Use of Seafloor Substrate Classification to Estimate Kelp Habitat Suitability Following Elwha Dam Removals

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Abstract

Dam removals induce large scale disturbances to a system, having wide-spread impacts on the physical and biological characteristics of the rivers and coastal waters downstream. Removal of two large dams on the Elwha River, Washingtion has resulted in increases in sediment delivery to the Elwha delta affecting substrate composition and biological communities. Pre-dam removal monitoring has characterized substrate and community composition but uncertainties on the extent of deposition and resulting community responses to increased deposition remain. The relationship between acoustic backscatter of the seabed, seafloor substrate, and macrofaunal habitat was examined using sidescan sonar data and physical grab samples taken on the Elwha delta. Backscatter intensity analysis was combined with grain-size distribution allowing for classification of 'suitable' versus 'probably suitable' habitat. Habitat suitability pre and post dam removal was determined based on shifts in substrate on the subaqueous delta following dam removal. Acoustic backscatter results suggest an increase in fine-grain sediment, increasing the area of unsuitable habitat by 0.7 km^2 since pre-dam removal conditions. Physical grab samples taken pre-dam removal reveal seafloor substrate was composed of primarily of gravel and sand, whereas post-dam removal conditions to date were characterized by sand and mud. Grain-size analysis from 2014 suggests a continuation of the shift toward fine-grained sediment. In the short-term it appears sediment supply in post-dam removal conditions is high enough to support the accumulation of mud on the delta, modifying the seafloor substrate and likely resulting in loss of kelp habitat. Whether these trends persist and kelp is permanently displaced remains unknown.

1. Introduction

Construction of the Elwha Dam, approximately 8 km upstream of the mouth of the Elwha River, was completed in 1913. Fourteen years later the Glines Canyon Dam was constructed 22 km from the mouth, effectively preventing transport of sediment to the lower river and delta regions (Duda et al., 2011). Lack of fish passage combined with the opportunity to restore the watershed to pre-dam conditions motivated the U.S. Department of the Interior to initiate dam removal almost 100 years after they were installed (USBR, 2014). Removal of the two dams began in the fall of 2011 and as of April 2014, only a small fraction of the upper dam remains intact (NPS, 2014). An estimated 5 (+/-3) x10^6 m^3 of sediment was trapped behind Glines Canyon Dam in Lake

Mills and another 4 (+/-2) x10^6 m^3 behind the Elwha Dam in Lake Aldwell (NPS, 2014). Approximately 50% of the sediment in Lake Mills was coarse-grained material composed of sand, gravel and cobble, while the remaining half was fine-grained silt and clay (USBR, 2014). Approximately 7-8 x10^6 m^3 of sediment is expected to leave the river basin (Duda et al., 2011).

The largest increases in sediment delivery to the coast are expected to occur within the 3-5 years following the initiation of dam removal in September of 2011 (Duda et al., 2011). While sediment will likely decline after the initial influx, sedimentation to the delta will remain higher than when dams were intact, analogous to inputs expected from a free flowing river (Shaffer et al., 2008). High rates of sediment transport from the river and subsequent deposition to the seafloor within the Elwha delta are expected to impact the establishment and survival of algal species (Duda et al., 2011). Research suggests that scour, light attenuation and substrate composition have the biggest impact on in the Elwha delta (Berry, 2013). Scour due to the increased transport of sand, decreases the ability of kelp to anchor on hard substrate. Reduced light within the water column due to higher turbidity decreases the depth at which kelp can grow. Fining of seafloor sediment decreases the ability of kelp to establish (Berry, 2013). In general kelp can grow on any hard surface in relatively shallow water (Mumford, 2007), but were found to occur in the higher densities when particle size was $\geq$4 mm (Rubin et al., 2011). It is important to note that overall, macroalgal diversity may benefit from the combined effect of increased habitat patchiness and reduced competition for space (Airoldi and Cinelli, 1997).

The term kelp generally refers to floating and non-floating species of large brown algae found in marine environments. There are three main classes of kelp: floating, canopy-forming kelp, and non-floating stipitate and prostrate kelps. While it is not assumed that every species of kelp will respond to change equally, because all forms of kelp require hard substrate to establish and propagate, for the purposes of our study the term kelp refers to all large brown algae found within the study area (see Duda et al., 2011 for complete list). Exceptions are made in reference to independent studies.

This study combines physical samples with acoustic backscatter intensity to characterize the seabed on the Elwha delta. While physical samples accurately characterize the seabed at a single location, their spatial resolution is often limited. Conversely, sonar data has a broader spatial extent but reduced accuracy when defining seafloor substrate at a specific location. By combining these two data types, we hope to increase both the certainty and extent of seafloor substrate characterization in an effort to determine its influence on kelp habitat suitability. This analysis was focused in the area surrounding the river mouth and into Freshwater Bay (Fig. 1) because it was likely to experience change in substrate due to proximity to river mouth (Warrick et al., 2008), as well as known kelp densities prior to dam removal (Berry et al., 2005). In this study we determine that sonar backscatter data can be used in conjunction with physical substrate samples, and use this combination of tools to define areas of suitable versus unsuitable kelp habitat. Second, we determine the impact of sediment influx due to dam removal on kelp habitat by comparing pre-dam removal unsuitable area to post-dam removal unsuitable area. These data will be an important contribution to the current effort in resolving impacts of dam removal to the Elwha delta. Furthermore, this study hopes to provide insight into the initial response of nearshore vegetation to large sediment increases following dam removal that provide a foundation for understanding long-term impacts of restoration to natural sediment regimes.

2. Background

2.1 Regional setting

The Olympic Mountains formed from the convergence of the continental North American plate and the oceanic Juan de Fuca Plate at the Cascadia subduction zone, and include some of the highest peaks in Washington State (Fig. 1) (Warrick et al., 2011). At the center of the Olympic Mountains, the Elwha River watershed covers an area of 837 km^2 (Warrick and Stevens, 2011). Continuing uplift of the central Olympic Mountains leads to the steeply sloped, high-gradient stream characteristic through much of the 75-km long Elwha River (Warrick et al., 2011). Steep elevation changes from the upper and lower basin are mirrored by a steep precipitation gradient within the drainage. While annual rainfall averages 550 cm the upper basin, the lower basin receives closer to 100 cm per year (Duda et al., 2008). The majority of precipitation occurs between October and March and peak discharge is seen during spring snow melt and winter and fall rainstorms (Duda et al., 2008). The average discharge for the last 99 years – while dams were intact – was approximately 43 m^3/s, with high flow events reaching 1,200 m^3/s (USGS; nwis.waterdata.usgs.gov). The Elwha River flows northward to the southern shore of the Strait of Juan de Fuca, the channel connecting the Pacific Ocean to Puget Sound and Strait of Georgia (Fig. 1). The morphology of the Elwha changes dramatically by the time it reaches the Strait of Juan de Fuca. The lower 7.8 km is characterized by an anabranching river (Warrick et al., 2011) as it meanders through a flat terrace composed of glacially deposited sediment with grain-sizes ranging from silts to small boulders (Miller et al., 2011).

