Impacts of physical processes and sediment sources on the grain-size distribution of the Elwha River delta

Yiyan Ge[1]

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[1] Program on the Environment, University of Washington, Seattle, WA 98195

Contact information:
Yiyan Ge
Program on the Environment
College of the Environment
012 John M. Wallace Hall (ACC)
3737 Brooklyn Ave NE
Seattle, WA 98195
geyiyan@uw.edu

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Abstract

Grain-size distribution, one of important parameters reflecting sediment sources, transportation, and deposition, helps people understand and predict shoreline and bathymetric changes. For this study, wave-orbital velocity and tidal bed shear stress were compared to grain-size distribution of the Elwha River delta in order to find correlations between physical processes and the seabed composition. Grain-size distributions of sediments from the river, the bluff, and the delta were also examined to determine sources of sediments from the delta. The sand-dominant region found at the west side of the river mouth and some local landward coarsening patterns suggested that grain-size distribution was under influences of waves. Though no strong correlation was found between tidal bed shear stress and grain-size distribution, other evidence was provided that suggest the impacts of tidal-induced currents on grain-size distribution. We found the poorly sorted region at the western offshore of the river mouth and the coarse-grains dominant regions near the river mouth; it is possibly due to focused and strong currents that causes high bed shear stress in those regions. Moreover, tidal-induced currents have a net northeastward flow which brings fine sediments toward the east. Therefore, we observed a region of fine sediments at the east of the river mouth. Last, our results suggested that the bluff in Freshwater Bay supplies the delta with coarse sediments and the river mainly provides fine sediments.

1. Introduction

To predict shoreline and bathymetric changes, many studies have focused on interpreting sediment transport and deposition patterns. Grain-size distribution is one of the most important parameters in terms of describing the morphology of shoreline features, such as deltas. Since previous work has shown that grain-size distribution patterns respond to both hydrodynamic processes and sediment sources (Liu and Zarillo, 1993), this study explains how these two factors influence grain-size distribution of the Elwha River delta. The Elwha River delta is subject to changes in waves and tides. Exposure to energetic waves and tides largely define the delta's features by determining dispersal of sediments (Warrick et al., 2011). In addition, the sediment of the delta is supplied by several sources, which also affect grain-size distribution. In this study, a Geographic Information System (GIS) is chosen as a primary tool to find relationships between grain-size distribution and factors mentioned above. Considering that large volumes of sediment are being released from the reservoirs by the removal of the dams, strong evidence may be provided to help understand how grain-size distribution of the delta is influenced by sediment sources and physical processes, including waves and tides.

2. Background

2.1 Physical Setting

The Elwha River delta lies between Freshwater Bay and Ediz Hook, extending northward into the Strait of Juan de Fuca. Its sediment is supplied by eroding bluffs and the Elwha River, which is a 72-km long river draining from the Olympic Mountains into the ocean (Fig. 1). The Elwha River delta formed from geologic, coastal, and fluvial forces and is still gradually changing (Warrick et al., 2009). After the formation of the Olympic Mountains, a result of the convergence of the oceanic Juan de Fuca plate and the continental North American plate (Warrick et al., 2011), glacial processes and sea-level changes continued to shape the region, which resulted in the development of Elwha River delta (Galster and Schwartz, 1990). One evidence of these historical processes is the exposed poorly sorted bluffs, which became a modern source of sediments (Warrick et al., 2011). Modern processes continue shaping the delta today. Wave climate at the delta is under influences of processes in the Strait of Juan de Fuca and the Pacific Ocean. Waves are generated by local winds and swells from the Pacific, with a typical height

USGS).

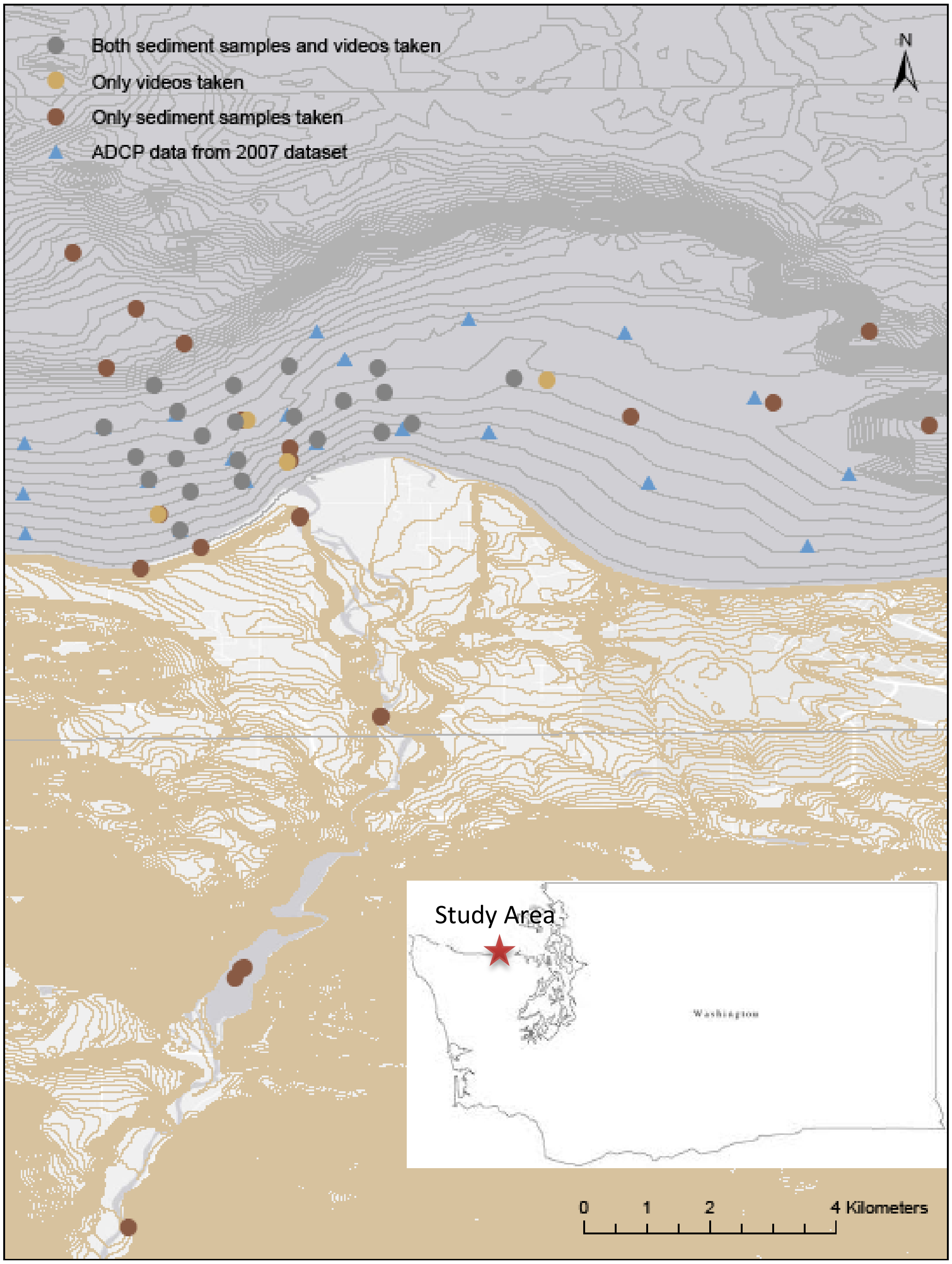

Figure 1. The Elwha River delta extending northward into the Strait of Juan de Fuca. Stations where data were collected were marked on the map (bathymetry DEM from USGS).

around 0.5 m and occasional height over 1-2 m (Warrick et al., 2011) (Fig. 2A). It is also worth noting that northwest wave directions and ocean swell usually dominate the wave condition at the delta. Due to both diurnal and semi-diurnal cycles of water-level changes, the delta is located in a mixed meso-tidal region (Warrick et al., 2011) (Fig. 2B). The tidal range (the difference between mean higher high water and mean lower low water) is about 2.15 m at Port Angeles and 2.43 m at Neah Bay (tidesandcurrents.noaa.gov). Additionally, discharge of the Elwha River has one peak in winter due to substantial rainfall and another in late spring and early summer because of snowpack melt (Warrick et al., 2011) (Fig. 2C). Altogether, modern processes including waves, tides, and river discharge largely define the features of the delta, especially the grain-size distribution.

