing channel morphodynamics (Burroughs et al., 2009; Major et al., 2012; East et al., 2015). Whereas most dam removals have been on relatively small rivers with sediment reservoirs measuring from $10^3 – 10^5$ m^3 (Heinz, 2002; Major et al., 2012; O'Connor et al., 2015), the removal of Glines Canyon and Elwha Dams released ~ 7.1×10^6 m^3 of sediment (East et al., 2015; Gelfenbaum et al., 2015; Magirl et al., 2015; Randle et al., 2015; Warrick et al., 2015).

Studies following smaller dam removals describe sediment waves that inundate the river channel with sediment within the first few kilometers (2 – 5 km) downstream of the dam breach, filling riffles and pools (Doyle et al., 2003; Burroughs et al., 2009; Major et al., 2012). The sediment then propagates downstream in the years following the breach (Doyle et al., 2003; Burroughs et al., 2009; Major et al., 2012). One such case is the Marmot Dam on the Sandy River, Oregon, which was removed in 2007, releasing 7.5 x 10^5 m^3 of sediment. Deposition primarily occurred in the first 2 kilometers of the breach site (Major et al., 2012). Following the initial sediment inundation, the sediment was transported further downstream during and after large flows associated with different storm events (Matzek, 2011; Keith, 2012; Major et al., 2012), suggesting that the sediment was redistributed from its point source and propagated downstream throughout the river channel with the changing hydrology of the river (Lawrence and Ripple, 1998; Burroughs et al., 2009; Major et al., 2012). However, the sediment reservoir behind Marmot Dam was an order of magnitude less than the next-largest dam removals, the Milltown and Condit dams on the White Salmon River, with sediment reservoirs of 1.8 x 10^6 m^3 (Condit Dam) and 5 x10^6 m^3 (Milltown Dam) (PacifiCorp, 2009; Czuba et al., 2011; Johnsen, 2011; Magirl et al., 2010).

The Milltown Dam located on the Clark Fork River in Montana was the first restoration project (2008) that fit the Heinz Center's (2002) definition of a large dam removal (>10^6 m^3). However, because the site was contaminated by mine tailings, much of the sediment was excavated (2.2 x 10^6 m^3) prior to release (Wilcox, 2010; Czuba et al., 2011; Johnsen, 2011). This excavation meant that the river did not transport the total amount of sediment downstream. As a result, the geomorphic effects following the dam removal were small when compared to the total sediment that was impounded behind the dam (Wilcox, 2010; Czuba et al., 2011).

The Condit Dam located on the White Salmon River in Washington was removed in 2011 just prior to the Elwha River Restoration project. The removal of the Condit Dam released the bulk of its 1.8 x 10^6 m^3 of sediment in a single day following the total breach at the base of the dam (PacifiCorp, 2009; Mead and Hunt et al., 2011; Czuba et al., 2011; Major et al., 2012). Due to the nature of the bedrock canyon directly below the Condit Dam, the sediment deposited directly into the Columbia River rather than on the channel margins of the White Salmon River (PacifiCorp, 2009, Mead and Hunt et al., 2011; Wilcox et al., 2014). Subsequently, there were few downstream geomorphic effects to the river channel during the removal process (PacifiCorp, 2009, Mead and Hunt et al., 2011; Wilcox et al., 2014). This is in contrast to the Elwha Dam removal, which was slowly removed over an entire year and had a large flood plain and several kilometers in which to deposit its sediment.

Elwha River Restoration Project

The Elwha River watershed is approximately 833 km^2, and 83% is located in the Olympic National Park; it is also a World Heritage Site and an International Bio-Reserve (Duda and Magirl, 2011; East et al., 2015). This status provides a unique opportunity because the river system has remained unaltered by human activity with the exception of the instalment of the dams and park road. This is unique, because it allows for the uninterrupted study of the geomorphic change before the river system enters inhabited lands further downstream (Duda and Magirl, 2011). The other 17% of the Elwha River watershed is split between private ownership and Klallam tribal lands. The tribe is currently experimenting with engineered log jams within the lower river system to create better spawning habitat, enhance sediment deposition, and increase the fish population (Pess et al., 2012).

The goal of the Elwha River Restoration Project is to increase migrating fish populations and to reinstate a free-flowing river that has been blocked for nearly 100 years (Duda and Magirl, 2011). Historically the Elwha River supported some of the largest numbers of salmon spawning habitat in the Olympic Peninsula prior to the installation of the dams (Wunderlich et al., 1994). With the loss of the fish habitat and the need to relicense the dams, a management plan had to be put into place to adhere to the change in federal fishery regulations for the passage of anadromous fish species. In 1992, the U.S. Congress passed the Elwha River Ecosystem and Fisheries Restoration Act (PL 102-495), which required the full restoration of the Elwha River watershed (U.S. Department of the Interior, 1995; Magirl et al., 2010). Following the 1992 Elwha Restoration Act, the National Park Service decided that in order to fully restore the Elwha River watershed, both dams on the Elwha River would need to be removed (U.S. Department of the Interior, 1995; Magirl et al., 2010).

Following the decision to implement an incremental dam removal strategy, the removal process was expected to take up to 3 years to complete (Magirl et al., 2010). In June 2011, the physical removal process started to take place with the simultaneous removal of the both dams from the top down. In September 2012 the downstream Elwha Dam was fully removed and the removal of the upstream Glines Canyon Dam was still underway. Two years later, in September 2014, the upstream Glines Canyon Dam was removed completely as well. As a result, the restoration project produced the largest intentional sediment release into a river system ever attempted, as more than 20×10^6 m^3

of sediment that was impounded behind the dams was freed to flow after both dams were removed (Czuba, 2011; Duda and Magirl, 2011; East et al., 2015). Following the complete removal of the Glines Canyon Dam, it is estimated that 6×10^6 m^3 of reservoir sediment flowed from the dam during the removal process (Czuba, 2011; East et al., 2015).

Geologic Setting

Prior to the removal of the dams on the Elwha River, there was a significant loss of large woody debris and sediment flow due to the lack of downstream deposition in the middle and lower reaches of the Elwha River. The primary location for the collection of the woody debris and sediment prior to the dam removal was in the upper reservoir behind the Glines Canyon Dam. With the lack of sediment and large woody debris over the lifetime of the dams, the Elwha River became incised and armored over time. In response, significant amounts of riparian vegetation stabilized the existing mid-channel bars, creating an anabranching river system. Consequently, the main channel of the Elwha River is a series of branching channels that intermingle with each other. As a response, prior to the dam removal the middle reach of the river had a channel migration rate of ~2.5 meters per year from 1994-2009. Furthermore, the annual sediment load, that flowed from the upper reach and impounded behind the Glines Canyon Dam ranged from $1.4 \times 10^5 – 3.4 \times 10^5$ m^3 (Curran et al., 2009; Czuba, 2011; East et al., 2015). In conjunction with the annual sediment load the large woody debris that was found in the upper reservoir prior to the dam removal ranged from 1-5 m long cut logs (cut to clear the reservoir land) to old and second growth trees with root balls from the upper reach (Fig. 4). In turn the removal of the dam represents several years' worth of sediment and woody debris flowing through the system during the dam removal process (Curran et al., 2009; Czuba, 2011; East et al., 2015).

Figure 4: Example of large woody debris collected in the river during the dam removal process. Notice the TLS on the left side of the photo.
Photo location: Site 3, downstream end of the river bend on the right-hand bank, August 2014

The bedrock of the Elwha River watershed is composed of the accretionary wedge of the Cascadia Subduction Zone (Draut et al., 2011; Duda and Magirl, 2011; Pazzaglia and Brandon, 2001; Warrick, 2011). Two metasedimentary complexes derived from oceanic basalt provide the sediment source to the Elwha River: the Olympic Subduction Complex (OSC) and the Coastal Range Terrace (CRT) (Pazzaglia and Brandon, 2001; Warrick, 2011). Rapid uplift along with alpine and Pleistocene glaciation created steep slopes that provide the river with steep, landslide-prone walls along its floodplain (Fig. 1) (Wegmann and Pazzaglia, 2002).

The Elwha dams have been largely operated as “run of the river” with only a small amount of flow diverted for hydroelectric power (Wegmann and Pazzaglia, 2002; Duda and Magirl, 2011). With the exception of some landslide dams in the upper reaches of the river, there have been very few cases of the rivers flow being completely regulated by natural or mechanical systems (Acker et al., 2008). The highest flow recorded on the Elwha River prior to the dam removal was 1,016 m^3/s (35,500 ft^3/s) on December 3rd, 2007 (Draut et al., 2011; Magirl, 2011). This discharge is a full order of magnitude larger than what was recorded during the dam removal process.

Study Site Locations

Four reaches of the river channel were surveyed between the upper (Glines Canyon) dam and lower (Elwha) dam to ascertain the geomorphic change in the middle reach of the river (Fig. 3). The survey locations are referenced as Sites 1 – 4 and are measured in kilometers downstream from the upper dam to the first point in the river where the survey begins (upstream end). To tie in with other work on the Elwha, each of the sites are also referenced in kilometers upstream from the mouth of the Elwha River at the Strait of Juan de Fuca. Each of the study sites range from 300 – 800 meters in length along the main channel. The length of each survey site was dependent on the dominating river geometry being measured (Table 1). Each of the following survey location descriptions includes the initial observations prior to the reservoir sediment release in October, 2012.

TABLE 1. SURVEY SITE DESCRIPTION DATA

Site Number	River Kilometer (RK) from outlet	River Kilometer (RK) from Glines Canyon Dam	Length of Survey site (m)	Description
Site 1	19.5	1.6	300	Initial expansion to flood plain
Site 2	18.1	3	400	Moderate bend with point bar
Site 3	17.1	4	560	Large U-shaped bend
Site 4	15.5	5.6	800	Single straight channel

Site 1

Site 1 (RK 19.5) is 300 m long and is located immediately downstream of the 1.6 km long, bedrock Glines Canyon Dam (Figs. 3 and 5a; Table 1). This reach encompasses the first expansion of the alluvial river channel downstream of the Glines Canyon Dam site at the head of the bedrock canyon. The site has four armored and incised channel flowing through its entire length. Site 1 has a large complex of gravel bars and large woody debris at the head of each of the heavily vegetated, established islands.

Site 2

Site 2 (RK 18.1) is 400 m long and is located 3 km downstream of the Glines Canyon Dam in an area where multiple channels and islands converge to form a single channel system (Figs. 3 and 5b; Table 1). It includes a moderate bend in the river with a prominent point bar and cut bank morphology. Prior to the reservoir sediment release in October, 2012, the point bar was armored with cobbles and very little large woody debris.

Site 3

Site 3 (RK17.1) is 560 m long and is located 4 km downstream of the Glines Canyon Dam (Fig. 3; Table 1). This reach of the river is composed of a large U-shaped bend. Prior to the reservoir sediment release this area was laden with large boulders and very little large woody debris. Some boulders are natural, and some have been placed along the river bank to armor the cut bank below the road. The river splits into three channels just before the bend starts its apex with three prominent islands and a set of boulders forming a rapid at the downstream end of the bend (Figs. 3 and 6a; Table 1).

Site 4

Site 4 (RK 15.5) is approximately 800 m long and is located 5.6 km downstream of the dam (Fig. 3; Table 1). It is at the National Park boundary, and in 2012 was primarily an armored cobble bar with abundant alder and vine maple trees 5-10 cm in diameter growing upon it (Fig. 6b; Table 1). At this point, the separate branches of the river rejoin, widen, and the flow velocity decreases. The single channel here is relatively straight compared to the upstream sites (Fig. 3).

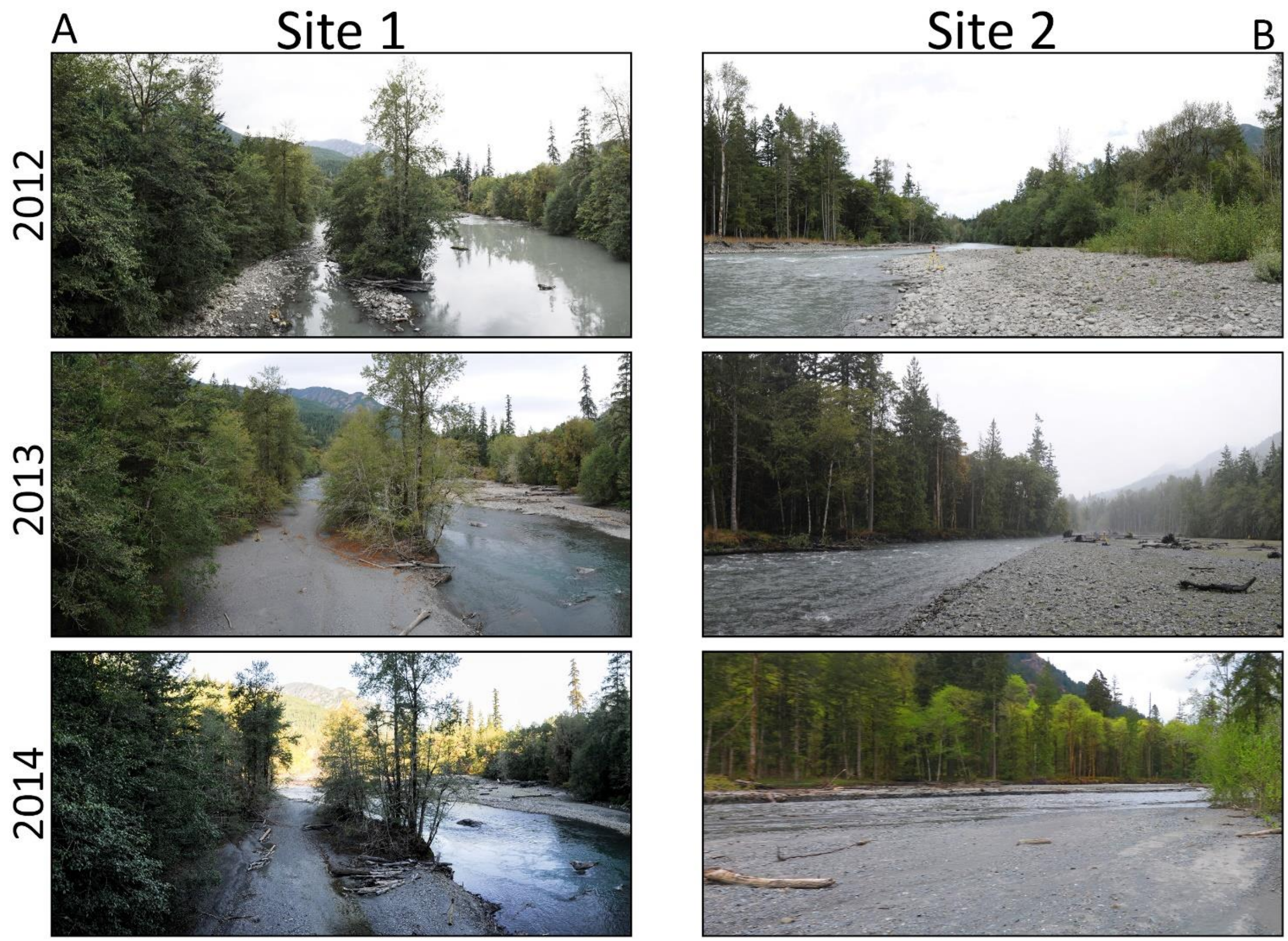

Figure 5a-b: Time series photos of Site 1 and Site 2. Photo series before during and after the dam removal. Each photo was taken during the Terrestrial Laser Scanning (TLS) surveys in late August. A: Site 1, there was a loss of the multiple channels and dramatic decrease in sediment size. B: Site 2, Notice the lateral progradation of the bar to river left and the decrease in sediment size

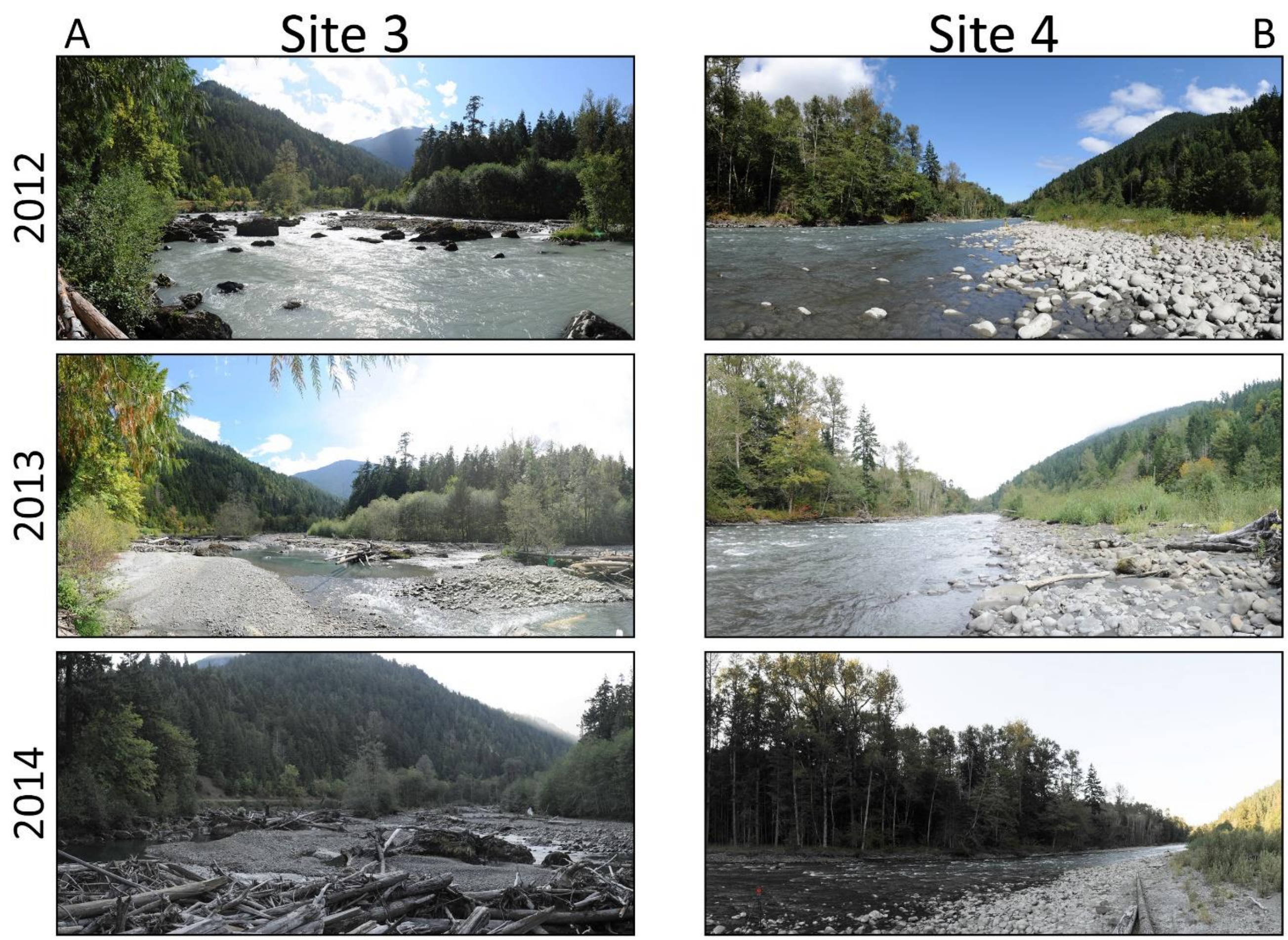

Figure 6a-b: Time series photos of Site 3 and Site 4. Photo series before during and after the dam removal. Each photo was taken during the Terrestrial Laser Scanning (TLS) surveys in late August. A: Site 3, there was a dramatic increase in Large Woody Debris and the forced migration of the multiple channels into the point bar. B: Site 4, there was an overall decrease in sediment size as it interstitially filled the existing cobbles that were in the site

CHAPTER II

METHODS

High-resolution topographic data were collected during the 2-year period after the Glines Canyon Dam was lowered to the base of the reservoir. This spanned the time from the beginning of the reservoir sediment release to the completion of the dam removal. I conducted three annual high-resolution topographic surveys in August, 2012, August, 2013, and August, 2014 (Fig. 7). More frequent surveys of sediment distribution and large woody debris were conducted during the intervening months throughout the total study period. The bimonthly sediment-distribution surveys were timed to quantify the progress of the sediment as the channel evolution progressed, while the mapping of large woody debris either followed large flow events or coincided with the sediment distribution surveys. Furthermore, the rates of historical channel changes in the river prior to the dam removal were documented using satellite images from Google Earth.

Four field sites downstream of Glines Canyon Dam (Figs. 1 and 3; Table1) were surveyed in August of three successive years during the dam removal. The first field season was in August 2012, prior to the release of the reservoir sediment into the system, which occurred in October 2012 (Fig. 7). The second and third seasons in 2013 and 2014 encompassed the remaining period of the dam removal. Each season consisted of Terrestrial Laser Scans (TLS) for high-resolution topographic data, large woody debris mapping, and sediment distribution surveys.