The Elwha River delta is composed of subaerial and subaqueous zones (Fig. 2). Following the last glaciation period (~14,000 ybp) relative sea-level dramatically dropped (-60 m by ~9900 ybp) due to isostatic rebound. It is thought that the present day subaqueous portion of the delta was created during this low sea-level period (Mosher and Hewitt, 2004, Warrick et al., 2008). While the dams were in place, the subaerial delta had a shape consistent with a wave-dominated delta that protruded approximately 2 km, and the subaqueous delta extended another 4 km (Warrick et al., 2008). Erosion of the subaerial delta increased to an averaged 0.54 m/yr during 1939 to 1996, and was focused on the western region of the delta (Warrick et al., 2008 citing unpublished report by Schwartz and Johannsessen, 1997). While many changes to the subaerial delta were observed after dam construction, it is less certain how the reduction in sediment affected the subaqueous delta (Warrick et al., 2008).

2.2 Topical background

Characterization of nearshore substrate type and distribution prior to dam removal was described by Warrick et al. (2008). Using high resolution (0.25 m) sonar backscatter combined with seafloor video imagery, Warrick et al., (2008) found the majority of the region to the west of the river mouth to be coarse substrate, ranging from gravel to cobble, with boulders increasing in frequency shoreward (Fig. 3a). Accumulation of sand occurred along the shoreline directly west of the river mouth (Fig. 3b). They also found this area to be devoid of any fine-grained sediment (silt and clay), which is of particular interest to our study. While their study area did not cover east of the river mouth in detail, the area immediately east of the river mouth was characterized by sand (not visible in figure due to inability of sonar to survey shallow, near shore area).

Canopy-forming kelps (*Nereocystis luetkeana* and *Macrocystis pyrifera*) were mapped by Berry et al. (2005) using annual low-tide aerial photographs, and were found to exist within Freshwater Bay as well as northeast of the river mouth (Fig. 3c) (Berry et al., 2005). When substrate distribution was compared to canopy kelp distributions from Berry et al. (2005), Warrick et al. (2008) found the majority of hard substrate (boulders and bedrock) at depths ≤15 m to be associated with kelp beds (Fig. 3, b and c). In areas of mixed substrate and sand, kelp was observed in 18% to 20%, respectively, of the area characterized by these substrate types. Historically, kelp in Freshwater Bay was found to cover a greater area, over longer time frames (Warrick et al., 2008). The area of kelp canopy within Freshwater Bay was found to remain relatively constant from 1989 to 2004 (Berry et al., 2005). Conversely, the less persistent kelp canopy found east of the river mouth occurred in mixed sediment (gravel to cobble) (Warrick et al., 2008). From these observations it is hypothesized that kelp existing in mixed substrate to the east of the river mouth maybe more vulnerable to increases in sediment deposition due to dam removal.

Dive surveys conducted pre-dam removal (2008) inventoried density and richness of the ten species of kelp found in the subaqueous delta, two of which are canopy forming and eight understory species at or near seafloor (Rubin et al., 2011). Highest densities of kelp were found in mid Freshwater Bay and west Freshwater Bay, close to shore. Understory kelp dominated the delta around the mouth of the river and were found in highest densities in the 15-18 meter depth stratum. The majority of kelp was found within 10 meters of the surface and on harder substrate types. Areas of bedrock/boulder reef habitat (mid Freshwater Bay) were dominated by canopy forming kelps, creating a nearly continuous canopy at the water surface combined with a diversity of understory kelp. No kelp was seen on substrate composed of very fine gravel and smaller (particle size less than 4 mm) (Rubin et al., 2011).

3. Methods

3.1 Data collection

Substrate grab samples were collected aboard the R/V Barnes from 11-13 April 2014 (Fig. 2). Grab samples were collected using a Shipek sampler at water depths ranging from approximately 6 to 45 m. In general, samples were collected at regular intervals across bathymetric lines (Eidam et al., in Prep). Additional sites have been added over the years in an attempt to characterize areas of the delta undergoing the greatest change. In order to describe the change in substrate since dam removal, additional grab sample data were obtained from research cruises in November, 2011 and April, 2013 (Fig. 2). Acoustic-backscatter data used in our analysis was collected by the USGS between 22 February and 3 March, 2010; and March, 2013 (Finlayson et al., 2011; Cochrane et al., 2008). Grab samples collected in 2011 were used in conjunction with 2010 sonar data to describe substrate pre-dam removal. Any change in substrate between 2010 and 2011 was assumed to be insignificant for the purposes of this study and therefore we compared the two datasets as if they were collected concurrently.

3.2 Data analysis

Shipek sediment samples were divided into four categories: heterogeneous, homogenous, mixed, and scant (<20 g). In order to determine the grain-size distribution, each sample was wet sieved at 4 phi to remove the fine-grained mud from coarser-grained sediment. The distribution of the mud fraction (>4 phi) of the sample was determined based on settling velocity in a method modified from the University of Washington's sediment lab protocol (UW, 1998). Coarser sediment (-4 phi to 4 phi) was then dry sieved in whole phi increments, with each grain size weighed individually. The results from the fine and coarse grain analyses were analyzed together to determine the percentage weight of each grain size class for each grab sample. Grain-size classification was based on the Wentworth (phi) grain size classes (Wentworth, 1922). The percent of gravel, sand and mud were calculated for each sample using Gradistat statistical software (Blott, 2010). Additionally, we calculated the percent of 'large gravel', defined as particles ≥ 4 mm and ≤64 mm.

Acoustic backscatter data used in our study was obtained from swath sonar surveys conducted in 2010 (Finlayson et al., 2011) and 2013 (Cochrane et al., 2008). The survey completed 195 survey lines over an area of 7.2 km^2, with elevations ranging from +1.0 m to -90 m in a NAVD88 projection (Finlayson et al., 2011). For more information regarding sonar frequency, depth and accuracy refer to Finlayson et al. (2011). Raw backscatter, a measure of the intensity of sound waves reflected off the seafloor, was produced from sonar data and converted into georeferenced, backscatter grids with 0.05 m resolution (Finlayson et al., 2011). The backscatter data were normalized for sonar beam differences and variations in signal over time (Finlayson et al., 2011). For the purposes of this study, sonar data has been re-gridded to a 5 m resolution. Backscatter was then imported into ArcGIS as raster data where backscatter (pixel) intensity value was assigned to each pixel. By overlaying the locations of physical samples, we determined the intensity value for each waypoint using the Spatial Analyst tool (Fig. 4). By defining intensity at each sample location, we were able to determine whether a relationship can be seen between sonar and grain size of grab samples. Because the normalization process for the 2010 and 2013 data was identical, the maximum and minimum intensity value is equal between the two data sets, therefore we can define a metric for a single data set and apply data points from 2011 and 2013.

In order to define the study area, the two sonar maps in Figure 6 were layered and any pixel without a corresponding pixel in the alternate year was removed. The remaining pixels were totaled for each year, forming an area in which analysis was limited to (Fig. 6, study area). Grain size versus intensity analysis was therefore limited to points that fell within the overlapping backscatter data. To delineate between physical habitat that is suitable for kelp growth and habitat that is not, the fraction of large gravel (4 to 64 mm) in the grab samples was plotted against backscatter intensity values (Fig. 5). An intensity value of 17,000 was determined to be the cutoff between unsuitable and likely suitable habitat, creating two bins in which the pixel values were grouped (Fig. 5, red and green zones). The resulting classification of unsuitable versus likely suitable was used to observe the percent change in suitable kelp habitat from 2010 to 2013 (pre and post dam removal). Although we did not analyze sonar data for 2014, physical grab samples were analyzed using the same technique and the percent of gravel, sand and mud were determined. To assess whether trends seen between 2010 and 2013 have continued, the 2014 substrate composition was compared to the previous years.

