Grain size on the Elwha River delta intertidal beach: impacts of dam removal and implications for Pacific sand lance (*Ammodytes hexapterus*)

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Abstract

Small mountainous rivers, such as the Elwha River in Washington State, play a key role in the sedimentary processes that form and maintain the structure and function of their neighboring shorelines. The Elwha River was dammed from 1910 to 2011, and construction of the dams has been attributed to coarsening and erosion of its delta and adjacent shorelines. In turn, the habitat made available to marine organisms was altered for nearly 100 years. This study examined the median (D_{50}) of the grain sizes, sand fractions, and respective elevations of physical samples from the Elwha delta using dry and wet sieve methods, as well as average surface grain sizes using photographic methods, to evaluate the impacts of dam removal of the restoration and/or expansion of Pacific sand lance (sand lance) spawning habitat. Of the 34 physical samples collected and as of 12 and 13 April 2014, the findings suggest 10 sample locations west and 8 samples locations east of the river mouth met the three parameters documented as preferred sand lance spawning habitat. Each of the 18 locations within the study area had grain-size distributions with medians ranging between ~0.2 and 2.0 mm, the bulk sand fractions of each sample ranged between ~60 and 98%, and their respective elevations were between +1.33 and +2.22 m MLLW. Potentially suitable spawning habitat for sand lance was found ~1,230 m west and ~1,500 m east of the river mouth.

1. Introduction

Anthropogenic modifications to the landscape are often associated with unintended consequences that reverberate through the ecosystems in which they are placed. The construction of dams is one such example, and the ecological changes associated with the construction of dams are well documented. A given dam disrupts the sediment flux of a watershed by trapping sediment behind the dam within its reservoir (Syvitski et al., 2005; Warrick et al. 2009a). Numerous studies indicate the ecological consequences of preventing sediment from being distributed downriver and has the potential for morphological changes along the coastlines adjacent to the river mouth; these impacts may include wetland loss, reduction of coastal biological productivity, and shoreline erosion (Stanley and Warne, 1993; Anthony and Blivi, 1999; Kowalewski et al., 2000; Poulos and Collins, 2002; Frihy et al., 2008). The Elwha River on the Olympic Peninsula of Washington State is a prime example of how dams drastically alter the abiotic and biotic structure of an ecosystem.

Although the sediment discharge rates of the Elwha River prior to and after construction of the Elwha and Glines Canyon dams have not been measured satisfactorily, estimates of sediment accumulation within the Elwha River reservoirs suggest that 40,000 to 85,000 m^3/year were trapped by the dams (Gilbert and Link, 1995; Warrick et al., 2009a). Between 1939 and 2006, an estimated 100,000 m^2 of land was lost from the coastal plain of the Elwha drift-cell (Warrick et al., 2009a). The dramatic loss of land was likely due to erosion from wave energy outpacing the supply of sediment leaving the river (Warrick et al., 2009a). Additionally, the Lower Elwha Klallam Tribe reports that, prior to the dams, the central and eastern portions of the delta were once sandy low-tide beach, ideal for harvesting shellfish (Reavey, 2007). During the last half of the 20th century, after construction of the dams, it is evident that the same shoreline has substantially coarsened (Warrick et al., 2009a). However, during the first two years following dam removal, it is estimated that 2.7 million cubic meters (mcm) of sediment, out of 15 mcm of sediment expected to leave the reservoirs, have been delivered to the

Elwha nearshore (Shaffer et al., 2013), which implies spawning habitat for sand lance may improve.

Myriad fish species are endemic to the Elwha River and/or utilize the habitat of the Elwha nearshore (Shaffer et al., 2008). Pacific sand lance (*Ammodytes hexapterus*), a forage fish commonly found in the waters of the Strait of Juan de Fuca, are a critical component of the marine food web, as they are a source of high-energy prey for many marine mammals, birds, and piscivorous fish (Penttila, 2007), including Pacific salmon (Fresh, 2006; Shaffer et al., 2008). Increased sediment grain sizes along the upper intertidal zone of the Elwha drift-cell is particularly concerning because Pacific sand lance (sand lance) prefer spawning habitat with the majority of sediment between 0.2 and 0.4 mm in diameter (Penttila, 2007).

According to sand lance spawn surveys conducted from November 2001 through February 2002, December 2012, and January, November, and December 2013, evidence of spawning activity have not been found along the shorelines adjacent to the Elwha delta, which were located farther from the Elwha River mouth than the area focused on in this study (Moriarity et al., 2002; Shaffer et al., 2013). The goal of this study is to assess the impacts of the Elwha River dam removals, initiated in 2011, on sand lance spawning habitat by analyzing changes in the grain-size distribution of the upper intertidal zone of a portion of Freshwater Bay and the Elwha Bluffs.

2. Regional Setting

The Elwha River is located on the northern Olympic Peninsula of Washington state, west of the city of Port Angeles, and flows from its headwaters in the Olympic

Mountains into the central Strait of Juan de Fuca (Fig. 1a). The mean annual precipitation is ~600 cm at the headwaters and ~100 cm at the river mouth, with most of the precipitation typically occurring between October and March (Duda et al., 2011).

Small glaciers extending from the highland valley of Olympic Mountains and “tongues” of larger glaciers flowing from the Frasier River Canyon in British Columbia, Canada, scoured the landscape of the Olympic Peninsula and deposited substantial volumes of sediment upon their retreat (Terich, 1987) between 15,000 and 20,000 calendar years before present (Warrick et al., 2009a). The sediment composition of the Olympic Peninsula, and the greater Puget Sound, shows evidence of as many as four distinct periods of glacial scouring and deposits (Terich, 1987).

Freshwater Bay, Elwha Bluffs, and Ediz Hook are collectively described as the Elwha drift cell (Parks et al., 2013). A drift cell is a segment of coastline proximal to an identified source of sediment, area of net directional sediment transport, and area of sediment deposition (Parks et al., 2013). The sediment transport and deposition processes of the Elwha drift cell are highly influenced by the lengthy fetch within the Strait of Juan de Fuca and swells from the Pacific Ocean that propagate as large, energetic waves, which break along the shoreline at an oblique angle (Warrick et al., 2009a).