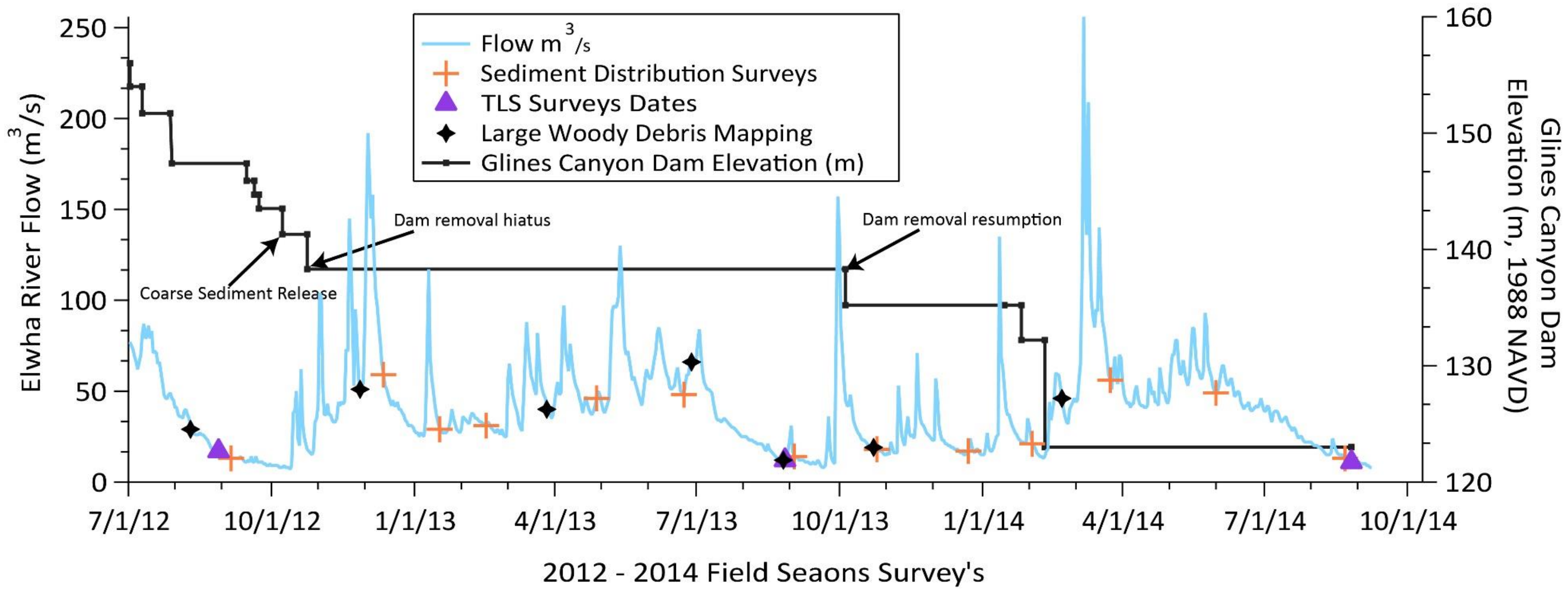

Figure 7: Elwha River hydrograph. The data was collected from the USGS gauging station # 12045500 located at the downstream end of the middle reach of the Elwha River at McDonald Bridge (RK 12.1). Each of the different survey dates, wood mapping and, dam draw down periods are plotted to see the connection of the Elwha River flow with the data collected.

High-Resolution Topographic Surveys

The annual topographic surveys were scheduled for maximum channel coverage during the yearly average low flow of the river from August 28th – September 2nd (Table 2). The first survey was timed just before the release of the reservoir sediment (sand and gravel) from the base of the reservoir to characterize the initial geomorphology at each of the survey sites (Fig. 7). The second survey took place just before the resumption of the dam removal after a 12-month hiatus (Fig. 7). The third survey took place a full year later at the same time as last few feet (~5ft) of the dam were being removed (Fig. 7).

TABLE 2. AVEAGE FLOW DURING TLS AND ALSM SURVEYS (USGS 15 MINUTE DATA)

	Survey Dates	Minimum (m^3/s)	Maximum (m^3/s)	Mean average Discharge (m^3/s)
TLS	8/26 – 28/2012	~16	~17	**~16**
TLS	8/27 – 28/2013	~11	~44	**~17**
TLS	8/26 – 27/2014	~9	~12	**~11**
ALSM	10/10 – 17/2012	~7	~85	**~23**

At each site, the surface topography was documented with repeat surveys using a Riegl VZ-400 terrestrial laser scanner (TLS), allowing for volumetric changes to be calculated by differencing topography. The XYZ coordinates of the point cloud data were resolved to a geographic location using targets mounted with Trimble Net RS Global Positioning System (GPS) units, and the data were differentially corrected using the Online Positioning User Service (OPUS) provided by the National Oceanic and Atmospheric Administration (NOAA).

The TLS point cloud was processed using the RiScan Pro software suite. First and partial returns were removed, and a deviation filter was applied to remove edge effects from the TLS scan. Next, the data were decimated to a point spacing of 1 cm. Both the living vegetation and the large woody debris were selected manually and removed from the point cloud data to ensure that only the changes in the sediment would be included in the differencing calculations between the subsequent TLS survey dates. The large woody debris data were saved into a separate data file for future use.

The post-processed "bare earth" point cloud file was imported into Quick Terrain Modeler 8 (QTM) to build a digital elevation model (DEM) using a Minimum Z interpolation algorithm, which downgraded to a 10 cm cell resolution. For areas of the floodplain not covered by TLS, I included aerial laser swath mapping (ALSM) (Figs. 1 and 3). The United States Geological Survey (USGS) collected ALSM data in October, 2012 (Fig. 7) during the time of "leaf off" to measure and map the expanse of the Elwha River prior to the reservoir sediment release. The mean average discharge at the time of the ALSM acquisition was ~20 m^3/s, larger than the discharge during the TLS surveys (Table 2). However, only the surface of the flood plain was used from the ALSM dataset and all of the in channel changes were measured from the TLS data. The flow regime of the river during the 3 years of dam removal did not reach above 250 m^3/s, meaning it did not overtop the riverbanks and there was no significant change to the floodplain during the time of the Glines Canyon Dam removal. For that reason, the single ASLM survey could supplement all three TLS surveys to derive DEMs.

By subtracting DEMs from one year to the next, it was possible to calculate a change in sediment volume at each study site and describe the distribution of sediment over the three survey dates during the removal of the Glines Canyon Dam. Each survey was imported into the Geomorphic Change Detection (GCD) software (Wheaton et al., 2010a) within ArcGIS 10.2. The raster calculator function of ArcGIS was used to subtract DEMs from one another. The resulting data is a DEM of difference (DoD) which documents the change in elevation, assumed to be due to deposition or erosion from one year to the next over the entire surface of the DEM. These changes in elevation were used to calculate a change in volume.

When differencing DEMs, it is difficult to differentiate between error in the DEM and low magnitude elevation change (Wheaton et al., 2010b). I accounted for the errors associated with the multiple sets of point cloud data by creating spatially varied error models for each topographic survey. The error models were created by generating a slope degree surface of the original DEM and a point density surface from the TLS and ALSM point cloud data. The slope and point density surfaces were combined in a fuzzy interference system (FIS) in MATLAB to generate the error model for a single survey. The resulting data is a raster with probabilistic error values for each given cell (the output cell resolution is the same as the original DEM) (Wheaton et al., 2010a). By combining the error models and the DEMs in the raster calculator for differencing, GCD separates the raw differencing values from the probabilistic error and the resulting output is a probabilistic DEM of difference.

TABLE 3: AVERAGE VERTICAL DIFFERENCE IN WATER SURFACE ELEVATION

Survey Site	2012-2013 Change Water Elevation (m)	2013 - 2014 Change Water Elevation (m)
Site 1	0.28	0.38
Site 2	0.65	0.39
Site 3	1.88	0.38
Site 4	0.19	0.16

The laser on the VZ400 does not penetrate water, which is why the annual TLS topographic surveys were scheduled during the yearly average low flow of the river for maximum channel coverage (Table 2). However, there were still minor differences in the flow (and thus the river elevation) from year to year. For these analyses, the areas where the change in elevation was solely due to a change in the water surface were removed from the DEMs of difference (Fig. 8; Table 3). First, water-to-water data was removed and indicated as *no data* (Fig. 8). Second, areas where the channel simply dewatered exposing the original bed surface but not necessarily acting as erosion were removed (Fig. 8). Finally, areas were water surface was overtaken by new deposition were counted as minimum elevation changes and therefore only minimum volumetric changes were reported (Fig. 8).

Sediment Distribution Analysis

To quantify changes in surface sediment-size distribution over the course of the study, sediment distribution surveys including pebble counts and photographs of each site were collected approximately bi-monthly from August 2012 to August 2014 (Fig. 7). With this survey schedule, it was possible to obtain a high temporal resolution of the change in sediment distribution throughout the study reach following large flow events. Using a variation of the Wolman (1954) pebble count method, transects were measured perpendicular to the river channel across the top, middle, and bottom of bars by laying out a tag line with a 50 meter measuring tape. The major axis of the sediment grains ≥1 mm was measured every meter from the bank to the water's edge. A minimum of 100 measurements were taken at each site, which sometimes required multiple closely-spaced transects. Repeat photographs were shot from the same location along with additional photographs to document specific changes. Overall, the photographs provided a qualitative representation of the physical changes that occurred at each of the study sites.

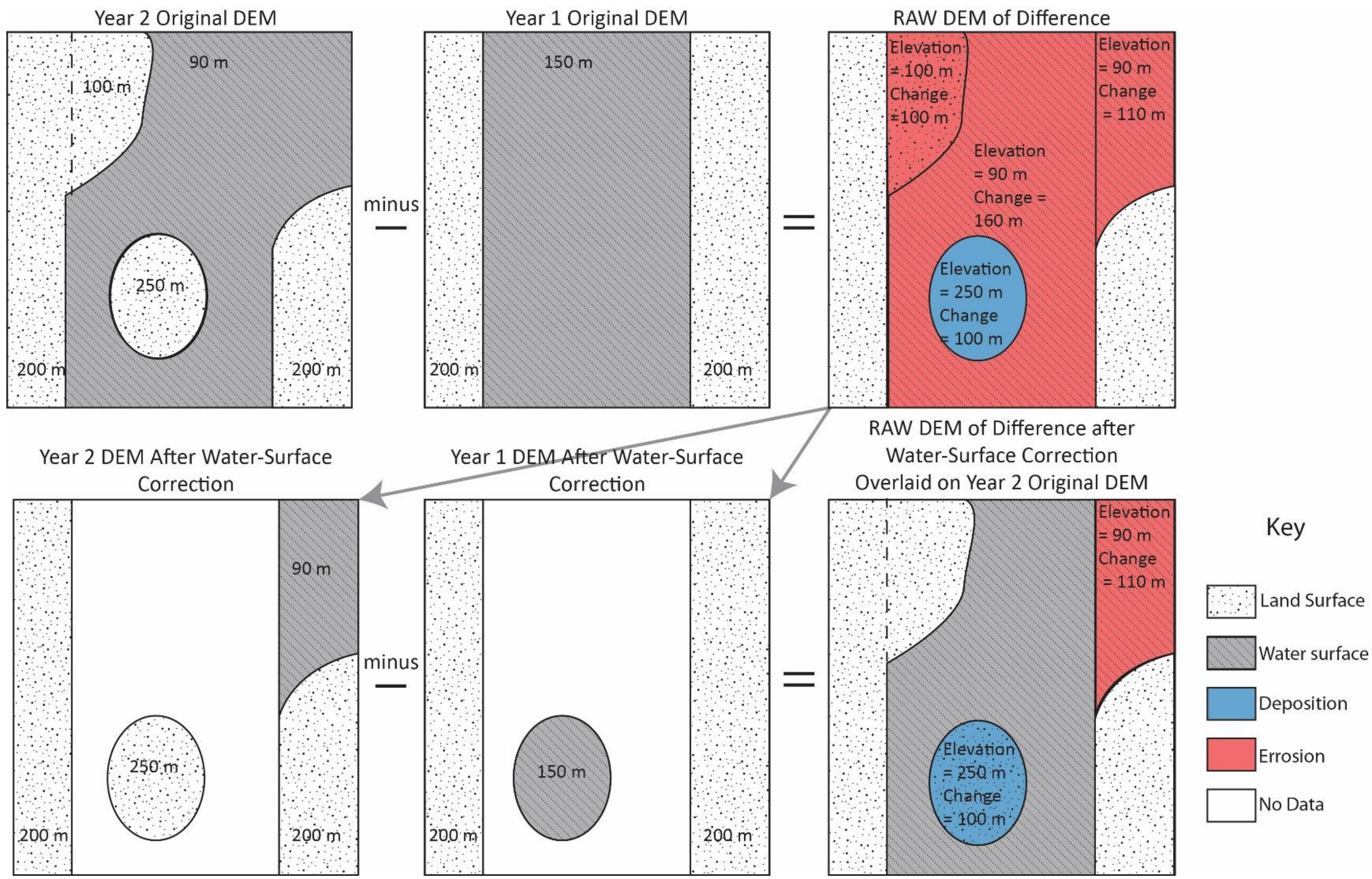

Figure 8: Conceptual figure accounting for water surface differencing error

Large Woody Debris

The large woody debris was counted and mapped on aerial orthographic photographs taken by the National Park Service between August, 2012, and August, 2014 with a total of six sites co-located with the TLS and sediment distribution sites (Ritchie et al., 2015). Log jams were defined as three or more logs touching or in close proximity to one another (< 1 meter apart) and were mapped as polygons in ArcGIS 10.2. Individual logs exceeding 2 m in length were mapped using polylines. Each large woody debris survey was confirmed in the field during the sediment distribution surveys.

CHAPTER III

RESULTS

In an effort to better understand how each of the individual geomorphic properties affect the middle reach of the river the results are organized by each of the datasets that were collected. First reported is the geomorphic changes at each site over the entire dam removal process, followed by the changes in the sediment distribution and woody debris at each site.

Geomorphic Change

Site 1

Site 1 is located 11.6 km downstream of the Glines Canyon Dam and is 300 m long (Fig. 3; Table 1). It is located where the river initially opens up to the floodplain from the Glines Canyon. There were four flowing channels through the reach at the beginning of the study period (Figs. 3 and 9a). The measurements of topographic change indicate that the subaerial bar surface increased by 105% in the first year of dam removal with an overall increase of 9,140 m^2 (Fig. 10a; Table 5). Along with the subaerial changes, the measurable topographic changes indicate that there was a net increase in sediment volume of 5,040 $\pm$ 1,860 m^3 which, equates to an average vertical change of 0.28 m (Figs. 5a and 10a; Table 4). With the increase in sediment, there was vertical aggradation throughout the entire site. In the left-hand river channel, approximately two vertical meters were deposited, and the river abandoned the far left channel (Figs. 5a, 9a and 10a). In conjunction with the deposition of the sediment in the left-hand channel, the river also deposited sediment at the upstream end of the two right-hand channels,

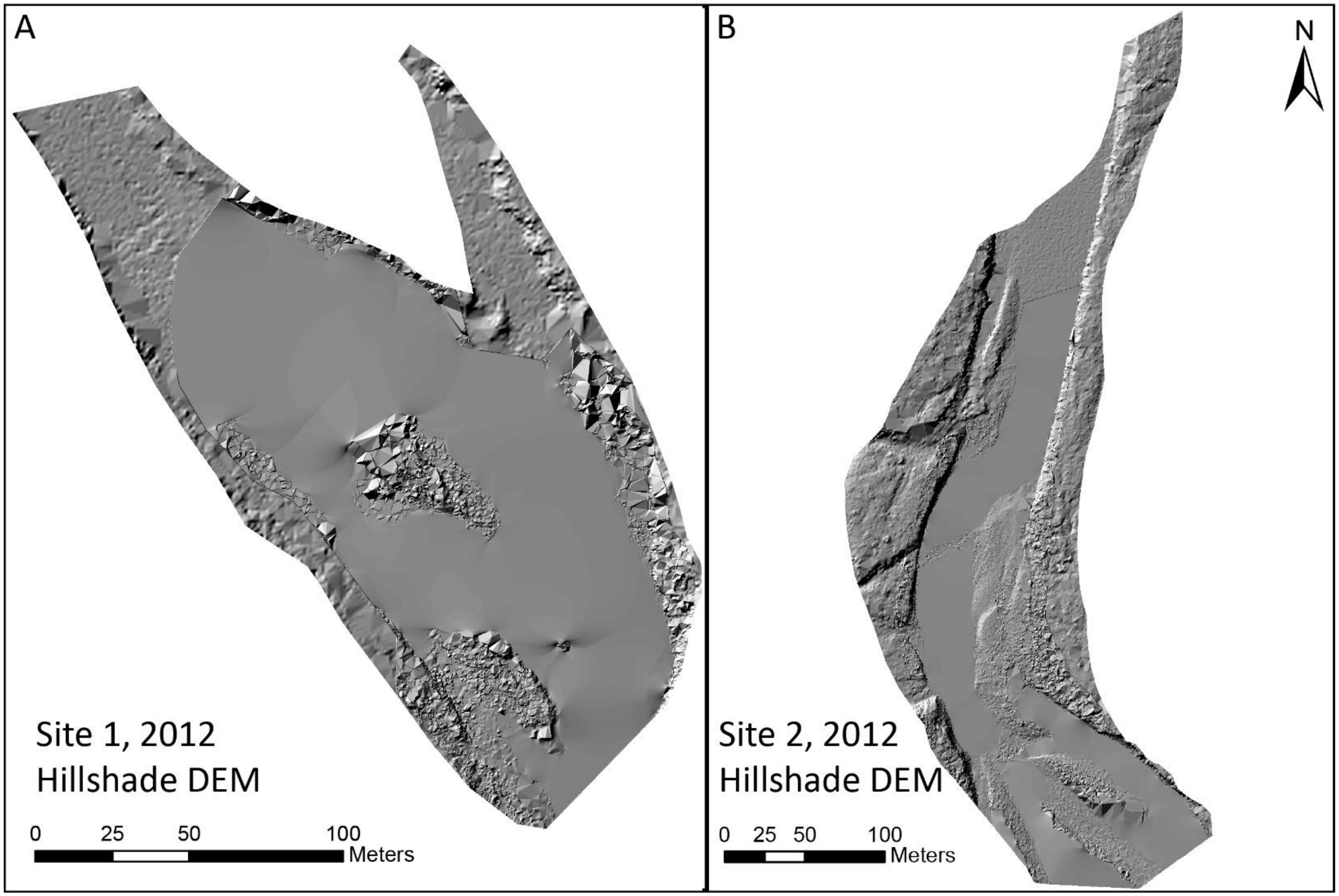

Figure 9a-b: 2012 Hillshade of Site 1 and Site 2. A**:** Site 1, August 2012, hillshade surface prior to coarse sediment release with several flowing channels. B**:** Site 2, August 2012, hillshade surface prior to coarse sediment release with a single channel and prominent point bar.