2.2 Topical background

Though few studies have been done on how grain-size distribution reflects its sources and mechanisms of physical processes on the Elwha River delta, similar studies were done in other regions such as Long Island, New York (Liu et al., 1989, 2000), and the Tseng-wen River system in Taiwan (Liu and Zarillo, 1993). Both studies demonstrated that grain-size distribution patterns depend on the sources and reworking of sediments by hydrodynamic processes due to differing effects on sediment grain sizes by these two variables. In regard to factors driving sediment transport, the study by Nittrouer and Wright (1994) demonstrates that physical and bottom boundary layer processes are important in determining particulate transport. A study done in Taiwan (Liu et al., 2000) found that the agitation by waves played an important role in sorting sediment in the region, suggesting that waves are a key factor in determining sediment transport. Thus, wave-orbital flow, whose velocity is a function of wave amplitude, period, and water depth, is chosen as one parameter in this study to examine the effects of waves on grain-size distribution. Bed shear stress, a measure of frictional force generated at the bottom boundary

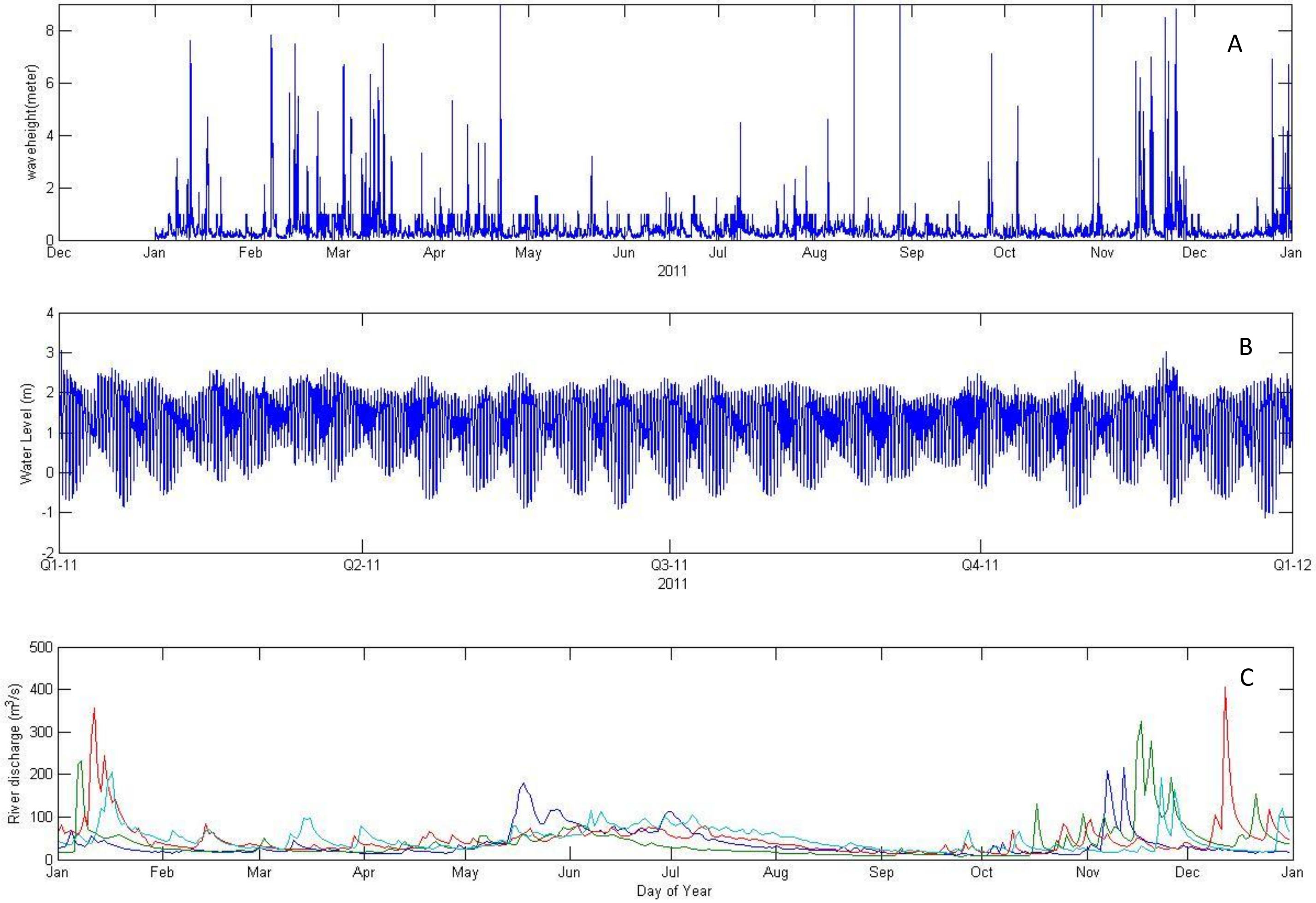

Figure 2. Wave height in Hein Bank through year 2011 (A). Water level from tidal gauge in Port Angeles through 2011 (B). River discharge from gauge at McDonald Bridge from 2008 through 2011 (C).

layer, is another key factor in determining the movement of sediment (Open University, 1989). Specifically, tidal current-induced bed shear stress is examined in this study. A study by Mitchell et al. (2010) has shown that there is a general agreement between seabed sediment grain-size distribution and bed shear stress magnitudes and vector directions with evidence such as high maximum bed shear stress coincident with sand-dominated regions within the Elbe Strait. Aside from sediment-transport processes, information concerning sources of material is also implied by grain-size distribution (Liu and Zarillo, 1993). Building on previous studies, this paper examines sediment sources and aspects of sediment-transport mechanisms on the Elwha River delta.

3. Method

3.1 Fieldwork

Sediment samples and seabed videos were taken at each of the marked stations (Fig.1) on the subaqueous portion of the Elwha River delta during research cruises from April 2nd to 6th and on April 17th, 2012. A Shipek grab sampler was used to collect sediments on the surface of the delta, and these samples were packed into sample bags labeled with dates, station numbers, and water depths. An underwater video camera was lowered to the bottom of the water for approximately 1-2 min at each station in order to capture images of the seabed. In addition, current data was collected with a 600 kHz acoustic doppler current profiler (ADCP) along transect lines. In order to determine the sources of sediments on the delta, sediments from the river and the bluff in Freshwater Bay were also collected.

3.2 Laboratory work

Sediments were sorted by phi (Φ) size. Pebbles over -4 Φ were measured individually from other sediments in terms of size and weight. A 35-50 g sub-sample of each sample bag was sorted using a combination of wet sieving and dry sieving. A 4 Φ sieve was used to separate mud from sub-sample. Left wet sediments were dried overnight using the oven and sorted using a stack of sieves with sizes from -4 Φ to 4 Φ with interval of 1 Φ. Weights of different grain-size groups were measured and recorded. For mud less than 4 Φ, pipette analysis was used to separate sediments.

3.3 Other collected data

ADCP data from the research cruise in June, 2007 was collected and combined with recent dataset. Wave data was collected from the NOAA national buoy data center (www.ndbc.noaa.gov), and station 46088 (Hein Bank) was chosen as our data source due to its relatively close location to the Elwha River Delta and no significant barrier between two locations. Tide data was collected from the NOAA tides and current database (tidesandcurrents.noaa.gov), with Port Angeles station number 9444090 chosen as data source.

3.4 Data analysis

3.4.1 Seabed video

Records of seabed video in terms of grain size and sorting were made based on 10-second interval at each station, in order to provide evidence whether collected sediment samples were representative of the true grain-size distribution.

3.4.2 Characteristic wave-orbital velocity

The maximum horizontal velocities of to-and-fro motion at the bottom of 12 different water depths, from 5 m to 60 m with 5-m interval, were given by (Komar and Miller, 1975),

$$u_m = \frac{\pi H}{T\sinh(\frac{2\pi h}{L})},$$

where H and T were determined by top 10% wave height and wave period calculated based on collected wave data. Relationship curve between characteristic wave-orbital velocity and water depth was simulated based on these 12 values. Velocity at each station with known water depth was calculated and mapped using ArcMap.