Due to the construction of the Elwha Dam from 1910 to 1913, and the Glines Canyon Dam from 1925 to 1927 (Duda et al., 2011), the output of sediment from the Elwha River was reduced by 98% for the last one hundred years (Draut et al., 2011; EIS, 1996; Shaffer et al., 2008; Warrick et al., 2009a). Other anthropogenic modifications to the Elwha River system include physical reduction of the river mouth from multiple channels to a single distributary channel (Todd et al., 2006; Draut et al., 2008) and separating the river from its natural floodplain with levees on the east and west sides of the distributary channel near the mouth (Duda et al., 2011). Additionally, shoreline armoring is present to the east of the river mouth along East Beach and extends to the end of Ediz Hook (Duda et al., 2011; Parks et al., 2013; Galster, 1989; USACE, 1971).

Collectively, the manmade changes to the Elwha River system have drastically altered the sediment transport and deposition processes of the Elwha drift cell by depriving the beaches of sediment, increasing the beach sediment grain size, and reducing beach width (Johannessen and MacLennan, 2007; Shipman, 2008; Warrick et al., 2008, 2009). Increased sediment grain sizes (coarsening) along the upper intertidal beach of the Elwha drift cell is particularly concerning to the ecology Pacific sand lance (*Ammodytes hexapterus*), a forage fish commonly found in the waters of the Strait of Juan de Fuca, as they prefer spawning in the upper intertidal zone on a substrate that mainly consists of sand with grain sizes ranging from fine to very coarse sand (0.2 to 2.0 mm) (Penttila, 1995 and 2007).

3. Materials and Methods

3.1 Study area

The upper intertidal zone of Freshwater Bay and the Elwha Bluffs of the Elwha drift cell was sampled during a +0.75 m lower-low tide on 12 April 2014 and a +0.53 m lower-low tide on 13 April 2014 (NOAA Station Id 9444122; tidesandcurrents.noaa.gov). A rod-mounted Real Time Kinematic Differential Global Positioning System (RTK-DGPS) was used to collect waypoints in State Plane Coordinates, Washington Zone

North, using vertical data referenced to North American Vertical Datum of 1988 (NAVD88) and horizontal data referenced to North American Datum of 1983 (NAD83). The subject study area extends along the seaward extension of the subaerial delta and ~1,650 m west, along a portion of Freshwater Bay, and ~1,940 m east of the mouth of the Elwha River, along the Elwha Bluffs in cross-shore transects ~100 m apart (Fig. 1b). A total of 100 waypoints were collected to document and map their respective locations along the upper intertidal zone of Freshwater Bay and the Elwha Bluffs. Physical samples and grain-size photographs were collected at 34 and 98 of these locations, respectively.

3.2 Sediment sampling & characterization

Two methods were used to determine grain-size distributions: grain-size photograph analysis and physical samples. For photographic analysis, a small blackboard with an attached 15-cm scale was placed on the surface of the beach at each waypoint and a photograph was taken using a standard digital camera. Each photograph was processed using methods modified from Cobble Cam analysis (Warrick et al., 2009b). Analysis of each grain-size photograph provided statistical data about each sample location, and the average grain size (mm) was used for the purposes of this study.

Physical samples were collected at 34 sites within the study area. The selection of sample locations was based on observed changes in the grain size along the shoreline, parallel to the water's edge. A small hand trowel was used to collect sediment samples from the surface to a depth of ~15 cm. The sediment grain-size distribution for 31 beach samples was determined using the dry sieve method modified from Haynes et al. (2007). Samples consisting of only sand, gravel, and cobble were placed in small tins and dried in an oven for approximately 24 hours. After drying, individual samples were added to the top of a stack of 9 sieves ranging from -4ϕ to 4ϕ (16 to 0.063 mm) and agitated in a mechanical shaker for 10 minutes. If a sample contained cobble greater than -4ϕ (16 mm), the individual cobbles were hand-measured with electronic digital calipers to the nearest 0.1 mm. Each separate grain-size class was weighed to the nearest 0.01 g with an electronic balance.

Three samples that contained trace amounts of clay and silt were analyzed using the wet sieve method modified from the UW Sediment Procedures Manual (UW, 1998). A subsample ranging from ~30 to 60 g, depending on the sand-gravel consistency for each wet sample, was placed in a 4ϕ (0.063 mm) sieve and rinsed with 0.05% sodium metaphosphate ($NaPO_4$) dispersant to separate clay and silt from larger sediments. The grain-size distributions for clay and silt fractions of wet samples were determined using pipette analysis and the application of Stokes' Law. The sand and gravel fractions of each wet sample were then processed according to the methods previously described.

3.3 Grain-size analysis & mapping

The grain-size data were recorded for each of the 34 physical samples and analyzed using GRADISTAT (Blott and Pye, 2001). Results from GRADISTAT analysis were used to map the median (D_{50}) of the grain-size distribution for each sample by geographic location within the study area and with respect to their distances from the mouth of the Elwha River, examine the relationship between D_{50} and sand fractions for each sample, and determine the relationship between the sand fractions and elevation (m MLLW) for each sample.

The average surface grain-size data were obtained from Cobble Cam analysis for each of the 98 photo samples. Each of the 98 photos was run through Cobble Cam analysis three times and the mean (mm) was averaged for use in spatial analysis. The average surface grain-size for each of the 98 photo samples was mapped by geographic location within the study area and their respective distances from the mouth of the Elwha River.

The distances between the mouth of the river and each sample location were calculated using a script in MatLab (developed by Ramin Shamshiri, 2008). ArcMap was used to map the overall study area, the grain-size photo and physical sample locations within the study area, and potentially suitable sand lance spawning locations.

4. Results

4.1 Physical sample analysis

Grain-size analysis of the 34 physical samples collected at varying elevations along portions of the upper intertidal zone of Freshwater Bay and the Elwha Bluffs reveals median grain-sizes ranging from 0.2 to 9.0 mm. Specifically, 11 of the samples had a median grain-size from 0.2 to 0.4 mm; 8 ranged from 0.5 to 0.6 mm; 5 ranged from 0.7 to 1.0 mm; 6 ranged from 1.1 to 4.0 mm; and 4 ranged from 4.1 to 9.0 mm (Fig. 2).