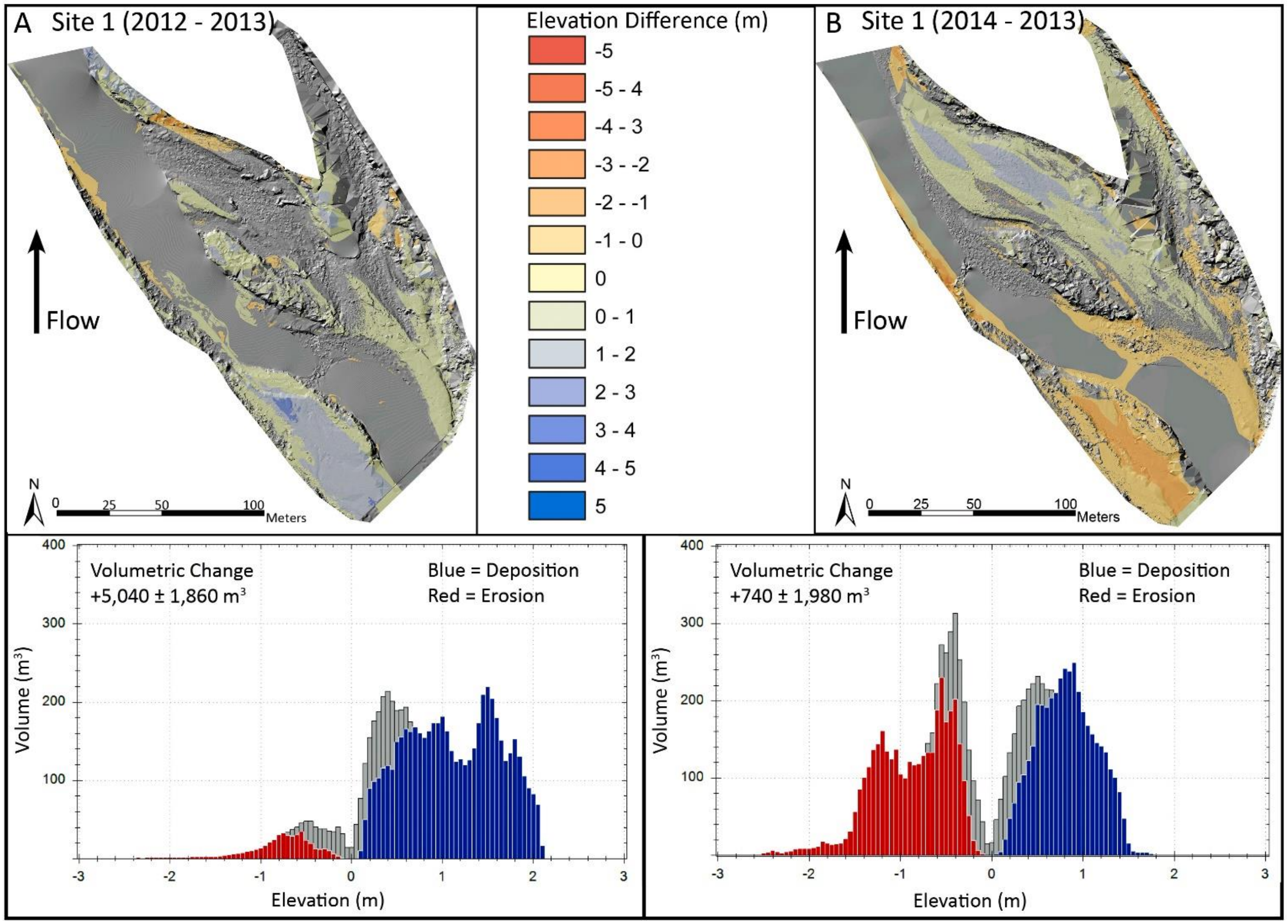

Figure 10: DEM of Difference (DoD), Site 1, demonstrates the in vertical elevation of the ground surface between TLS surveys. Large amounts of deposition can be seen in Year 1 of dam removal where as in Year 2 there appears to be an equal amount of deposition vs. erosion. Grey areas in the map are surfaces that were not used in the differencing calculations due to the water surface errors discussed. The histograms depict the volume change over the elevation the grey indicates the potential error in the volume over the change in elevation.

TABLE 4. VOLUMETRIC DIFFERENCES (m^3)

Site 1 (1.6km)	2013-2012				2014-2013			
	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)
Total Volume of Erosion (m^3)	760	460 ± 260	57%	0.03	4,220	3,310 ± 1,250	38%	0.17
Total Volume of Deposition (m^3)	6,300	5,500 ± 1,840	33%	0.31	4,900	4,050 ± 1,530	38%	0.20
Total Volumetric Change (m^3)	7,060	5,960 ± 2,100	35%	0.33	9,120	7,360 ± 2,780	38%	0.37
Net Volumetric change (m^3)	5,540	**5,040 ± 1,860**	37%	0.28	680	**740 ± 1,980**	268%	0.04
Site 2 (3km)	**2013-2012**				**2014-2013**			
	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)
Total Volume of Erosion (m^3)	10,710	10,100 ± 2,110	21%	0.25	11,440	9,650 ± 3,160	33%	0.27
Total Volume of Deposition (m^3)	30,720	29,140 ± 6,530	22%	0.74	7,480	6,050 ± 2,260	37%	0.17
Total Volumetric Change (m^3)	41,430	39,240 ± 8,640	22%	0.99	18,920	15,700 ± 5,420	35%	0.44
Net Volumetric change (m^3)	20,010	**19,040 ± 6,860**	36%	0.48	-3,960	**-3,600 ± 3,890**	-108%	-0.10

TABLE 4 (CONTINUED).

Site 3 (4km)	2013-2012				2014-2013			
	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)
Total Volume of Erosion (m^3)	170	90 ± 60	67%	0.00	3,430	2,230 ± 1,150	52%	0.05
Total Volume of Deposition (m^3)	59,240	58,680 ± 9,830	17%	1.95	8,070	5,690 ± 2,680	47%	0.12
Total Volumetric Change (m^3)	59,410	58,770 ± 9,890	17%	1.95	11,500	7,920 ± 3,830	48%	0.17
Net Volumetric change (m^3)	59,070	**58,590 ± 9,830**	17%	1.94	4,640	**3,460 ± 2,920**	84%	0.07

Site 4 (5.6km)	2013-2012				2014-2013			
	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)
Total Volume of Erosion (m^3)	2,270	890 ± 540	61%	0.03	2,930	1,460 ± 800	55%	0.05
Total Volume of Deposition (m^3)	5,840	3,970 ± 1,750	44%	0.14	2,470	1,260 ± 710	56%	0.04
Total Volumetric Change (m^3)	8,110	4,860 ± 2,290	47%	0.17	5,400	2,720 ± 1,510	56%	0.09
Net Volumetric change (m^3)	3,570	**3,080 ± 1,830**	59%	0.11	-460	**-200 ± 1,070**	-535%	-0.01

TABLE 4 (CONTINUED)

Entire Study Area	2013-2012				2013-2014			
	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)	Raw (m^3)	Thresholded DoD Estimate: (m^3)	% Error	Per unit Area (m)
Total Volume of Erosion (m^3)	13,910	11,540 ± 2,970	26%	0.10	22,020	16,650 ± 6,360	38%	0.12
Total Volume of Deposition (m^3)	102,100	97,290 ± 19,950	21%	0.84	22,920	17,050 ± 7,180	42%	0.13
Total Volumetric Change (m^3)	116,010	108,830 ± 22,920	21%	0.94	44,940	33,700 ± 13,540	40%	0.25
Net Volumetric change (m^3)	88,190	**85,750 ± 20,170**	24%	0.74	900	**400 ± 9,590**	2399%	0.00

VOLUMETRIC METRICS
On a cell-by-cell basis, the DoD erosion depth multiplied by cell area and summed
On a cell-by-cell basis, the DoD deposition depth multiplied by cell area and summed
The sum of erosion and deposition volumes (a measure of total turnover)
The net difference of erosion and deposition volumes (i.e. deposition minus erosion)

TABLE 5. SURFACE AREA CHANGES (m^2)

	Inital Surface Area			Surface Area Differences				
	Survey Year	Total Exposed Surface (m2)	Point Bar Surface	Differencing Year	Change in total Surface Area (m2)	Percent change	Point Bar	Percent Change (Point Bar)
Site 1	2012	8720	N.A.					
	2013	17860	N.A.	2013-2012	9140	105%	N.A.	N.A.
	2014	19961	N.A.	2014-2013	2100	12%	N.A.	N.A.
Site 2	2012	36370	4899					
	2013	39610	15170	2013-2012	3240	9%	10271	210%
	2014	35860	12201	2014-2013	-3750	-9%	-2970	-20%
Site 3	2012	23150	N.A.					
	2013	30150	N.A.	2013-2012	7000	30%	N.A.	N.A.
	2014	46750	N.A.	2014-2013	16600	55%	N.A.	N.A.
Site 4	2012	25320	N.A.					
	2013	28390	N.A.	2013-2012	3070	12%	N.A.	N.A.
	2014	30890	N.A.	2014-2013	2500	9%	N.A.	N.A.

* N.A = Not Applicable

diverting the flow to the center channel. In response to the change in flow dynamics, Site 1 became a single channel site by the end of the first year of dam removal.

In the second year of dam removal, the topographic measurements show a 12% increase in the subaerial bar surface and an indeterminate change in sediment volume due to the large error compared to the net change in sediment volume (740 $\pm$ 1,980 m^3) (Fig. 10b; Table 4). A large contribution to the topographic change was the largest flood event during the dam removal process. In March of 2014, the river discharge reached ~250 m^3/s (Fig. 7) and overtopped the bars that were created in the previous season. This event deposited a blanket of sediment ranging from 20 cm to 1.5 m thick on the bar on river right and eroded up to ~1.5 vertical meters from the bar on river left (Fig. 10b). However, the overall average vertical increase in sediment deposition was only 0.04 m (Table 4).

The error associated with the net volume change is 3 times greater than the reported net value of 740 m^3 (Fig. 10b; Table 4). However, the locations where the topographic change data indicate deposition and erosion of sediment were verified in the field. The large amount of error is associated with the need to account for the small changes in elevation that are close to the vertical resolution of the survey (+/- 0.68m). As described by Wheaton et al. (2010b), it is difficult to differentiate the error from a survey from the low magnitude change in the differencing calculations. In the case of the 2013 – 2014 survey, a large portion of the topographic change occurred over the right hand bar. In this area, the measurements of topography indicate that the vertical change ranged from 0 – 1 m which introduces the possibility of the change being part of the noise in the DEM.

Site 2

Site 2 is a ~400 m long reach located 3 km below the Glines Canyon Dam (Fig. 3; Table 1). This is an area where two channels merge together at a bend in the river which forms a prominent point bar on river right (Figs. 3 and 9b). In the first year of dam removal, the subaerial surface of Site 2 increased by 9%, totaling 3,240 m^2 (Fig. 11a; Table 5). The largest morphological change in the reach was on the point bar, which grew by 210% or 10,271 m^2 (Fig. 11a; Table 5). The discrepancy of the total change and the point bar accumulation is due to the loss of subaerial surface caused by cut bank erosion on the left bank (Fig. 11a; Table 4). With the enlargement of the point bar, the measurable topographic change indicates a net volumetric increase of 19,040 $\pm$ 6,870 m^3 (Fig. 11a; Table 4) and an average vertical increase of 0.48 m. The expansion of the point bar forced the river to laterally migrate left by ~30 m, eroding into the cut bank of the flood plain. As described at Site 1, the error associated with the sediment volume calculations is generated by the small differencing calculations that are close to the level of resolution in the DEM.

During the 2013-2014 season, the channel morphology laterally migrated left and increased in sinuosity. The subaerial surface of the entire survey reach decreased by 10% totaling a loss of 3,750 m^2. This value includes the 20% (-2,970 m^2) decrease of total surface area on the point bar (Fig. 11b; Table 5). In conjunction with the loss of surface area, the measured topographic change indicates a decrease in overall volume with a net change of -3,590 $\pm$ 3,880 m^3 (Fig. 11b; Table 4), equating to an average decrease in vertical elevation of 0.10 m. However, as described in at site 1, the errors associated with

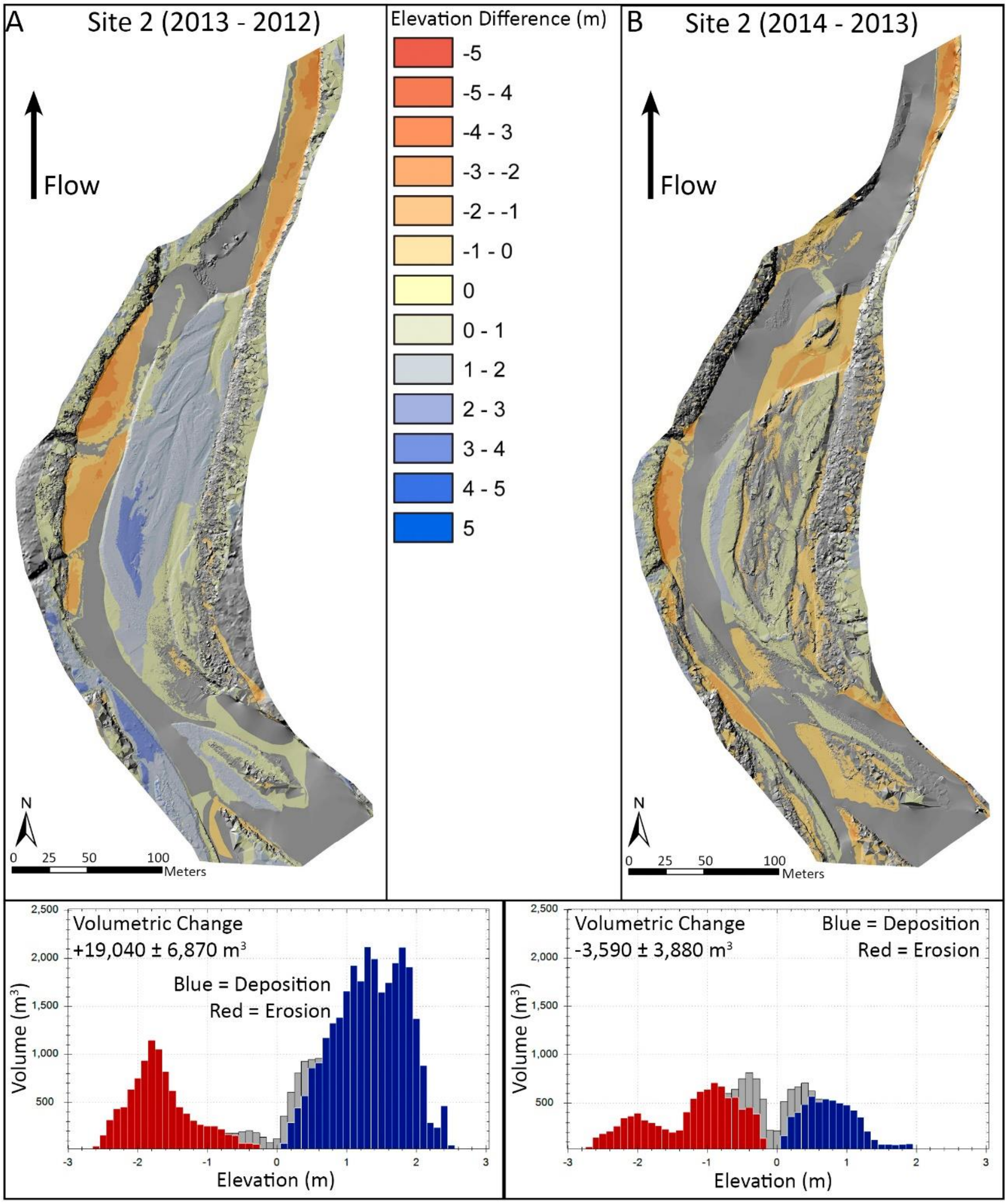

Figure 11: DEM of Difference (DoD), Site 2, demonstrates the change in vertical elevation of the ground surface between TLS surveys. Channel migration and vertical deposition can be seen as the point bar prograde river left with the subsequent excavation of the cut bank in Years 1 and 2. Grey areas in the map are surfaces that were not used in the differencing calculations due to the water surface errors discussed. The histograms depict the volume change over the elevation; the grey indicates the potential error in the volume over the change in elevation.

the volumetric changes indicate that there is an indeterminate change in net volume when comparing erosion to deposition.

Site 3

Site 3 is a 560-m-long, large u-shaped bend in the river located 4 km downstream of the Glines Canyon dam (Fig. 3, Table 1). This site experienced the greatest amount of geomorphic change in the entire study. Prior to the reservoir sediment release, this large bend had some prominent rapids, large boulders, and exposed bedrock in the river channel and was split between three flowing channels (Fig. 6a and 12a). In the first year of dam removal (2012-2013), the measurements of topographic change show that the subaerial surface increased by 30% with a total change of 7,000 m^2 (Fig. 13a; Table 5). Synchronous with the increase in surface area was a measurable topographic change that indicates a net volumetric increase of 58,590 $\pm$ 9,830 m^3 of sediment throughout the survey area and an average vertical increase of 1.94 m (Fig. 13a; Table 4). Following the increased sediment load and new sediment deposition there was transformation of the main thalweg at the far right channel into a deep slow-moving pool and the abandonment of the center channel. As a result, the flow was redirected into the farthest left hand channel at the inside of the river bend (Figs. 6a and 13a).

Over the second year of dam removal, the subaerial surface increased by 55% with an overall increase of 16,600 m^2 (Fig. 13b; Table 5). In contrast to the large increase in surface area, the topographic measurements indicate an indeterminate change in net volume measuring 33,470 $\pm$ 2, 910 m^3 this is likely due to the same error assessments that each of the other sites have experienced. Overall, there was still an average vertical change of 0.07 m (Figs. 6a and 13b; Table 4). During this time, the topographic changes

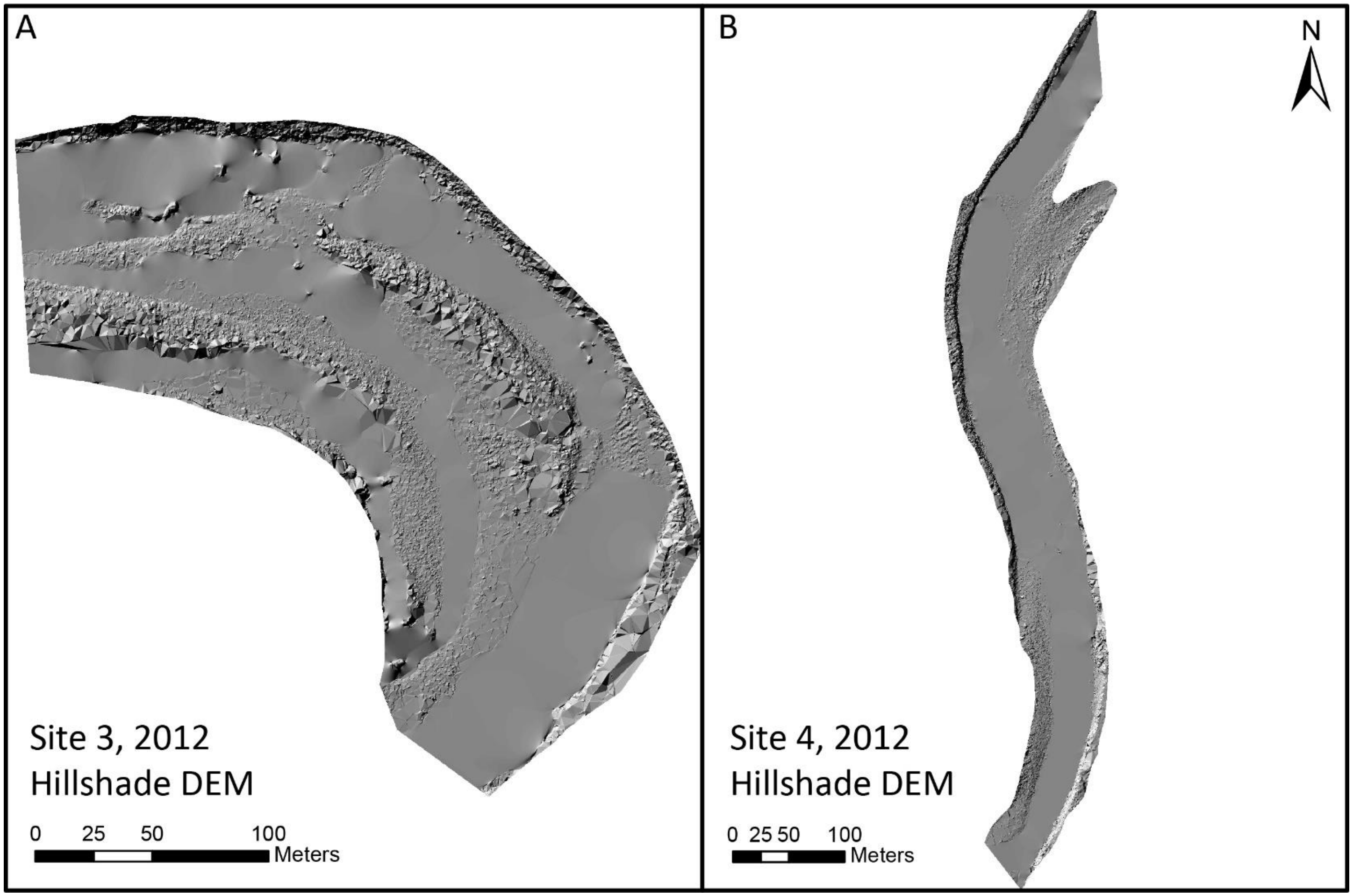

Figure 12a-b: 2012 Hillshade Site 3 and Site 4. A**:** Site 1, August 2012, hillshade surface prior to coarse sediment release with several flowing channels. B**:** Site 2, August 2012, hillshade surface prior to coarse sediment release with a single channel and prominent point bar.