4. Results

4.1 Intensity versus grain size

There were 26 grab sample stations that also fell within the study area defined by the sonar data (8 in 2011, and 18 in 2013) (Fig. 6). A linear relationship was seen when plotting the percent of gravel (4 - 64 mm) in each sample versus the intensity value at each site. In general, intensity increased with increasing amounts of gravel (4-64mm) in the sample (Fig. 5). Perhaps the strongest trend occurred at lower intensity values. Every sample with intensity values less than 17,000 contained 0% gravel. However, at four sample stations, samples containing less than 10% gravel had intensity values of ~30,000 or higher (Fig. 5). One possibility that could explain these outliers is that the seafloor is mostly coarse-grained material with a layer of mud over it. Due to limitations in the sampling device as well as the inability of the sonar to identify thin layers of mud over cobble, our analysis of these outliers would have been improved by the addition of underwater video. The relationship between intensity and grain-size seems to be limited to an intensity value of approximately 42,000. More samples collected in high intensity areas would help distinguish whether this is due to limitations of the Shipek sampler or the sonar.

4.2 Grain-size analysis

Seafloor grain-size distributions on the Elwha delta were estimated using Shipek grab sample data from November, 2011 and April 2013. Substrate distribution was spatially dependent, and variations depended on location relative to the river mouth. Three distinct areas of grain-size distribution (W, C, E) were identified in the delta based on physical samples (Fig. 6). Area W includes the area west of the river mouth, area E includes the area east of the river mouth, and area C describes the area northeast of the river mouth (Fig. 6). In the first year of grain size data (2011), out of the 41 grab samples analyzed for grain size distribution, nine were determined to be scant samples, and assumed to be composed of >50% gravel. Overall, the area west of the river mouth was characterized by sand and gravel (area W in Fig 6). Out of the 18 samples taken in area W, 8 samples contained >50% gravel, 10 samples contained >50% sand, and all of the samples contained < 8% mud, and 3 samples were scant. In contrast, the region directly north of the river mouth (area C in Fig.6) was dominated by gravel. Out of the 11 samples taken in area C, 6 were ≥90% gravel, and 5 samples were scant. Only 12% of the total composition from the 11 samples collected in area C was either sand or mud. The area east of the river mouth was dominated by gravel (area E in Fig. 6). Of the 12 sample stations in this area, 9 were >50% gravel, 2 were >50% sand and 1 was scant.

Physical sample locations in 2011 were not spatially replicated in 2013 but general patterns were still visible (Fig. 6). Overall, 2013 grain size samples experienced a reduction in sand and an increase in gravel and mud fractions. Of the 19 samples collected in area W, two samples contained >50% gravel, 11 samples contained >50% sand, and seven of the samples contained >30% mud (area W 2013, Fig 6). As in 2010, the region directly northeast of the river mouth was dominated by gravel but showed an increase in mud and sand fractions as well as a reduction in the number of scant samples. Out of the 5 samples taken in area C, three were ≥50% gravel, one sample was >90% sand, and the fifth was mixed (Fig 6; area C, 2013). Samples taken in area E were dominated by gravel with increasing fractions of sand nearer to shore and moving east. Of the 10 sample stations in this area, eight were >50% gravel, two were >50% sand and one was over 45% mud (area E 2013, Fig 6). To visualize change from pre to post-dam removal, the seventeen sample locations from 2011 that were repeated (within 100 meters) in 2013 were averaged and compared visually (Fig 8, A-B). In the two years between samples it appears the gravel has been replaced by sand and mud. The mud fraction increased by 14% while the gravel fraction decreased by 7% (Fig 8, A-B).

In 2014, three years after dam removal began, the western delta was characterized by sand with the largest mud fractions occurring in the area immediately west of the river mouth (Fig. 7). Four samples; three in the center area, and one in the east, were determined to be scant samples (Fig. 7). Although sample stations did not have the same spatial coverage as in 2013, there were select locations that were suitable for comparison. In an effort to determine continuing trends, grab samples taken within 100 meters of each other in 2013 and 2014 were compared (Fig. 9, A-B). Between 2013 and 2014, there was a 10% increase in the average mud and sand fractions, and a 20% decrease in the average fraction of gravel (Fig. 9, A-B).

4.3 Backscatter intensity analysis

The total area of backscatter data used in our analysis was limited to the area where sonar data collected in 2010 overlapped with 2013 sonar data (Fig 4., brown polygon). The overlapping area was determined to cover a total of 6.74 km^2. The majority of unsuitable habitat in 2010 was confined to shallow areas near shore and was focused in Freshwater Bay (Fig. 6; 2010). Additional unsuitable habitat was found in small patches 300-350 m northeast of the river mouth, as well as along the eastern edge of the subaerial delta (Fig. 6; 2010). March 2013 data reveals that the area of unsuitable habitat in Freshwater Bay extended seaward, to the northeast across the delta. Fine-grained sediment was also shown to accumulate in two areas directly east of the newly formed subaerial delta and off of the river mouth (Fig. 6, 2013). Based on our definitions of unsuitable versus likely suitable kelp habitat, the majority (~89%) of likely suitable habitat in 2010 remained suitable for kelp growth in 2013 (Fig. 6). The area determined to be unsuitable kelp habitat (intensity values <17000) covered approximately 2.4% (0.161 km^2) of the total area in 2010, and increased to approximately 11% (0.736 km^2) in 2013 (Fig. 6).

5. Discussion

5.1. Relationship between backscatter intensity and substrate

The relationship between backscatter intensity and the percent of gravel (4-64 mm) in grab samples suggests a relationship between backscatter and grain size (Fig. 5). This relationship suggests a suitability threshold value of 17,000, with backscatter intensities below the threshold described as unsuitable habitat for kelp growth in the subaqueous delta. Physical sample sites located in areas deemed unsuitable (intensity <17,000) were entirely composed of well sorted substrate less than 4 mm (Fig. 5). A suitability threshold of 17,000 was therefore considered to be a conservative cutoff value. It is important to note that there were only four grab samples associated with intensity values <17,000 and all four had gravel values of 0%. Increasing the number of grab samples in areas of lower backscatter intensity, would improve the confidence of the suitability threshold value as well as increase our confidence in the relationship between intensity and grain size at low intensity levels.

