

**Sediment Deposition on the Elwha Submarine Delta: Changes in Substrate  
Composition and Conditions for Fine-Grain Deposition**

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## **Abstract**

The coarse Elwha River Delta is now exposed to an influx of fine-grained sediment from the removal of two dams. The coarse substrate of the delta and energetic oceanographic processes will result in complicated sediment deposition patterns. This study used grain-size distribution and water velocity data compared with prior studies to conclude where change in the delta substrate has occurred and under what conditions deposition is likely to occur. Grab samples and video footage were used to map the substrate and a shipboard acoustic Doppler current profiler was used to measure water velocity and subsequently to estimate bed shear velocity. Currents west of the river were on average lower than on the east suggesting deposition is likely to occur on the west side. Deposition of fine sediment was found west of the river while the seabed east of the river has remained coarse. Deposition of sand is likely to occur during periods of low shear velocities during ebb and slack tides. This study provided background work for future research on the oceanographic processes that allow deposition on the west side of the river.

## **1. Introduction**

Small mountainous rivers play a key role in sediment supply to their surrounding coastal environment (Wright et al. 1995). These river basins often have high sediment yields and have seasonal floods that discharge fine-grained sediment during winter storms or spring freshets (Warrick et al., 2011b). When a river exits into an energetic oceanographic system, the substrate is often coarse because waves and tides transport the fine-grained sediment (sand and mud) away from the delta (Colling et al., 1989).

Sediment dispersal patterns on coarse-substrate deltas become complex. The coarse substrate affects the bottom boundary layer and friction creates turbulent flows, which increases the potential for sediment remobilization (Colling et al., 1989). Waves and tides further mix the sediment into the water column and transport it farther from the river mouth.

The Elwha dam removal is a unique opportunity to study the processes following an influx of fine-grained sediment over a coarse-substrate. Mud and sand have been trapped behind two dams for near a century and recently have been released to flow to the coast. Erosive processes have had a significant effect on the morphology of the nearshore environments over the past century, removing much of the fine-grained substrate layer (Warrick et al., 2009). The winds and currents are expected to move most of the newly introduced sediment east (Warrick et al., 2008). It is unclear whether the nearshore substrate will return to their pre-dam state with sediment accumulation or if the strong currents and waves will continue to remove any newly deposited sediment.

This study aims to gain a better understanding of where sediment is likely to disperse over the coarse substrate and under what conditions deposition is likely to occur. The measured currents over the different tidal cycles will help reveal the conditions that might allow sediment deposition. Investigation of the nearshore substrate over multiple years allows any change in the composition to be measured. Waves and currents will ultimately determine where the sediment will deposit and accumulate to change the substrate.

## 1. Background

### 2.1 Regional setting

The Elwha River is a small mountainous river that drains northward from the Olympic Mountains into the Strait of Juan de Fuca, located in Washington State, USA (Fig. 1) It has a watershed of 831 km<sup>2</sup> (Warrick et al., 2009) and an average discharge of 40 m<sup>3</sup>s<sup>-1</sup>, which increases with spring freshet and winter storms (Warrick et al., 2011b). The Elwha Dam was constructed in 1913, 8 km upriver from the river mouth followed by the Glines Canyon Dam in 1927, 22 km from the mouth. In spring 2012, deconstruction of the Elwha Dam was complete with the remainder of the Glines Canyon Dam pending fall 2013. National parks service estimated that 26x10<sup>6</sup> m<sup>3</sup> of sediment was trapped in reservoirs (NPS, 2013) of which one-third is expected to disperse onto the Elwha Delta (Gelfenbaum et al., 2011). This sediment is comprised of roughly 50% mud and 50% sand and gravel (Warrick et al., 2009). The present subaerial delta extends 2 km into the Strait while the submarine delta extends 4 km (Warrick et al., 2008). Nearshore physical processes consist of mixed mesotidal semidiurnal tides, strong baroclinic residual currents, and swells originating from the Pacific Ocean (Warrick et al., 2009). Northwestern winds are dominant in the summer and southerly winds in the winter; however, the Olympic Mountains block these winds significantly, reducing winter storm's effects on the Elwha Delta (Warrick et al., 2011b). These processes will mix, resuspend, and transport the newly deposited fine-grained sediment in complex dispersal patterns.

## *2.2 Topical background*

A river's delta morphology, sediment yield, water discharge, coastal oceanographic processes, and substrate composition all affect its sediment dispersal system (Wright et al. 1995). Coarser sediment deposits close to the river mouth and under strong currents and wave action is moved as bed load (Wright et al. 1995). Fine-grained sediment exits the river in a buoyant plume while currents and waves transport the suspended sediment as it settles gradually (Wright et al. 1995). In energetic fluvial systems, river discharge and currents often transport suspended sediments kilometers away from the river mouth (Nittrouer et al., 1994). High river discharge and turbidity during flood events or large storms creates the greatest morphological change to deltas (Barnard et al., 2010). The roughness of the substrate, which is dependent on grain-size and composition, affects the height above the seabed at which friction causes the water velocity to reach zero (Nittrouer et al., 1994). While the Elwha's water discharge and coastal processes have not changed significantly since the construction of the dams, the sediment yield has drastically reduced and as a result, the substrate has coarsened (Gelfenbaum et al., 2009)..

## *2.3 Previous research*

Past studies on the Elwha mapped the delta substrate and determined the composition of sediments before dam removal. Prior to dam removal, the delta substrate was mostly sand and coarse-grained cobble, with sand found closest to the river mouth, mixed sand and cobble in the nearshore (depths of 20 m and less), and cobble beds offshore (depths of 20m and greater) (Rubin et al., 2011). Historical records mention clamming and other shellfish gathering, which indicates there was a muddier nearshore

substrate in the past (Duda et al., 2011). Already observable change has occurred on the substrate that could affect local ecology and promises more fine-grained deposition (Elwha Science Symposium, 2012).

Sand particles exiting the river mouth was predicted by USGS surveys to follow the wave and current directions and head primarily to the east (Gelfenbaum et al., 2009). However, the topography of the delta creates asymmetry in water movement allowing mud to disperse evenly across the west and east side of the delta (Gelfenbaum et al., 2011). The oscillatory tidal currents combined with the shallow nearshore bathymetry creates eddies near the delta (Warrick et al., 2011). Tidal currents are strong enough to re-suspend most of the fine-grained sediment after any initial deposition and transport it farther along the submarine delta (Gelfenbaum et al., 2009). Spring freshets and winter storms increase the turbidity of the Elwha and could deposit enough sediment to create a new layer that would remain between tidal exchanges (Rubin et al., 2011).

### **3. Methods**

#### *3.1 Data collection*

The majority of this study's data came from substrate sediment grabs and video recording used to map grain-size distribution on the Elwha submarine delta. Further data included shipboard ADCP (acoustic Doppler current profiler), tidal records, and past cruise data. Grab samples, video footage, and shipboard ADCP were taken aboard the *R/V Barnes* April 13 to 15, 2013 (CAB998) and additional grab samples were taken aboard the *R/V Centennial* April 25, 2013 (CT03). Sites (Fig. 2) were chosen to sample

the main substrate types (sandy, cobbly, and mixed) based on pre-dam surveys conducted by USGS (Rubin et al., 2011).

Grab samples were gathered using a Shipek sampler on the *Barnes* cruise and on the *Centennial* cruise, a Van Veen sampler. If after multiple grab attempts the sample was scant (wet weight of less than 50 g). Fifty-seven samples were obtained; fifty-three off the *Barnes* and four off the *Centennial*.

Video footage was taken near grab sites (Fig. 2) in order to visually determine substrate composition. A downward facing USGS SideWinder Color Underwater Video Camera was lowered to the seabed and recorded onto a Sony digital cassette. A visual scale was determined with two parallel lasers that created an 11 cm scale or a ruler creating a 13 cm scale. Videos were recorded as the ship drifted away from the grab sites, and new waypoints were logged as needed.

Currents were obtained during the April 2013 cruise from a shipboard ADCP that was attached to the *Barnes* 4.08 m below the water surface. This ADCP measured water movement every 30 s in 2 m bins at 614.4 KHz. Currents were obtained during the April 2008 (CAB4\_08) and November 2011 (CAB967) cruises from a shipboard ADCP that was attached to the *Barnes* 0.87 m below the water surface and measured water velocity every 20 s in 0.5 m bins at 614.4 KHz.

Tides were determined for the Elwha Delta from a NOAA tidal gauge (station 9444090, <http://tidesandcurrents.noaa.gov>) located in Port Angeles Harbor.