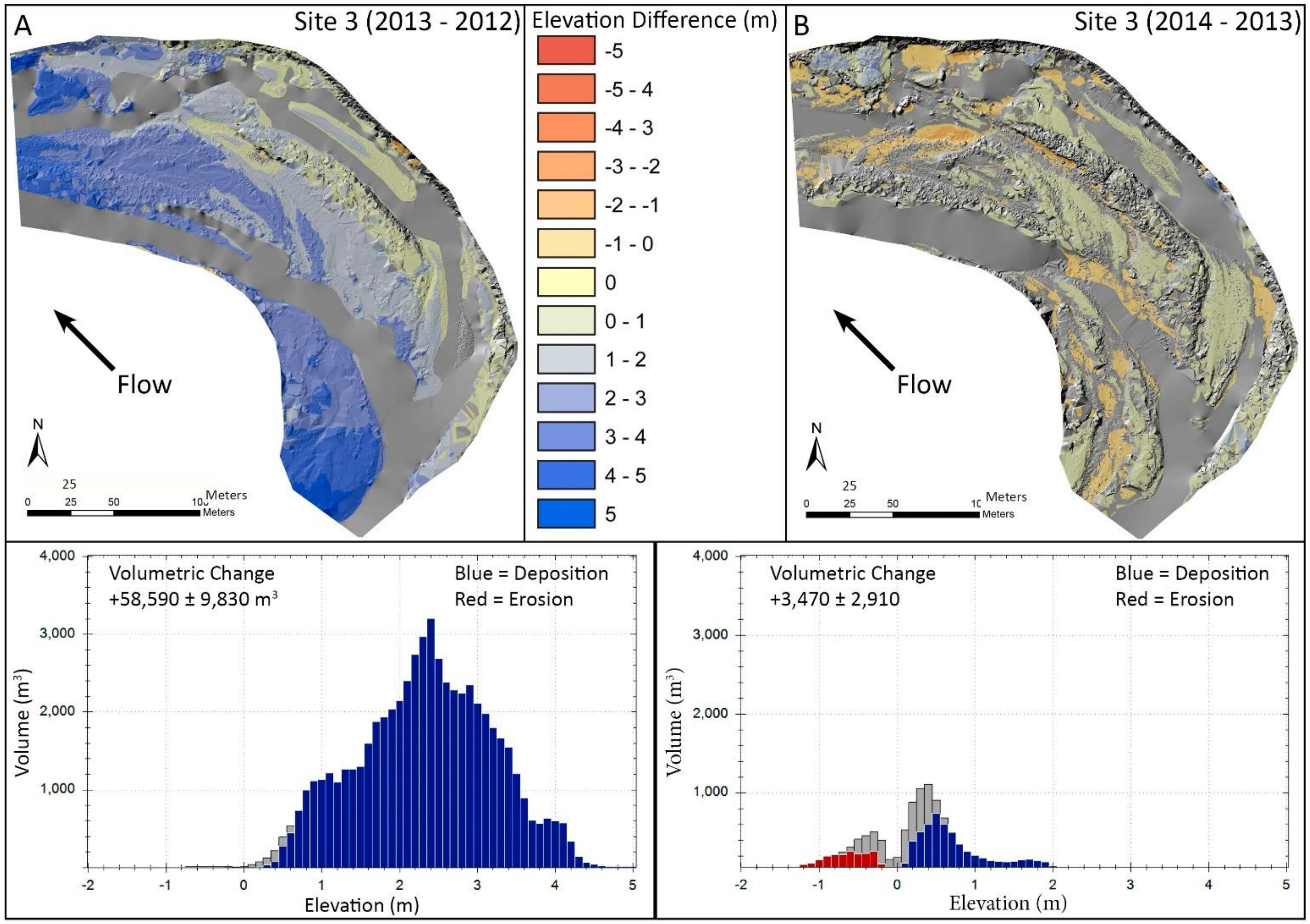

Figure 13: DEM of Difference (DoD), Site 3, demonstrates the change in vertical elevation of the ground surface between TLS surveys. Copious amounts of sediment deposition can be seen in Year 1 and 2 of dam removal. There was a loss of the multiple channels from the outside bend of the river moving the primary flow of the river to the inside bend. Grey areas in the map are surfaces that were not used in the differencing calculations due to the water surface errors discussed. The histograms depict the volume change over the elevation; the grey indicates the potential error in the volume over the change in elevation.

show that the right channel was subject to more sediment deposition than that of the inside point bar and small vertical changes on the surface of the bars throughout the study reach (Fig. 13b). In turn, the center channel of the river was fully abandoned and the left most channel took on the greatest proportion of flow (Figs. 6a and 13b).

Site 4

Site 4 is a 700-meter long reach located 5.6 km downstream of the Glines Canyon dam at the boundary of the Olympic National Park (Fig. 3; Table 1). The reach has a slight meander with no branching channels and very little exposed bar surface (Fig. 12b). Over the first year of dam removal, the measurements of topographic change show a 12% growth in the subaerial surface totaling 3,070 m^2 (Fig. 14a; Table 5). In conjunction with the growth in surface area, the measurable topographic change also indicates a volumetric growth of 3,080 $\pm$ 1,830 m^3 indicating an average vertical increase of 0.11m throughout the study reach (Fig. 14a; Table 4). During this time, there was little change in the morphology of the river channel, but there was some sediment collection and growth of a new mid-channel bar at the center of the reach (Fig. 14a). The sediment that did deposit in this area was found along the channel margins and interstitially filled the cobbles that made up the original bed surface in 2012 (Figs. 6b and 14a). In contrast to sites 1-3, Site 4 did not experience any channel migration or redirection.

At the end of the second year of dam removal, there was a 9% increase in subaerial surface totaling 2,500 m^2 (Fig 14b; Table 5). However, the topographic measurement indicate an indeterminate change in net volume of -2200 $\pm$ 1,070 m^3 (Fig. 14b; Table 4). The upstream end of the northern bar experienced the greatest amount of

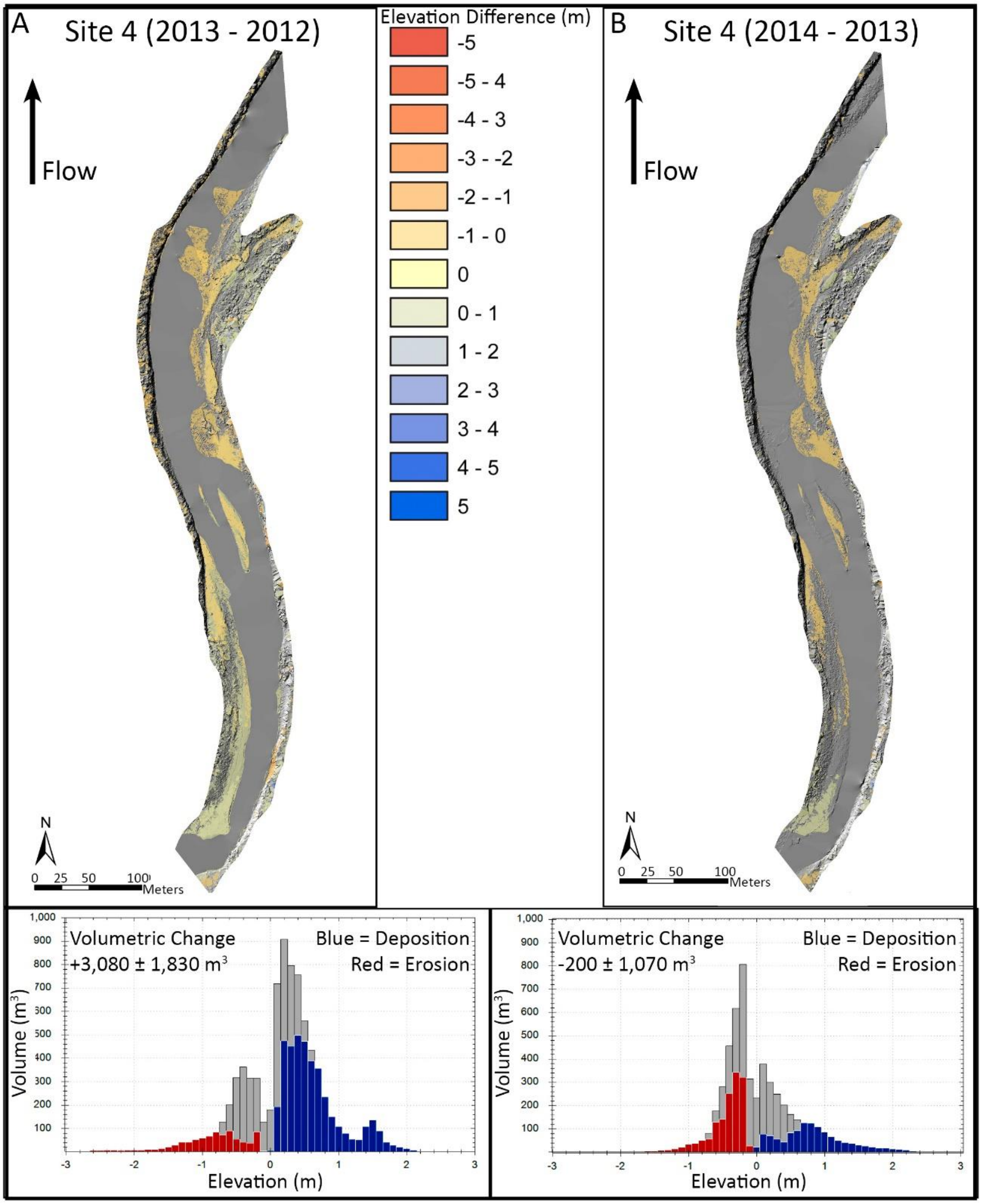

Figure 14: DEM of Difference (DoD), Site 4, demonstrates the change in vertical elevation of the ground surface between TLS surveys. The change that occurred at Site 4 is minor when compared to the other 3 sites. However, sediment did deposit as seen in the histograms. The primary sedimentation in year 1 is at the upstream end of the survey site. Grey areas in the map are surfaces that were not used in the differencing calculations due to the water surface errors discussed. The histograms depict the volume change over the elevation; the grey indicates the potential error in the volume over the change in elevation.

Change during this period. The measurable changes in topography indicate low level vertical losses of sediment on the upstream end of the bar surface (Fig. 14b).

Sediment Size and Distribution

Site 1

The initial sediment distribution in September 2012 shows that the D_{84} was approximately 590 mm (Figs. 15a and 15b). Following the initial reservoir sediment release from the reservoir in October 2012 (Fig. 7), by December 22012 the D_{84} had decreased to 24 mm (Fig. 15a, 15b and 18a). The D_{84} continued to decrease to 9 mm into May 2013 (Fig. 15b). It was not until September 2013 that the sediment at Site 1 coarsened again and the D_{84} increased to 12 mm (Fig. 15b). Between September and October 2013 there was a large flow event (Fig. 7), and the D_{84} decreased to 11 mm (Figs. 15b and 16b). During this time, the dam lowering events resumed after a hiatus of almost 1 year, and sediment was allowed to flow from the reservoir again.

There was a continued decrease in sediment size into December 2013, when the D_{84} measured 7 mm (Fig. 15b). At this point, the winter seasonal flows started to emerge and the D_{84} started to increase again (Fig. 7). By February 2014 the D_{84} increased to 14 mm (Fig. 15b). After the February 2014 sediment survey, the largest flood event (Fig. 7) occurred on the Elwha River and ended just before the March 2014 survey. During that time the D_{84} increased to 17mm (Figs. 15b and 16c). The seasonal flows continued into May 2014 where the D_{84} measured to be 23 mm (Fig. 15b). By the last survey in August 2014 the D84 had continued to increase to 39 mm (Fig. 15b)

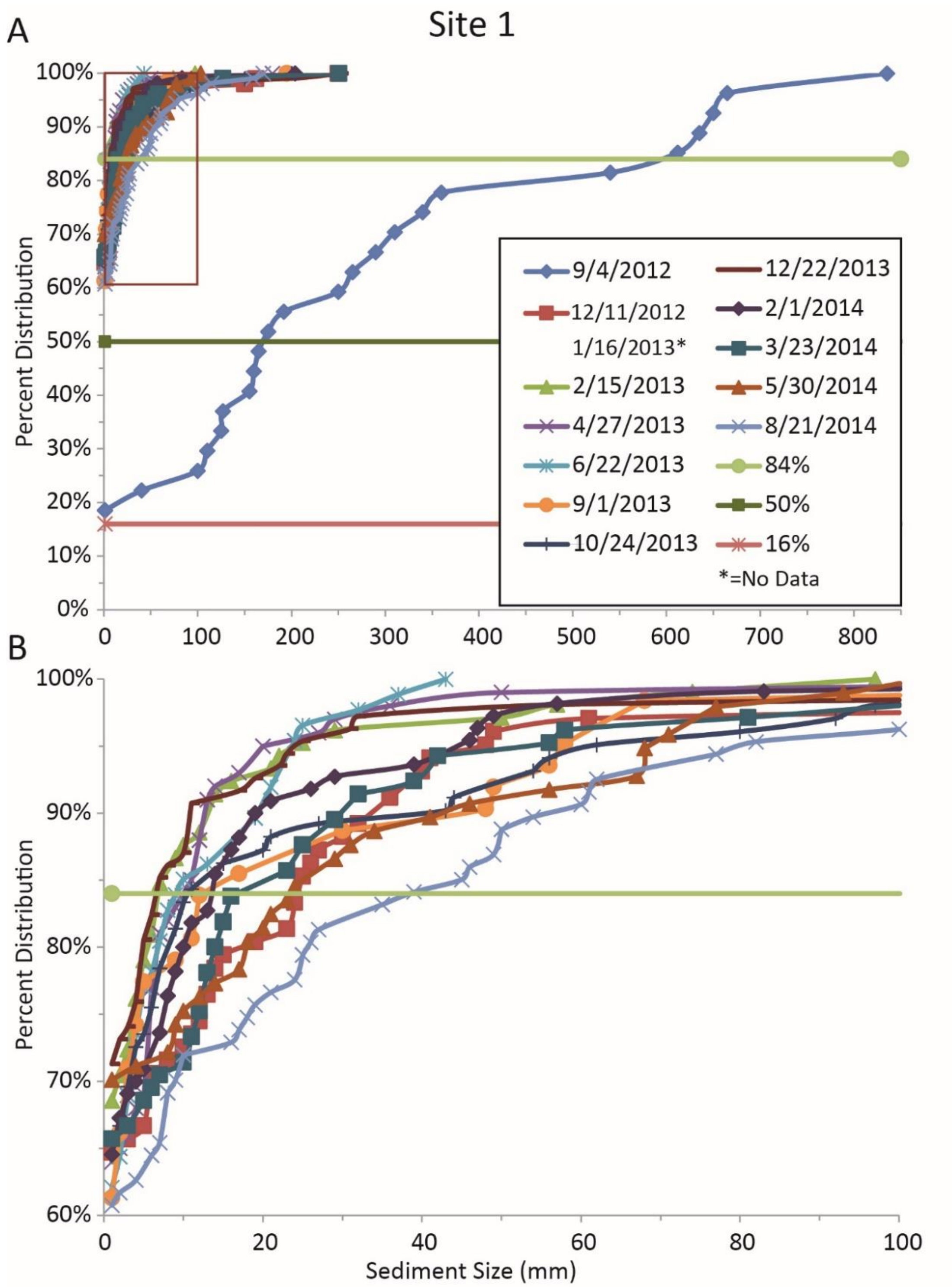

Figure 15: Site 1, surface sediment distribution. A: Surface distribution of sediment over the entire survey period. Notice the change from a primarily cobble system to a sand dominant system in the first 2 months following the coarse sediment release. Red box indicates the change in scale for 15b. B: Zoomed in surface distribution to see the change following the coarse sediment release.

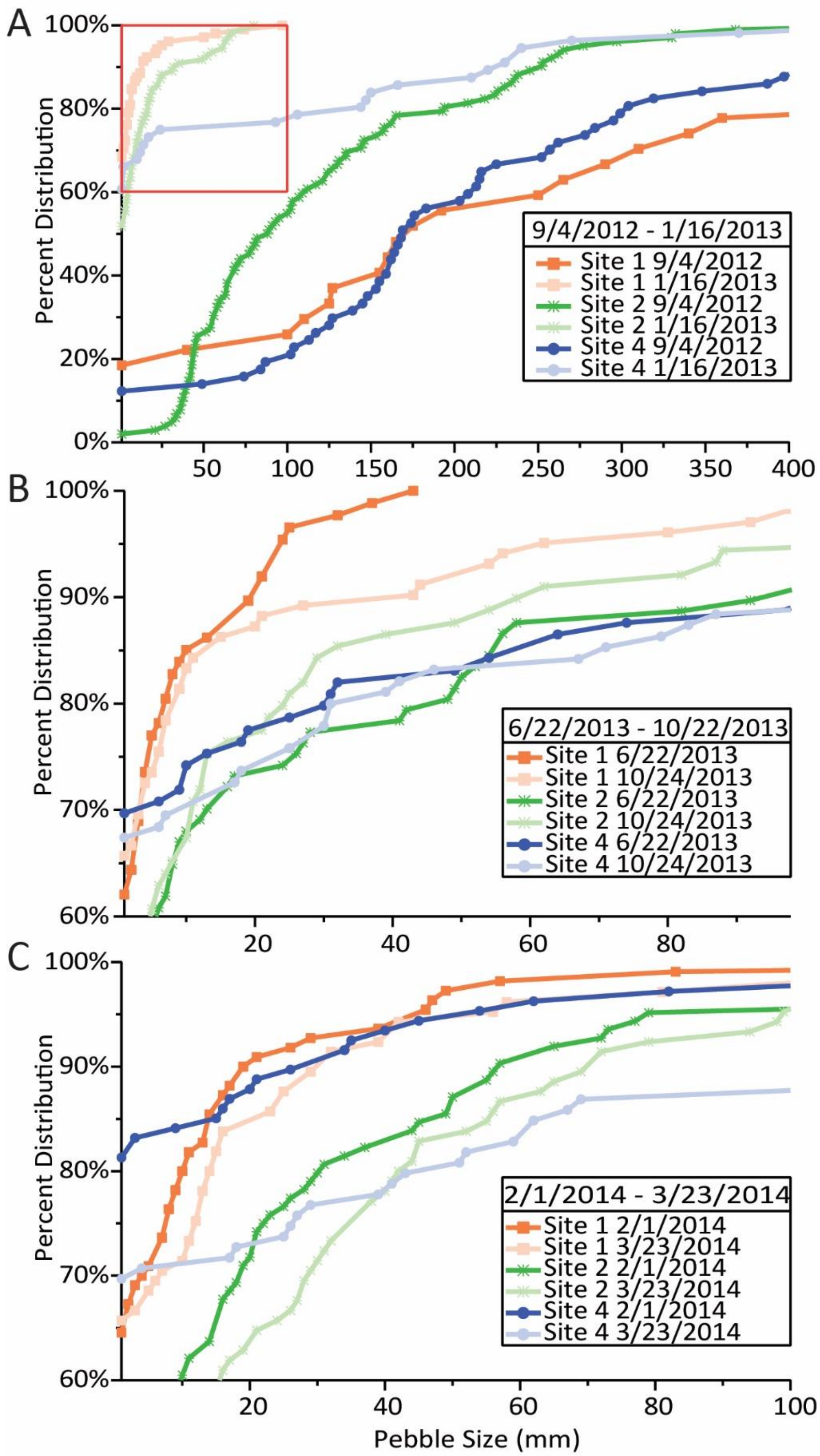

Figure 16 a-c: Sediment distribution surveys spanning the pre coarse sediment release and the two high flow events that took place during dam removal until the end of dam removal. The red box in 16A outlines the change in scale for 16B and 16C

Site 2

The initial sediment distribution in September 2012 shows that the D_{84} was approximately 225 mm (Figs. 16 and 17a). Following the reservoir sediment release in October 2012 (Fig.7) and by January 2013 the D_{84} had decreased to 19 mm (Figs. 16a and 16b). Unlike Site 1, there were no measurements in December 2012 due to Site 2 being flooded (Fig. 7). The D_{84} continued to decrease to 18 mm following the February 2013 survey (Fig. 17b). The D_{84} at Site 2 then started to increase, measuring 37 mm by the end of April 2013 and 53 mm by the end of June 2013 (Fig. 17b). At the end of the first year of the dam removal, the D_{84} had decreased slightly to 50 mm in September 2013 (Fig. 17b).

Between September 2013 and October 2013, there was a large flow event and the D_{84} decreased to 29 mm (Fig. 7, 16b and 17b). During this time, the dam lowering events resumed and sediment was allowed to flow from the reservoir as well. In contrast to Site 1, where there was a continued decrease in sediment size, the D_{84} at Site 2 increased to 72 mm by the end of December 2013 (Fig. 17b). Following the December 2013 survey, the D_{84} decreased again and by the beginning of February 2014 the D_{84} measured 44 mm (Fig. 17b). After the February 2014 sediment survey, the largest flood event occurred on the Elwha River and ended just before the March 2014 survey. During that time, the D_{84} increased to 53 mm and continued to increase into May 2014, when the D_{84} measured 61 mm (Figs. 7, 16c and 17b). By the last survey in August 2014, the D_{84} had decreased to 49 mm (Fig. 17b).