3.4.3 Bed shear stress

Bed shear stress was given by,

$$\tau = \rho u_{star}^2,$$

where ρ is the density of the fluid, which was determined as 1.020 ppt for our purpose, and u_{star} is the shear velocity, which was calculated based on ADCP data from both 2007 and 2012 datasets. Results were divided into four groups based tidal conditions (strong ebb, strong flood, weak ebb, and weak flood) and were mapped using ArcMap.

3.4.4 Grain size analysis

Folk and Ward methods (1957) and GRADISTAT program were used to perform grain-size analyses. D_{50}, the median grain size of each sample, was mapped using ArcMap based on GPS locations taken in the field. Also, grain-size distributions of sediments from the delta, river, and bluff were compared in order to examine the sediment sources of the Elwha River delta.

4. Results

4.1 Characteristic wave-orbital velocity

Characteristic wave-orbital velocities at water depth from 5 m to 60 m with 5-meter interval were calculated based on the top 10% wave height and wave period obtained from historical wave summaries (July 2004 – December 2008) at the Hein Bank buoy for each month of the year. All velocities at different water depths showed seasonal changes with a peak during December through January and a minimum in late summer or early fall (Fig. 3). Examination of the correlation between the annual average wave-orbital velocity and the water depth showed that the velocity decreased as the water depth increased (Fig. 4). For example, the wave-orbital velocity was ~0.33 m/s at 7-m water depth, whereas near the edge of the delta, where the water depth was around 40 m, the wave-orbital velocity was only 0.065 m/s.

4.2 Bed shear stress

Bed shear stresses, which were calculated based on the logarithmic vertical velocity profile, were separated into four tidal phases and mapped. It should be noted that data points on Fig. 5 corresponding to grain-size locations on Fig. 6 were evaluated using 2012 data, while data points at other locations were evaluated using 2007 data. The minimum bed shear stress of close to 0 N/m^2 appeared during the weak-flood phase, whereas the maximum value, 0.0681 N/m^2, happened during strong ebb. A pattern could

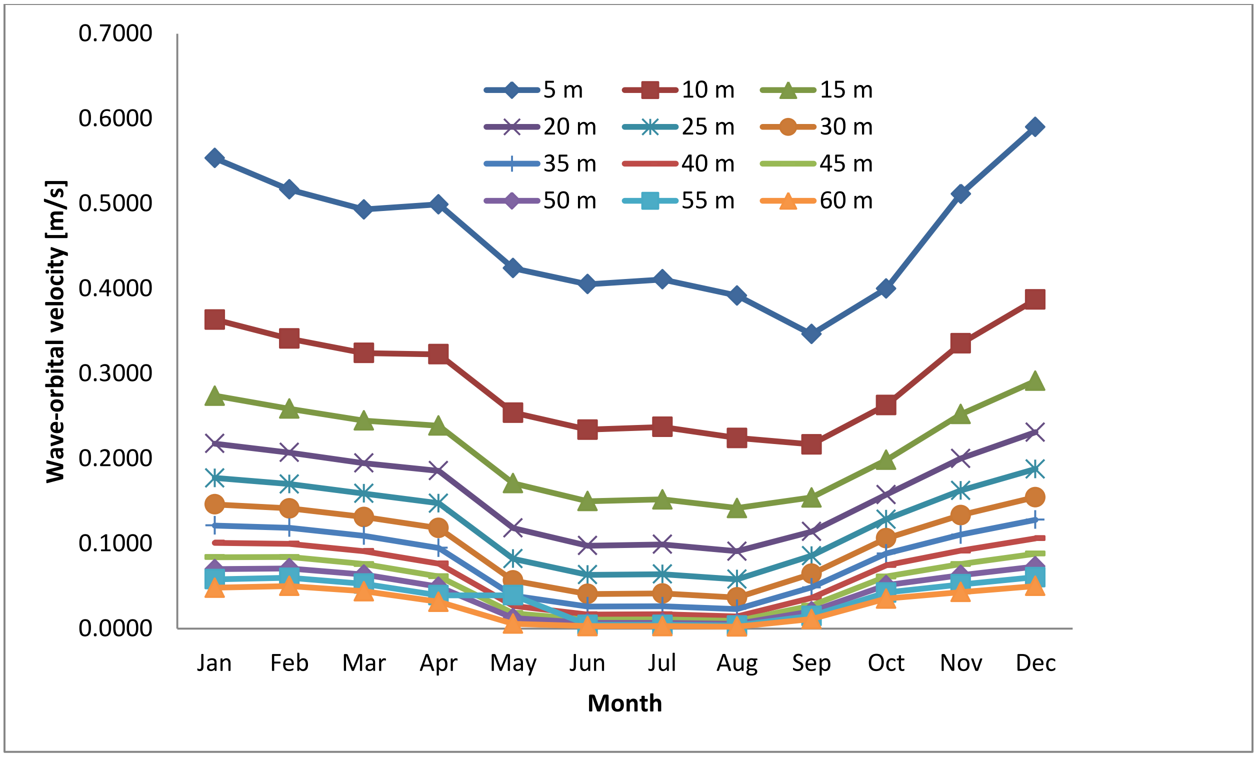

Figure 3. Mean monthly wave-orbital velocity at 12 water-depth values using data from July, 2004 to December, 2008. Wave-orbital velocity was calculated based on top 10% wave height and wave period values of each month by using linear wave theory calculations (woodshole.er.usgs.gov).

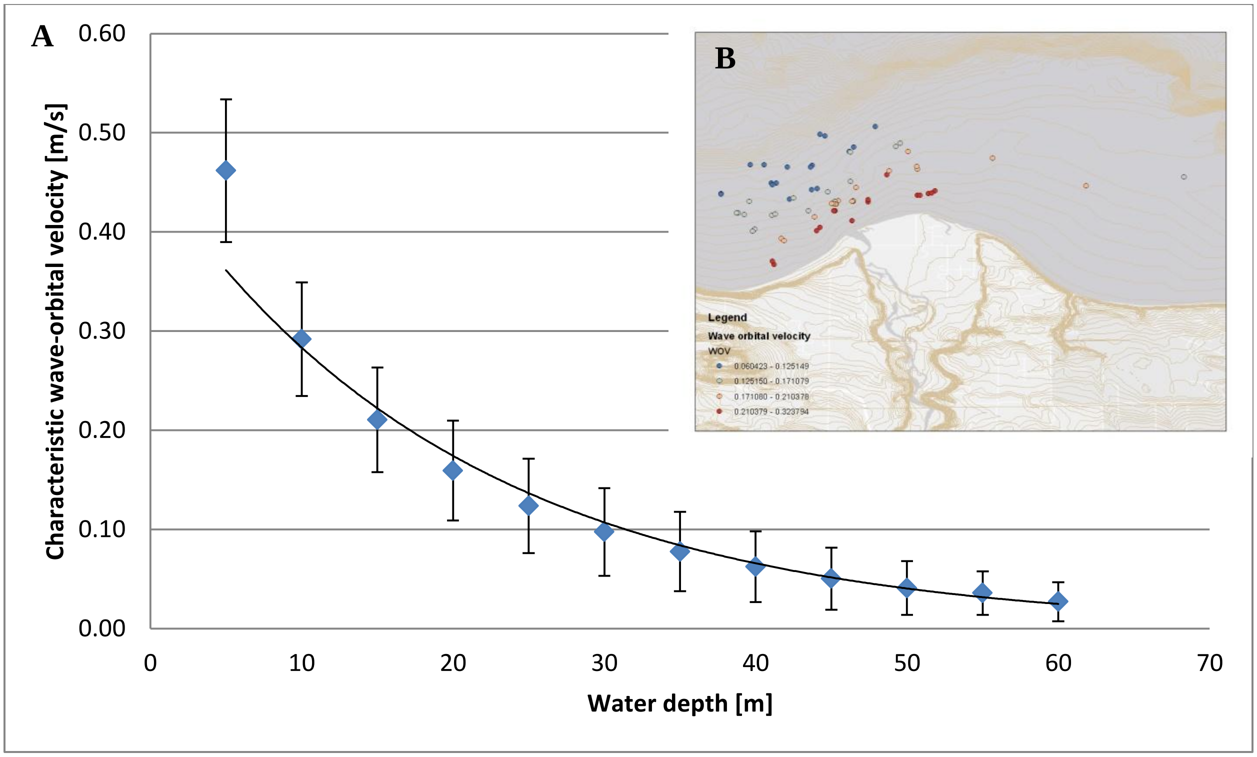

Figure 4. (A) Mean wave-orbital velocity (±1 Standard deviation) at different water depths calculated based on data from July, 2004 to December, 2008. Exponential curve (black line) with R^2 value 0.9858 was added to simulate the trend. (B) Characteristic wave-orbital velocities of each station on the Elwha River delta (bathymetry DEM from USGS). The values were calculated based on the simulated curve in (A).