### 3.2 Lab analysis

The sediment samples were later sieved at Friday Harbor Laboratories and characterized according to the Wentworth grain-size chart. Samples were sorted into four

categories: heterogeneous, homogenous, mixed, and scant. The first three categories of samples were wet sieved at  $4 \phi$  to separate the fine and coarse particles. The sand and gravel was dry sieved at  $-4 \phi$  to  $4 \phi$  in  $1 \phi$  units. The mud size fractions were determined using pipette analyses (UW, 1998). Detailed descriptions of scant samples were logged before their wet and dry weight was taken. Folk & Ward (1957) statistics was used to analyze sediment-size distribution. The results were mapped using ArcGIS to create a visual representation of the grain-size distribution on the delta. These grain-size distributions were compared with past studies completed by UW Sediment Dynamics Lab in April 2008 (CAB4\_08) , November 2011 (CAB967), April 2012 (CAB970), June 2012 (CAB977), and October 2012 (CAB989) (Lee et al., 2008) and USGS data reports (Duda et al., 2011 ch6).

The footage from 35 videos was edited into 17 min segments using Microsoft Movie Maker and categorized according to the type of substrate seen: cobble, sandy, and mixed. The results were mapped using ArcGIS and compared to footage taken by the UW Sediment Dynamics Group on past cruises in November 2011 (CAB967), April 2012 (CAB970 and CT01), and June 2012 (CAB977) (Lee et al., 2008).

The measured current magnitude affecting the substrate was extracted from the raw ADCP data from the November 2011 and April 2013 cruises using the program, WinADCP. Velocity profiles were used to find shear velocity ( $u_*$ ) and bed stress ( $\tau$ ) using the quadratic stress law. Shear velocity and bed stress was found from plotted velocity profiles using the law of the wall for the April 2008 cruises (Lee et al., 2008). Threshold of motion was determined using a shear velocity versus grain diameter graph (Miller et

al., 1977) at sites where there was appropriate shear velocity data and the collected grain-size data.

## **4. Results**

### *4.1 Video seabed characterization*

Video footage along the submarine delta provided a visual interpretation of the substrate type. Over the course of five cruises between 2011 and 2013, the dominant substrate types remained sandy, mixed, and cobbly (Fig. 3), though many of the individual site substrates changed since the first cruise in November 2011 (Fig. 4). During the November 2011 cruise the tidal difference was 2.5 m MLLW with visibility clear enough to determine substrate type. Footage from this cruise was collected at the sites marked with diamonds in Figure 4. Sandy substrate was found west of the river mouth close to shore in Freshwater Bay. Mixed substrate was found deeper in Freshwater Bay and offshore east of the river mouth. Cobble substrate was seen east of the river mouth. North of the river mouth, there appeared to be a combination of mixed and cobble substrate. On the April 2012 cruises (CAB970 and CT01) the tidal differences were 1.7 m and 1.2 m MLLW respectively. Footage sites are represented as triangles and crosses on Figure 4. There was little change in the location of the substrate types except for sandier substrate directly north of the river mouth. The tidal difference for June 2012 was 2 m MLLW, but did not limit visibility. June sites are shown as squares in Figure 4. Sandier substrates appeared near the river mouth and one deeper area in Freshwater Bay. April 2013 had a tidal difference of 2.3 m MLLW that created enough drift to limit the visibility at some sites. Sites are labeled as circles on Figure 4.

## *4.2 Grain-size analyses*

Grain-size analyses of sediment samples provided details of seabed composition. The most recent sample collection from the cruises April 2013 revealed that the Elwha Delta substrate composition was not evenly distributed along the submarine delta but rather segregated into three areas: eastside, the Elwha River mouth, and Freshwater Bay. These areas are further categorized as nearshore or offshore portions of the delta. The grain-size percentages of the sample sites are presented in Figure 5 with cobble shown in red, sand in yellow, mud in green and scant samples as empty circles.

The nearshore substrate on the eastside comprised of mixed sand and cobble with higher sand percentages (50-70%) closer to shore. Farther offshore, the substrate was cobbly. In-between nearshore and offshore the substrate was mixed.

The river mouth substrate was the least uniformly sorted area of the delta. Nearshore and to the west the substrate was a muddy sand while east it was mixed sandy and coarse gravel. Offshore from the mouth, the substrate was mixed with small percentages of mud. Sand percentages ranged from 11% to 70% and mud percentages 2% to 75% although greater concentrations of mud were on the west side.

Freshwater Bay to the west of the river was a uniform area with respect to cobble, mixed, and sandy substrates. The dominant sediment type in the bay was mixed to sandy substrate. Mud percentages of 5% to 50% and sand percentages of 10% to 75% were found at all the sites. Scant samples were found nearshore mid bay.

Overall, coarser sediment was found offshore and east of the river mouth and finer sediment was found nearshore west of the mouth. The changes in grain-size composition over the multiple studies from April 2008 to April 2013 are presented in

Figure 6. These example sites characterize the different locations of the delta and substrate type. The substrate on the eastside has not changed except for some small variations in percent compositions. The substrate west of the river, especially close to the river mouth, has become finer with largest percentages of mud found on the delta in this area.

#### *4.3 Currents and bed stress*

Strong tidal currents are always present on the Elwha Delta. The water velocity near the seabed ranged from about  $10 \text{ cm s}^{-1}$  to over  $1 \text{ m s}^{-1}$ . The water velocities measured 100 cm above the seabed can be as low as  $10 \text{ cm s}^{-1}$  and as high as  $100 \text{ cm s}^{-1}$ . The shear velocities and bed stresses from different locations on the delta, tidal periods, and cruises (April 2008, November 2011, and April 2013) are presented in Table 1. Both east and west of the river experience high shear velocities during flood tides although the velocities in Freshwater Bay are on average a magnitude lower. Shear velocities were lowest (less than  $3 \text{ cm s}^{-1}$ ) during slack and ebb tides on both sides of the river. These low shear velocities were measured over coarse substrates (mixed and cobbles). The magnitudes of the shear velocities did not vary seasonally or over the years.

### **5. Discussion**

#### *5.1 Changes in the substrate*

The biggest change in Elwha Delta substrate was seen west of the river mouth, and little to no change was seen to the east. This contradicts the predictions made by the USGS during pre-dam surveys, i.e. sand would deposit mainly to the east, and a thin layer of mud would cover much of the delta (Gelfenbaum et al., 2009). Sites that best represent the change measured from this study are mapped in Figure 6.

The changes west of the river mouth include a significant increase in mud near the shore (Fig. 7). This input of mud occurred sometime between June 2012 and April 2013. At station Z6, the mud concentration increased by about 65%. Farther from the mouth at station B11, mud concentrations increased by 27%. However, the amount of fine-grain deposition decreased farther off shore from the west river mouth past 20 m deep. Site B25 did not gain any significant amount of mud and decrease in sand from October 2012 to April 2013 could be a sampling error.

In Freshwater Bay, the substrate offshore has become sandier with small amounts of mud and the substrate nearshore has remained sandy while gaining mud (Fig. 7). Before the removal of the dams, sandy substrate was found near the shore close to the river mouth (Lee et al., 2008). After April 2013, the entire bay was comprised mostly of sand and some areas of mixed substrate. Mud was found in most of the samples (Fig. 5). The changes in fine-grained deposition were gradual, mostly occurring continuously since the removal of the dams. At station Z7, the mud fraction gradually increased since the removal of the dams. Farther from the river mouth along the Strait, including near shore, the substrate remained coarse in April 2013. Station Z8 was scant and had been cobbly or mixed during past cruises. Prior to dam removal, a USGS survey found this area to have exposed bedrock (Warrick et al., 2008). Deposition does not appear to be occurring on the bedrock in Freshwater Bay.

Much of the newly introduced sediment from the dam removal was expected to travel east but very little change was found at the sites at the east river mouth and eastside of the delta (Fig. 7). The substrate remains cobbly offshore and mixed nearshore. The

nearshore sites Z3 and Z1 are sandy but have remained that since the first grain-size analyses in April 2008.

### *5.2 Current velocity and threshold of motion*

Strong tidal currents on the Elwha Delta rework the seabed sediment and influence where sediment is transported and deposited. The currents in the Strait of Juan de Fuca can exceed  $100 \text{ cm s}^{-1}$  (Frisch et al., 1981) and the submarine delta currents measured with shipboard ADCP in this study exceed  $100 \text{ cm s}^{-1}$ . These strong currents can prevent deposition of fine sediment along most of the delta and transport the fine material in suspension. However, a thick layer of deposited mud occurred on the west side of the river mouth and in parts of Freshwater Bay (Fig. 5).

One factor that allows sediment deposition is periods of low bed stress (Fries et al., 2003). Possible driving factors for lower bed stress include location on the submarine delta, time during a tidal cycle, and substrate composition. A threshold of motion chart (Fig. 8) shows the conditions on the delta when deposition may occur. The plotted points are based off the shear velocities (calculated from bed stress) and grain-sizes from the samples taken. Deposition of gravel is capable everywhere with bed load transportation possible under high shear stress conditions. Mud is always in suspension even at sites with the lowest shear velocity. At only a few sites and tidal cycles are the conditions right for sand to settle. These sites are B11, Z8, and YQ55 during slack or ebb tides. Other scenarios are possible because shear velocities and grain-size are not uniform on the delta but this model provides a good description of the conditions during the study periods.