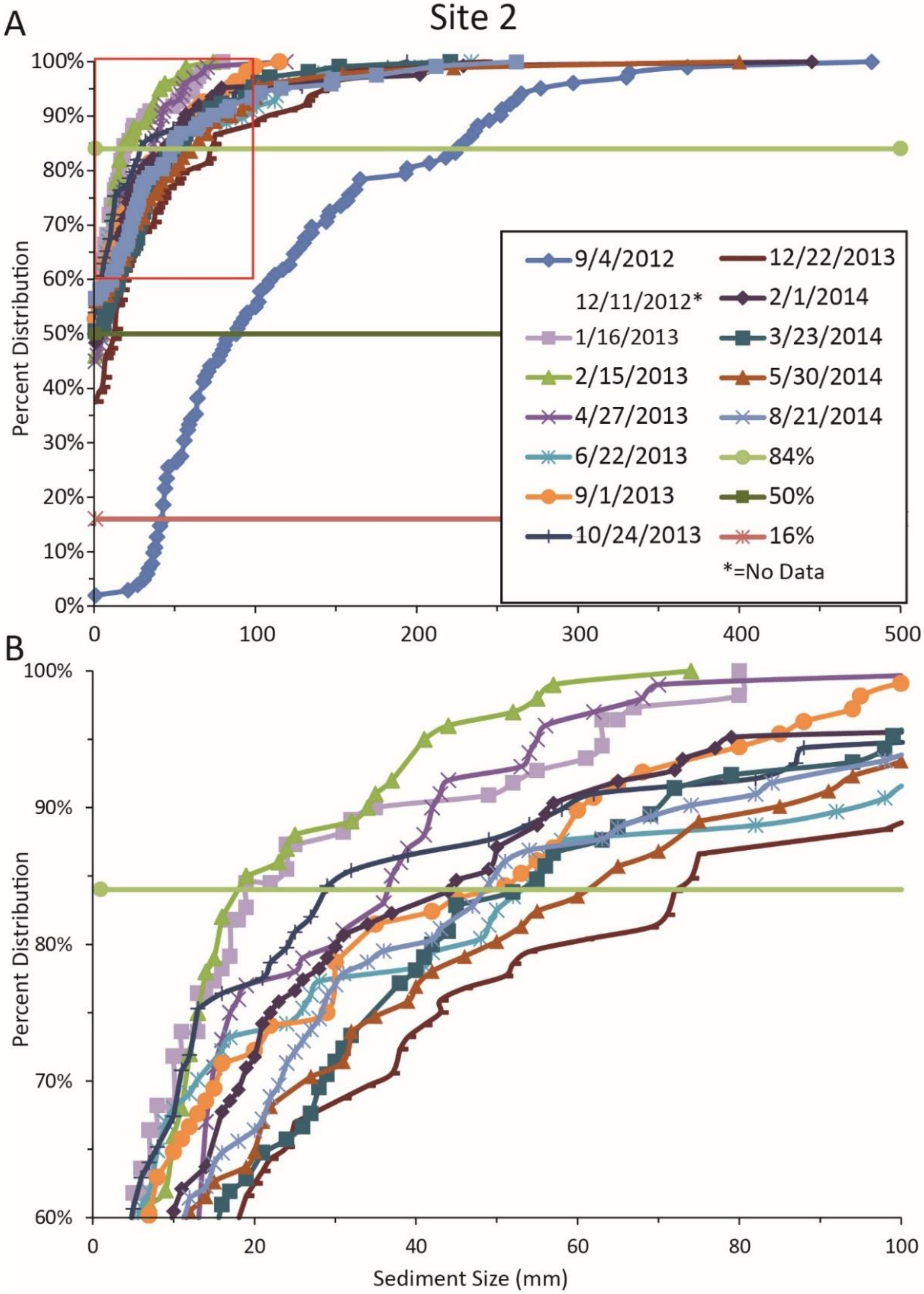

Figure 17a-b: Site 2, surface sediment distribution. A: Surface distribution of sediment over the entire survey period. Notice the change from a primarily cobble system to a sand dominant system in the first 2 months following the coarse sediment release. Red box indicates the change in scale for 17B. B: Zoomed in surface distribution to see the change following the coarse sediment release

Site 3

Sediment distribution data were not collected at this site due to the dangers of crossing the river to reach the exposed gravel bars. Photographs before and after the dam removal and the DEM of Difference data both show lateral and vertical growth of the exposed gravel bars (Figs. 6a, 12a and 12b), which implies an addition of new sediment from the reservoir.

Site 4

The initial sediment distribution in September 2012 shows that the D_{84} was approximately 345 mm (Figs. 18a and 18b). By December 2012, following the reservoir sediment release in October 2012 (Fig. 7), the D_{84} had decreased to 196 mm (Figs. 16a, 18a, and 18b). In February 2013, the D_{84} decreased slightly to 184 mm (Fig. 18b). It was not until April 2013, when the D_{84} decreased to 25 mm, that there was a decrease in the sediment size comparable to that at Sites 1 and 4 (Fig. 18b). However, the D_{84} increased again by the end of June 2013 to 53 mm (Fig. 18b). At the end of the first year of dam removal in September 2013, the D_{84} was 68mm (Fig. 18b). Between September 2013 and October 2013 the dam removal process resumed and there was large flow event but there was only a slight change in the D_{84} measuring at 63 mm (Figs. 7, 16b and 18b).

There was a continued decrease in sediment size into December 2013 when the D_{84} measured 13 mm (Fig. 16b). By February 2014, the D_{84} was 8 mm (Fig. 18b). Following the February 2014 sediment survey, the largest flood event occurred on the Elwha River and ended just before the March 2014 survey. During that time, the D_{84} increased to 61 mm (Figs. 7, 16c and 18b). The seasonal flows continued into May 2014

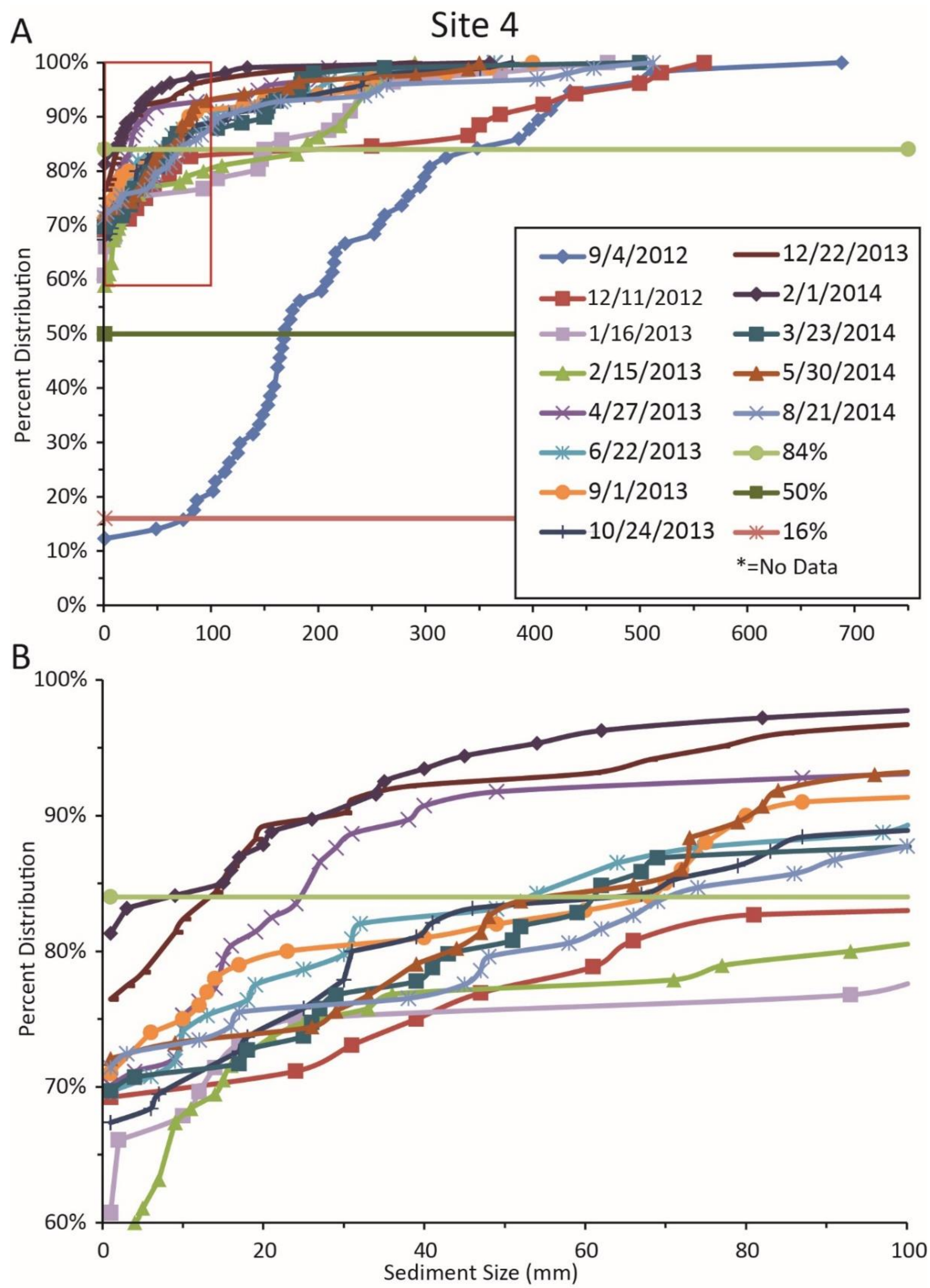

Figure 18: Site 4, surface sediment distribution. A: Surface distribution of sediment over the entire survey period. Notice the change from a primarily cobble system to a sand dominant system in the first 2 months following the coarse sediment release. Red box indicates the change in scale for 18B. B: Zoomed in surface distribution to see the change following the coarse sediment release.

when the D_{84} decreased again to 56 mm, and by the last survey in August 2014, the D_{84} had increased again to 71 mm (Fig. 18b).

In summary, there was rapid and substantial decrease in the average sediment size between September and December 2012, which encompassed the initial sediment release from the reservoir. Over the next 2 years, there were minor fluctuations in the D_{84}, and a slight coarsening by the end of the study period, but the sediment size remained much finer than it was when the dam was in place.

Large Woody Debris

The large woody debris was mapped from August 2012 to August 2014. However, only the data from August 2012 to February 2014 are reported in this thesis due to a discrepancy in mapping methods.

Site 1

The August 10, 2012 large woody debris mapping indicated as few as 26 logs and a single log jam at the apex of the main island (Figs. 19a, 19b and 20; Table 6). The November 27, 2012 map indicates a loss of woody debris with 11 logs and a continuation of the single log jam (Figs. 20a and 20b; Table 6). This loss of wood took place even though the mapping occurred directly after the reservoir sediment release in October 2012 (Fig. 7). However, after a minor flood event (<120 m^3/s) that occurred in May 2013 (Fig. 7), there was an increase in woody debris as seen on the June 28, 2013 map (Fig. 20). During this time, 50 individual logs and 3 log jams were counted (Figs. 19a, 19b and 20; Table 6). Two of the log jams were located at the apex of the islands in the branching river and the third was located on the downstream end of the middle channel on river

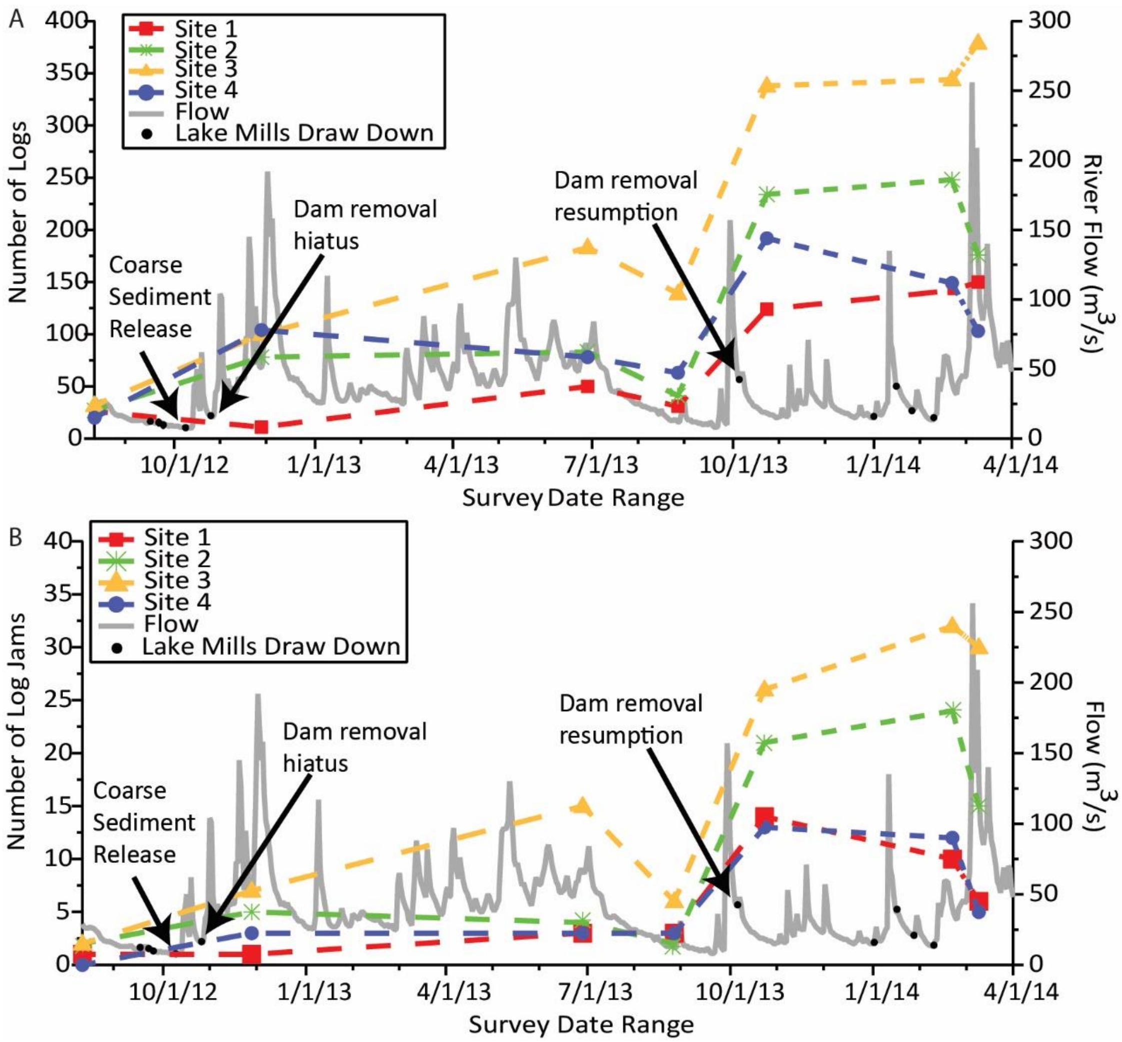

Figure 19 a-b: Large woody debris mapping. Dashed lines draw to the next point on the graph and are not meant to convey a trend. Following the coarse sediment release and the pause in dam removal the large woody debris data indicates a steady increase in individual logs and log jams until the low summer flows of 2013. The following year after the dam removal resumed there is a significant increase in large woody debris A: Number of logs >2m in length on the surface of the bar at each site. B: Number of log jams on the surface of the bar at each site.

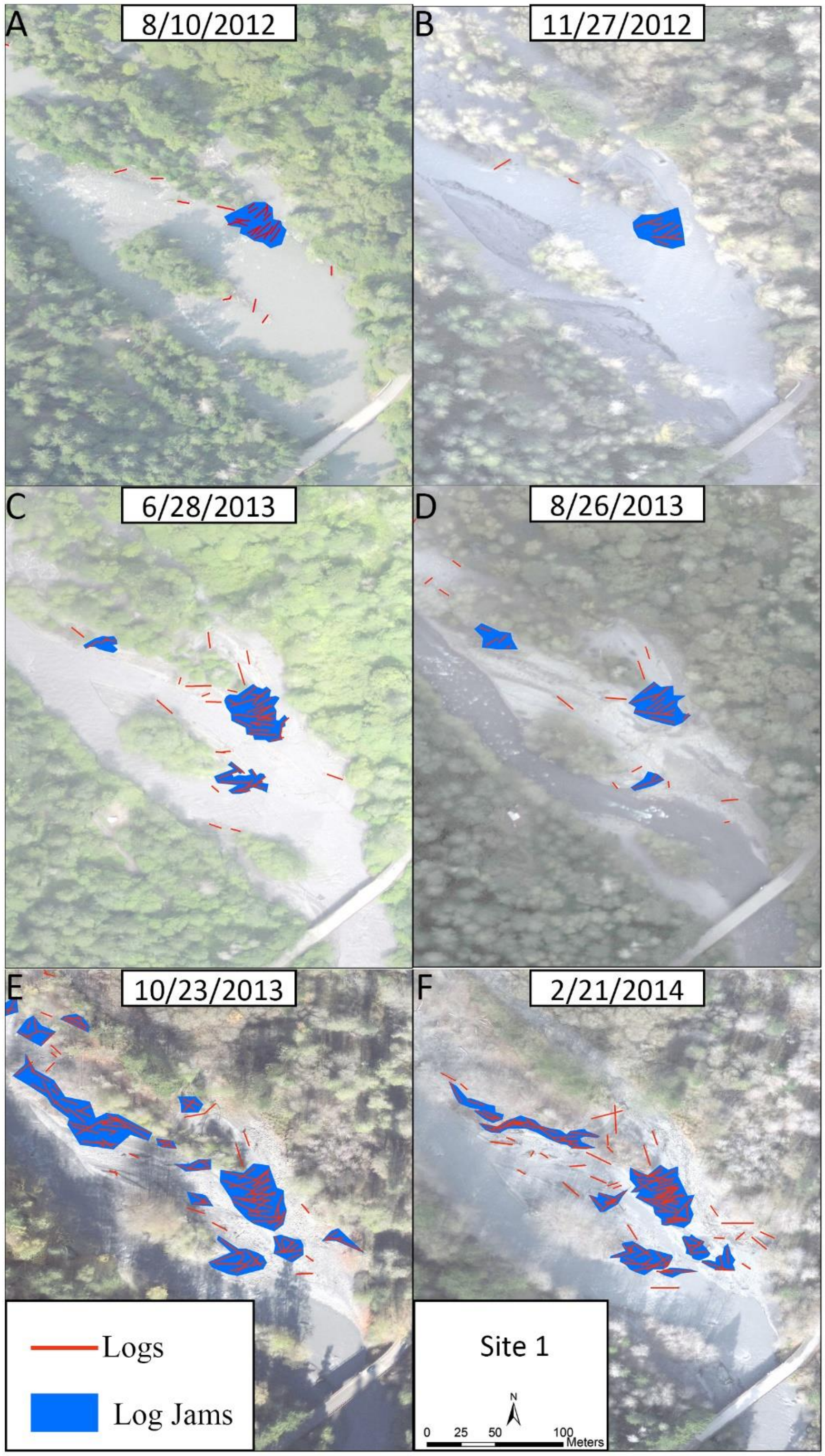

Figure 20: Site 1, Mapping showing the flux of woody debris at the survey site on orthophotographs taken from August 2012-February 2014. Blue = Log Jam Red = Individual logs >2 m in length.

right (Fig. 20). Following the June woody debris mapping, there was another loss in woody debris. At the end of the first dam removal season, the August 26, 2013 mapping indicated 31 logs and the same 3 log jams (Figs. 19a, 19b and 20; Table 6).

TABLE 6. LARGE WOODY DEBRIS MAPPING

Mapping Dates	Number of Logs				Number of Log Jams			
	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
8/10/2012	26	27	32	20	1	2	2	0
11/27/2012	11	78	100	104	1	5	7	3
6/28/2013	50	83	183	78	3	4	15	3
8/26/2013	31	41	139	63	3	2	6	3
10/23/2013	124	234	338	192	14	21	26	13
2/21/2014	142	248	344	149	10	24	32	12

After the dam removal resumption in October 2013 (Fig. 7), the log count quadrupled from 31 logs in August 2013 to 124 logs and 14 log jams on October 23, 2013 (Figs. 19a, 19b and 20; Table 6). This influx of woody debris followed the second largest flood event (>150 m^3/s) during the 2-year dam-removal period (Fig. 7). The new woody debris collected throughout the bar surface that was exposed during the previous year's channel abandonment sometime between June 2013 and August 2013 (Fig. 20). Following the October 2013 deposition of woody debris, the February 21, 2014 mapping indicates a minor loss in woody debris with 142 individual logs and 10 log jams (Figs. 19a, 19b and 20; Table 6).

Site 2

The August 10, 2012 large woody debris mapping indicated as few as 27 logs and 2 log jams within the survey site (Figs. 19a, 19b and 21; Table 6). In the November 27, 2012 map, there was an increase in woody debris with 78 logs and 4 log jams that formed at the downstream end of the survey reach and one log jam that formed on a mid-channel bar at the upstream end of the survey reach (Figs. 19a, 19b and 21; Table 6).