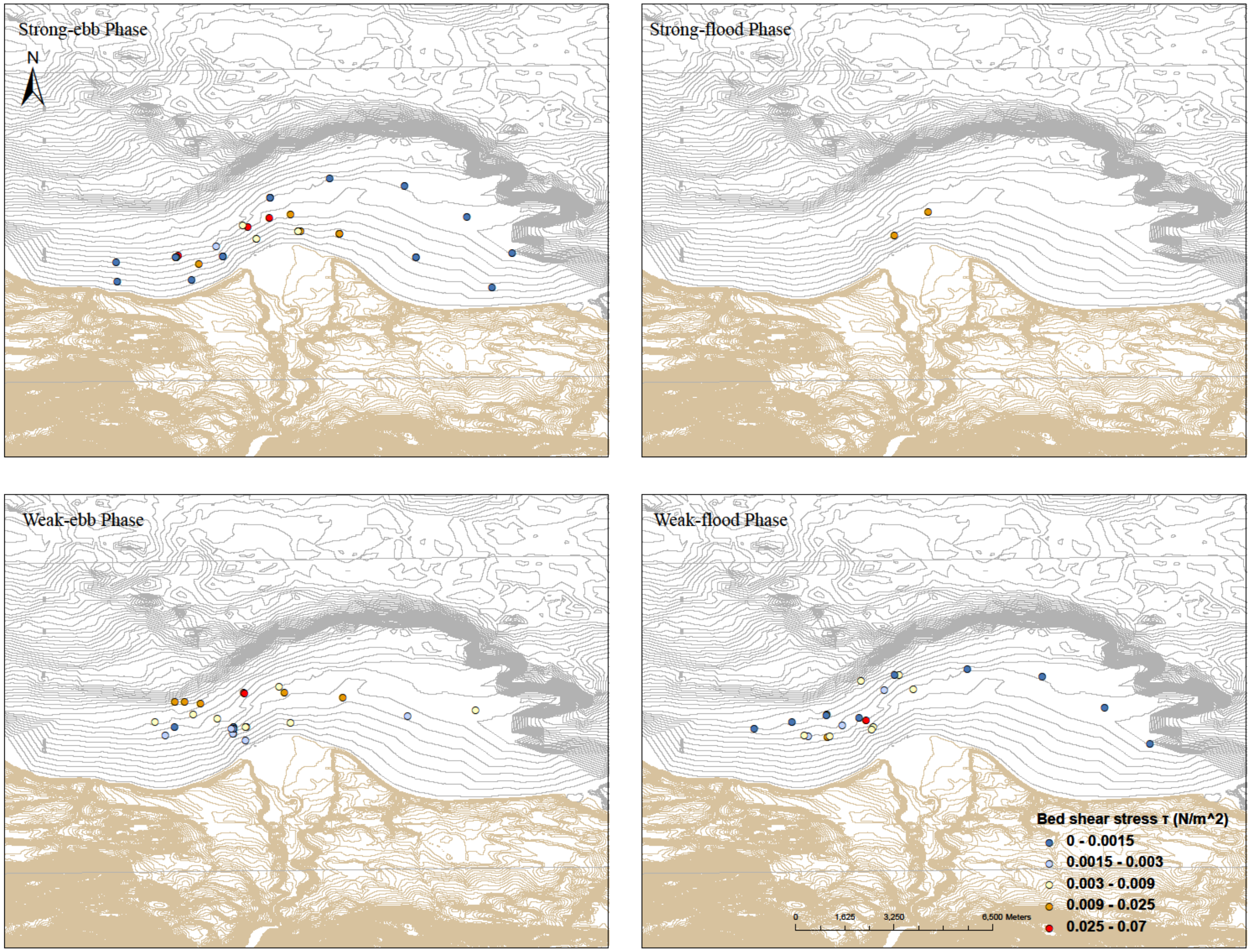

Figure 5. Bed shear stress T (N/m^2) for each station in four tidal phases (bathymetry DEM from USGS).

be noted in the weak-ebb phase, which included more data points than other phases. In this case, lower bed shear stresses occurred west of the river mouth while higher values were found offshore (Fig. 5).

4.3 Grain size

The median grain size (D_{50}) and sorting of each sample was calculated using Folk and Ward statistics (1957) and mapped. The maximum D_{50}, -5.49 Φ, was located near the river mouth in ~20-m water depth, and the minimum size was 7.40 Φ found east of the river mouth (Fig. 6). Solely based on D_{50}, it appears that sediment grain size was smaller at the river mouth, where silt was dominant. However, it increased offshore and sediments were mostly pebbles varying from medium to very coarse in size. Moreover, sediments collected at the west side of the sampling area showed smaller D_{50} values compared to those at the river mouth. In regards to sorting, sediments at the river mouth were generally better sorted than offshore. However, all sediment samples were categorized between moderately sorted and very poorly sorted with an exception that sediments near the river mouth at ~20-m water depth were very well sorted.

Additionally, grain-size histograms were generated for all sediment samples including ones taken from the river bank, exposed Lake Aldwell, and the bluff in Freshwater Bay. Two characteristic patterns were shown for samples taken from the delta (Fig. 7). Grain-size distribution on the west side of the sampling area showed a much higher percentage of sand than the middle part, while gravel was mostly found near and west of the river mouth. No characteristic pattern was observed for sediment samples taken from the east of the river mouth because grain-size distributions in that region showed high variability, possibly due to the limited number of samples. Three distinct patterns were observed for samples taken from the land. One of samples taken from the exposed Lake Aldwell showed similar grain-size distribution as samples taken from the river bank south of the reservoir. All showed high percentages of sand and low percentages of mud, but none had grain sizes larger than very fine pebbles (Fig. 8A). However, other two samples taken from the same region displayed another pattern which was also seen in samples taken from the river bank near pedestrian footprint bridge and the river mouth. The grain-size histogram had a peak value in very fine silt but a lack of grains ranging from median to coarse silt (Fig. 8B). Sediments ranging from very coarse sand to median pebbles were present throughout, though varied in percentages at different locations. Two other river-mouth samples showed a third characteristic pattern, with around 80% ~ 90% of grain sizes falling in categories of medium and coarse silt and no sediment larger than very coarse pebbles or smaller than fine silt (Fig. 8C). One sample was taken from the bluff nearshore and it had high percentages of both gravels and sand (Fig. 9).

4.5 Seabed video

Video of the seabed was used to obtain qualitative observations of grain size and sorting. Though variability existed within each station, results showed that sediments near the west shoreline of the river mouth were better sorted compared with sediments in other regions, and that sediments tended to be very poorly sorted offshore especially west of the river mouth (Fig. 10). Moreover, on the west side of the delta, sand was dominant