Sixteen of the physical samples were collected east of the river mouth and 18 samples were collected west of the river mouth (Fig. 3a). Fourteen of the samples collected between ~70 and ~1,500 m east of the river mouth had a median grain-size under 1.0 mm. Fifteen of the samples collected west of the river mouth had a median grain-size that increased between ~120 and ~730 m, then decreased between ~850 and ~1,330 m. Beyond ~1,330 m west of the river mouth, the median grain-size of physical samples was larger and varied between ~3.7 and ~9.0 mm. Twenty-seven (~79%) of the physical samples collected in the upper intertidal zone of Freshwater Bay and the Elwha Bluffs had a median grain size characterized as fine-to-very coarse sand (~0.2 to 2.0 mm) (Fig. 3a), according to the Wentworth scale. The cumulative fine-to-very coarse sand fractions for the 27 samples collected in the upper intertidal zone of Freshwater Bay and the Elwha Bluffs ranged from ~60 to ~98%, high cumulative sand fractions found along the majority of the study area, and these ranges were highly variable in relation to their distance from the river mouth (Fig. 3b).

4.2 Sample sand fraction analysis

As previously noted, there were 27 physical samples that had a median grain-size between 0.2 and 2.0 mm. Further analysis of the 27 physical samples characterized as fine-to-very coarse sand (~0.2 to 2.0 mm) revealed a large fraction of their respective compositions was sand, few did not have any gravel, and most had trace amounts of mud (Fig. 6a).   As the median grain size increases, it appears the gravel fraction generally increases as well.

The fractions of fine, medium, coarse, and very coarse sand for each of the 27 physical samples with a median grain-size between 0.2 and 2.0 mm are represented in Figure 6b. The sum of the very coarse sand, coarse sand, medium sand, and fine sand fractions for each of the 27 samples yielded a minimum, maximum, and mean of 59.8%, 99.0%, and 86.1% respectively. The samples were collected at elevations ranging from

+0.64 to +3.33 m MLLW (Fig. 7). Eighteen of the 27 samples with a median grain-size between 0.2 and 2.9 mm were collected in the upper intertidal zone.

4.3 Cobble Cam analysis

Cobble Cam surface-grain-size analysis of 98 photo samples collected along portions of the upper intertidal zone of Freshwater Bay and the Elwha Bluffs revealed an average surface grain-size ranging from 0.4 to 130.0 mm (Fig. 4). Specifically, 5 of the photo samples yielded an average surface grain-size of 0.4 mm (minimum resolution of Cobble Cam); 37 ranged from 0.5 to 1.0 mm; 43 ranged from 1.1 to 30.0 mm; 8 ranged from 30.1 to 60.0 mm; and 5 ranged from 60.1 to 130.0 mm.

Forty-two of the photo samples were collected east of the river mouth and 56 samples were collected west of the river mouth (Fig. 5). East of the river mouth, the average surface grain-size between ~70 and ~400 m was under ~2.0 mm, and then varied considerably from ~400 to ~660 m. Between ~660 and ~1,140 m east of the river mouth, the average grain-size dropped below ~1.0 mm, and just beyond ~1,140 m the variability of the average grain size increased as distance from the river mouth continued to increase. All but one of the photo samples collected from ~120 to ~850 m west of the river mouth were under ~10.0 mm. Beyond ~850 west of the river mouth, the average surface grain-size of the photo samples varied from 0.5 to 75.4 mm. The data indicate 56 (~57%) of the photo samples collected in the upper intertidal zone had an average surface grain size characterized as medium-to-very coarse sand (~0.4 to 2.0 mm) (Fig. 5), according to the Wentworth scale.

5. Discussion

5.1 Relationship between sample grain size and distance from river mouth

Grain-size distributions exhibit greater variability with increased distance east and west of the river mouth; this trend is evident in both photographic estimates and physically measured grain-size distributions (Fig. 3a, Fig. 5). Samples with a median grain size between 0.2 and 2.0 mm were observed along the upper intertidal zone of the Elwha drift cell up to ~1,500 m east and west of the river mouth. Baseline studies prior to the removal of the Elwha and Glines Canyon dams indicate the bulk of the shoreline consisted of coarse gravel and cobble (Warrick, 2009; Shaffer et al., 2013). The findings of this study indicate the grain-size distribution along the upper intertidal zone of the Elwha drift cell has changed since dam removal began in September 2011 and, for the purposes of this study, suggest the presence of suitable spawning substrate preferred by Pacific sand lance (Penttila, 1995 and 2007).

Although the median (D_{50}) has commonly been used as a reliable metric for true grain-size distribution, it has the potential to be skewed if even a few large pebbles are present in a given sample. Despite a seemingly large D_{50} value for some samples, it was also valuable to consider their respective sand fractions for the purposes of this study.

5.2 Relationship between sample grain-size and sand fractions

Overall, the compositions of the 27 physical samples with median grain sizes between 0.2 and 2.0 mm were mostly sand (Fig. 6a). Physical samples with a median grain-size between 0.2 and 0.47 mm had larger combined fine-to-medium sand fractions than samples between 0.47 and 2.0 mm (Fig. 6b). The samples between 0.47 and 2.0 mm had much more variable sand fractions, which generally consisted of larger coarse-to-very coarse sand fractions (Fig. 6b). The median of the cumulative sand fractions was

89.8%, which suggests that samples yielding a median grain size between 0.2 and 2.0 mm consist mostly of fine-to-very coarse sand. These finding suggest environmental conditions suitable for sand land spawning habitat, and, as previous studies indicate, sand lance prefer the bulk of sediment in the upper intertidal zone to consist of fine-to-very coarse sand (Penttila, 1995 and 2007).

In some of the locations, Cobble cam data suggests average surface grain-sizes far too large for sand lance spawning habitat, while the bulk of the sediment that was also collected for physical sampling consists of fine-to-very coarse sand. Although Cobble Cam did show similar trends to those of the physical samples, and it is a time- and cost-effective method for grain-size surveys in the field, the output is quite variable and may not be representative of the true grain-size distribution at a given sample site due to multiple confounding variables, such as wet sand, organic debris, shadows, and highly variable surface grain sizes.

5.3 Relationship between cumulative sand fractions and elevation

When comparing the 27 physical samples consisting of cumulative sand fractions >59% with their respective elevations, it appears the sand fractions of samples increase as the elevation (m MLLW) along the upper intertidal zone increases (Fig. 7). Eighteen of the samples were collected at elevations ranging from +1.33 and +2.22 m MLLW, which fall within the various ranges that previous studies report as preferable to spawning sand lance (Penttila, 1995; Moriarity et al., 2002; Penttila, 2007); these differing ranges may be due to varying tidal ranges at differing geographic locations. For the purposes of this study, the elevation range of +1.33 to +2.22 m MLLW was selected based on the geographic location of the study area and the ranges reported in previous studies.