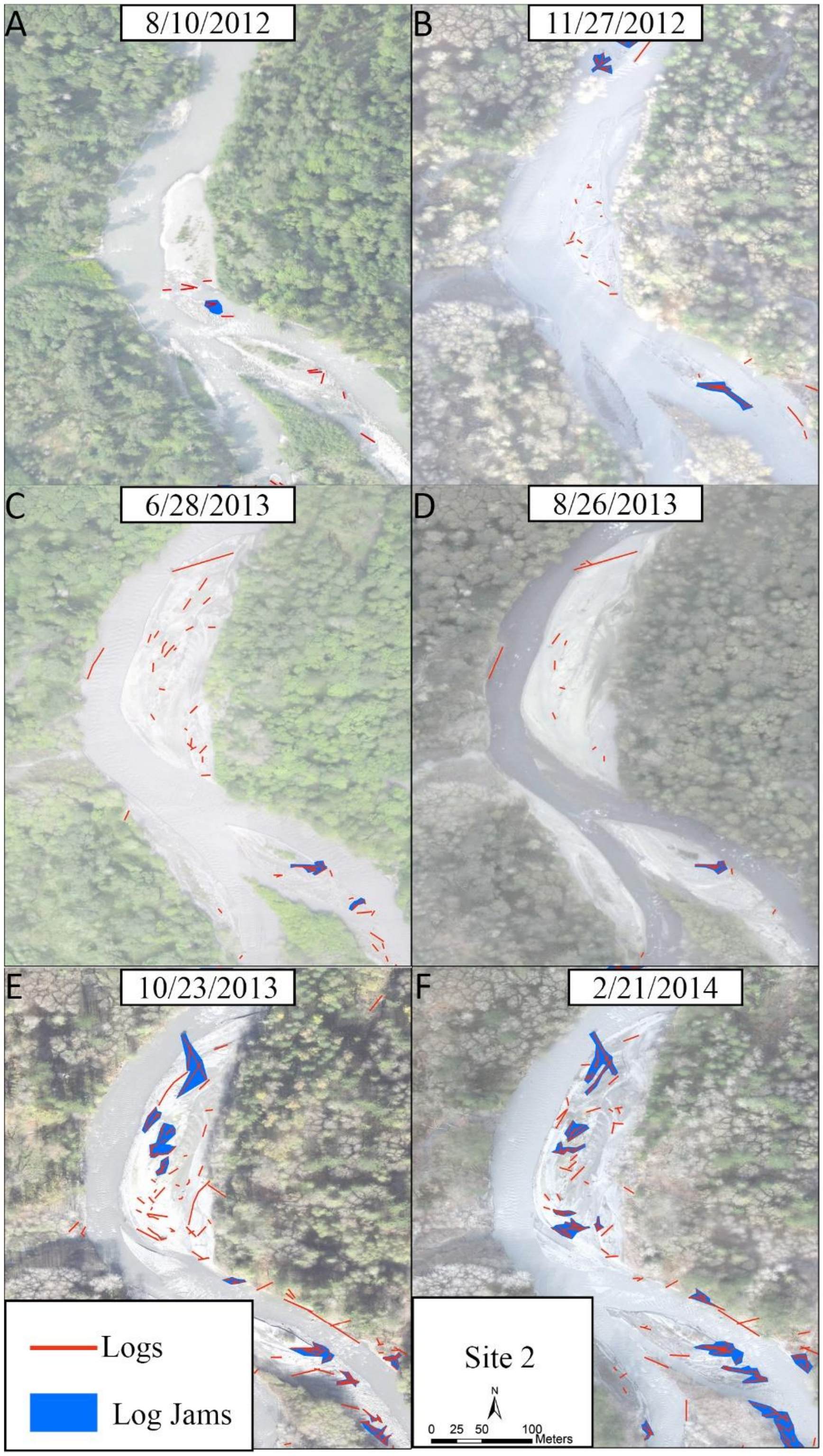

Figure 21: Site 2, Mapping showing the flux of woody debris at the survey site on orthophotographs taken from August 2012-February 2014. Blue = Log Jam Red = Individual logs >2 m in length.

In contrast to Site 1, this area saw an increase in woody debris in the first survey after the reservoir sediment release in October 2012 (Fig. 7). Following the minor flood event (<120 m^3/s) in May 2013 (Fig. 7), the June 28, 2013 map indicates an increase in individual logs totaling 83. However, there was a loss of 2 log jams on the downstream bar and the formation of a new log jam at the upstream end of the survey reach (Figs. 19a, 19b and 21; Table 6). At the end of the first dam removal season, the August 26, 2013 mapping indicated only 41 logs and 2 log jams remaining in the survey area (Figs. 19a, 19b and 21; Table 6).

After the resumption of the dam removal process in October 2013 (Fig. 7), the October 23, 2013 woody debris map indicated that the log count increased by two orders of magnitude with 231 logs and 21 log jams scattered throughout the entire study reach (Figs. 19a, 19b and 21; Table 6). This influx of woody debris followed the second largest flood event (>150 m^3/s) during the 2-year dam-removal period (Fig. 7). Following the October 2013 deposition of woody debris the February 21, 2014 mapping indicates a minor loss in woody debris with 248 individual logs and 24 log jams (Figs. 19a, 19b and 21; Table 6).

Site 3

The August 10, 2012 large woody debris mapping indicated as few as 32 logs and a single log jam initially spread throughout Site 3 (Figs. 19a, 19b and 22; Table 6). In the November 27, 2012 map, there was an increase in woody debris with 100 logs and 5 log jams. The new log jams can be seen collecting at the left hand margins of the center channel and the river right side of the downstream end of the bend (Fig. 22). This increase took place directly after the reservoir sediment release in October 2012 (Fig. 7).

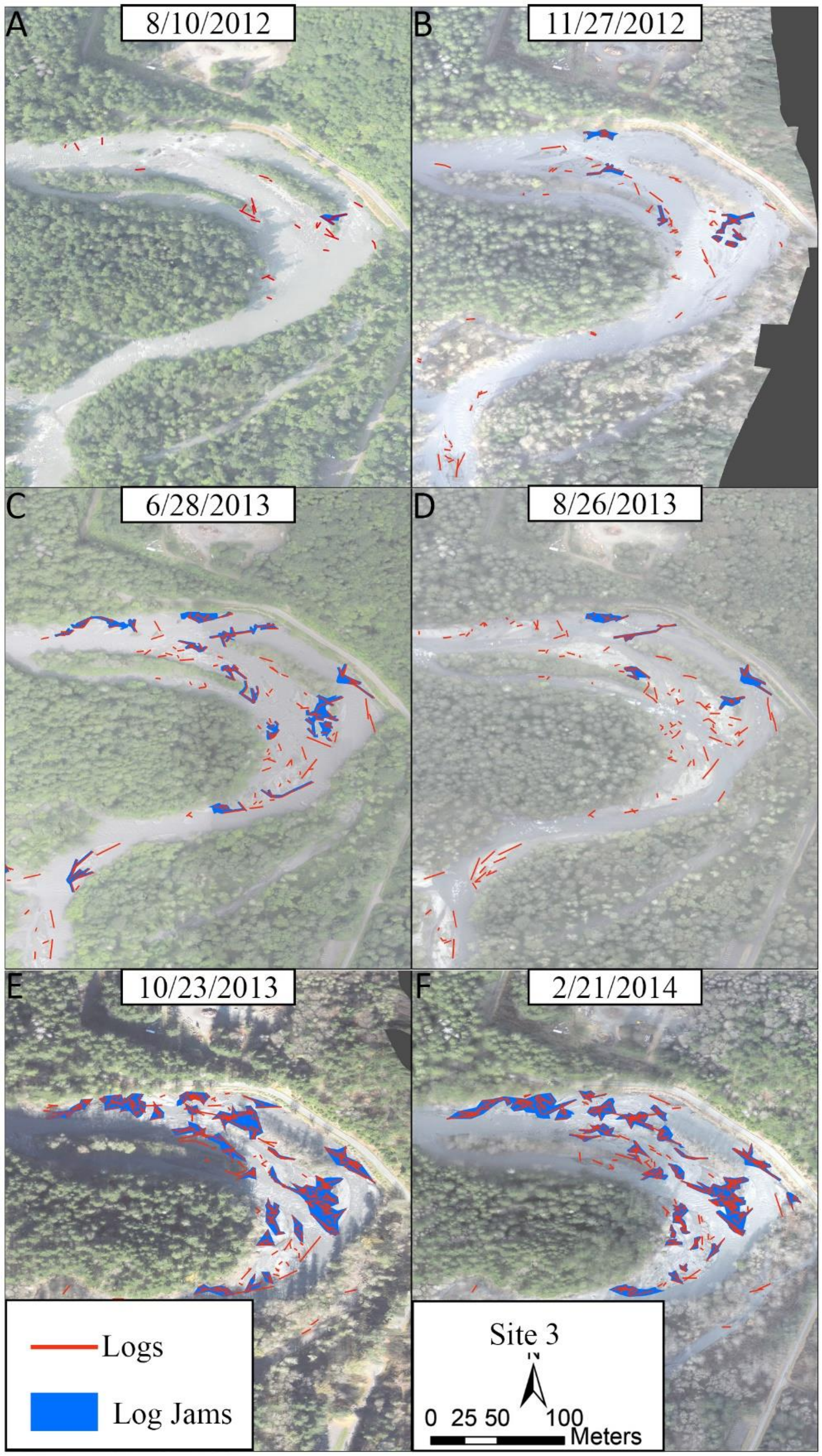

Figure 22: Site 3, Mapping showing the flux of woody debris at the survey site on orthophotographs taken from August 2012-February 2014. Blue = Log Jam Red = Individual logs >2 m in length.

After the minor flood event (<120 m^3/s) in May 2013 (Fig. 7), the June 28, 2013 map shows an increased woody debris count with 183 logs and 15 log jams (Figs. 19a, 19b and 22; Table 6). The collection of woody debris during this time appeared to collect in the same areas as before but in larger quantities with some new deposition of woody debris happening in the mid-channel bar that was forming at the beginning of the river bend (Fig. 22). Following the June woody debris mapping, there was a loss in woody debris. At the end of the first dam removal season the August 26, 2013 mapping indicated 139 logs and 6 log jams located in the same areas that the river experienced during the November mapping (Figs. 19a, 19b and 22; Table 6).

After the dam removal resumption in October 2013 (Fig. 7), the October 23, 2013 woody debris map indicated that the log count increased to 338 logs and 26 log jams (Figs. 19a, 19b and 22; Table 6). At this point, the woody debris was spread throughout the entire study reach. Most notably, the woody debris appeared to collect at the downstream end of the river bend on the margins of the right-hand river channel. This influx of woody debris followed the second largest flood event (>150 m^3/s) during the 2-year dam-removal period (Fig. 7). Following the October 2013 mapping, the February 21, 2014 map shows a continued increase in woody debris with 344 individual logs and 32 log jams (Figs. 19a, 19b and 22; Table 6). The deposition wood at this time appears to be in the same areas as in October 2013.

Site 4

The August 10, 2012 large woody debris mapping indicated as few as 20 logs spread throughout Site 4 without a single log jam (Figs. 19a, 19b and 23; Table 6). After the reservoir sediment release in October 2012 (Fig. 7), the November 27, 2012 woody

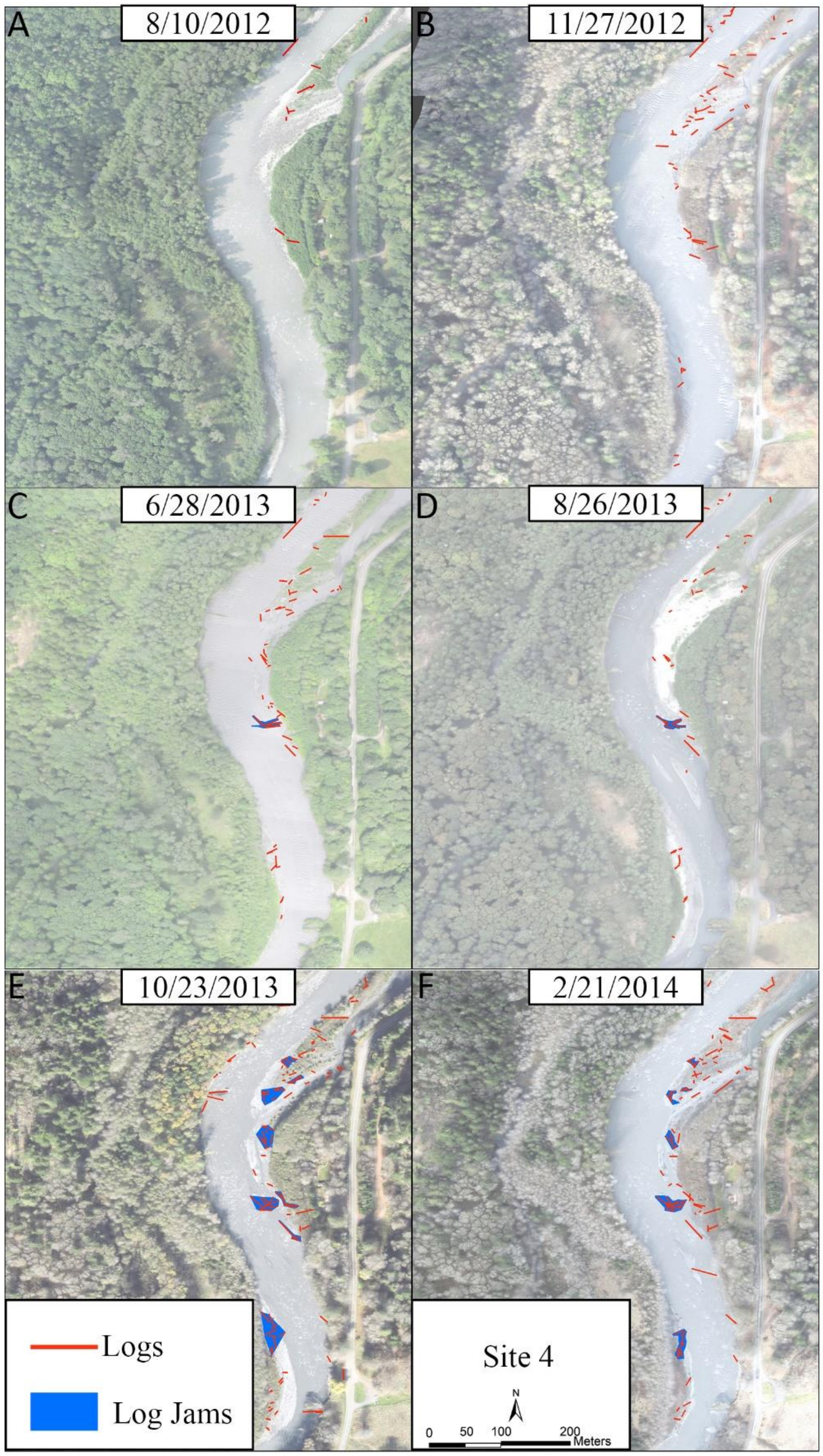

Figure 23: Site 4, Mapping showing the flux of woody debris at the survey site on orthophotographs taken from August 2012-February 2014. Blue = Log Jam Red = Individual logs >2 m in length.

debris map indicates an increase to 58 logs but individual woody debris did not coalesce to form log jams (Figs. 19a, 19b and 23; Table 6). After the minor flood event (<120 m^3/s) in May 2013 (Fig. 7), the June 28, 2013 map shows little change in the individual woody debris at Site 4 with 55 individual logs counted (Figs. 19a, 19b and 23; Table 6). However, the first formation of a log jam appeared at the same time at the upstream end of the point bar on the right hand margin of the channel (Fig. 23). Following the June woody debris mapping, there was yet another loss in the individual woody debris, and at the end of the first dam removal season the August 26, 2013 mapping indicated 45 logs and the existence of the same log jam found in the June mapping (Figs. 19a, 19b and 23; Table 6).

After the dam removal resumption in October 2013 (Fig. 7), the October 23, 2013 woody debris map indicated that the log count approximately doubled to 129 logs and 8 log jams (Figs. 19a, 19b and 23; Table 6). At this time, log jams had collected across each of the bars without the appearance of preferential placement (Fig. 23). This influx of woody debris followed the second largest flood event (>150 m^3/s) during the 2-year dam-removal period (Fig. 7). The final woody debris mapping that took place ended on February 21, 2014 with loss of woody debris. The mapping indicated a total of 96 individual logs and 7 log jams scattered throughout the study reach (Figs. 19a, 19b and 23; Table 6).

CHAPTER IV

DISCUSSION

In an effort to understand how the middle reach as a whole reacted to the dam removal, I first discuss geomorphic changes at each site over the entire dam removal process. Then the changes in the sediment distribution through the entire reach are discussed to explain how the sediment dynamically flowed through the system. Finally, the large woody debris is discussed relative to each of these two factors because of the influences that it had on both.

Geomorphic change

The topographic changes that occurred at each of the sites were directly affected by the massive influx of sediment to the river. The goal of this section is to explain the influences on the type, amount, and timing of geomorphic changes following the sediment dispersal. In the first year (August 2012 – August 2013) following the reservoir sediment release in October 2012 (Fig. 7), the initial sediment breach inundated the entire river channel in a very short period of time. As seen in Figures 15a, 17a and 18a, the sediment distribution fined dramatically in the first couple of months following the breach. This blanket of new sediment can also be seen in the repeat woody debris aerial photographs in Figures 20-23.

Site 1

In the first year of the dam removal, Site 1 reacted to the sediment release in two different ways. The initial reaction to the sediment perturbation was the migration of the left-hand river channel toward the right in the first couple of months following the sediment release (October 2012 – December 2012) (Figs. 15a, 20a and 20b). This migration of the river happened in response to the rapid burial of the cobble-filled left-hand channel (Fig. 9a). The left channel aggraded over 4 m in places and was completely abandoned and pushed the dominant flow toward the center of the river (Figs. 5a, 10a and 20). The burial of the left hand channel was likely due to the flow not being able to maintain the entrainment of the massive amount of sediment flowing through the system. The bulk of this sediment was deposited while the river flowed over the shallow exposed cobbles on river left (Figs. 10b, 20a and 20b). The downstream end of the center island grew in conjunction with the burial of the left-hand channel and effectively channelized the flow, increasing the stream flow and erosional processes in the center channel (Figs. 20a and 20b). The growth of the island was likely due to sediment flowing around the island and depositing in the eddied flow on the downstream side (Figs. 9a, 20a and 20b).

Following the initial geomorphic response, the additional channel changes in the first year were more flow-dependent and occurred over a longer time scale. Ultimately, the continued evolution of the river channel resulted in the complete abandonment of the two right-hand channels by the end of the first year of dam removal (August 2013) (Figs. 6a, 10a, and 20d). The loss of these channels and exposure of the bed surface were due to several geomorphic processes, as explained below.

After the initial response, the river experienced several minor flows that fluctuated between 25 m^3/s and 85 m^3/s between the months of January 2013 and June 2013 (Fig. 7). During this this time, the river regularly overtopped the left hand bar and flowed throughout the system, entraining the deposited sediment at peak flows and depositing new sediment during the waning flows along the channel margins (Figs. 20 and 24). The change from a unimodal sediment curve at the finer sediment range in April

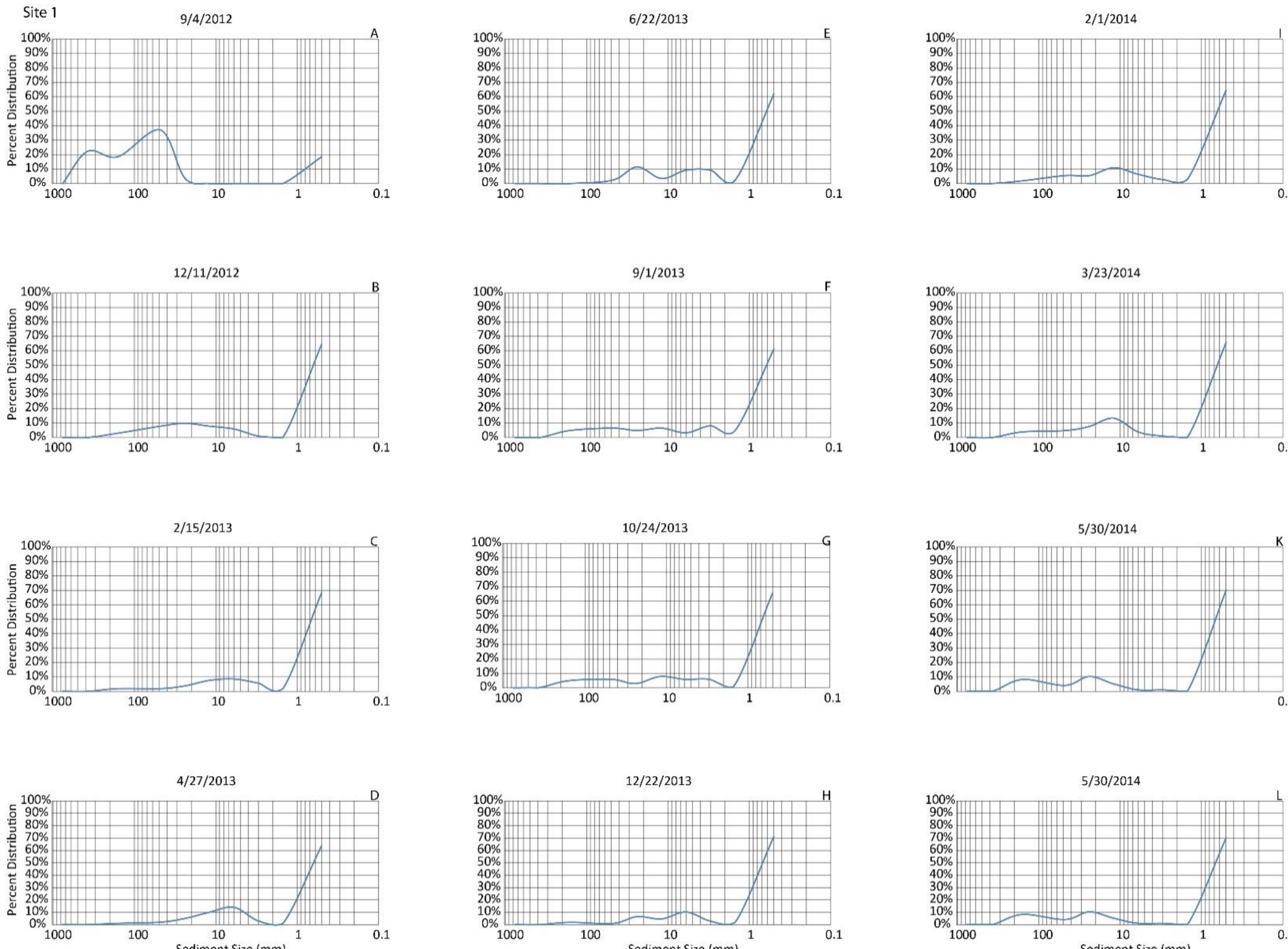

Figure 24: Site 1, sediment distribution for each survey indicating the evolution of the surface sediment flux during the dam removal process.