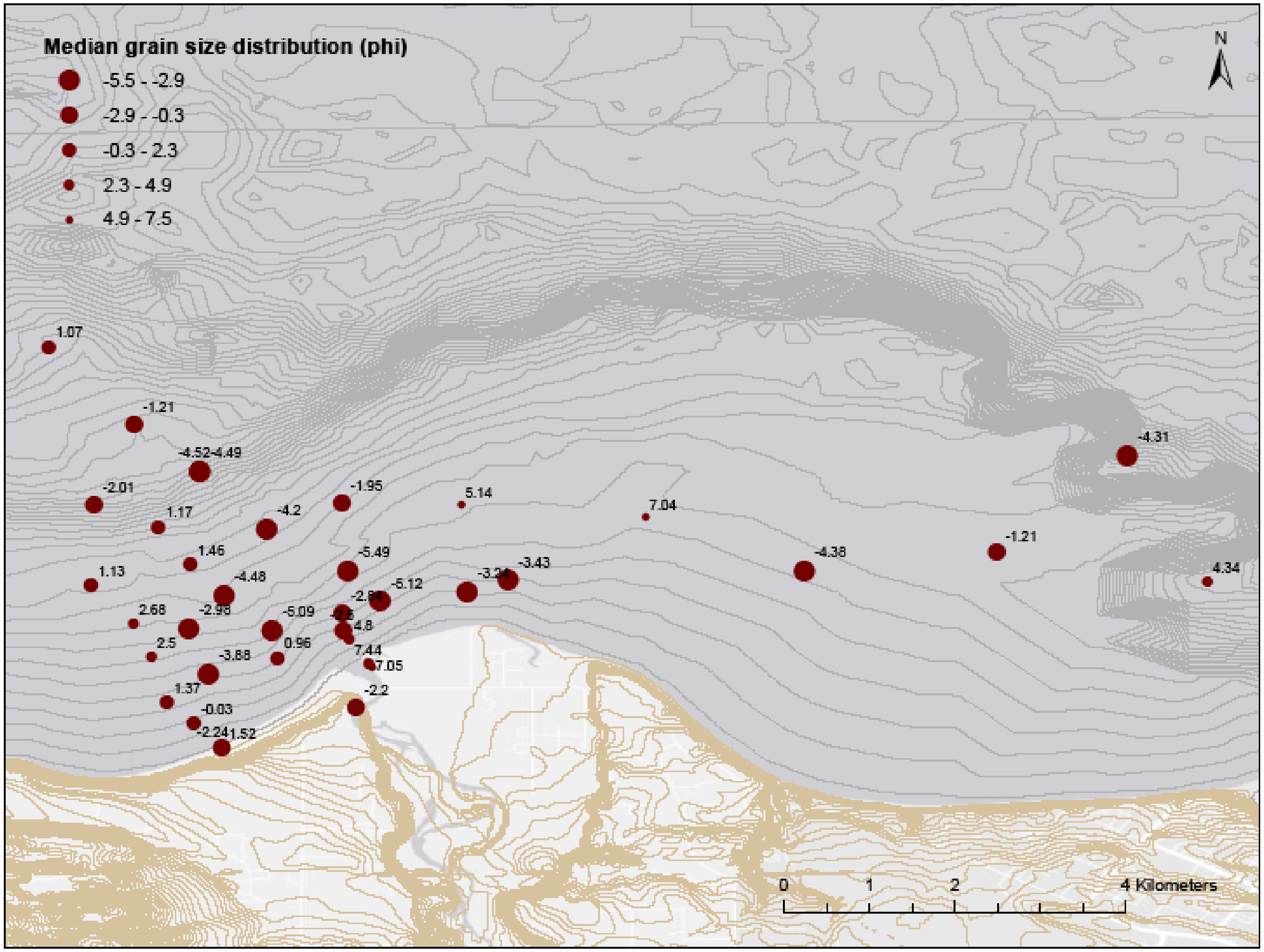

Figure 6. Median grain size, D_{50} (Φ), distribution on the Elwha River delta (bathymetry DEM from USGS).

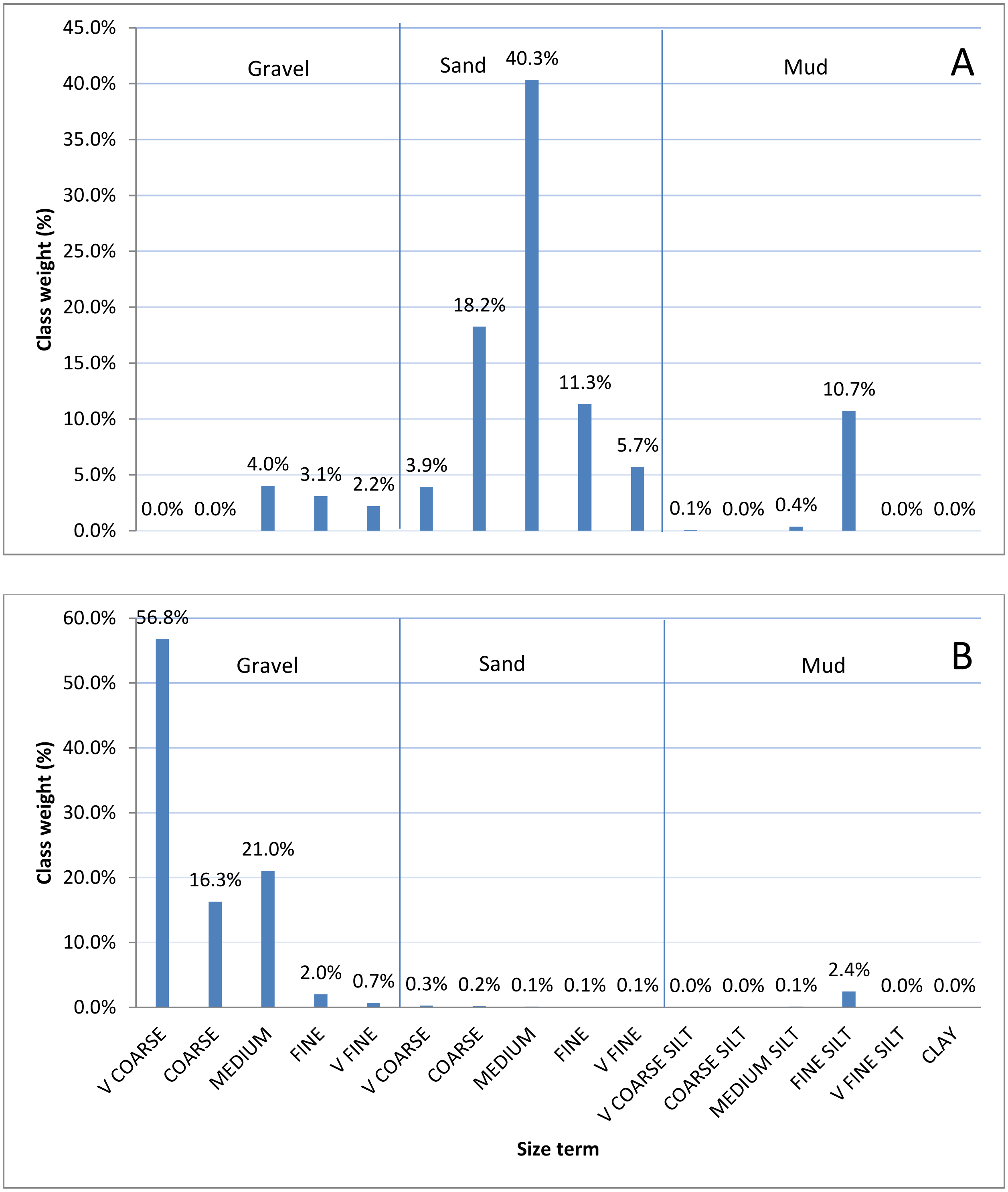

Figure 7. Representative grain size distributions of sediment samples taken at the west side of the sampling area (A) and near the river mouth (B).