It is possible that the cobbles create hydraulic roughness high enough to slow water velocity 100 cm above the seabed enough for deposition of fine sediment (Fries et

al., 2003). The lowest shear velocities were seen over coarse substrates, but three stations is not enough to determine if it was a driving factor for deposition or a mere coincidence. Change in substrate was not seen over coarse substrates and only occurred west of the river on a predominantly sandy to mixed substrate. It remains unclear whether the coarse substrate of the Elwha Delta is affecting sediment deposition.

Observations from the USGS suggest that tidal currents generate eddies on either side of the delta (Warrick et al., 2011b). These eddies have the capability to slow the transportation of suspended sediment, allowing more time to settle. Eddies form on the east side during flood tides and on the west side during ebb tides (Warrick et al., 2011a). These eddies do not accumulate mud on the seabed but rather inhibits sediment transport (Gelfenbaum et al., 2009). For deposition of mud to occur, another process is required to counter act the strong tidal currents.

### *5.3 Mechanisms of seabed change*

As sediment exits most rivers, oceanographic processes alter the dispersal and deposition patterns of the particles depending on the currents, waves, and grain-size (Wright et al., 1995). Deposition of the fine-grain sediment is dependent on its size and concentration. During flood events, the dispersing river water is often turbid and the finer sediment can deposit close to the river mouth (Warrick et al., 2004). If the Elwha River floods and bring large amounts of sediment from the reservoirs to the delta, the fine-grained sediment will tend to settle immediately off the river mouth (Gelfenbaum et al., 2009). This river model can explain the muddy substrate just off the west river mouth (Fig. 5). The currents along the submarine delta are still strong enough to resuspend any mud that has been deposited (Fig. 8). However, if a thick layer of mud had settled after a

flood event then enough can remain after strong currents and ultimately change the substrate. Similar processes have occurred during a study of flood events at the Santa Barbara River in California (Warrick et al., 2004).

Waves affect the substrate on either sides of the river differently. The waves at the west side are aligned with the beach, while the waves reaching the east side are oblique (Warrick et al., 2011a). This difference causes the sediment west of the river to remain, while the sediment east of the river is transported eastward by long shore drift. Limited wave action lowers bed stress and allows sediment remobilization (Hequette et al., 2008). As a result, the substrate in Freshwater Bay and the west river mouth are protected from the transport effects of waves.

Littoral drift is the dominant process transporting sediment, coarse and fine, east of the river (Warrick et al., 2009). Wave action can move cobbles up to  $100 \text{ m day}^{-1}$  along the shoreline (Miller et al., 2011). Waves and tides could trap sand nearshore and rapidly transport it eastward (I. Miller, pers comm.). It is likely that sand deposits close to shore but the strong currents and waves are resuspending the sediment. There is no evidence from this data set of this change as no samples were collected shallower than 10 m in this study.

#### *5.4 Evaluating change on coarse substrates*

##### *5.4.1 Video relationship to grab samples*

In general, the videos matched the outcome of the grain-size analyses of the April 2013 cruise samples (Fig. 9). Sandy substrates in Freshwater Bay appeared sandy in the videos and coarse substrates (cobbles and mixed) east of the river and off shore in Freshwater Bay were coarse in the videos. This comparison is helpful when determining

the substrate of any scant samples. Wherever a sample was scant, video footage showed cobbly or mixed substrate. The sample failure could have been because the substrate was too coarse for the grab sampler or that a rock jammed the equipment and any finer sediment fell out.

#### *5.4.2 Spatial sampling limitations*

Since the first survey cruise in 2008, grain-size percentages appear to fluctuate while the substrate is not changing. This information may be misleading due to the strong drift inhibiting the boat to re-sample the exact location. Very coarse samples could alter the grain-size statistics significantly because of the small sample sizes. Fewer rocks collected could make the sample appear finer while in reality it has remained coarse.

There were some variations in substrate type determined from video footage during different years (Fig. 4). For example, Z5 has changed from mixed to cobbles and back again since the first video cruise in November 2011. This is likely due to the drift of the boat, not drastic change in substrate composition. Strong drift could also limit visibility and inhibit the viewer from accurately determining the substrate type.

Measuring how the currents affect the seabed requires precise equipment and planning. When the focus of study is the 100 cm of water column above the seabed, the size of the bins is important. Two-meter bins cannot accurately measure the bottom boundary layer and its change over different substrate types. The majority of the ADCP data during the cruises on the Strait of Juan de Fuca could not be used because the boat drift or the size of the bins limited by the accuracy of the measurement within bottom boundary layer.

## 6. Conclusion

The Elwha Delta substrate was recently classified with the combination of grain-size analyses and video footage. As of April 2013, substrate east of the river is coarse, cobbles to mixed substrate, while substrate west of the river is finer (mixed to sandy). Areas close to the river mouth had high mud concentrations. Changes in the substrate were only found west of the river. Freshwater Bay's substrate became sandier, and areas west of the river mouth became muddier nearshore but remained the same offshore. Little change in the substrate composition occurred east of the river.

Evaluation from shipboard ADCP data and grain-size analyses combined threshold of motion and the conditions when deposition of different sizes of sediment can occur. Cobbles will not move except when they are fine cobbles and the shear velocities are high. Bed load transportation is possible if these conditions are present. The currents are too strong to allow mud deposition and the fine-grained sediment will remain in suspension. Sand is capable of settling, but only at low shear velocities, and if the sand is coarse.

During turbid flood events, deposition of mud near the river mouth is possible because high fine-grain sediment concentrations deposit immediately off the river mouth while eddies and aligned waves keep the sediment near shore. Sand can deposit in Freshwater Bay because of the lower shear velocities, especially during ebb tides, and aligned wave direction inhibiting littoral drift. Fine-grained sediment can deposit east of the river but because of the higher shear velocities during flood tides and oblique wave direction, most of the sediment is being transported farther east.