Higher intensity values show variation in the corresponding gravel fractions (Fig. 5). Intensity values from approximately 32,000 to 42,000 were shown to correlate to a wide range of gravel fractions (0.004 to 0.97), therefore this method may not be a useful tool for describing the specific substrate characteristics within the suitable area. Rather, our methods are better suited to describe the state of seafloor at a given point in time and the trends observed over time. However it is also important to note that a wide range of grain sizes for a small range of intensity values may be explained in part by the variability in backscatter intensity due to factors such as rugosity or vegetation cover. While sonar was collected in March to reduce interference from vegetation, certain species of kelp persist year-round in the coastal environment adjacent to the Elwha river mouth (I. Miller, pers. comm.), which could result in low intensity values in areas of coarse substrate. Another pattern observed in Figure 5 is that above a certain intensity level (~42,000), the relationship deteriorates. Field observations suggest that the Shipek sampler is rarely able to collect samples where very coarse gravel to cobbles (approximately 50 mm or greater) are present. Furthermore, anecdotal evidence from dive surveys suggests that kelp tend not to establish on grain sizes smaller than about 20 mm (I. Miller, pers. comm.), which would suggest a higher intensity threshold value be set for determining the boundary between suitable and unsuitable habitat.

5.2 Patterns of substrate change

Our analysis of data collected pre-dam removal (2011) versus post-dam removal (2013) revealed a significant increase in the area of mud present directly west of the river mouth. A reduction in grain size, from gravel-dominated to mixed gravel, sand and mud, was observed directly off the river mouth (Fig. 7). While the majority of sites still contain gravel, all sites west of the river mouth also contain some mud post-dam removal. Backscatter intensity comparison also suggests an increase in the area of finer-grained sediment (<4 mm) along the eastern shore of the delta (Fig. 6). These findings are consistent with Gelfenbaum et al. (2009) predictions that suggest deposition in bands on either side of the river mouth when sediment supply is large enough. Formation of large eddies to the east, and smaller eddies to the west of the delta during slack tide may also contribute to deposition of fine-grained material in these areas (Gelfenbaum et al., 2009). While a reduction in grain size was observed in all three zones (W, C, E), it was not uniform change. A shift to fine-grained substrate was focused on the western delta and close to shore on the eastern delta. The largest proportion of sand deposition was focused centrally, just off the river mouth (Fig. 6). These results are consistent with modeling of sediment transport on the Elwha River delta (Gelfenbaum et al. 2009). Gelfenbaum et al. (2009) suggests the uneven distribution of fine grained sediment east and west of the river mouth is tidally influenced and the asymmetry of the tides will dictate where sand and silt is focused. Gelfenbaum et al. (2009) also accurately predicted sand would be deposited east of the river mouth in higher percentages but incorrectly predicted that silt deposition would be evenly distributed east and west of the river mouth. Our results suggest that deposition of fine-grained substrate occurred predominately west of the river mouth.

5.3 Implications for kelp

While some areas were still dominated by gravel in 2013, the large increase in the percent of mud indicates that this habitat may no longer be suitable to kelp due to a layer of mud covering the surface (Fig. 8, B). Underwater video would be a useful tool in confirming this theory. Based on sonar data, the area of finer (< 2 mm) substrate has increased by 8.6% in the three years following dam removal (Fig. 6). In the sort-term, burial of kelp that has already established, or interference of kelp settlement by sediment in transport may contribute to the suitability of the environment to support kelp (Shaffer and Parks, 1994). In the long-term, if finer-grained substrate persists, we can assume this would lead to a permanent decrease in the total area of substrate suitable to sustain kelp communities (Warrick et al., 2008; Berry et al., 2005; Gelfenbaum et al., 2009). Based on changes observed in the sonar data from 2010 to 2013, areas most influenced by substrate change include the eastern portion of Freshwater Bay, especually directly west of the river mouth, and along the eastern edge of the subaerial delta from ~0 - 5 m in depth (Fig. 6). In particular, accumulation east of the river mouth was focused in two distinct areas near the shore (Fig. 6).

Preliminary data collected in years following dam removal by Rubin at al. (2014), show marked declines in the total area of canopy, prostrate and stipitate kelps within the Elwha drift cell. Out of the ten species of kelp characterized, all were shown to decline within the first year after dam removal, with density values decreasing the most near the river mouth. In the first year following dam removal the mean kelp density near the river mouth decreased 77% and continued declining to 95% in year two (Rubin et al., 2014). While our results are consistant with these findings due to the large increase of mud near the river mouth, kelp decline was observed over a much larger area than our results would have suggested if declines were solely due to changes in substrate. This discrepancy may be due to a reduction in light availability from the river plume or increased scour (Rubin et al., 2014, Warrick and Stevens, 2011). At this point in the post-dam removal phase, it may be hard to delineate between light, scour and substrate as drivers for reduced kelp densities. If the trend of finer substrate on the subaqueous delta persists after river sediment stabilizes, seafloor substrate may dictate distribution and density of kelp in the subaqueous delta in the future.

6. Conclusions

Following removal of two large dams on the Elwha River, large increases in sediment delivery to the subaqueous delta have led to both physical and biologic changes. By combining sonar backscatter data with physical substrate samples, we have demonstrated the ability to classify substrate into two categories: unsuitable and likely suitable kelp habitat. Based on these definitions, the area of unsuitable habitat was determined to have increased 8.6% in the first two years following dam removal. Our analysis suggests that backscatter intensity and percent gravel seem to be positively related. Further investigations into this relationship would be improved by increasing the number of physical samples in areas of low intensity. Ground truthing using underwater video could also be employed to determine the cause of outlying data points (i.e. where high intensity values are associated with low gravel fractions). In-situ observations of decreased kelp density in the subaqueous delta (Rubin et al., 2014) supports our findings of a reduction in the area deemed suitable for kelp. Our results highlight initial changes in seafloor substrate, one of three overarching factors contributing to kelp decline in the Elwha Delta. As the effects of light attenuation and seafloor scouring are reduced with reduced sediment input, the dominant factor influencing kelp habitat suitability may be revealed. The degree to which this will be true in the long-term depends on whether fine-grain sediment persists in the shallow subaqueous delta or continues offshore as sediment inputs decrease over time.