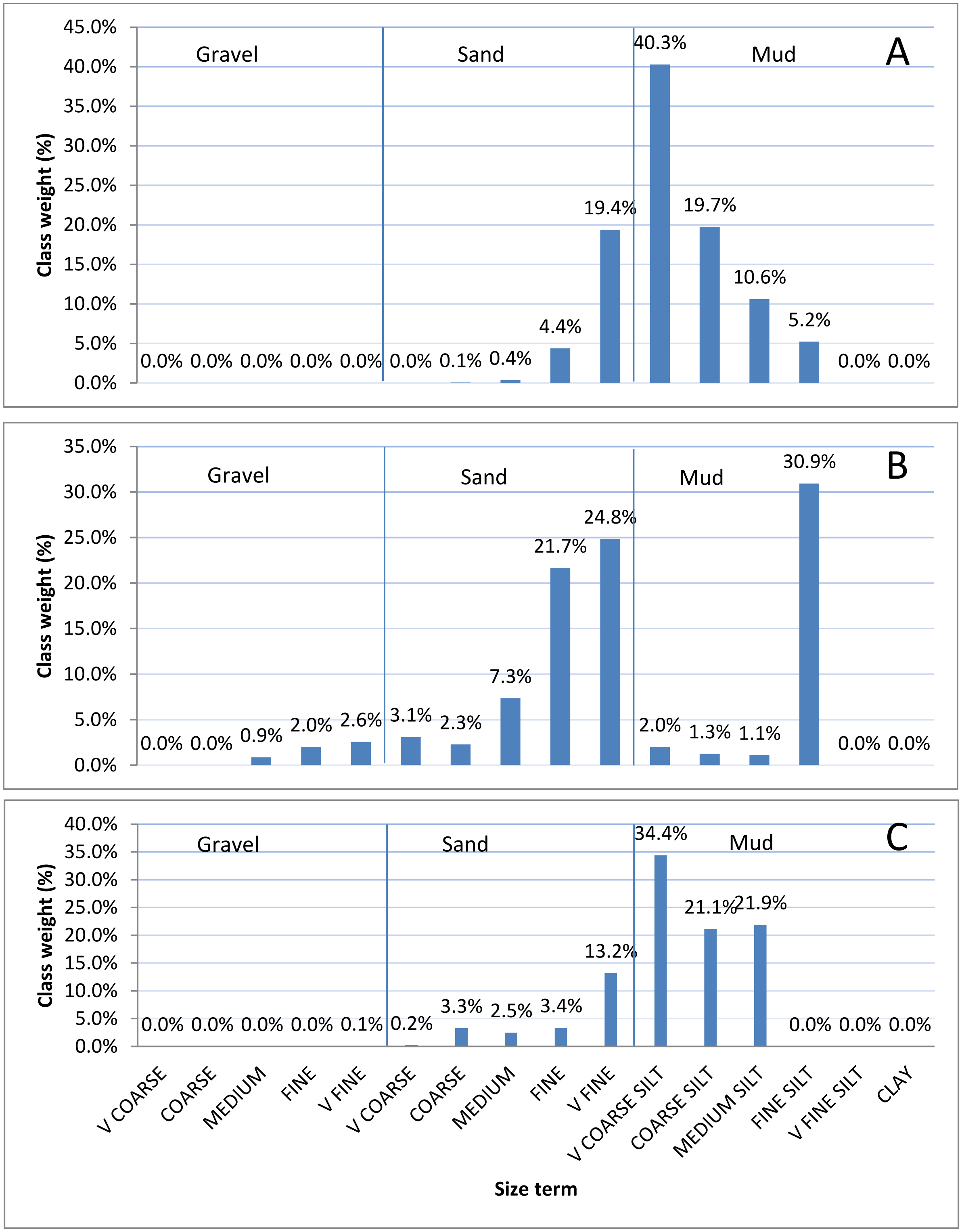

Figure 8. Representative grain-size distributions of sediment samples taken at the river bank south of Lake Aldwell (A), Lake Aldwell (B), and the river mouth (C).

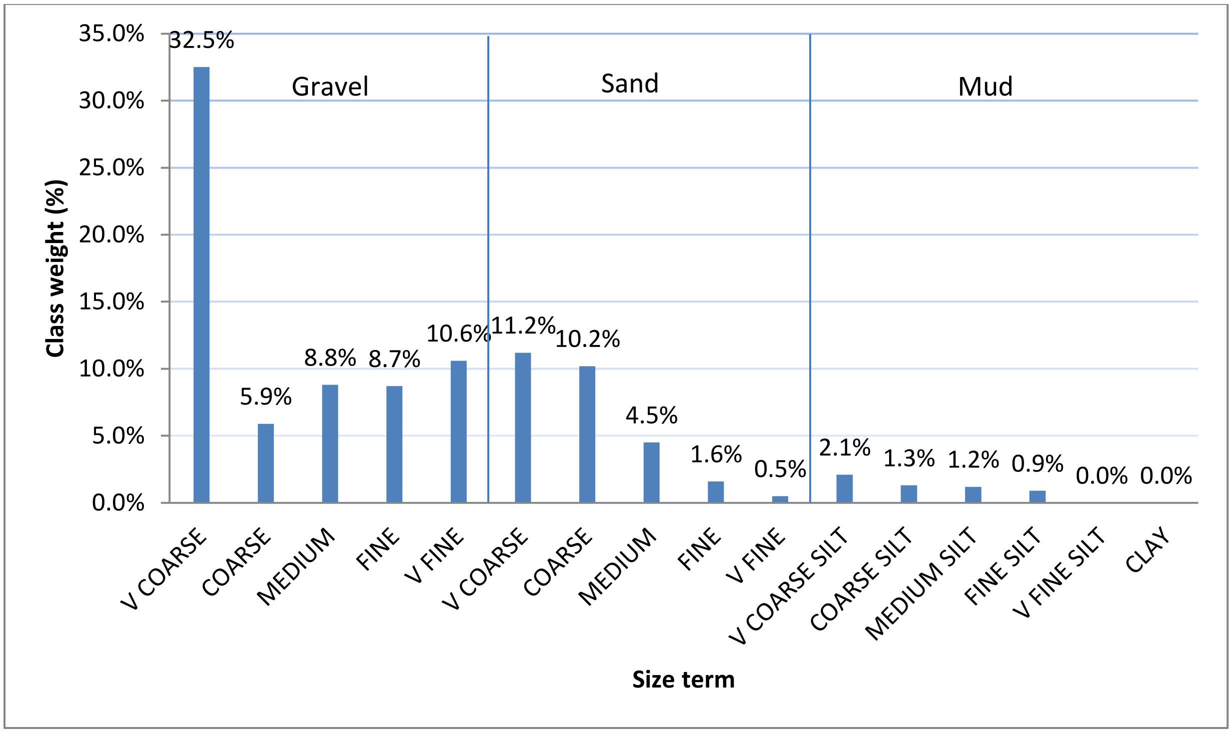

Figure 9. Grain-size distribution of the sediment sample taken from the bluff near the shoreline.