2013 to a coarsening bimodal curve in June 2013 (Fig. 24) indicates that the sediment is being entrained and stripped off the top of the bar eroding down to the pre-dam removal cobbles.

At the same time, deposition was occurring along the channel margins, indicated by the preferential alignment of woody debris along the margins (Figs. 20 a-d) and the sediment accumulation in the repeat TLS surveys. Up to 2 m of deposition at the head of the right-hand bar (Fig. 10a) created a levee that rerouted the channel left towards the center of the river into the exposed riffle and toward the steeper section of the river channel. In response, the channel on river right was abandoned, exposing a new bar surface that was originally submerged and doubling the surface area of the exposed bars (Figs. 6a and 10a; Table 5).

Prior to the dam removal the branching channels were largely devoid of large woody debris and there are no predictive models that portray how a wood-starved system will respond to the sudden influx of new woody debris. The size of the woody debris ranged from neutrally buoyant chips to fully grown trees as large as 2 meters in diameter (Fig. 4). During the first year the individual pieces of large woody debris did not appear to contribute to the large changes in the channel morphology. The areas where sediment accumulated were not necessarily where individual woody debris accumulated. However, the topographic change data and field observations show that the woody debris was a catchment for sediment in the areas where log jams were sustained throughout the entire year (Figs. 10a and 20a-d). For example, a persistent log jam (Fig. 20) accumulated and retained new sediment that contributed to the increase in sediment volume (Fig. 10a) prior to the abandonment of the right hand channel.

In the following year (2013-2014), Site 1 did not experience any new channel change; rather, there was a large influx of woody debris, erosion of some sediment that was deposited the year before, and new deposition of sediment within the abandoned right hand channel. The indeterminate net change in sediment volume was due to the equal amounts of erosion and deposition (Fig. 10b). These changes most likely occurred during the two large flow events (>100 m^3/s) (Fig. 7) that happened during the second year of dam removal (October 2013 and March 2014).

The first large flow event (~150 m^3/s) that took place in Year 2 occurred in early October 2013 at the end of the 1-year hiatus in the dam removal (Fig. 9). During this event, the river flowed from bank to bank, overtopping the subaerial gravel bars. As a response, the river eroded some of the fine sediment from the surface of the bars, exposing the underlying cobbles and coarsening the sediment distribution (Figs. 15b, 24f and 24g). Due to the lack of new sediment during the hiatus in the dam removal, very little new sediment was deposited during this event. This can be seen in Figures 24d-g, in which the sediment distribution coarsens through the end of the first dam removal then gets finer suddenly after the resumption of the dam removal in October 24, 2013. In contrast, during the March 2014 flood event (>250 m^3/s) when the river overtopped the subaerial surfaces again, the dam removal process had resumed and there was new sediment exiting the reservoir again. This time the river scoured the surface sediment as it did before, but new sediment was also deposited at the downstream end of the right-hand bar.

Woody debris started to collect throughout Site 1 during Year 2. The primary addition of woody debris came after the resumption of the dam removal in late October

2013. Within the first month the count of individual logs and log jams doubled on the subaerial surfaces (Figs. 19 and 20; Table 6). The increase in log jams was likely due to the consolidation of woody debris that was already on the bar and the accumulation of new wood from the reservoir. Due to the lack woody debris data for the end of August 2014, it is impossible to ascertain what effects the woody debris had on the morphology during this season. However, by February 2014 the abandoned channels on right and center are filled with wood and log jams. This could further stabilize the new gravel bars in that part of the channel, whether or not it played a role in the original channel change.

Site 2

In the first year of dam removal, Site 2 was affected by the sediment release continuously throughout the entire year. The initial reaction to the sediment perturbation was the 200% growth of the point bar accompanied by the simultaneous erosion of the cut bank on the opposite side of the river (Figs. 5b, 11a and 21). Prior to the dam removal the channel migration at this section of the river from September 1994 to September 2009 averaged 2.5 meters per year., as measured on satellite images from Google Earth. However, after the release of the reservoir sediment the channel migrated over 20 meters in the first year (August 2012 - August 2013; Fig. 12a). This rapid change in channel morphology and migration is eight times faster than the channel migration when the dam was in place. The increase in erosion rate is likely partially related to the deposition of the 19,042 $\pm$ 6,868 m^3 of sediment, which expanded the point bar on the right bank and changed the trajectory of the river channel toward the opposite bank of the river. The large amount of sediment in the water column could have also increased the scour effect on the cut bank, enhancing the channel migration rate (Sklar and Dietrich, 2001).

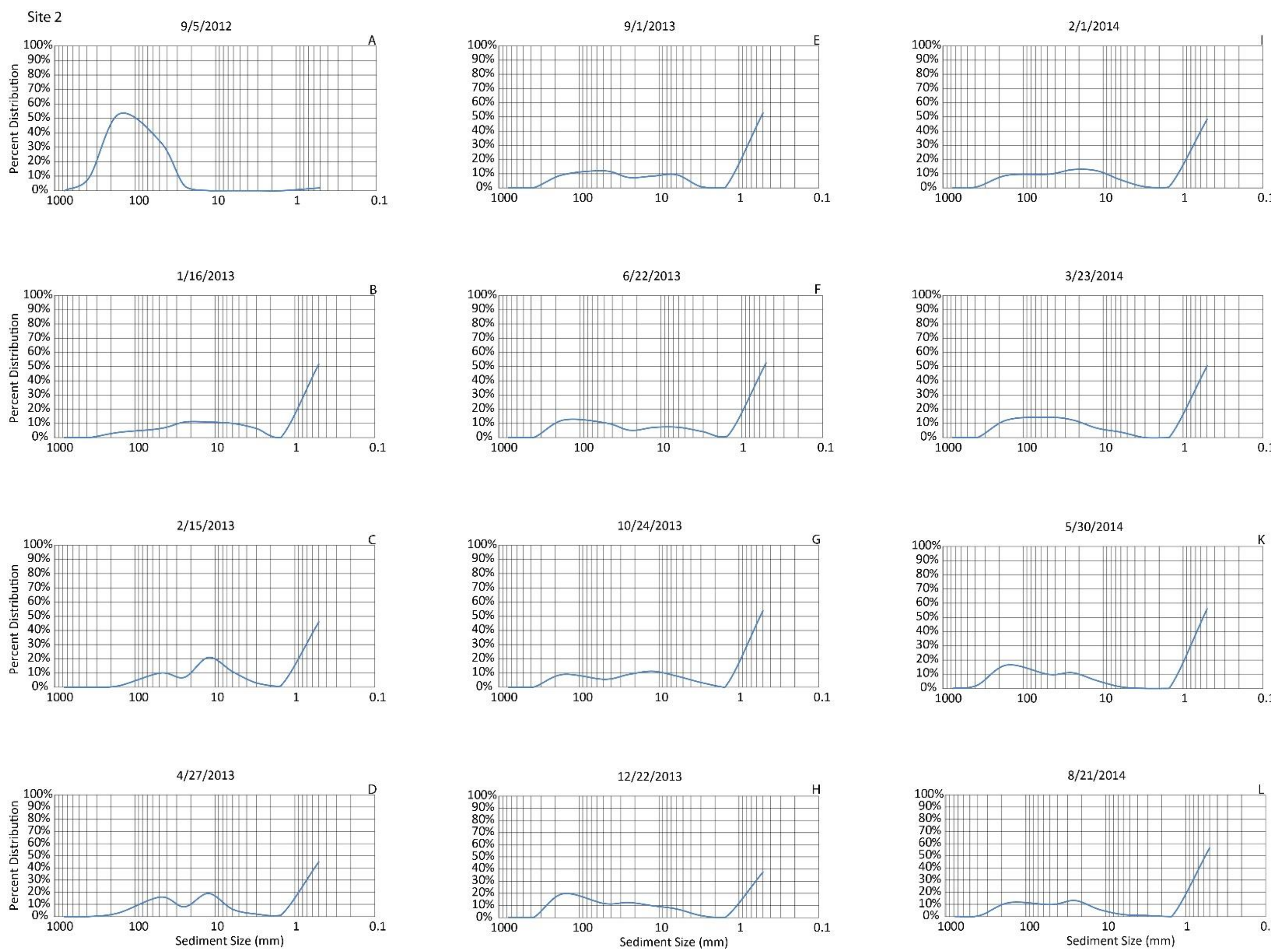

Figure 22: Site 2, sediment distribution for each survey indicating the evolution of the surface sediment flux during the dam removal process.

Along with the massive amount of deposition there were more subtle morphological changes that occurred on the surface of the point bar during the seasonal flows of the 2012-2013 year (Fig. 7). The flows reorganized the surface of the point bar and deposited new woody debris at the same time (Figs. 7, 11a and 25). The morphological changes and the surface erosion can be seen in Figure 10a with the visible flow structures that exist on the point bar and the change in sediment distribution (Figs. 21 and 25). A comparison of the sediment-size distribution from February 2013 to September 2013 shows a greater range in sediment size at the end of this period (Figs. 21 and 25). This is particularly important to understand the size of sediment that is building the bars within the river system. In particular, the point bar at Site 2 grew by 200% in area and up to 4 meters vertically. This is important because as the surface flows on the bar eroded the sediment, it was apparent that it did not erode down to the pre-dam removal sediment base at the downstream end of the bar (Figs. 7 and 11a). This indicates that the range of sizes that are flowing in the river can be on the larger end of the sediment distribution scale measured. In particular, this can be seen in Figure 25k where the coarse sediment is increasing at the same time as the fine sediment.

In conjunction with the sediment distribution and surface flows on the point bar there was an increase in large woody debris at Site 2 following the reservoir sediment release in October 2012. During this time, the morphological changes that occurred at Site 2 did not appear to be influenced by the addition of the woody debris. The large woody debris that accumulated at Site 2 during the first year of the dam removal did not appear to anchor within the survey area. Rather, a few individual logs were deposited temporarily on the surface of the point bar and within the channel margins but were transported further downstream by subsequent flows (Figs. 7 and 21). Overall there was no evidence of sediment-armoring log jams that would have caused slow water pools or channelized flow that would have created the conditions necessary to dominate this site by large woody debris. The changes at Site 2 were caused by the initial channel geometry and the amount of new sediment depositing within the survey site.

In 2013-2014, the morphological variance at Site 2 was not as extensive as during the first year. With the change in the channel morphology, there was a decrease in deposition and an increase in erosion. This occurred even though there was an increase in sediment introduced into the river following the resumption of the dam removal in October 2013. The little deposition that did occur built the apex of the point bar and was accompanied by an additional 20 m of lateral erosion of the opposite bank (Fig. 11b) that increased the sinuosity of the river channel. This movement of the channel subsequently tightened the curve in the river and, as a response, the downstream end of the point bar was removed (Fig. 11b). During this time, the hydrology of the river was more variable than that of the previous year with higher flows that occurred more often (Fig. 7). A driving factor in this change in morphology could be from the change in hydrological conditions enhancing the erosive attributes of the river as it flowed through the system.

During the same period as the morphological changes a large amount of large woody debris collected on the surface of the right bank point bar following the resumption of the dam removal (October 2013) (Fig. 21; Table 6). As observed in the previous year, the woody debris did not appear to have a direct effect on the main channel morphology. However, when looking at the position of the woody debris on Figure 21 and the surface morphology of the point bar in Figure 11b, the woody debris appears to influence the surface morphology on the bar during the times that the river overtopped the bar surface.

Site 3

In the first year of dam removal, Site 3 had the largest amount of volumetric change (Fig. 12a; Table 4). With the large bend in the river and complex channel system it was the most likely to collect woody debris and had the largest potential for sediment deposition due to its geometry. The initial response of Site 3 to the reservoir sediment release was to fill the riffles and pools in the first few months, similar to the observations at Site 1. The lack of sediment-size date for Site 3 precludes exact interpretations of the characteristics of the sediment that accumulated here. However, it can be inferred from the results at the other sites that the newly deposited sediment was finer than the previous coarse cobble bed

Site 3 experienced from 1-3 meters of vertical aggradation, creating new subaerial surfaces by the end of the first year of dam removal (Fig. 13a: Table 4 and 5). This new deposition of sediment indicates that there was a rise in the base level of the river channel as indicated by the addition of new mid-channel bars in Figure 22. The changes in channel morphology were due to more than just changes in sediment distribution and deposition. Following the reservoir sediment release, there was a new influx of large woody debris that became evident by November 2012 (Figs. 19 and 22). During this time the woody debris more than doubled and started preferentially aligning on the channel margins, contributing to the channelization of the river through the site (Fig. 22). As the woody debris collected throughout the year, several log jams formed within the Site 3 (Figs. 19 and 22b). In the first year, key jams formed at the apex of the bend on river right and at the downstream end of the river bend. These log jams created a backwater pool that slowed the flow and forced the majority of the river channel to relocate laterally to the left-hand channel on the inside of the bend (Figs. 13a and 22). A new mid-channel bar was created at the upstream end of the river channel where a new log jam formed on the riffle that led into the river bend (Fig. 22). The riffle spread farther upstream and created new shallow surfaces for large woody debris to accumulate. The deposition of this new large woody debris in the shallows of the riffle allowed the formation of parallel log jams that armored the center channel, allowing the sediment to deposit laterally and vertically and causing the eventual abandonment of the center channel.

Following the creation of these new large woody debris deposits and substantial deposition of sediment, the former trickle of flow on river left became the primary channel of the river. Leading into the second year (2013 – 2014), Site 3 continued to exhibit the same complexities that it did in the first year of dam removal. As before, the primary factor in the complexity was the large woody debris accumulation and the river geometry within the site. Following the resumption of the dam removal in October 2013 the large woody debris more than tripled within the study reach. In response the copious amounts of woody debris continued to collect in the bottle neck of the bend (Figs. 6a, 19 and 22). The largest, most obstructive of the log jams can be seen in Figure 5a in the foreground of the image. Located at the downstream end of the river bend, this complex log jam resulted from continued growth of the previous jams described in the first year. By forming on top of the bar at the downstream end of the reach where the channels merged, the log jam accumulated additional sediment that finally cut off the river right channel completely (Figs. 6a, 13 and 22).

Site 4

Located at the border of Olympic National Park, Site 4 is a long, single channel with low sinuosity. The relatively few changes in channel morphology and position at this site increase our understanding of how different channel geometries react to the changes in sediment size and supply. At 6 km downstream from the dam, Site 4 had a delayed response to the reservoir sediment release when compared with the timing of the initial sediment accumulation at Sites 1 and 2 (Fig. 16a). This lag in sediment accumulation can be seen in Figures 24-26a-d in which there is an abundant collection of sediment in the 0-1mm size range but the coarse sizes (32-1024 mm) continue to have a strong presence in the distribution.

The sediment deposition at Site 4 is the least in the entire study area. With the low sinuosity of the river bends (Figs. 14a and 23), the sediment deposition occurred along the two long point bars. The sediment that collected filled the interstices of cobbles that armored the bar surface (Fig. 6b). A new mid-channel bar also formed at the top of the riffle in this reach (Figs. 12b, 14a and 23). The formation of the mid-channel bar is an indicator that there was plenty of sediment flowing through the channel at the time, but not reaching the banks in the volume that was observed at the upstream sites. Furthermore, the formation of new bars downstream of Site 4 is evident from field observations while traveling to and from the field site, in the orthophotographs in Figure 27, and is corroborated by East et al. (2015). This confirmation of sediment accumulation farther downstream confirms that distance from the dam is not the controlling factor for the lower amount of sediment accumulation at this site. The more likely reason for the low amount of sediment accumulation is the differences in the channel geometry.

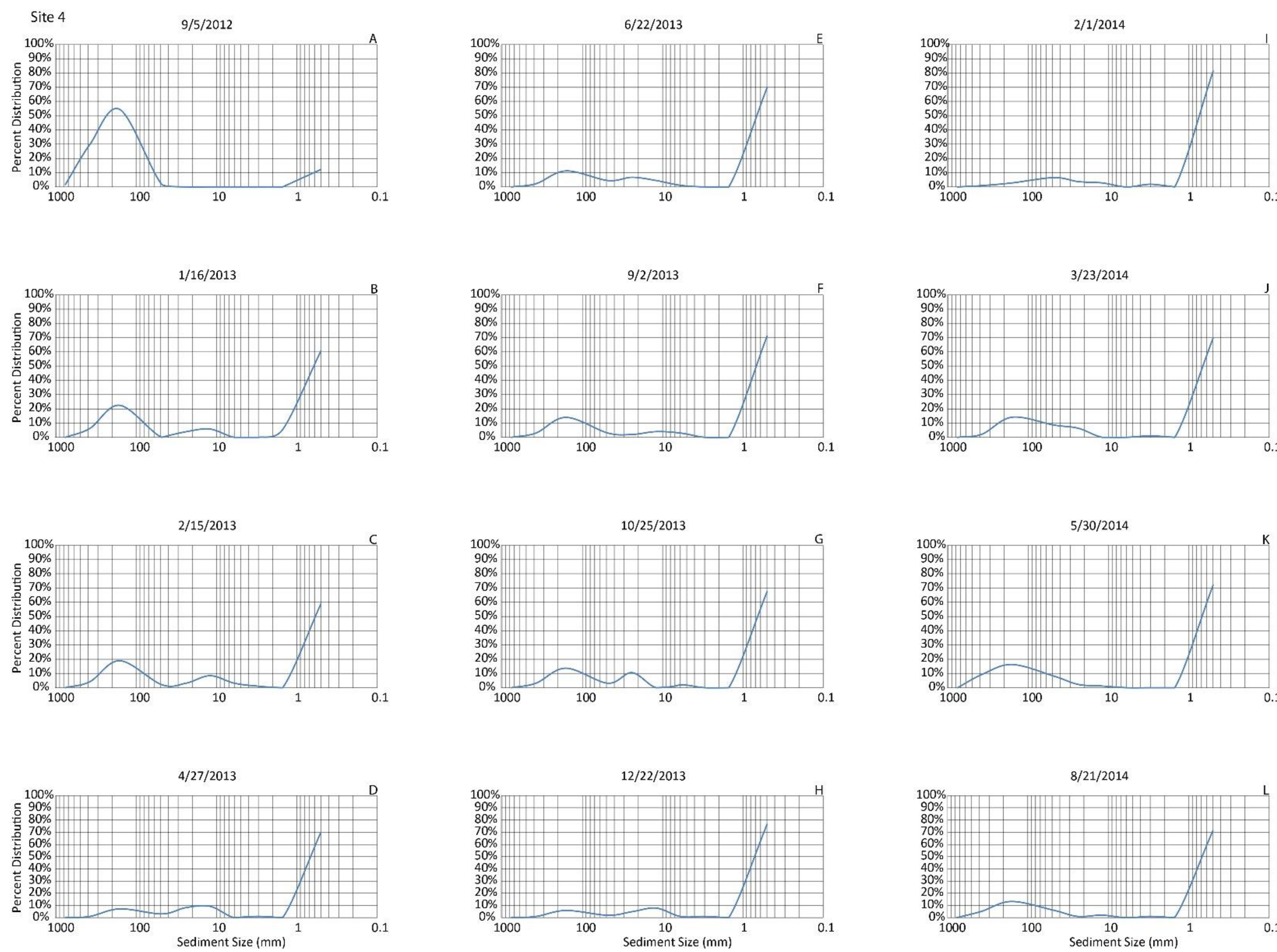

Figure 23: Site 4, sediment distribution for each survey indicating the evolution of the surface sediment flux during the dam removal process.