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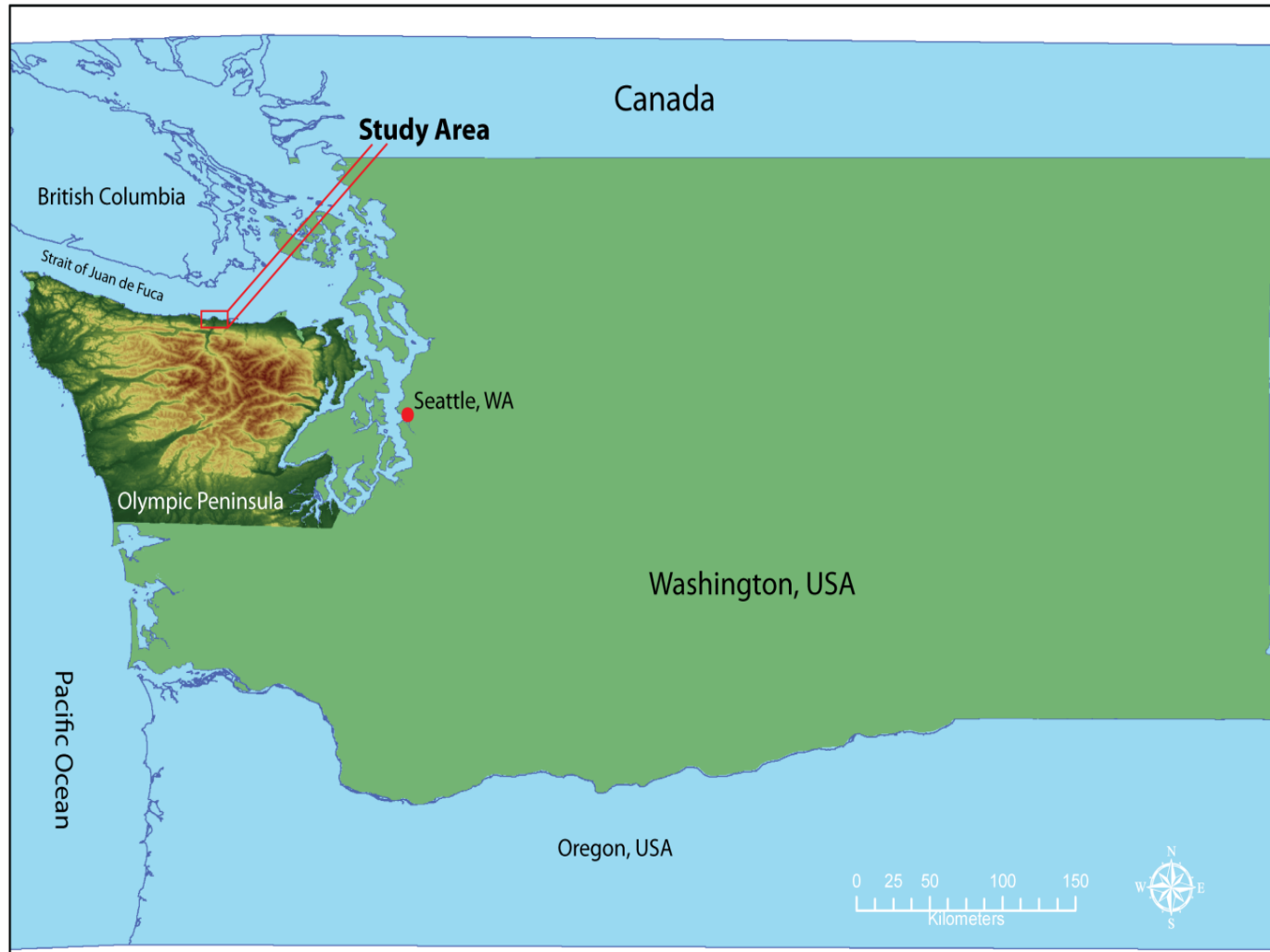
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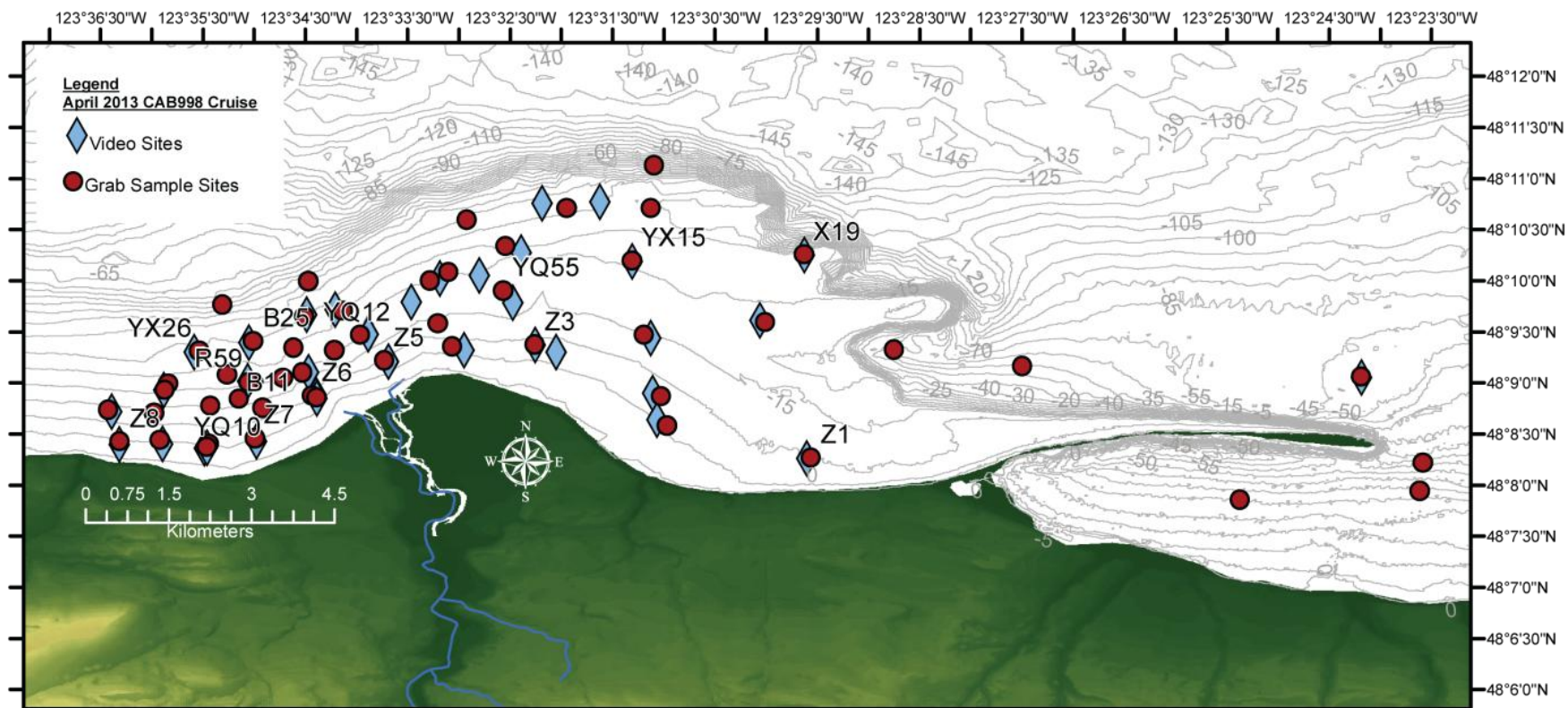
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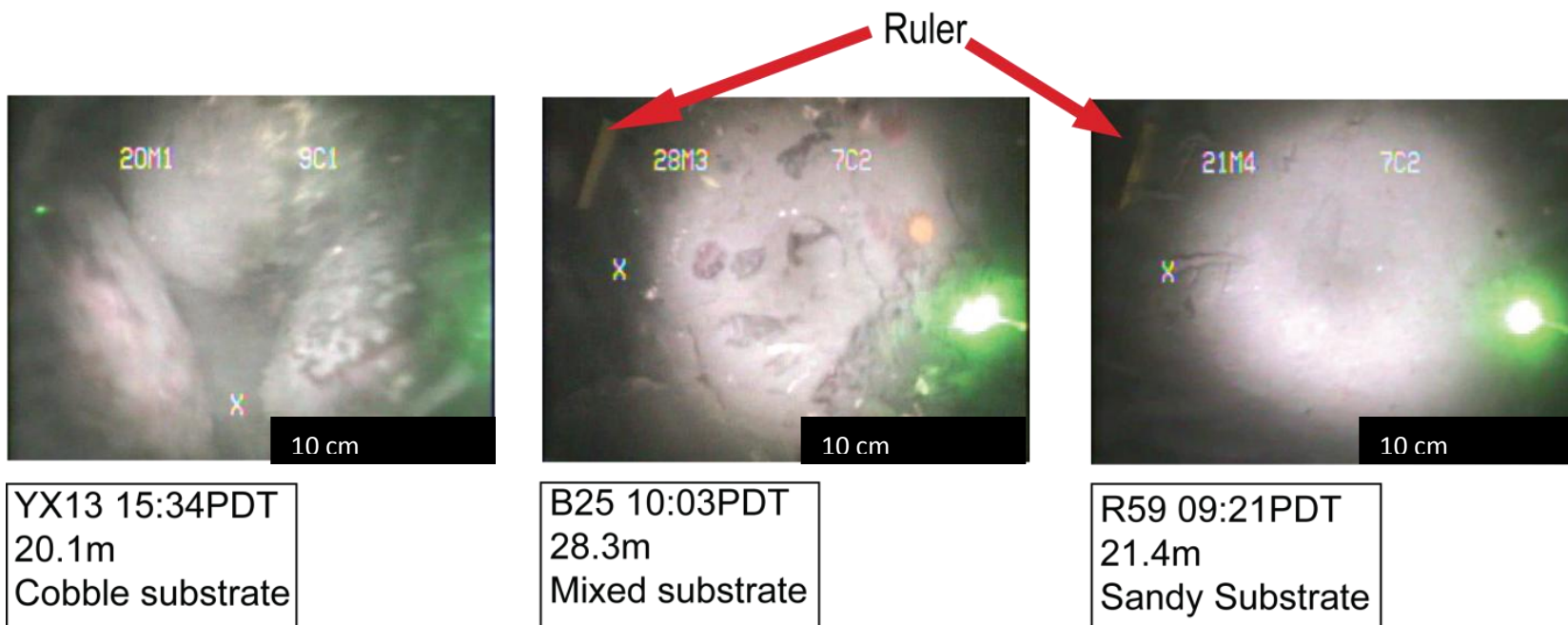
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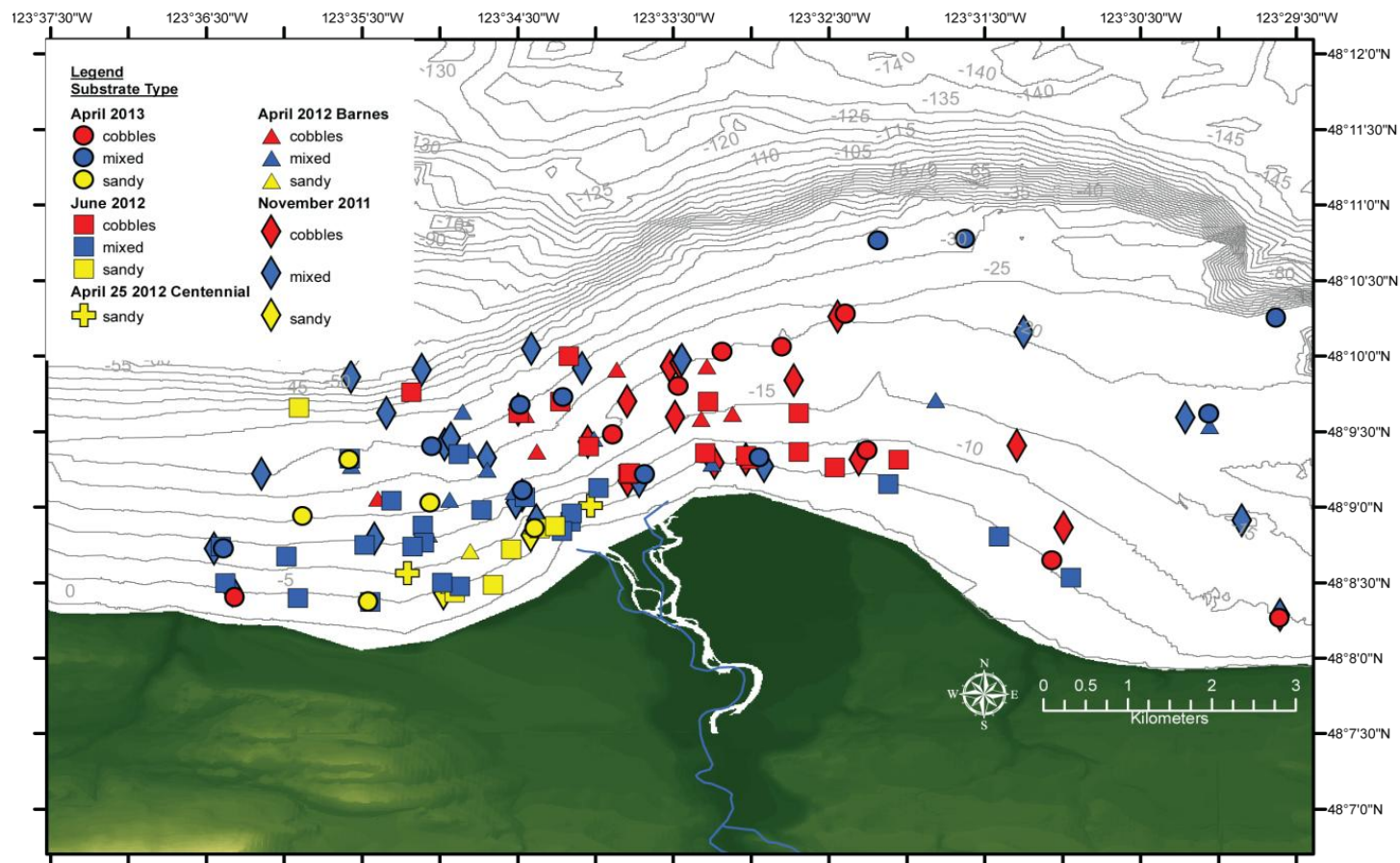
**Figure 1.** Map of the State of Washington and the surrounding area. Location of the Elwha River Delta squared in red. Topography of the Olympic Peninsula and the mountains mapped in detail. Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb>