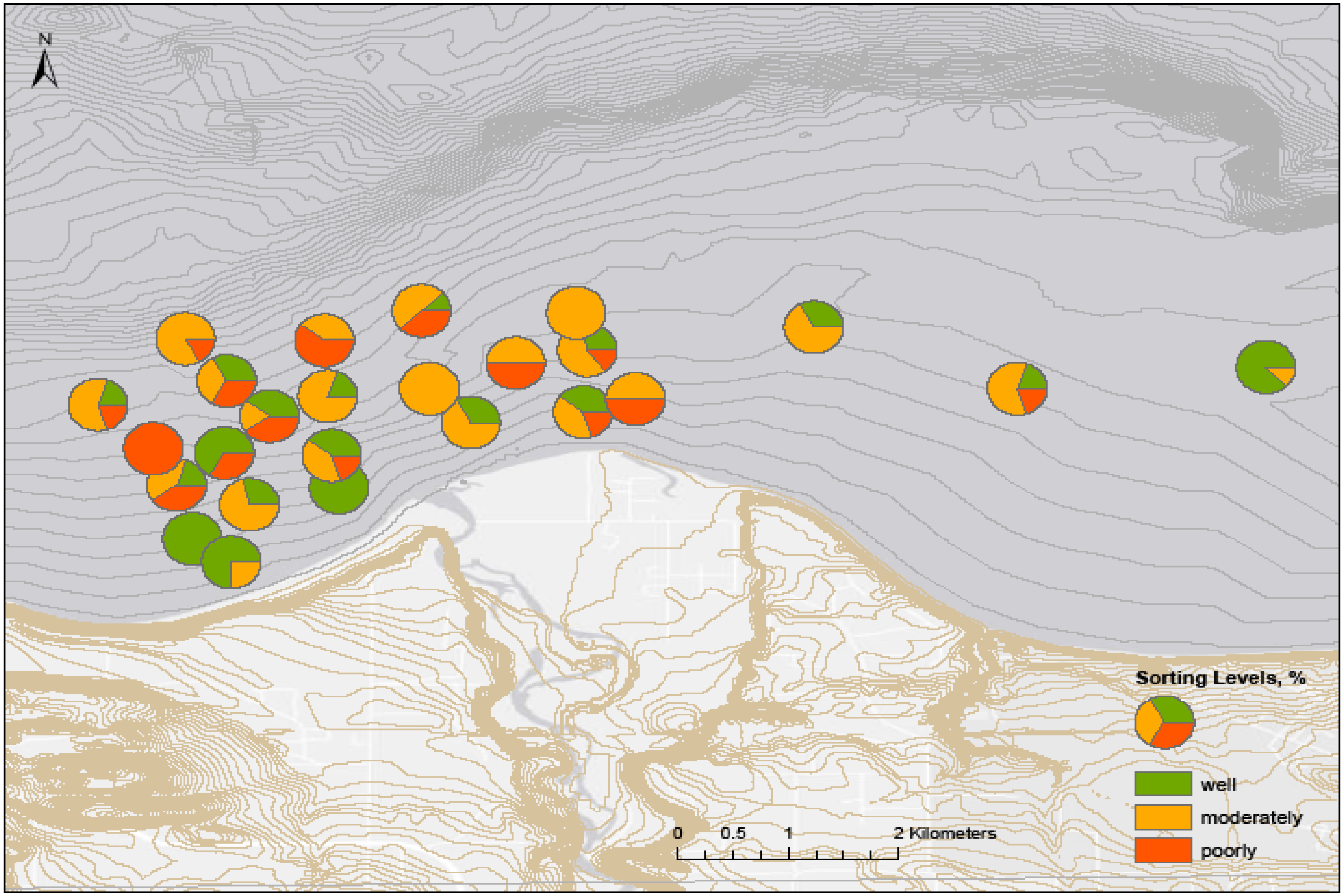

Figure 10. Observed percentages of sorting categories from seabed video. Sorting categories were based on qualitative observations (bathymetry DEM from USGS).

close to shore and sediments became coarser towards the east and north. No pattern was shown at east of the river mouth due to the limited number of stations.

5. Discussion

5.1 Correlation between grain-size distribution and characteristic wave-orbital velocity

Results showed that the median grain size, D_{50}, was largest at 10-20 m water depth near the river mouth and characteristic wave-orbital velocity was highest nearshore at even shallower depth. Though simple statistical analysis indicated very low correlation between median grain size and wave-orbital velocity, relationships could be observed in certain regions. Based on the estimated range of characteristic wave-orbital velocity on the Elwha River delta (Fig. 4) and the threshold orbital velocity curve by Komar and Miller (1975), sediments smaller than -1 Φ were expected to be transported by the waves near the river mouth. This is consistent with the observation that sediments near the river mouth were larger than -2 Φ. In other words, sediments finer than -2 Φ, which was similar to the predicted value -1 Φ, were transported by waves, therefore sediments larger than -2 Φ were left on the seabed, such as pebbles ranging from -2.6 Φ to -5.5 Φ as observed (Fig. 6). Moreover, as the water depth increased, the maximum sediment grain size that could be transported under waves decreased. For example, fine sand at 10-m water depth could be carried away by waves but it stays on the seabed at 20-m water depth due to lower wave-orbital velocity in deeper water. Consequently, wave conditions leaded to a landward coarsening pattern because fine sediments tend to deposit in deeper water, which decreases the median grain size of the site (Fig.11). Stronger landward coarsening pattern is expected if wave-orbital velocity could be calculated based on storm-wave conditions instead of low-wave conditions.

Another observed pattern was the existence of a sand-dominant region at the west of the river mouth (Fig. 11) which was also described by Miller et al. (2011). Two factors are assumed to cause this phenomenon. First, sediments on the beach are mainly supplied by erosion of bluffs in Freshwater Bay. Grain-size distribution of samples taken from the bluff showed high percentages of cobbles and very coarse sand, thus both grain sizes are expected to be dominant in the region. Second, waves on the Elwha River delta predominantly come from the northwest; therefore they hit the west side of the beach in Freshwater Bay at a more oblique angle than east side of the beach, causing more long-shore beach transport. Whereas on the east side of the beach, cross-shore transport is more dominant due to higher wave energy exerted perpendicularly to the shoreline. These two factors combined suggest coarse sand on the west side of the beach is carried along shore towards the east first, and then washed offshore by waves on the east side of the beach. Consequently, they deposit at the western foreshore of the river mouth. This assumption is supported by previous study performed by Miller et al. (2011), where it was found that lower mean grain size at the west site of the river mouth was consistent with a sandier foreshore of that site. Also, study by Bramato et al. (2012) revealed a similar pattern in a mixed sand and gravel beach located on the southeastern coast of Spain, where sand was transported cross-shore during erosion, leaving gravels exposed on the beach.

5.2 Correlation between grain size and bed shear stress

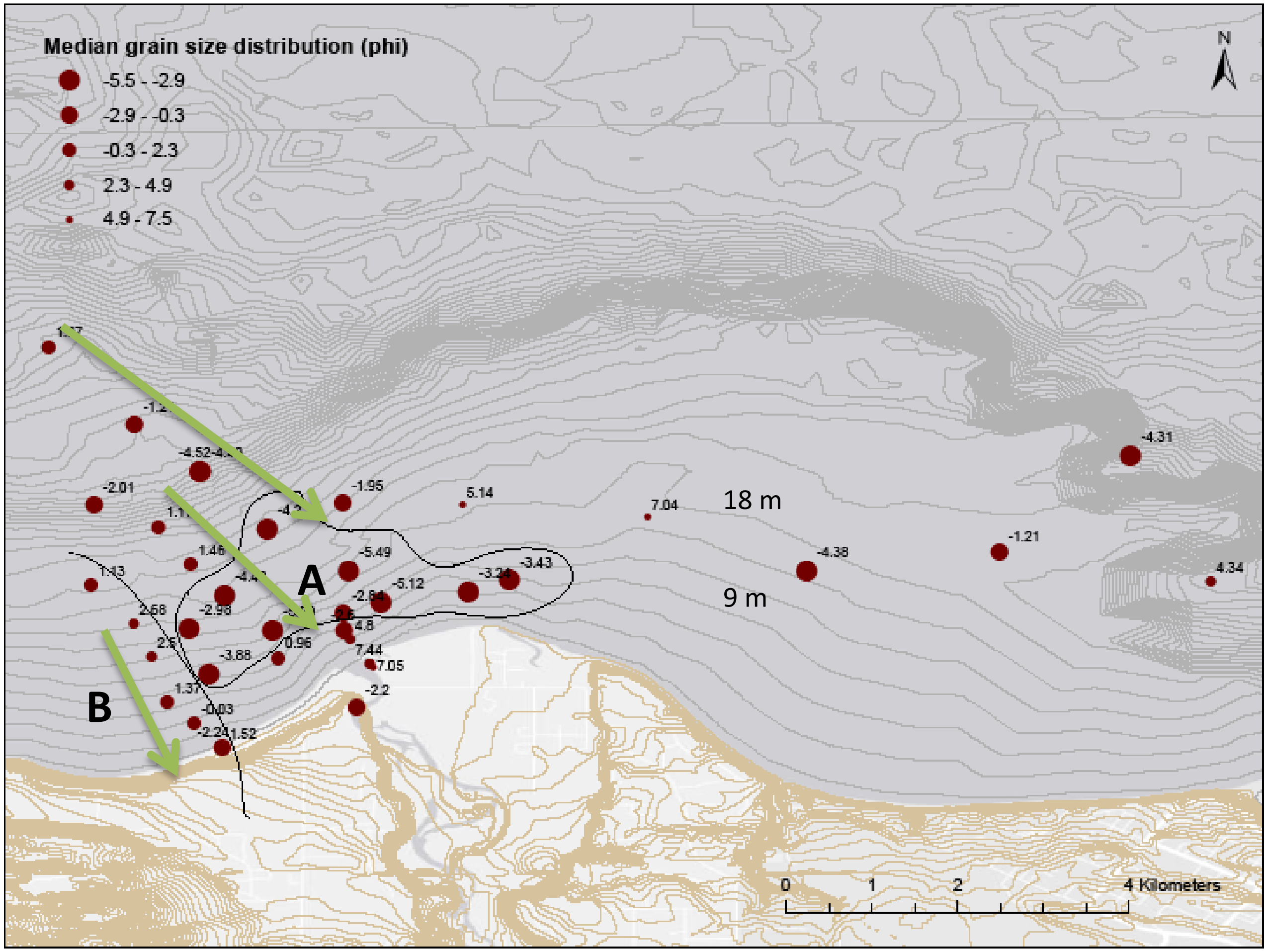

Figure 11. Median grain size, D_{50} (Φ), distribution on the Elwha River delta (bathymetry DEM from USGS). The zone marked A was dominated by coarse sediments larger than sand. The zone marked B was sand-dominant region. Arrows showed seaward fining patterns.