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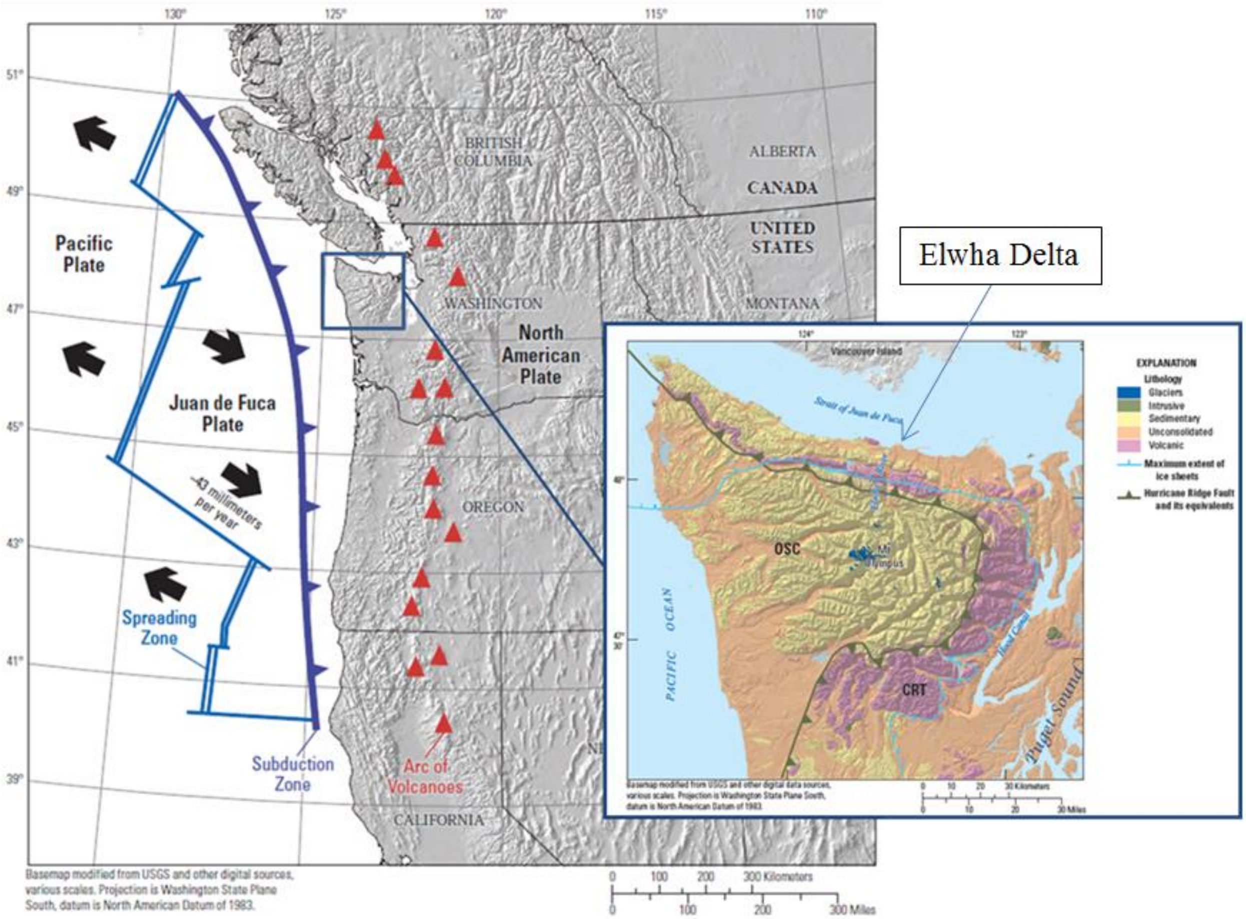


Figure 1. Generalized plate tectonics map depicting Cascadia subduction zone. Inset describes general geology of the Olympic Peninsula, Washington and its location in relation to the Puget Sound, Strait of Juan de Fuca and the Pacific Ocean (Modified from Warrick et al., 2011).

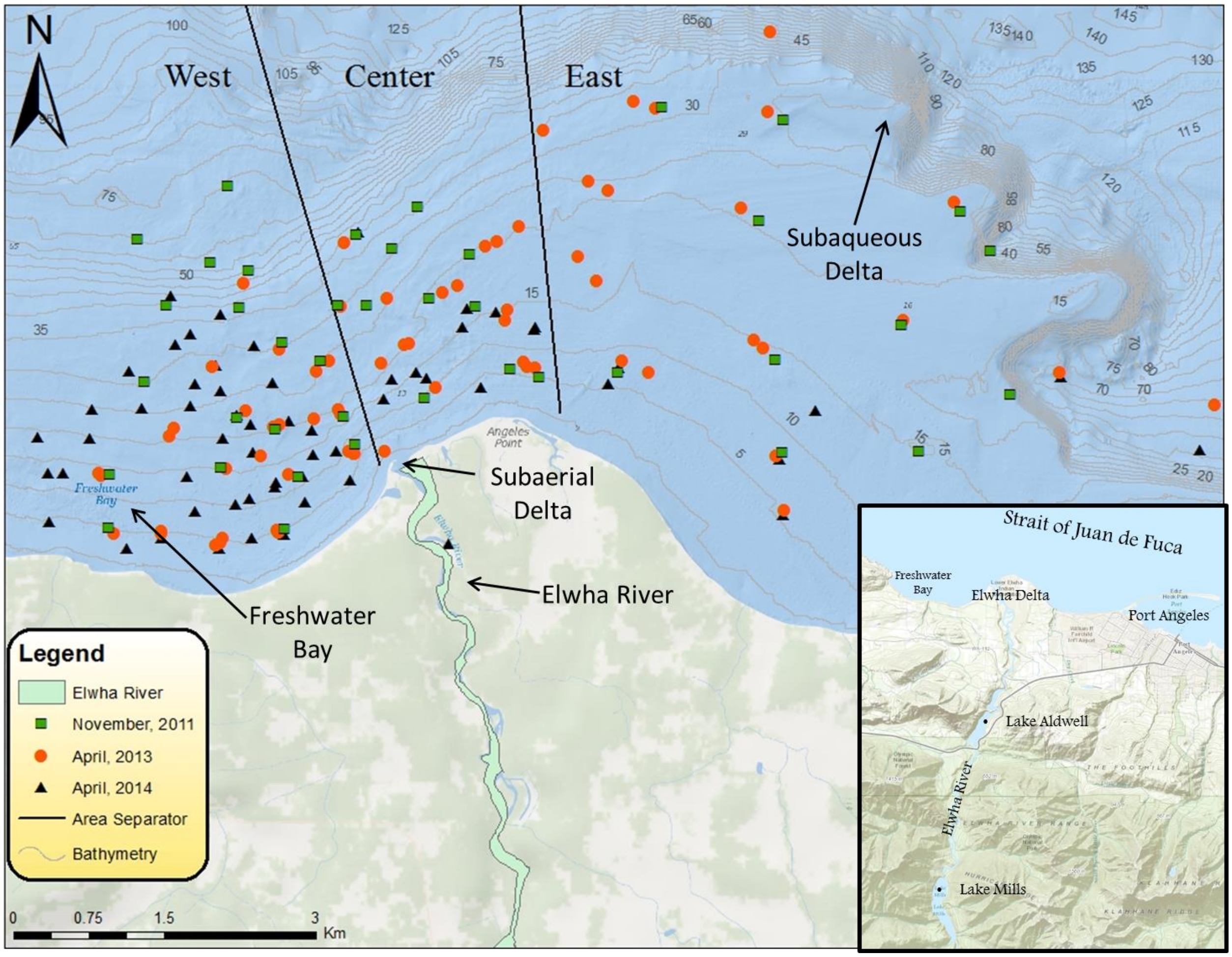
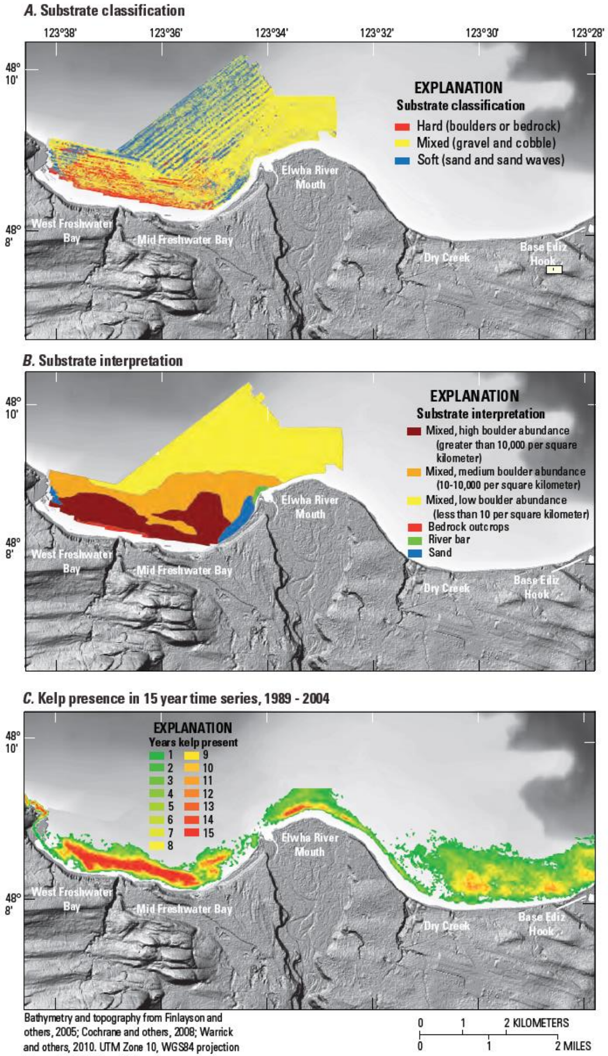