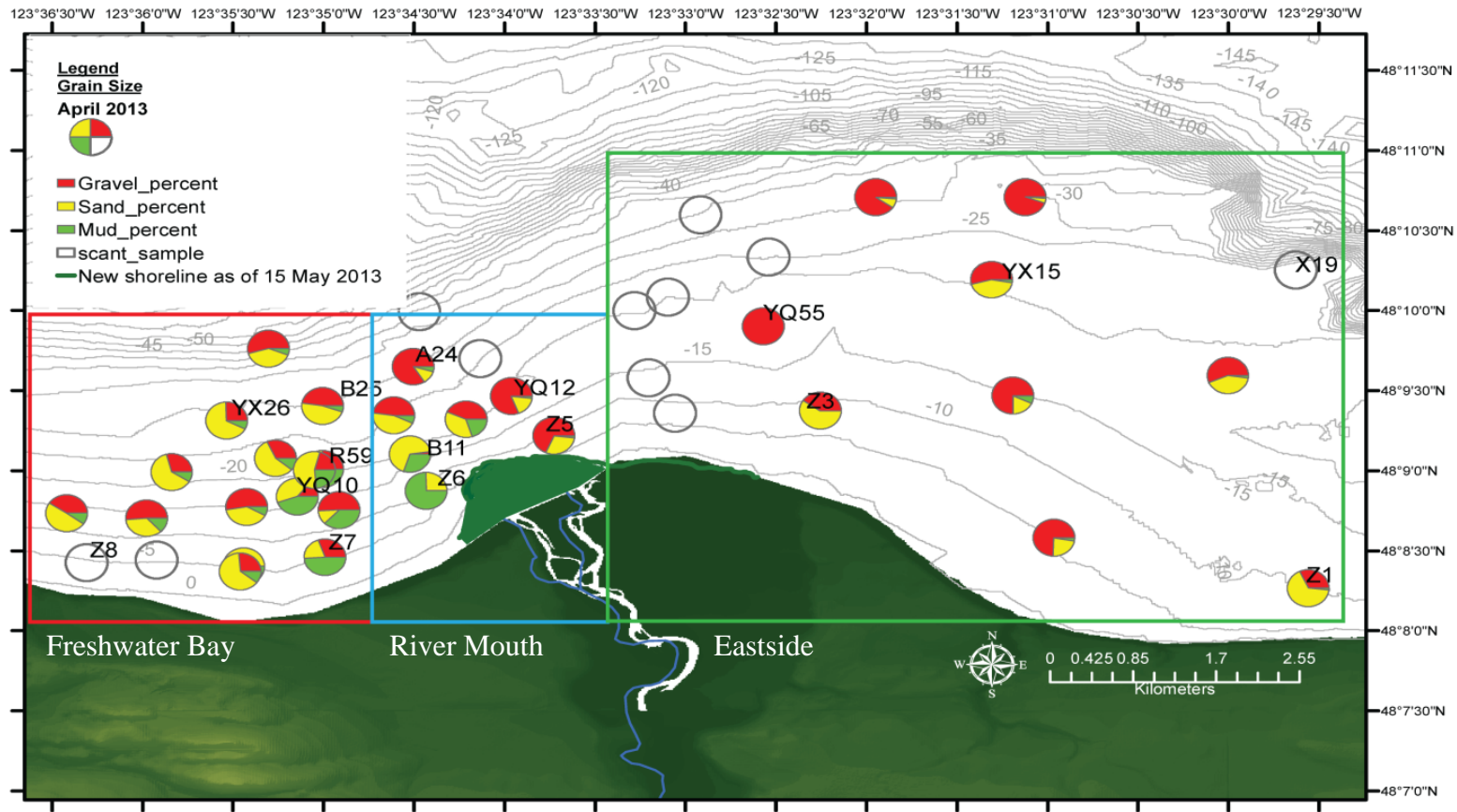
**Figure 2.** Video and sediment grab samples sites along the Elwha River Delta. Data was collected during the April 2013 cruise. Sites that were compared with past cruises and where water velocity was measured are labeled on this map. Bathymetry data from: UW Oceanography data set PSDEM2000 <http://www.ocean.washington.edu/data/pugetsound/> Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb>