The only clear pattern of bed shear stress on the Elwha River delta was available during the weak-ebb phase. Bed shear stress was stronger offshore and east of the river mouth, while weaker close to the river mouth and in Freshwater Bay where samples were taken (Fig. 5). Theoretically, it is expected that more and larger sediments can be carried away due to high bed shear stress, consequently leaving well-sorted sediments on the seabed. However, the observed pattern showed poorer sorting levels offshore than nearshore (Fig. 10). One possible reason is that, though most fine sediments are carried away by currents, some fine sediments are protected by coarse sediments from moving, causing a poor sorting level in that region. Since few samples were taken during strong-flood and strong-ebb tidal phases, no strong evidence is provided to suggest the impacts of tidal-induced currents on observed seabed composition.

Though little correlation between tidal bed shear stress and grain-size distribution is displayed in this study, other evidences were shown to support the argument that tidal-induced currents have impacts on grain-size distribution of the Elwha River delta. It is observed that high percentages of fine sediment were mostly found east of the river mouth (Fig. 12). Considering present fine sediment source, which is the Elwha River, eastward is possibly the dominant direction of fine-sediment transportation. A study by Warrick and Stevens (2011) stated that tidal-induced currents flow northeastward more frequently and faster as a result of a return flow forming on the downstream side of the delta. Therefore, fine sediments are carried towards the east due to northeast current movement and deposit in the region as observed. Moreover, strong tidal-induced currents near the river mouth cause high bed shear stress in that region. Consequently, only very coarse sediments are left on the seabed near the river mouth.

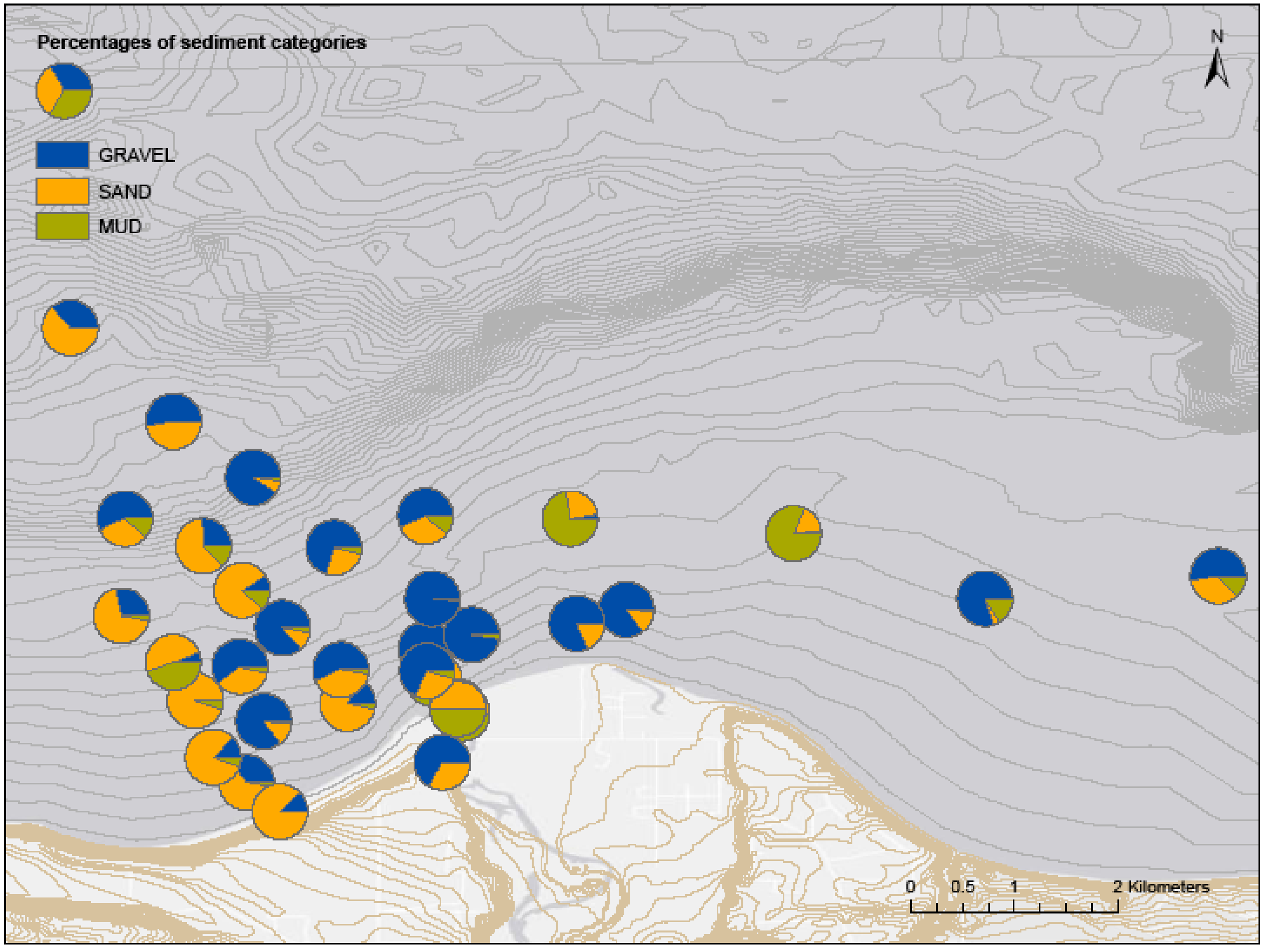

Figure 12. Percentages of mud, sand, and gravel in different locations on the Elwha River delta (bathymetry DEM from USGS).

5.3 Sources of sediment on the Elwha River delta

Results showed that sediments on the delta were mostly coarse grains larger than medium sand (Fig. 8A), whereas sediments supplied by the river were fine-grained smaller than fine sand (Fig. 8B). Based on the grain-size distribution of samples taken from the bluff near the shoreline, which was high in sand and gravels especially very coarse gravels (Fig. 8C), it is reasonable to conclude that the bluff is another major source of sediments for the delta and supplies the delta with coarse sediments. Though fine grains were not observed at the middle and western part of the sampling area, they were found at the river mouth and also east of it. It is believed that fine sediments found at the river mouth were in the process of transitioning, which means they deposited there temporarily. Once they reach out into the region where waves and tides act strongly and constantly, most of them are carried toward the northeast. Some of fine grains may deposit temporarily, but most remain in suspension. It suggests that sediment concentration in water samples should be taken into consideration when most fine sediments are in water column instead of on the seabed; it may provide stronger evidence of fine sediments in that region. Nevertheless, it is believed that the Elwha River supplies majorly fine sediments. Altogether, both the bluff and the river are major sources of sediments from the Elwha River delta.

6. Conclusions

In summary, we have found the grain size on the Elwha River delta has several distinct patterns that relate to impacts of waves. Because of landward increase in characteristic wave-orbital velocity, fine sediments are infrequently removed from offshore sites, and this consequently causes local landward coarsening patterns as we observed. The sand-dominant region at the west side of the sampling area reflects two characteristics of the western nearshore of the river mouth. Waves are dominantly from northwest and hit the shorelines in Freshwater Bay at different angles, which causes significant long-shore transport on the west end of the beach and cross-shore transport on the beach towards the river mouth.

Though a strong correlation between tidal bed shear stress and grain-size distribution was not found, some conclusions could be drawn based on the characteristics of tidal-induced current flows in the region. Since the net flow of currents is northeastward, fine sediments are carried toward the east and deposit there as we observed. Moreover, focused and strong currents near the river mouth, which cause high bed shear stress, leave coarse and poorly sorted sediments on the seabed. For further studies, we suggest that more data should be collected during strong tides and waves.

The comparisons between grain-size distributions of the delta and two possible sources suggest that the bluff in Freshwater Bay supplies the delta with coarse sediments especially gravels, and the Elwha River supplies it with fine sediments. Though little fine sediment was observed in sediments collected from the seabed, we believe it is because they tend to suspend in the water and can be removed from the delta easily. Overall, it appears that both the bluff and the Elwha River are major sources of sediments to the Elwha River delta.

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