The study area appears to have suitable sand lance spawning habitat ~1,230 m west and ~1,500 m east of the river mouth (Fig. 8). Based on the cumulative sand fractions at each of the locations, it appears the most conducive habitat is ~500 m west and ~1,000 m east of the river mouth. This trend was apparent based on sampling during 12 and 13 April 2014, and it suggests that sand being discharged to the shorelines from the previous reservoirs is being deposited along portions of the upper intertidal zone of Freshwater Bay and the Elwha Bluffs, which may be suitable for sand lance spawning habitat based on grain-size distribution, bulk sand fractions, and elevation (Fig. 8). Additionally, a sand lance was found during subaqueous sediment sampling of the Elwha nearshore on 7 May 2014 at ~11.5 m (unpublished data), which indicates sand lance are present near the study area.

6. Conclusions

Although Pacific sand lance have not been observed spawning in the upper intertidal zone at or adjacent to the Elwha delta as of 2013 (Shaffer et al., 2013), this study reveals multiple indicators that the morphological changes along the shoreline after removal of the dams may be associated with the expansion and/or restoration of suitable sand lance spawning habitat. It is well documented that the shoreline prior to the dam removals consisted mainly of gravel-to-coarse cobble (Warrick et al., 2009; Shaffer et al., 2013), but the findings of this study indicate median grain-size distributions between 0.2 and 2.0 mm in multiple locations at and adjacent to the delta. Additionally, the same sample locations had bulk sand fractions >59% and were found at elevations between +1.33 and +2.22 m MLLW, which are known sand lance spawning habitat preferences (Penttila, 1995; Moriarity et al., 2002; Penttila, 2007). While recent spawning surveys did not find any eggs present along the Elwha upper intertidal outside of the subject study area (Shaffer et al., 2013), the observed presence of sand lance at the Elwha nearshore (unpublished data) indicates their potential use of this habitat in the future.

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Figures

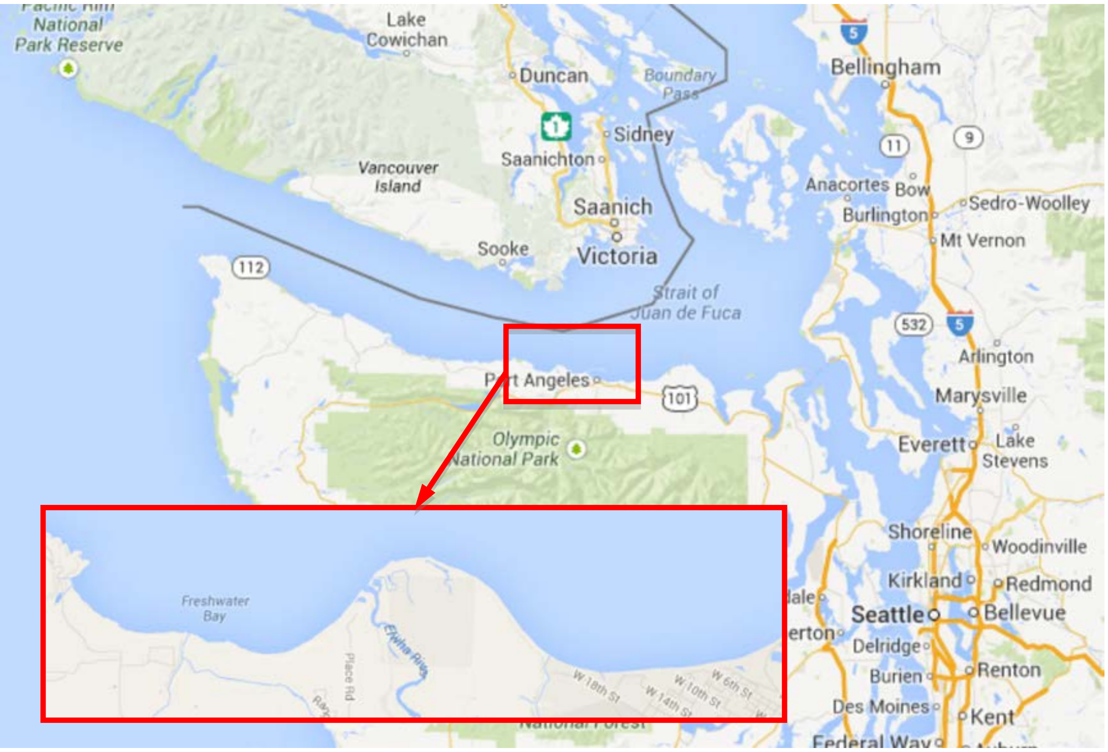

Figure 1a. Olympic Peninsula, Washington, USA. The study area is outlined in the red box and the inset is zoomed in on the general study area. Base maps from Google Maps, 2014.

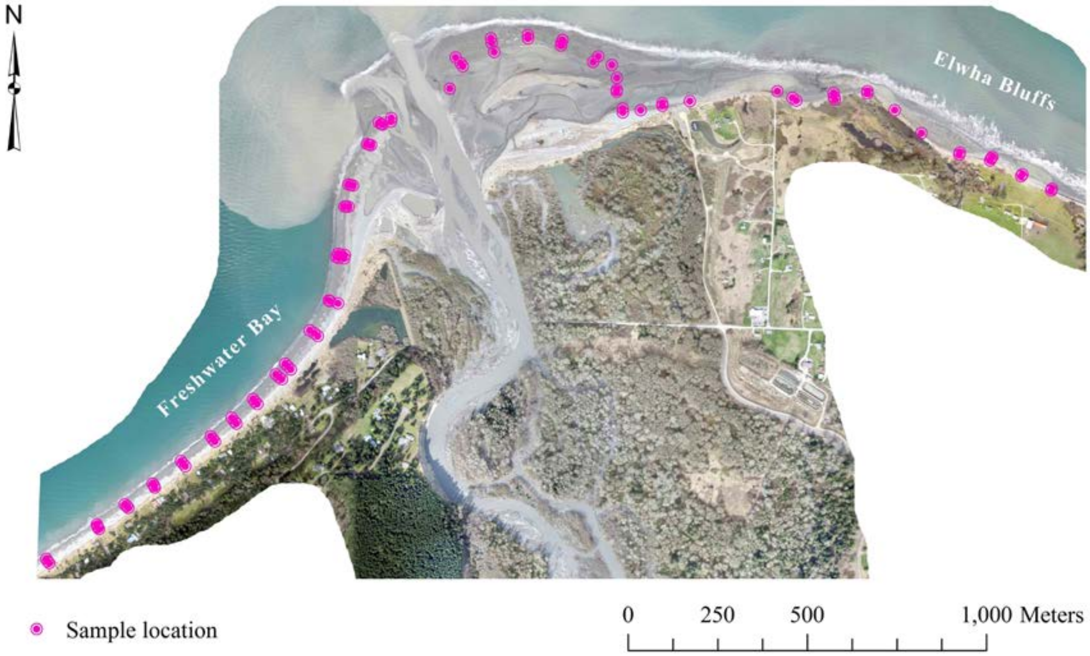

Figure 1b. All sample locations in the study area. Base map courtesy Andy Ritchie, Olympic National Park, 2014.