Figure 2. Map of Elwha Delta, depicting areas defined in text including areas West (W), Center (C), and East (E). Pre-dam removal stations (2011) are depicted in green and post-dam removal stations (2013 & 2014) are in orange and black.



Bathymetry and topography from Finlayson and others, 2005; Cochrane and others, 2008; Warrick and others, 2010. UTM Zone 10, WGS84 projection
Bare earth LIDAR from 2001

Figure 3. Image shows location of Freshwater Bay in relation to river mouth. (A) Substrate classification from acoustic backscatter data showing hard substrate in FWB. (B) Substrate interpreted from raw backscatter. (C) Results of annual aerial photos 1989-2004 depicting presence of canopy forming kelp (From Rubin et al., 2011).

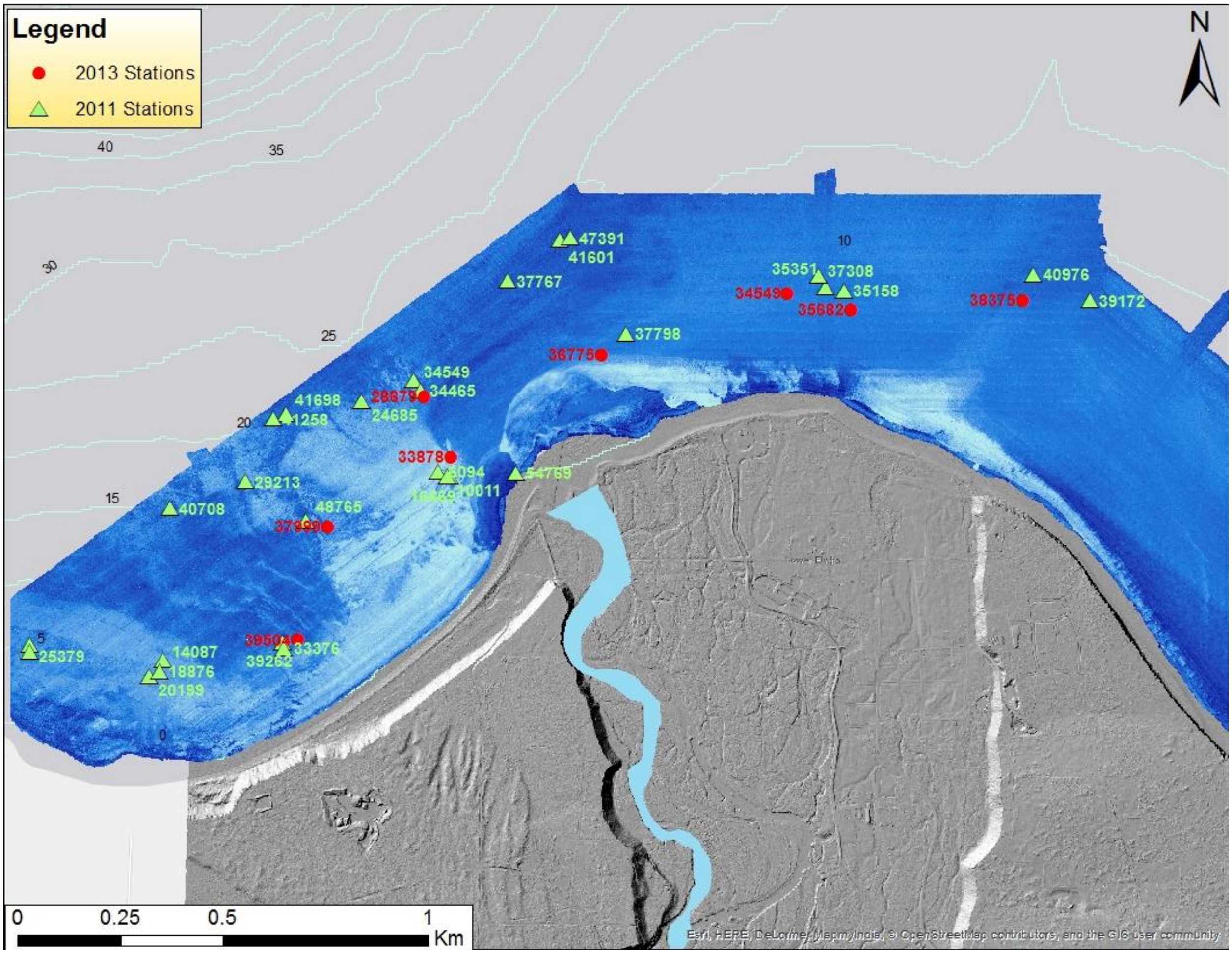
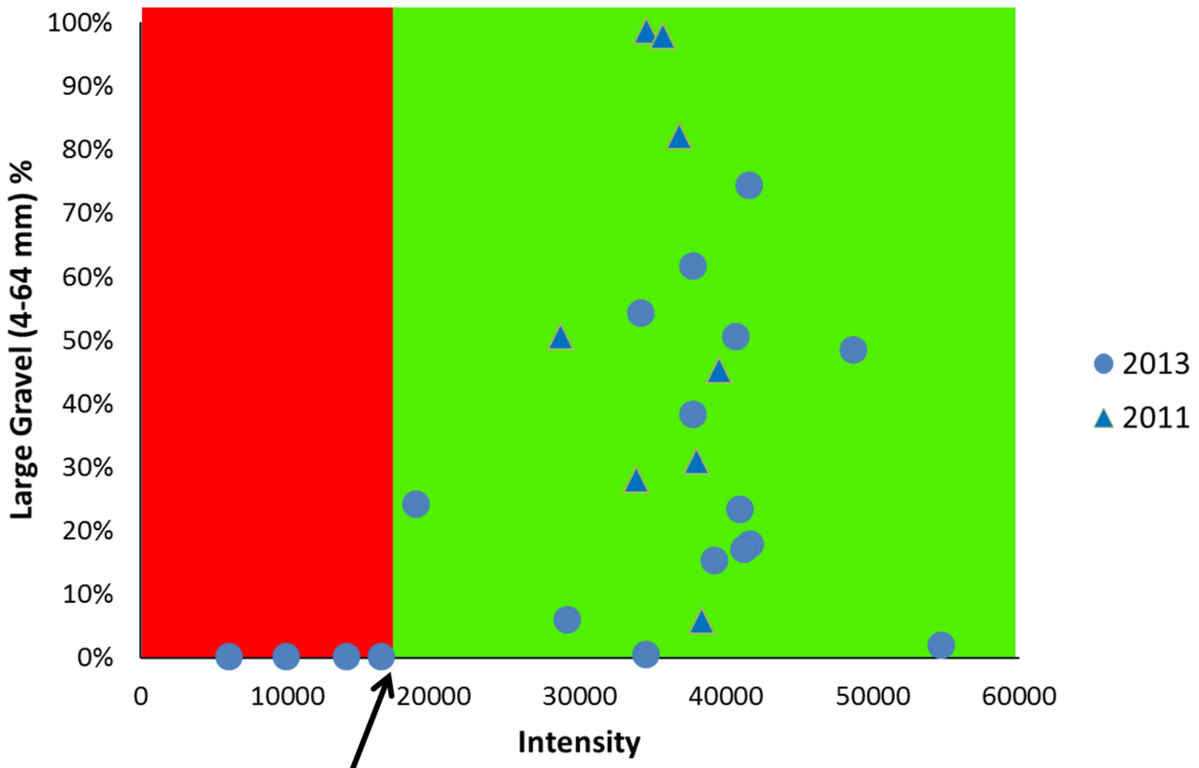