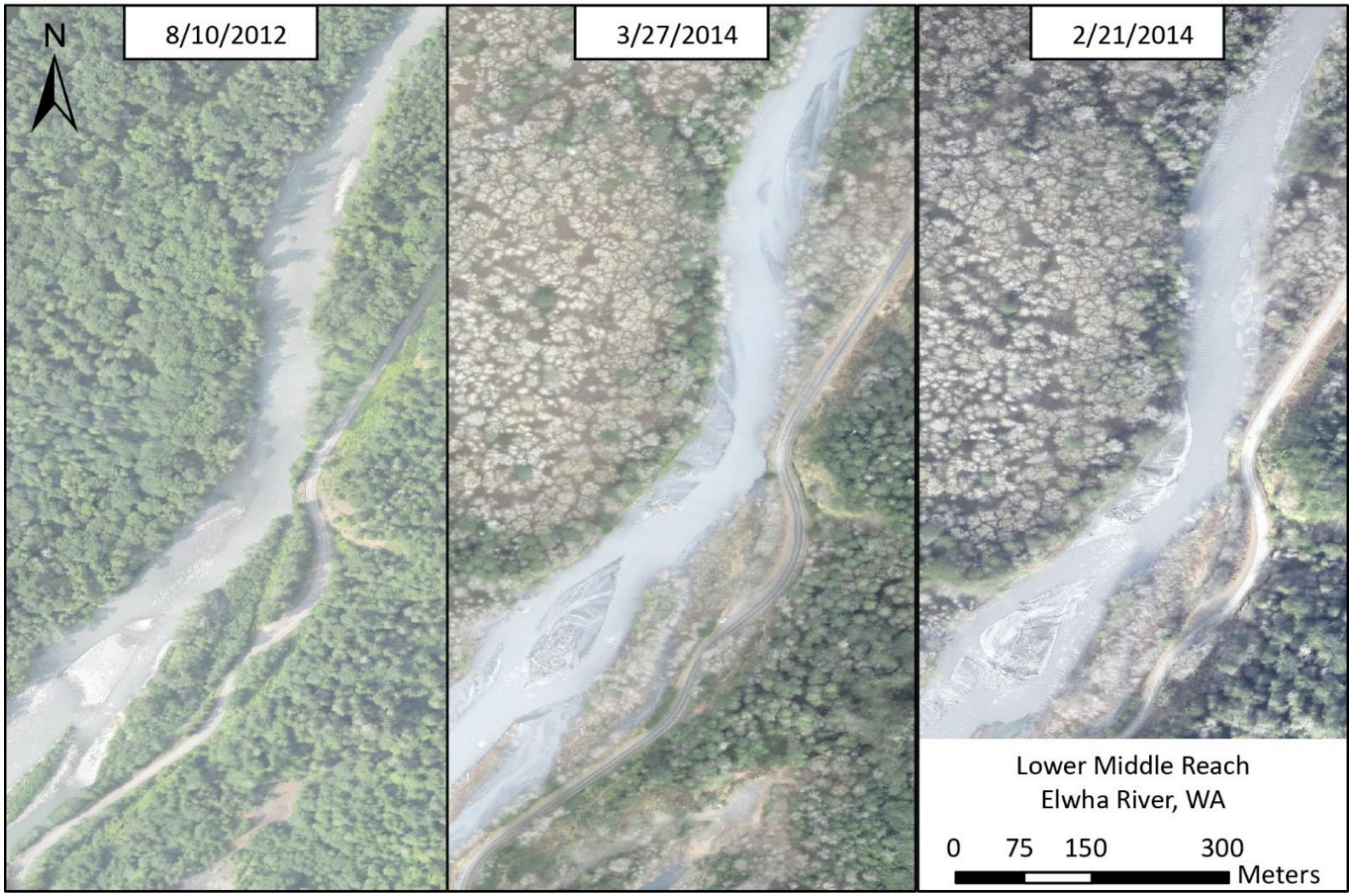

Figure 24: Orthophotographs taken downstream of Site 4 from multiple dates indicating sediment deposition downstream of Site 4.

Another possible reason for only a small amount of sediment accumulating on the bar surface when compared to the upstream sites is that the large woody debris was unable anchor on the either of the bars for a prolonged period of time. Large woody debris did deposit within the site; however, it peaked in December 2012 and steadily declined until August 2013 (Figs. 19 and 23).

During the following year (2013 -2014), Site 4 responded much the same as it did in the previous season. The long slightly meandering reach did not experience any great changes causing new formations or deviations of the river channel (Figs. 12b, 14 and 23). Site 4 did experience a large influx of new large woody debris in 2013-2014 (Figs. 19 and 23). However, even though there was a spike in the number of log jams and individual logs, Figures 6b and 19 show that the large woody debris did not remain within the area of Site 4. Site 4 does not contain channel complexity such as large boulders or bends in the river, and, as such, it is possibly less likely than the other sites to collect and anchor the large woody debris.

Sediment Distribution

The sediment transport through the middle reach of the Elwha River is complex due to the incremental removal of the dam. The lowering of the dam from 144 m to 138 m in October 2012 cut below the elevation of the sediment on the bottom of the Lake Mills Reservoir, which resulted in the initial flow of sand and gravel from the reservoir floor through the dam opening. As a response, the upstream river channel within the former reservoir started downgrading to match the base level of the new dam outlet elevation (J. Bountry, US Bureau of Reclamation, unpublished data, 2015). The incremental removal of the dam continued until August 2014. Each time the elevation of the dam was lowered, more sediment eroded out of the former reservoir and entered the downstream river channel.

Following the initial reservoir sediment release (October 2012; Fig. 6) the entire study area was inundated with fine sediment (0-1 mm) by January 2013 (Figs. 24 a-b through 26a-b). Furthermore, Sites 1 and 2 experienced the bulk of the sediment accumulation during this time. This can be seen in Figures 24b and 26b, in which the size of the surficial sediment from the pre-dam removal period (16 -1024 mm) changed completely to a much smaller sediment fraction (0-16 mm). However, the size of the surficial sediment at Site 4 did not completely change to from coarse to fine until April 2013, indicating that the sediment at this site did not respond to the reservoir sediment release in the same time frame as the rest of the study area.

Over the rest of the year leading to August 2013, the sediment flux was driven more by the magnitude of the river discharge than the process of the dam removal and the subsequent depositional changes were smaller. Following the initial sediment release in October 2012, there was a hiatus in the dam removal for an entire year. During this time, the river migrated from bank to bank in the Lake Mills Reservoir constantly reworking the sediment and continuously flushing it from the reservoir. However, the sediment data suggest that after April 2013 the river was no longer flushing large quantities of sediment from the reservoir. In particular this can be seen in Figure 24e and 26e in which the coarse fraction of the sediment is becoming apparent again due to the medium flows ($\leq$125 m^3/s) (Fig. 7) of the river overtopping the bars and flushing the finer sediment from the surface of the bar. This suggest that overall, during the first year of dam removal the sediment pulse was large in the first few months of the reservoir sediment release and then tapered out toward the end of the first year (Fig. 28).

The majority of the sediment deposition occurred during Year 1 of the dam removal (2012 – 2013), with a net total of 85,750 $\pm$ 20,180 m^3 of newly deposited sediment at all four sites compared to the indeterminate net change (410 $\pm$ 9,590 m^3) in Year 2 (Fig. 28; Table 4). In the second year of dam removal, the source of the sediment in the river system became more complex due to the entire study area becoming a source of remobilized sediment, rather than a single point source from the dam site.

There were three major periods when the river underwent significant events that could cause morphological changes. The first occurred on September 28, 2013 during the initial high discharge event of ~150 m^3/s; the second was 7 days later when the resumption of the dam removal process began (Fig. 7), allowing more sediment to flow from the reservoir. The third event was in March, 2014 when the river discharge exceeded 250 m^3/s, which was the largest flow recorded during the first two years of the dam removal process (Fig. 7). Each site was affected differently according to its specific geometry.

It is likely that the large flow that occurred in September 2013 was waning as the October dam draw-down was taking place. The diminishing flow may not have been sufficient to immediately transport the new influx of sediment downstream. As seen in the sediment-size distribution graphs spanning those dates (Figures 24 f-g and 26 f-g), there is a slow response in the loss of the coarse fraction of the surface sediment, indicating that the large cobbles that had been re-exposed from erosion during the hiatus in the dam removal had not been completely reburied with a new influx of finer sediment.

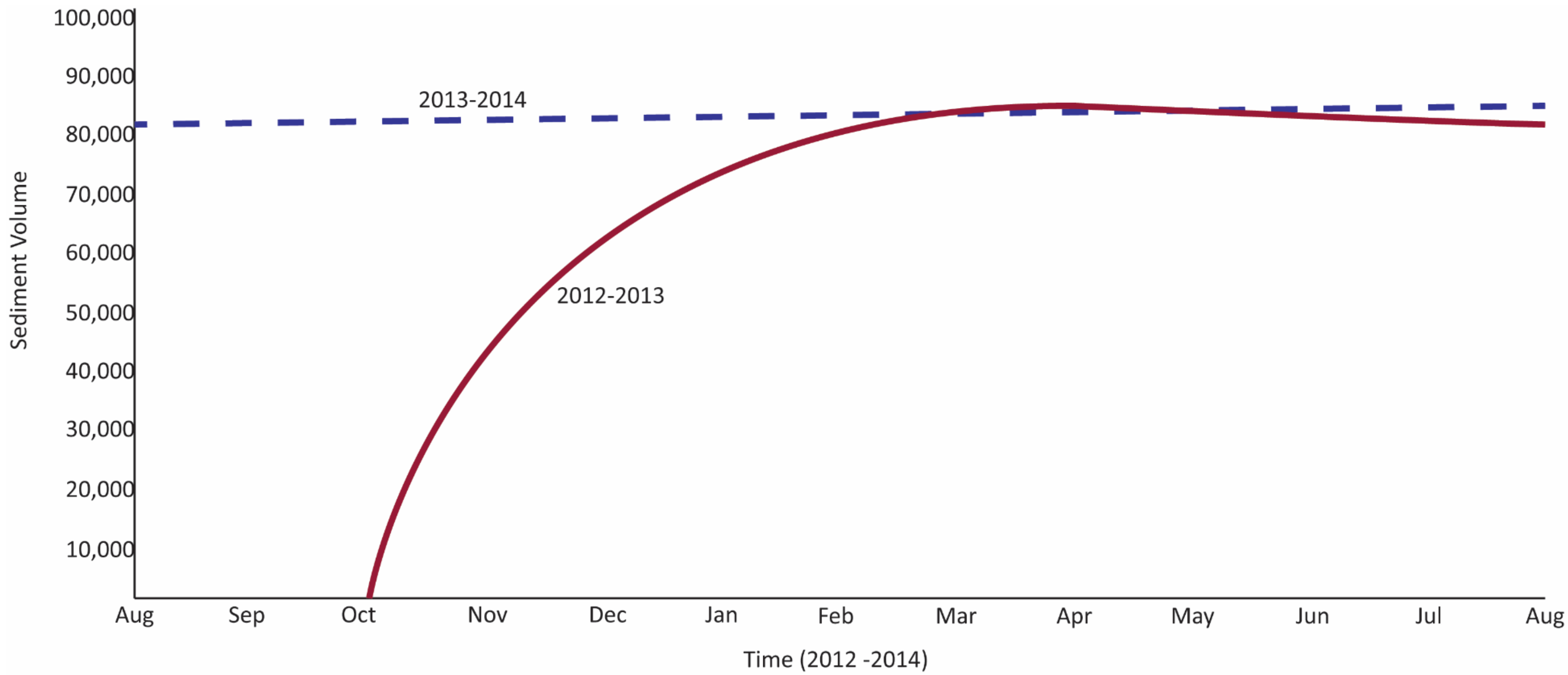

Figure 25: Conceptual total sediment inundation/flux in the entire middle reach of the Elwha River during the dam removal process. Year 1, the primary sediment load was deposited in the first few months after the dam breach. Year 2, there was equivalent deposition and erosion keeping the sediment levels relative to the first year's deposition.

By December 2013, Sites 1 and 2 experienced a complete burial of the coarsest size fraction, consistent with the new source of sediment from the dam drawdown. It was not until the flow event (≤125 m^3/s) in January 2013 (Fig. 7) that Site 2 caught up to the sediment change that occurred at Site 1 in the previous month (Fig. 25i). In contrast to the first year of dam removal, Site 4, farthest downstream, showed an overall fining of the surface sediment-size distribution during the October to February 2013 events. This is attributed to the entire study area being a sediment source following the initial deposition, therefore finer sediment could be transported from one section of the river to another (Figs. 14, 18 and 26i-l).

The high discharge in March, 2014 was the final flow event that resulted in significant changes to the channel morphology. The sediment size at Site 1 did not show any real change (Fig. 16c), but the distribution at Site 2 coarsened slightly as the finer sediment was redistributed downstream, exposing some of the larger cobbles that armored the channel when the dam was still in place. Site 4 experienced a change in sediment distribution with the exposure of some of the previous coarse cobbles (Fig. 26i-l), while at the same time the volume of sediment continued to increase with the addition of new sediment (Fig. 14; Table 4). One explanation is that while the river was flowing through Site 4, it was depositing finer sediment at the margins of the channel while excavating the sediment to the pre-dam removal surface further toward the center of the channel.

In summary, the two largest flows during the 2-year study period over-topped gravel bars and eroded stored sediment. Each of the sites was inundated by the initial pulse of new sediment released from the upstream reservoir as the sediment flowed through the river. Following the initial release of reservoir sediment, the overall period of the dam removal (2012-2014) was dominated by the dispersion of sediment that was a mixture of sediment that continued to flow from the dam site and sediment that was deposited and subsequently reworked along the river (Fig. 27).

Large Woody Debris and Sediment Deposition

Prior to the dam removal, the Elwha River had very little large woody debris within its channel system because large woody debris was not allowed to pass the dam. In the first year, of dam removal all of the sites saw an increase in woody debris. During the first year Sites 2 and 3 collected the most individual pieces of woody debris (Figs. 19, 21 and 22; Table 6). However, it was Sites 1 and 3 that had the most persistent log jams that influenced some of the sediment deposition and river migration (Figs. 20 and 22). The persistence of these log jams created eddies and pockets of slow-moving water that collected sediment and influenced the channel migration by armoring the channel margins. It is possible that the log jams collected in these areas due to the bends in the river and the complex islands that were obstructions in the river for the large woody debris. While the more linear, single-channel geometry at Sites 2 and 4 did collect a fair amount (more than Site 1) of individual pieces of woody debris, they did not accumulate as many log jams as the other sites did (Figs. 19, 20-23; Table 6). Overall, the deposition of large woody debris that can anchor long enough to influence the river flow can create areas in a river system where sediment can collect as seen with the persistent log jams in the middle reach in the first year (Figs. 20-23).

The bulk of the sediment deposition occurred in Sites 2 and 3, followed by Site 1 and finally Site 4. Site 3 also collected the most new large woody debris and the greatest number of log jams (Figs. 19 and 22; Table 6). This collection is consistent with the geometry of the river, which has the highest likelihood to collect woody debris due to the complexity of moving 2-meter long trees through the tight bend and multiple narrow channels. In contrast, Site 2 accumulated the second-largest amount of sediment (Table 4) and individual pieces of large woody debris, but it did not collect many log jams on the point bar. However, there were still copious amounts of sediment accumulation, which as stated earlier is attributed to the geometry and flow of the river. Site 1 collected very few individual pieces of woody debris but had the most persistent log jam within the study area. This jam armored the head of the right-hand island throughout the entire dam removal process and channelized the flow during that process (Figs. 19 and 20). A possible effect that this had on the deposition was to slow the flow on river right causing the waning flows to deposit sediment on that side of the channel. Subsequently, this deposition raised the base level of the river on the right side ultimately influencing the migration and abandonment of the river channel (Figs. 9a, 10 and 20). Site 4, with its long straight geometry, provided only temporary storage for sediment as it flowed through the system. With the lack of bends in the river and its narrow point bars, there was no place for the large woody debris to anchor, thus it could not trap and hold sediment. When comparing the overall deposition and the per unit volume, Site 4 also accumulated the least amount of sediment of any of the individual sites.

Overall, log jams appear to have a more direct influence on channel changes and related sediment accumulation than merely the number of individual logs. In some cases, such as Site 2, the channel accumulated sediment without a significant accumulation of logs or log jams. In other cases, such as Sites 1 and 3, the log jams appeared to play a more important role in the geomorphic changes that were observed.

CHAPTER V

CONCLUSIONS

This study provides insights necessary for modeling and predicting future dam removal projects based on observations of the channel changes, erosion and deposition of sediment, and flux of large woody debris during the removal of the Glines Canyon Dam on the Elwha River. The study monitored four different study sites throughout the middle reach of the Elwha River before, during and after the dam removal process over a period of two years, from 2012-2014. By using repeat Terrestrial LiDAR (TLS), sediment distribution surveys, and large woody debris mapping, it was possible to quantify the geomorphic changes that occurred at sites with different channel geometries.

In the period of time that the dam removal was completed, it became apparent that total volume of sediment that accumulated at each study site was the ultimate influence in the geomorphic change following the dam removal. However, the complexity of the river geometry was the major factor in the ability of the river to trap and accumulate the new influx of woody debris and sediment. After the river geometry, the next driving factor in the type and amount of channel change was the discharge of the river. The largest flow events were necessary to overtop the channel bars, redistribute sediment and large woody debris through the study reach, and erode channel banks. Finally, the large woody debris played a role in the accumulation of sediment but only when it formed persistent log jams that either directly trapped sediment or influenced channel migration or abandonment that in turn affected the sites of sediment deposition and erosion. Furthermore, the formation of the log jams was dependent on the preexisting channel geometry.

By conducting repeat TLS surveys, it was possible to create a detailed graphical representation of where topographic change occurred throughout the individual study sites. Based on the topographic surveys and sediment distribution surveys, it was possible to ascertain that the initial geomorphic effects on the river were due to a large sediment pulse that filled in the study area with sediment and then only small volumetric changes occurred (Fig. 28). However, the initial sediment perturbation continued to effect the channel geometry throughout the entire dam removal period. The initial pulse of sediment inundated the downstream river channel filling the riffles and pools throughout the entire middle reach of the river in a very short period of time. It was the river geometry that influenced where and how the initial sediment pulse deposited within in each of the study sites. This becomes particularly apparent in Sites 3 and 4. The sharp bend and multiple islands at Site 3 contributed to the greatest amount of sediment deposition at this site (Figs. 13 and 14; Table 4). In contrast the low sinuosity and lack of mid-channel islands at Site 4 were likely significant factors in the low volumetric change at this site (Figs. 13 and 14; Table 4).

Following the initial sediment pulse, the sediment distribution surveys indicate that the continued movement of sediment was controlled by the discharge of the river. The addition of new sediment was from dispersion from the dam site and reworking of sediment within the river (Figs. 20-23). In the first year of dam removal each of the study sites were initially filled in with copious amounts of sediment. However, by Year 2 the sediment in each of those sites was being eroded and reworked as a response to the changes in the river geometry (Figs. 9-14 and 20-23). Although an erosional response was occurring in Year 2, it was indeterminate due to the equal amounts of sediment deposition at each of the study sites as well (Table 4).

In addition to the sediment, a large influence on the channel changes was the addition of the large woody debris that was previously trapped behind the dam. During the dam removal process (2012-2014) new large woody debris anchored and accumulated on sediment bars to various degrees throughout the entire reach. The more complex the channel system (i.e. multiple channels, vegetated islands, riffles and pools, or a sharp channel bend), the more likely the woody debris was to collect and coalesce. Overall the woody debris appeared to collect at the apex of established islands and low points in the river channel rather than on mid channel bars. This in turn created more places for the sediment to collect and the channel changes to occur due to filling or redirecting channels.

Ultimately the dam removal process influenced the river geomorphology in multiple ways. The channel and flood plain continue to evolve to accommodate the massive influx of new sediment and change in flow dynamics. There are several different factors that could influence how the river channel reacts in the following years. One such influence is the unconsolidated reservoir sediment that remains within the former reservoir. There is a chance that a large flow event could mobilize the sediment and create a new large pulse that would affect the river in a similar manner. However, if no large discharge event occurs within the next few years, new vegetation could stabilize the remaining reservoir sediment. Other major factors that will influence the long-term effects of the dam removal are the continued reworking of the new sediment and woody debris within the system and the internal feedbacks of erosion and deposition within the river that was starved of sediment and wood for almost a century.

Overall, as future dam removals are projected to continue in the U.S. (Graf et al., 2010; Heinz, 2002), more studies of the downstream effects following the removal would be useful to help predict the response of different types of rivers to various styles of dam removal (Doyle et al., 2003; Heinz, 2002). This study has provided empirical data of the response of a gravel-bed river in a forested environment during a particularly large dam removal project. It has also provided data to test the channel evolution models that are being derived to predict the response of other large dam removals. Furthermore, this study has demonstrated that the use of TLS combined with surveys of large woody debris and sediment distribution can provide highly detailed information about the effects of a dam removal in different geomorphic settings in the downstream river channel.

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