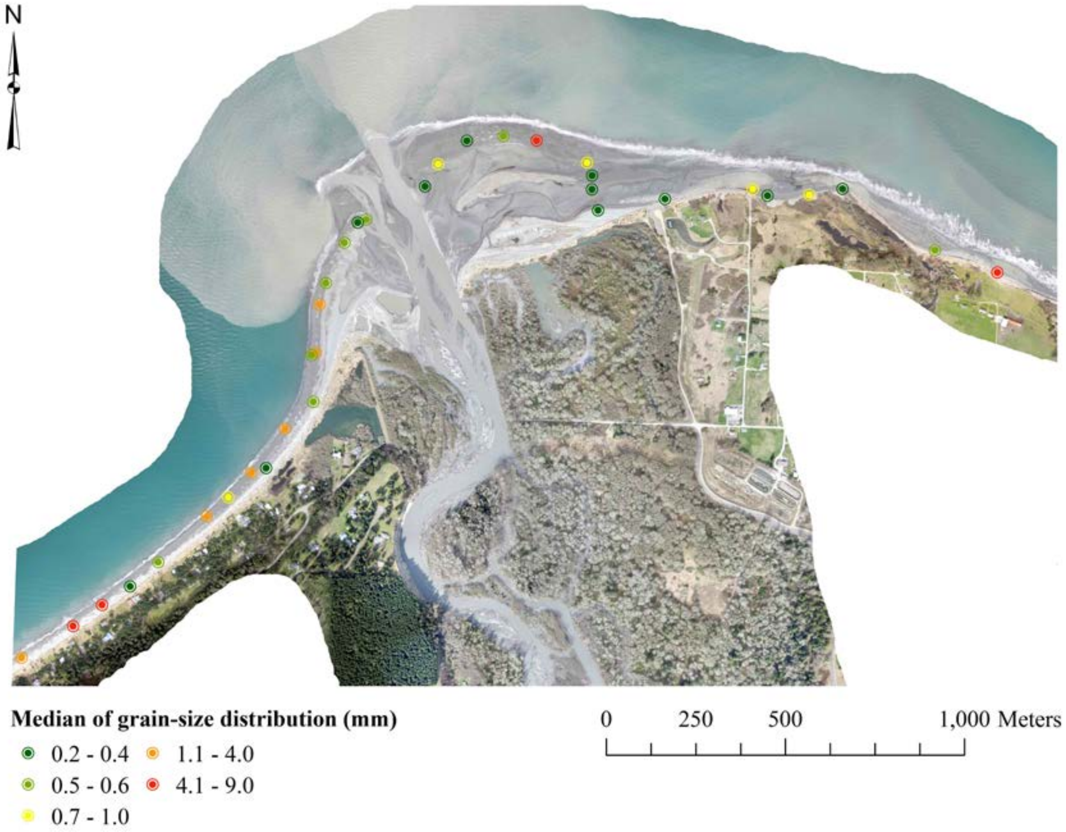

Figure 2. Locations of all physical samples collected along the study area. Base map courtesy Andy Ritchie, Olympic National Park, 2014.

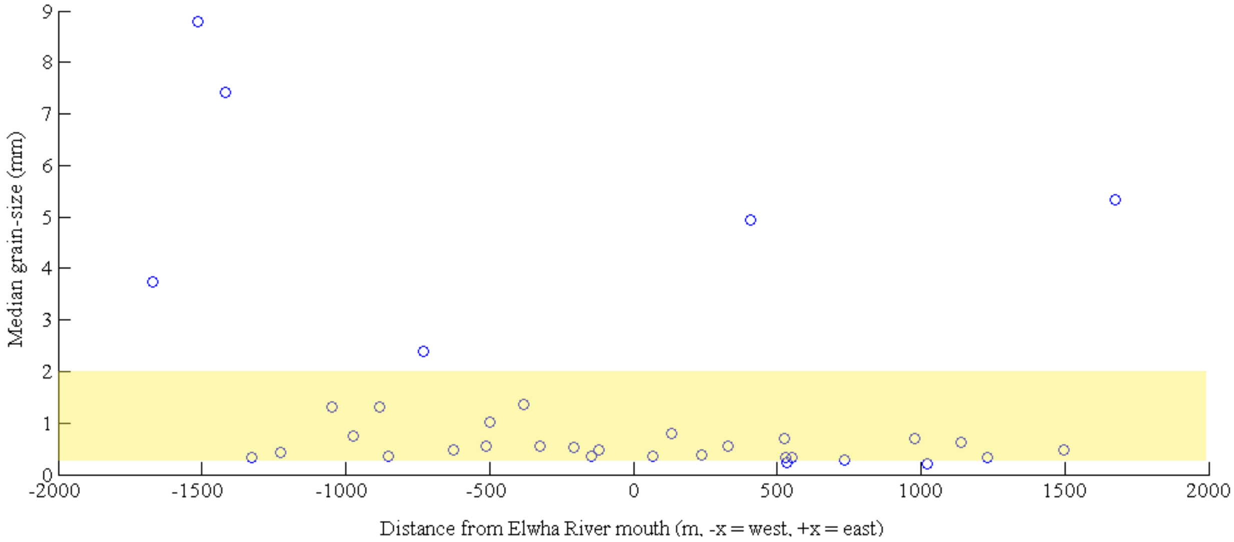

Figure 3a. Relationship between median grain-size distribution and distance from river mouth. The blue circles represent the physical samples; positive x-values represent their respective distances east of the river mouth and negative x-values represent their respective distances west of the river mouth. The yellow highlighted area represents a grain-size range of fine-to-very coarse sand (~0.2 to 2.0 mm).