Figure 4. Physical grab sample locations from 2011 (green) and 2013 (red) labeled with the backscatter intensity value for each sample station. Note these values define the y-axis in Figure 7.



- Suitability Threshold set at 17,000
    - Unsuitable = < 17,000
    - Likely Suitable = > 17,000

Figure 5. Grain size versus intensity values for sample stations in 2011 and 2013. The suitability threshold was set at an intensity value of 17,000. Unsuitable habitat (<17,000) is shown in red, and likely suitable habitat (>17,000) is shown in green. These colors correspond to red and green areas in Figure 5.

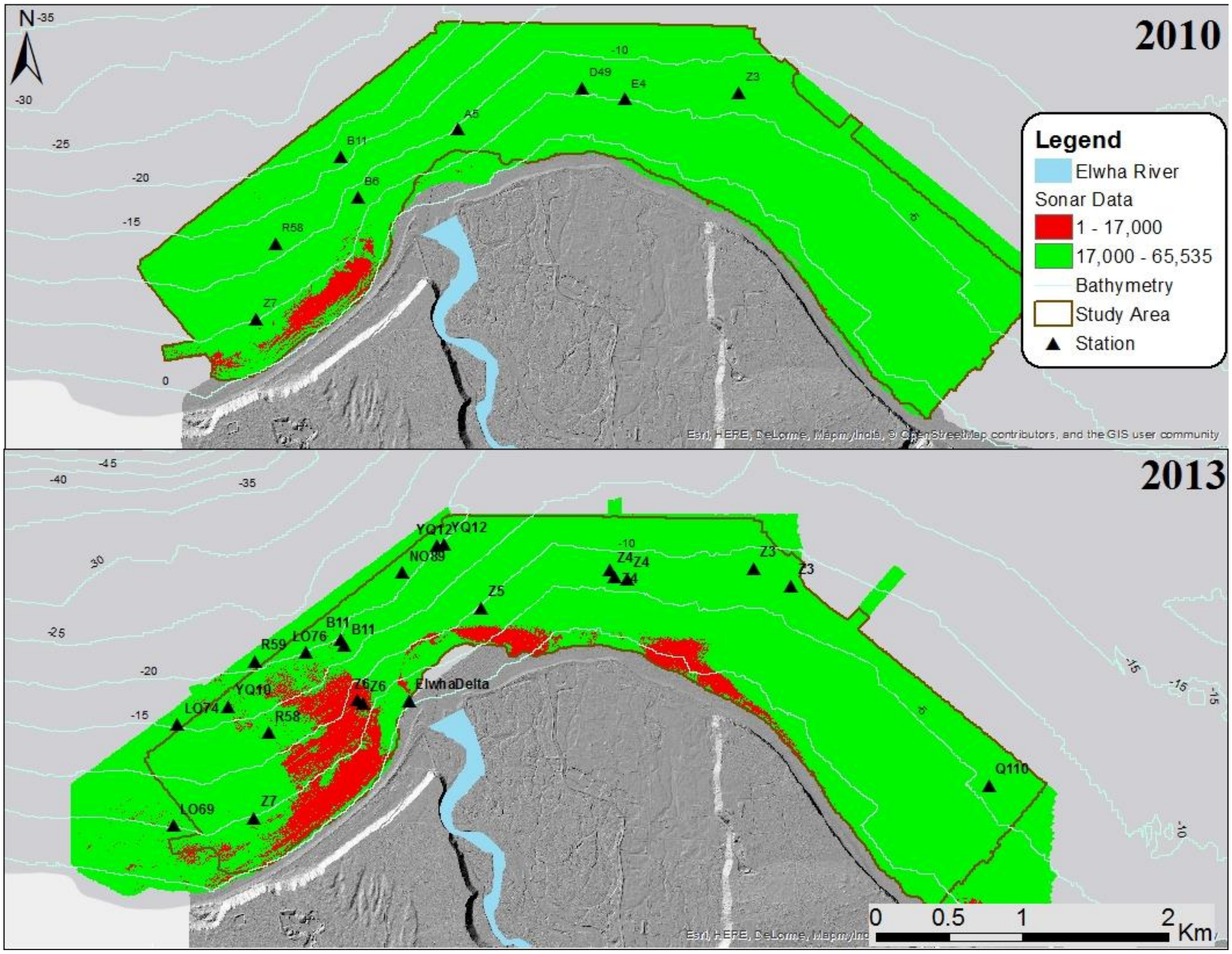
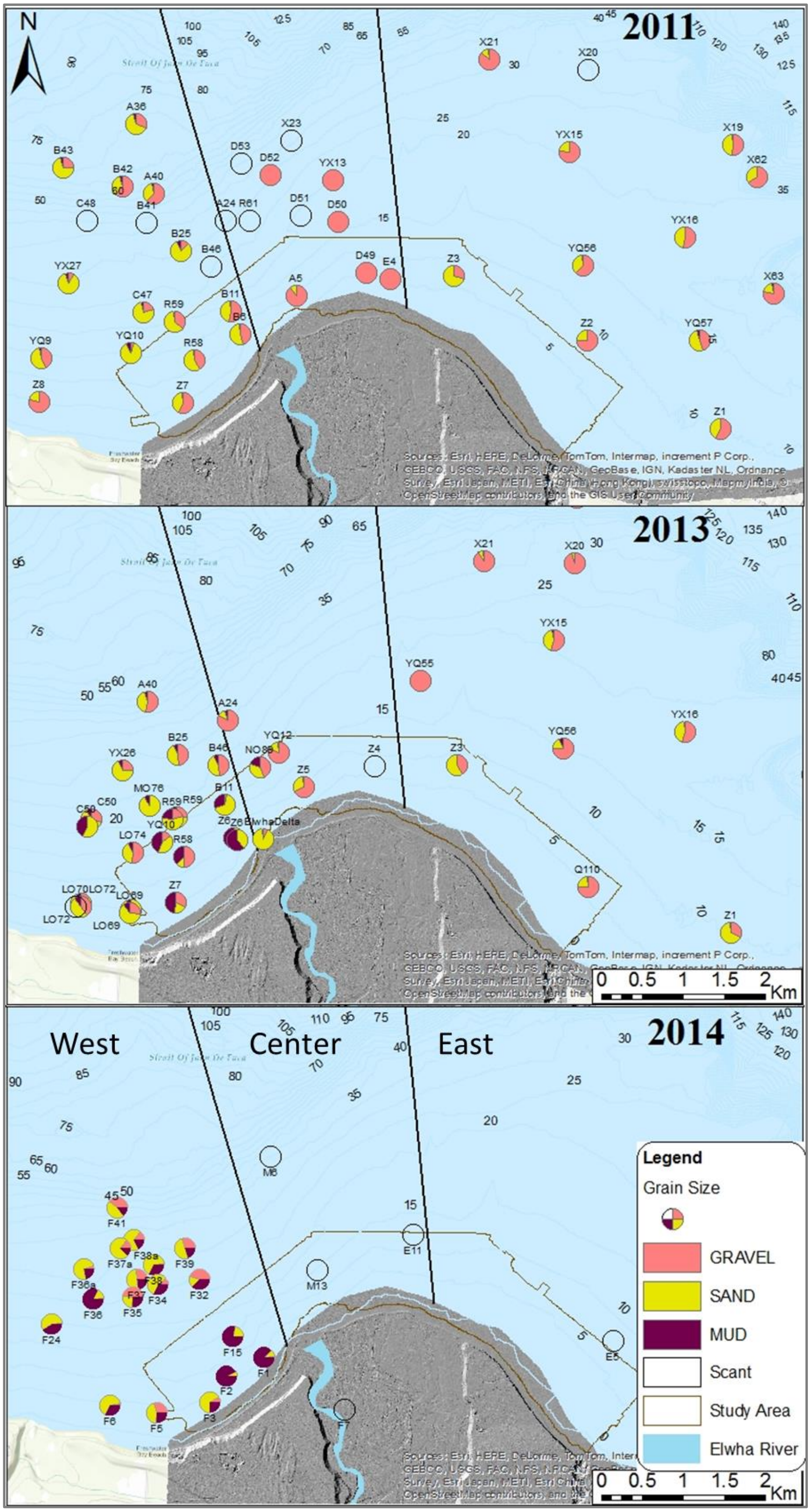