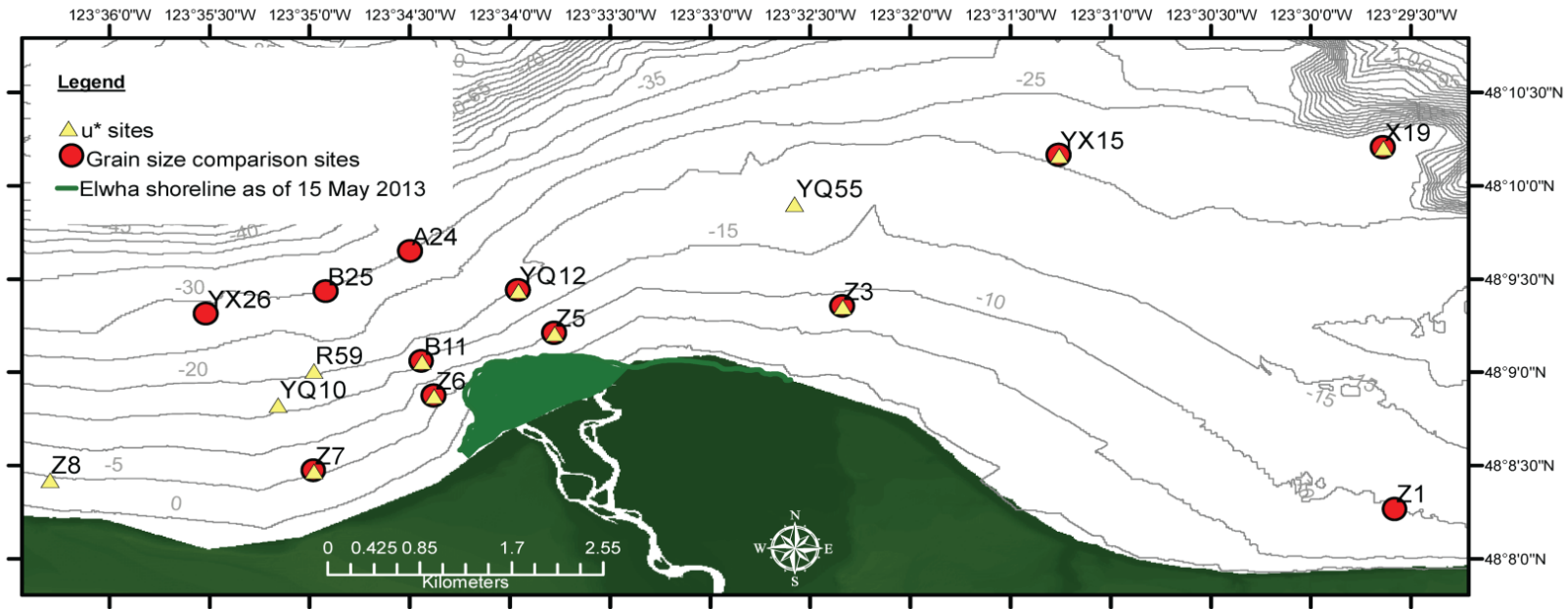
**Figure 3.** Still photos from video taken aboard the R/V Barnes showing a comparison between the three major substrate types; cobbles, mixed, and sandy. Footage taken April 15, 2013 and recorded with the USGS small camera system. The scale used was laser to laser: 11cm and laser to ruler: 13cm.



**Figure 4.** Video footage sites along the Elwha River Delta. Map of the study area showing video sites and the seabed substrate. Footage was taken from five different cruises over three years. The dates of the cruises are: November 29-30 2013 (CAB967), April 3-5 2012 (CAB970), April 17 2012 (CT01), June 26-28 2012 (CAB977), and April 12-15 2013 (CAB998). Bathymetry data from: UW Oceanography data set PSDEM2000 <http://www.ocean.washington.edu/data/pugetsound/> Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb>

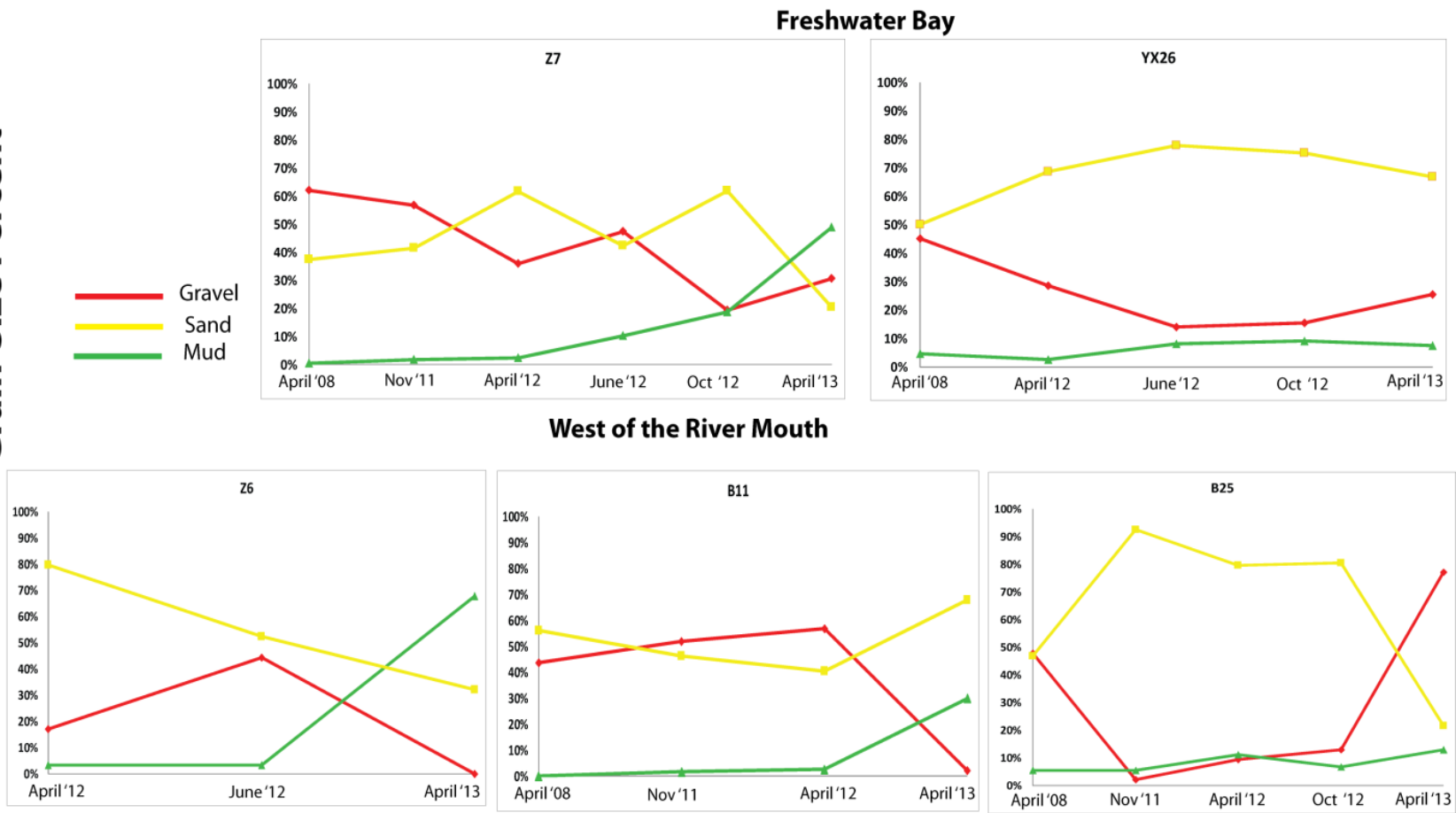


**Figure 5.** Grain size Distribution along the Elwha Delta. Grain size percentage collected from the most recent April 2013 cruise. Sites that were compared with past cruises and where water velocity was measured are labeled on this map. Shaded green area represents the new delta that formed after the removal of the dams. Red boxed area: Freshwater Bay. Blue boxed area: river mouth. Green boxed area: eastside. Bathymetry data from: UW Oceanography data set PSDM2000 <http://www.ocean.washington.edu/data/pugetsound/> Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb> New shoreline data from: Andy Ritchie, National Park Service, 2013.