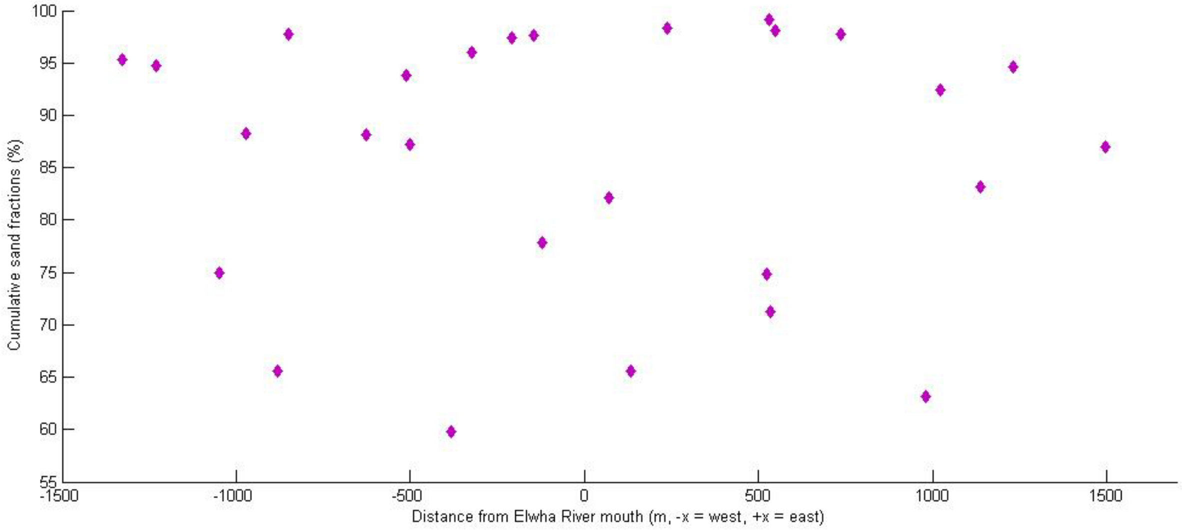

Figure3b. Relationship between cumulative sand fractions (fine-to-very coarse sand) and distance from river mouth. The magenta diamonds represent the 27 physical samples with median grain sizes ranging from 0.2 to 2.0 mm; positive x-values represent their respective distances east of the river mouth and negative x-values represent their respective distances west of the river mouth.

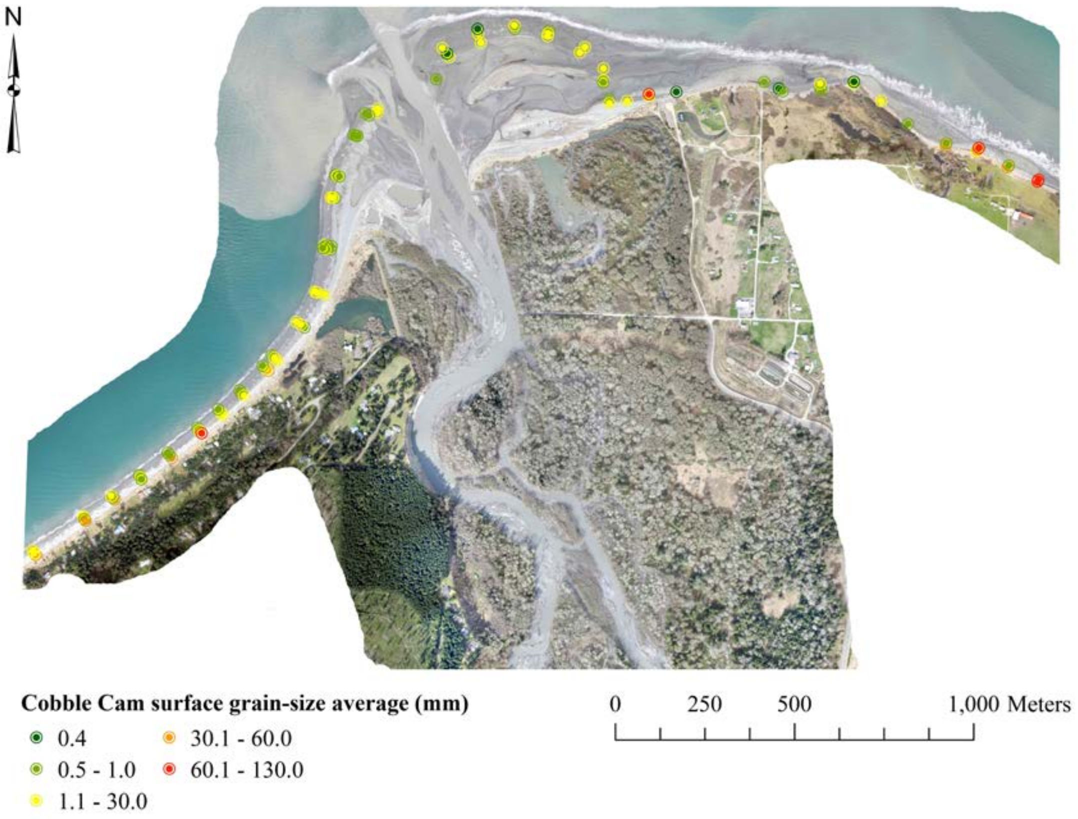

Figure 4. Locations and average surface grain-size of all photo samples collected in the study area. Base map courtesy Andy Ritchie, Olympic National Park, 2014.