Figure 6. Map of physical grab sample locations in 2010 and 2013 and the associated sonar image. Sonar image showing unsuitable habitat in red and likely suitable habitat in green (intensity value between 17,000 and 65,535).



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 7. Grain-size analysis results for pre-dam removal (2013) and post-dam removal (2014).

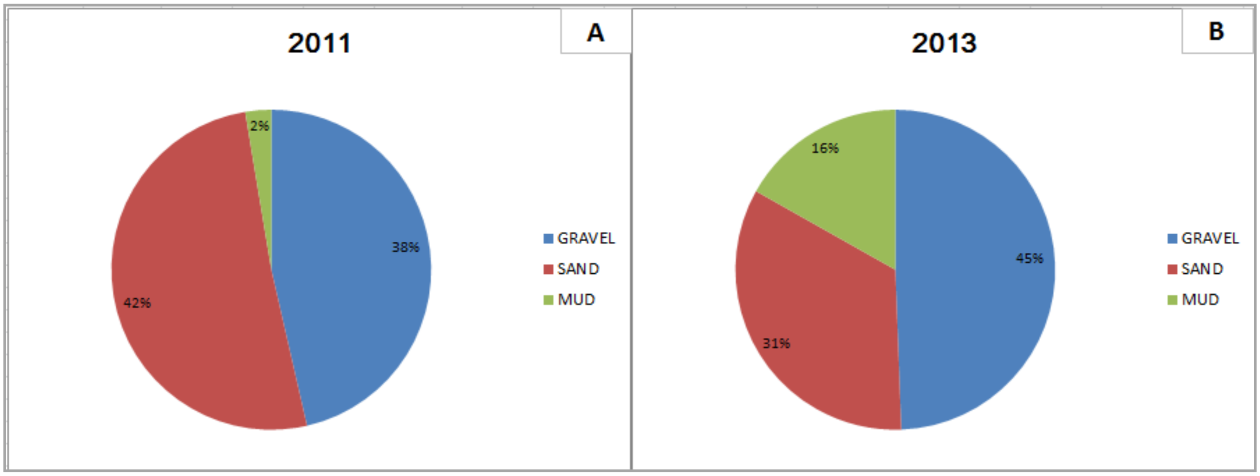


Figure 8. Average grain-size percentages of gravel, sand, and mud for the 34 spatially correlated sample stations (within 100 m) between sampling years 2011 and 2013.

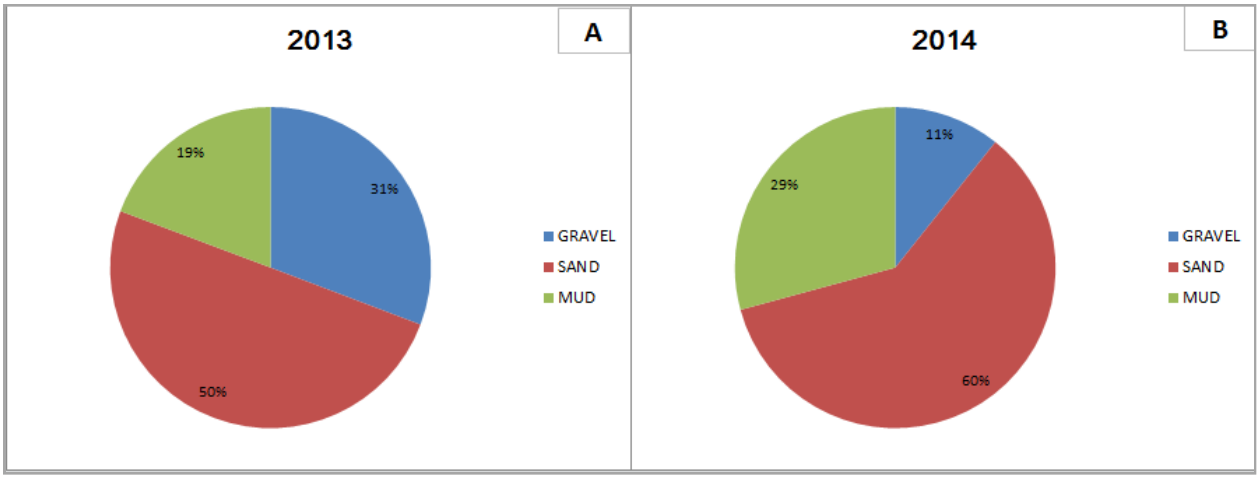


Figure 9. Average grain-size percentages of gravel, sand, and mud for the 8 spatially correlated sample stations (within 100 m) between sampling years 2013 and 2014.