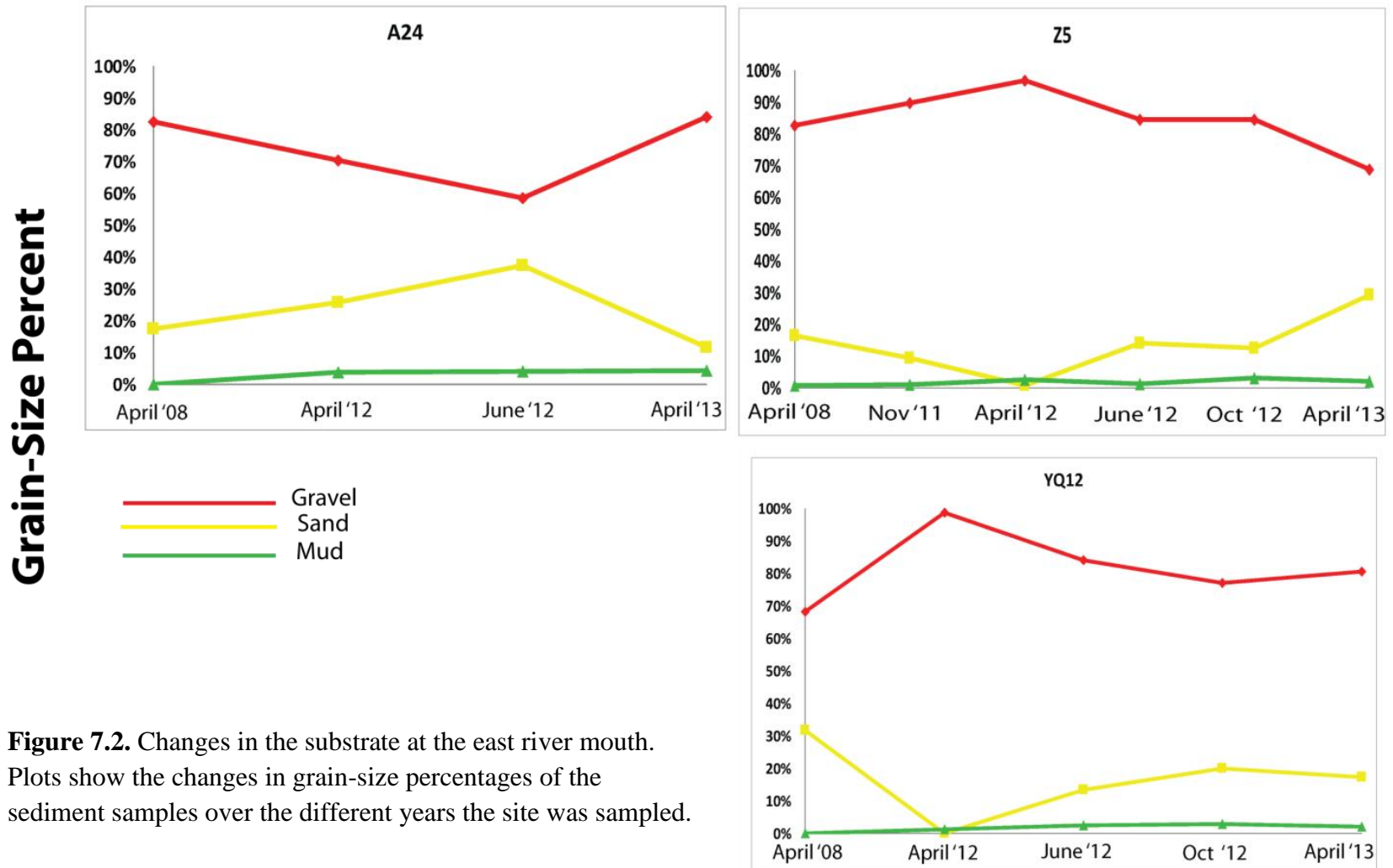
**Figure 6.** Grain size comparison and shear velocity stations. Map shows location of the sites that this study compares grain size from Figure 6 and sites that shear velocity ( $u^*$ ) was measured from the cruises April 2008, November 2011, and April 2013. Shear velocity, bed stress, and other information about the sites are presented in Table 1. Bathymetry data from: UW Oceanography data set PSD2000 <http://www.ocean.washington.edu/data/pugetsound/> Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb> New shoreline data from: Andy Ritchie, National Park Service, 2013.

Grain-Size Percent



**Figure 7.1.** Changes in the substrate west of the river. Plots show the changes in grain-size percentages of the sediment samples over the different years the site was sampled.

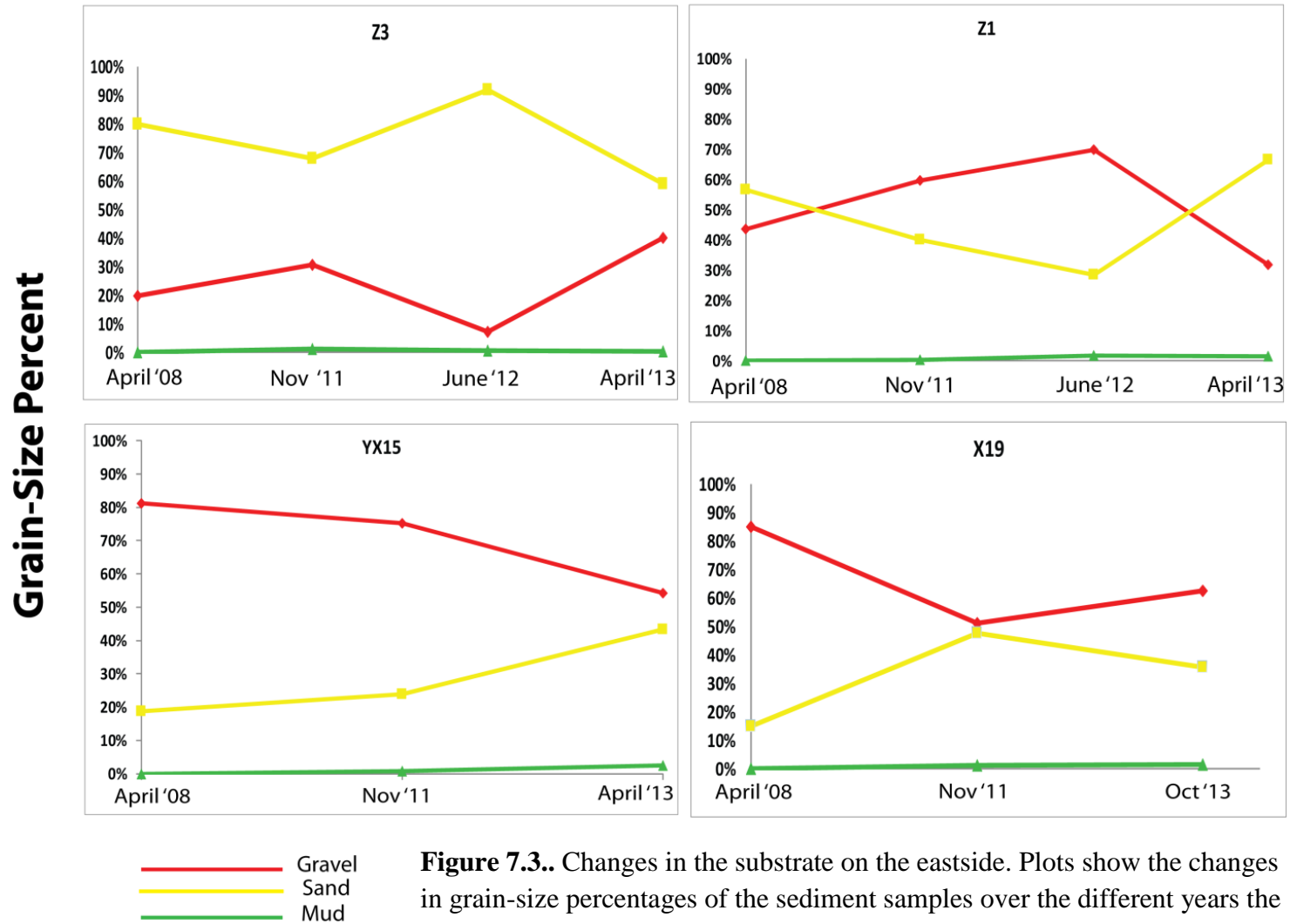
## East River Mouth



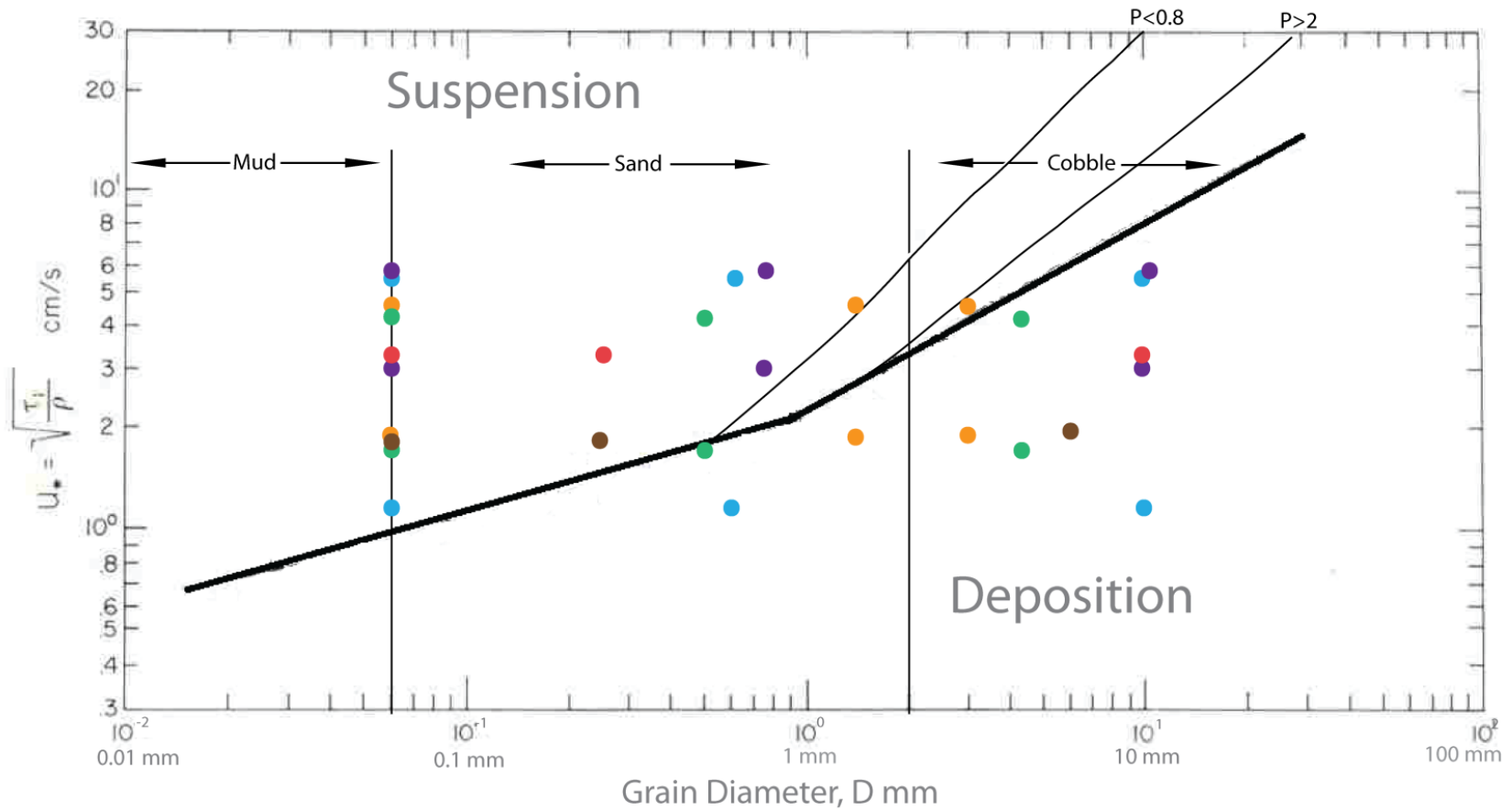
**Figure 7.2.** Changes in the substrate at the east river mouth. Plots show the changes in grain-size percentages of the sediment samples over the different years the site was sampled.