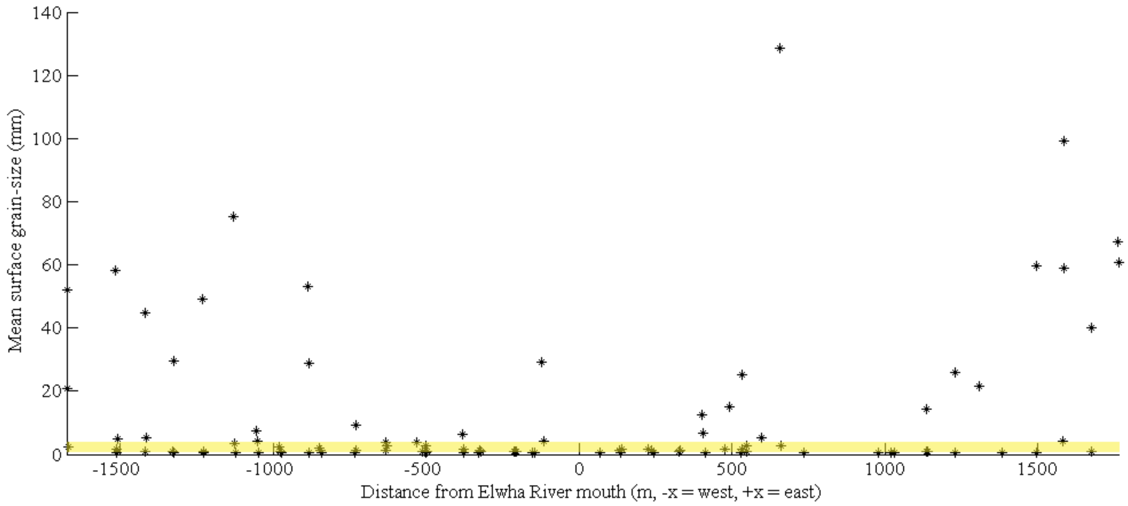

Figure 5. Relationship between average surface grain size and distance from river mouth. The black asterisks represent the photo samples; positive x-values represent their respective distances east of the river mouth and negative x-values represent their respective distances west of the river mouth. The yellow highlighted area represents a grain-size range of medium-to-very coarse sand (~0.4 to 2.0 mm).

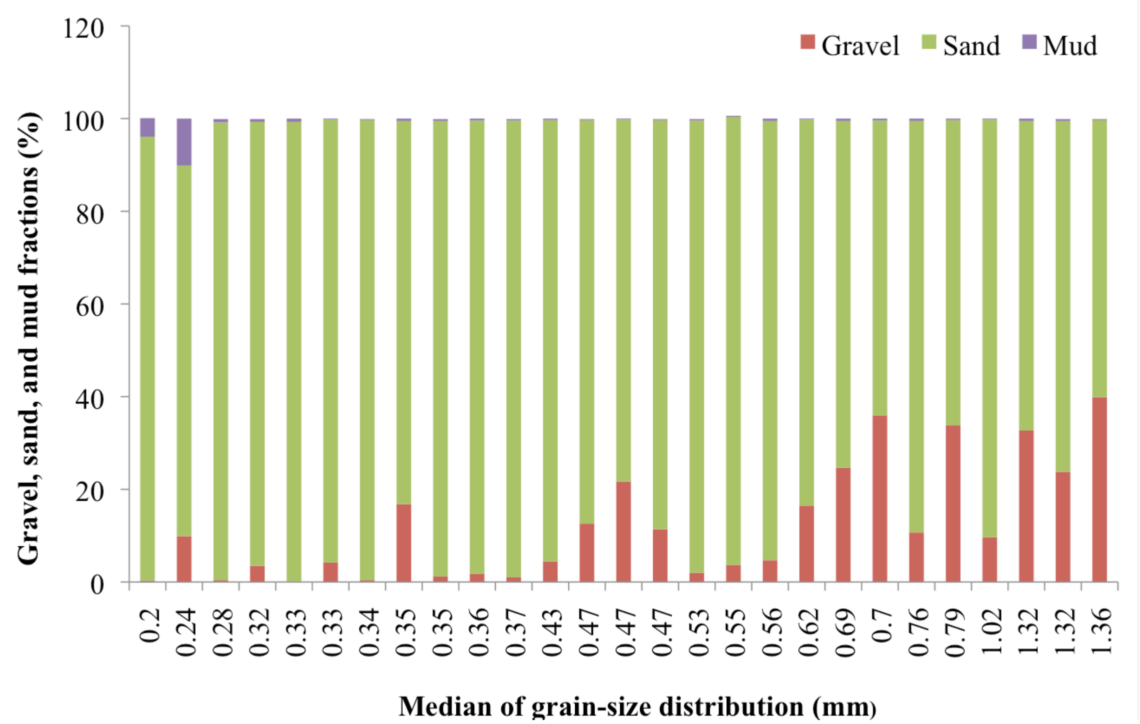

Figure 6a. Relationship between gravel, sand, and mud fractions and median of grain-size distribution.

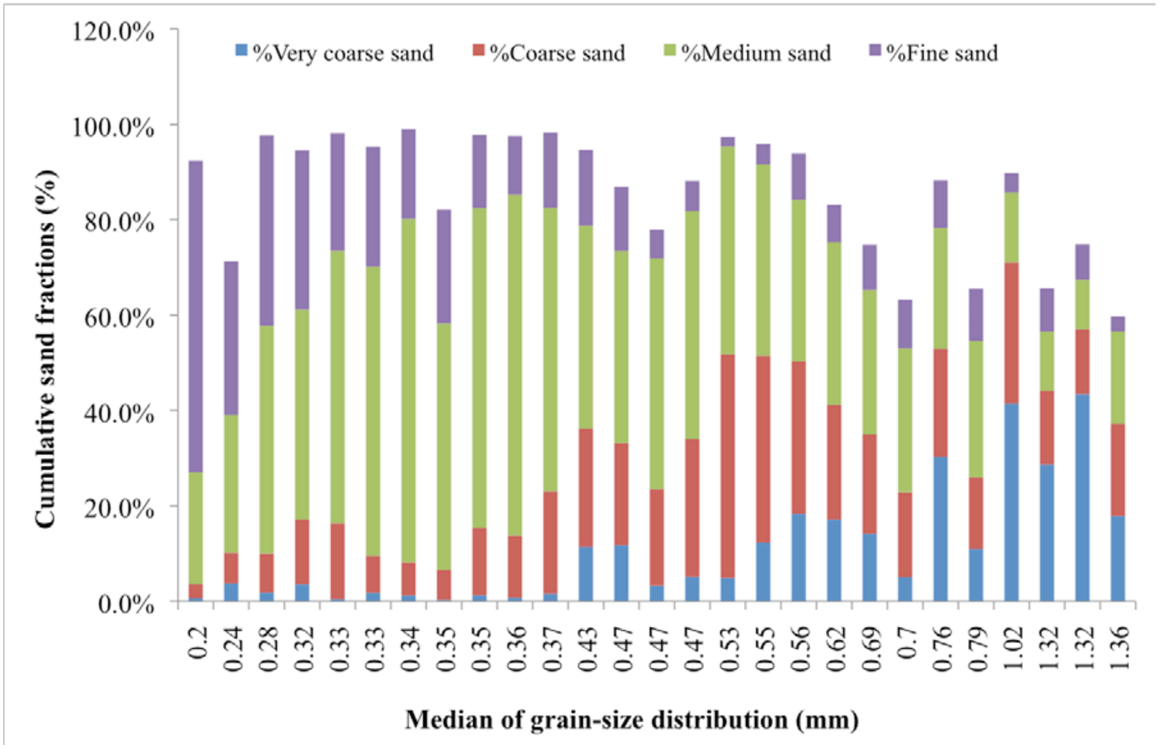

Figure 6b. Relationship between sand fractions and median of grain-size distribution.