## Eastside

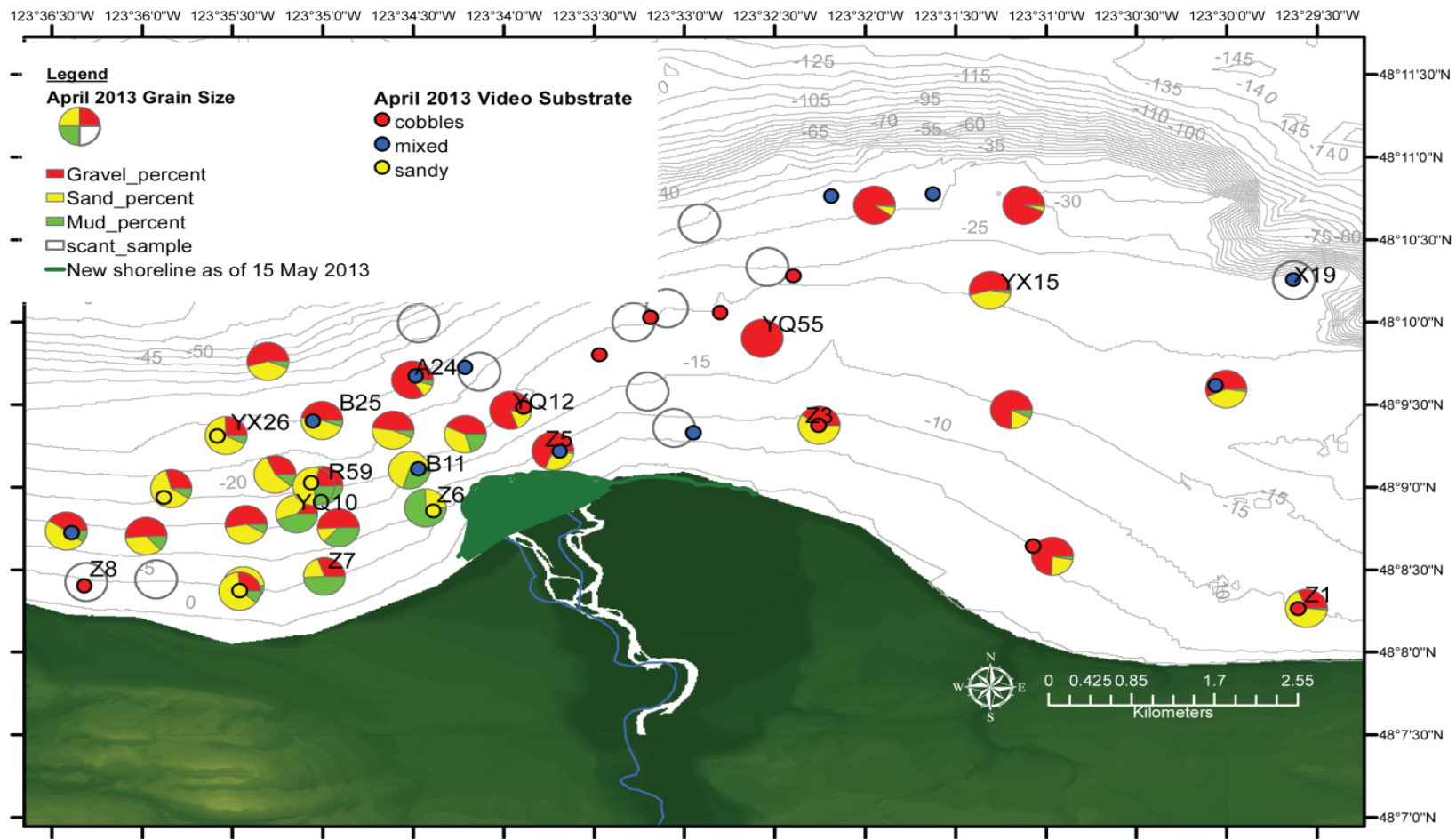


**Figure 7.3.** Changes in the substrate on the eastside. Plots show the changes in grain-size percentages of the sediment samples over the different years the site was sampled.



- B11
- Z8
- YQ55
- Z5
- YQ10
- X19

**Figure 8.** Threshold of motion chart. This chart shows conditions when deposition or suspension occurs. Points above the bold line show transporting sediment and points below show no movement.  $P$  is the Rouse parameter coefficient. Points above the bold line but below  $P > 2$  show sediment moving by bed load. Points below  $P < 0.8$  show sediment moving with increasing suspension. Chart modified from the Miller paper (Miller et al., 1977).



**Figure 9.** Video relationship to grab samples. Map shows the grain size percentages compared to the video footage taken from the April 2013 cruise. Bathymetry data from: UW Oceanography data set PSDEM2000 <http://www.ocean.washington.edu/data/pugetsound/> Topographical and base map data from: Elwha River Spatial Data Server <http://deptweb.wvu.edu/huxley/huxweb/elwha/ElwhaWeb> New shoreline data from: Andy Ritchie, National Park Service. 2013.

**Table 1.**

Shear velocities and bed stresses 100 cm above the seabed. Shows substrate types, location on the delta, tidal cycle, and dates of sampling. Shear velocities and bed stress at stations labeled with 'av' are averages of two different days that had similar values. Slashes under the tide column separate the sites with two samples. Respective dates separated with a dash under the date column. Stations labeled with 'f' or 'e' indicate the tidal cycle flood or ebb respectively.

Cruise	Station	$u^*$ ( $\text{cm s}^{-1}$ )	$\tau$ ( $\text{dynes cm}^{-2}$ )	Substrate	Location	Tide	Date
CAB4_08	B11	1.95	3.92	mixed	West river mouth	ebb	4/24/2008
April 2008	Z8 f	4.15	17.7	cobbles	Freshwater Bay nearshore	flood	4/9/2008
	Z8 e	1.89	3.69	cobbles	Freshwater Bay nearshore	ebb	4/10/2008
	YQ12	4.78	23.5	cobbles	East river mouth	ebb	4/25/2008
	Z3 av	5.04	26.07	sandy	East nearshore	end of slack-start of flood/ ebb	4/9-10/2008
	YQ10	3.35	11.5	sandy	Freshwater Bay nearshore	ebb	4/24/2008
CAB998	Z6 av	5.79	34.3	sandy	West river mouth	end low slack-start flood/end ebb start low slack	4/14-15/2013
April 2013	B11	4.97	25.21	sandy	West river mouth	flood	4/14/2013
	Z5 av	5.83	34.9	mixed	East river mouth	flood/ end low slack-start flood	4/14-15/2013
	YQ12	4.95	25.0	cobbles	East river mouth	flood	4/14/2013
	Z3	7.23	53.3	mixed	East nearshore	flood	4/14/2013
	YQ55	5.67	32.84	cobbles	East nearshore	flood	4/14/2013
	YX15	6.05	37.3	mixed	East offshore	ebb	4/14/2013
	Z7	4.7	23.0	mixed	Freshwater Bay nearshore	end low slack-start flood	4/14/2013
CAB967	Z5	3.02	9.29	mixed	East river mouth	ebb	11/30/2011
November 2011	YQ55	1.23	1.54	cobbles	East nearshore	slack	11/30/2011
	X19	2.98	9.04	mixed	East offshore	end ebb-start slack	12/1/2011
	R59	3.93	15.7	mixed	Freshwater Bay nearshore	end slack-start ebb	12/1/2011