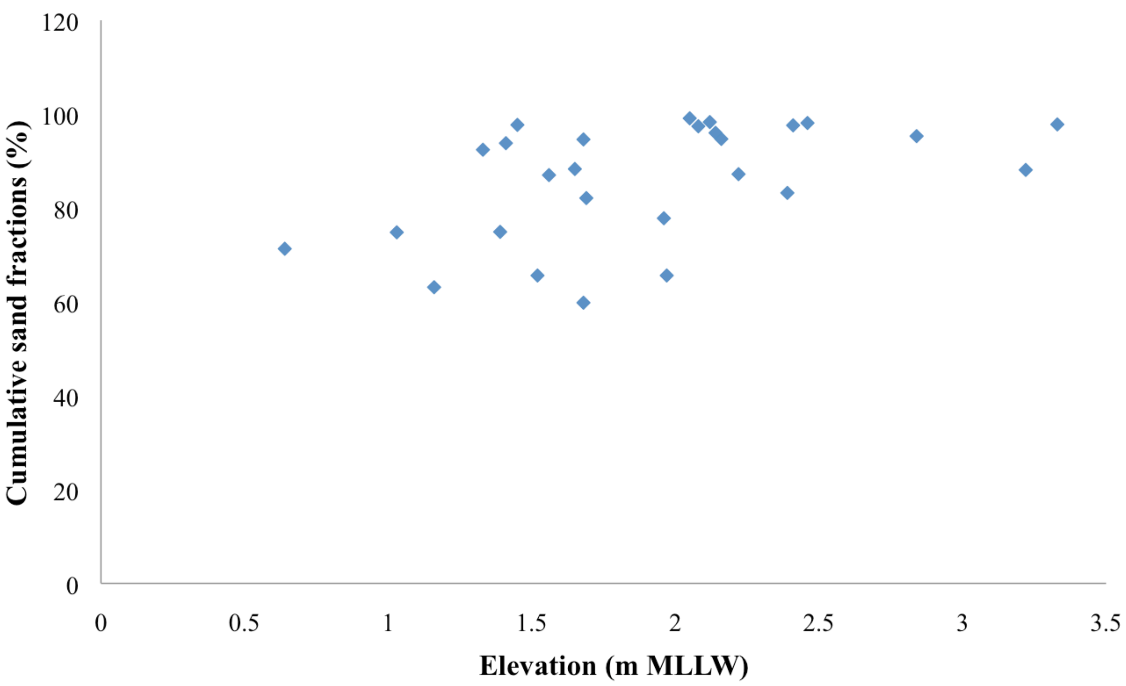

Figure 7. Relationship between cumulative sand fractions (sum of fine-to-very coarse sand) and elevation (m MLLW) for samples having a median diameter between 0.2 and 2.0 mm.

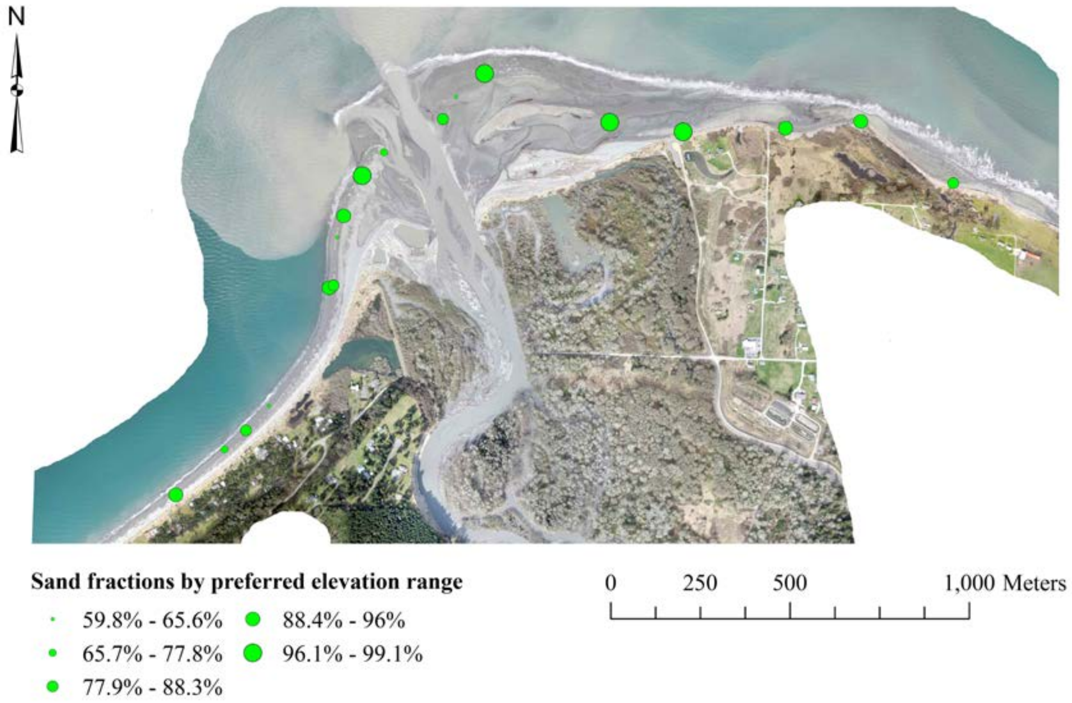

Figure 8. Map of sample locations with preferred median grain-size distributions between 0.2 and 2.0 mm, bulk sand fractions greater than ~60%, and preferred elevation range between +1.33 and +2.22 m MLLW that are conducive to sand lance spawning. The locations extend ~1,230 m west and ~1,500 m east of the river mouth.