

**Beach morphology and grain-size changes over short timescales at the Elwha River  
Delta, WA**

Kevin J. Simans<sup>1,2</sup>

Marine Sedimentary Processes Apprenticeship  
*Spring 2013*

<sup>1</sup> Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250

<sup>2</sup> School of Oceanography, University of Washington, Seattle, WA 98195

Contact Information:

Kevin Simans

University of Washington

School of Oceanography

Seattle, WA 98195

kevdude2@uw.edu

*Keywords:* Elwha River, dam removal, impacts, beach profile, beach morphology, grain size, erosion, sediment transport.

## **Abstract**

The Elwha River dam removal project is the largest such project carried out in the U.S., and offers a unique opportunity to study the effects of a sudden sediment flux from the river to the coastal environment. A huge amount of new littoral sediment has accumulated at the river mouth; however, it is unknown whether it will migrate eastward and accrete on the chronically eroding beaches, and on what timescales this will occur. In this study, grain-size data and beach elevation profiles were collected along three shore-perpendicular transects east of the river mouth in early March, and again for three consecutive days in mid-April, with the goal of observing short-term changes. Physical sediment samples were collected for grain-size analysis, CobbleCam autocorrelation was used to obtain mean grain size from digital photographs, and beach profiles were constructed for these periods of spring tides and large waves. Results indicate that the upper foreshore of the transect farthest from the river mouth (Line 198) lost up to 0.38 m of elevation between the two study periods, and the lower foreshore gained up to 0.41 m elevation. In addition, slope breaks on all transects migrated cross-shore, and foreshore sediments coarsened, both temporally (during the three-day April sampling period) and spatially (down the foreshore). These results demonstrate that daily changes can occur on the Elwha beaches. This study adds to our understanding of how new sediments will influence this region, and possibly of mixed grain-size beach dynamics in general.

## **1. Introduction**

The Elwha River Delta is a complex system affected by a combination of atmospheric, oceanic, and terrestrial forcing mechanisms from the river and the Strait of Juan de Fuca (SJF) (Cannon, 1978; Warrick et al., 2009a). However, anthropogenic

alterations, namely the two dams constructed on the river in the early 20<sup>th</sup> century, have changed this system (Kloehn et al., 2008; Shaffer et al., 2008; Warrick et al., 2009a; Wunderlich et al., 1994). The damming of rivers has been shown to dramatically reduce sediment supply to their coastal environments, especially deltas and beaches along the littoral drift cell (Anthony & Blivi, 1999; Hinderer, 2012). At the Elwha, the beaches downdrift (east) of the river mouth are characterized by a shallow-sloped low-tide terrace composed of large gravel to boulders, and a steep foreshore composed of sand to gravel. These beaches have been starved of fine-grained sediments for decades, and are chronically eroding at rates exceeding 1 m yr<sup>-1</sup> (average from 1990-2006; Warrick et al., 2009a). Ediz Hook is a large spit which forms the termination of the Elwha drift cell and acts as a natural barrier to the important deep-water harbor of Port Angeles, WA (Galster & Schwartz, 1990). This spit has also been experiencing erosion in recent decades, threatening both the harbor and the US Coast Guard base near its end.

This area has been intensely monitored for change on a seasonal to annual basis, both before and during dam removal. However, no studies have yet analyzed change during dam removal on a day-to-day timescale in order to place daily changes in the broader context of beach erosion and morphology change. Very short-term changes may be used to help understand changes over longer timescales, especially when the processes that influence the region can be correlated with these changes. The aim of this study is to build our understanding of sediment movement and beach variations during dam removal, but it will also contribute to our understanding of mixed beach morphodynamics in general, which is an underrepresented topic in beach dynamics literature.

It is thought that the Elwha beaches are very dynamic, and are becoming even more so as new sediment accumulates and migrates throughout the area (Miller, 2013). This study aims to evaluate short-term beach and grain-size changes on daily and monthly timescales, and compare two different methods of grain-size analysis. Data from both methods of grain-size collection are assessed over a range of grain sizes, and their relative accuracies and error sources are discussed.

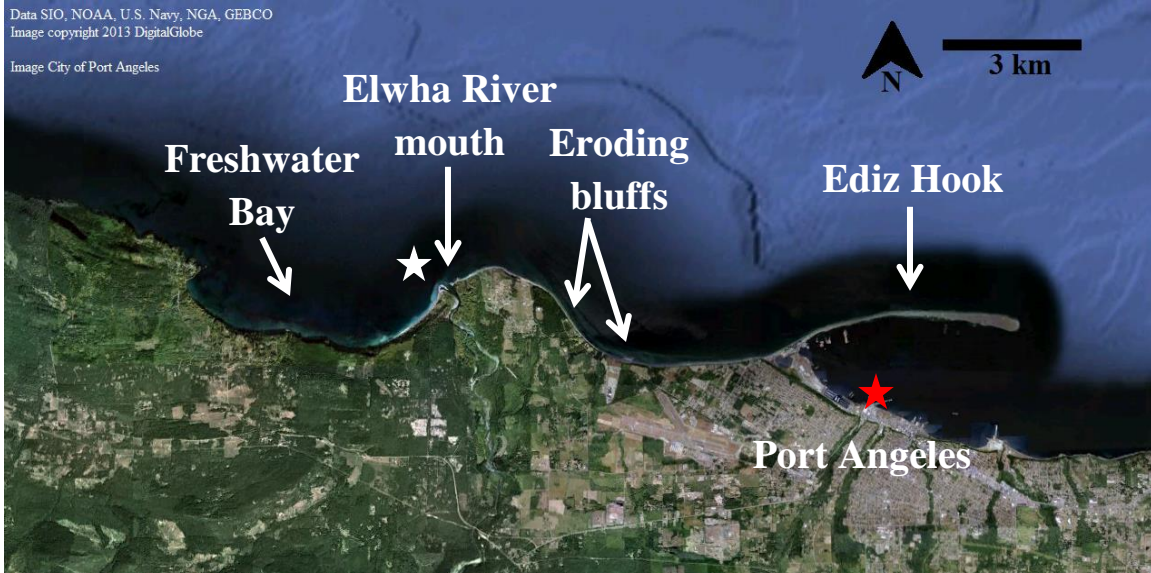
## **2. Background**

### *2.1 Regional setting and conditions*

The Elwha River is a small, 72-km-long, mountainous river located on the Olympic Peninsula of Washington State, USA (Fig. 1). It drains an area of 824 km<sup>2</sup> and is a major source of littoral sediments to the beaches and marine environment near its mouth in the Strait of Juan de Fuca (SJF). Sediment transport on the Elwha Delta is influenced by tidal, riverine, wave, and wind forcing mechanisms. This region experiences mixed semi-diurnal tides with an average spring range of 2.15 m (tidesandcurrents.noaa.gov). The discharge of the Elwha River varies seasonally, with a recorded minimum of 0.28 m<sup>3</sup> s<sup>-1</sup> (10/3/1938), overall mean of 42.7 m<sup>3</sup> s<sup>-1</sup>, and recorded maximum of 1178 m<sup>3</sup> s<sup>-1</sup> (11/18/1897) from the McDonald Bridge gaging station (#12045500; pubs.usgs.gov). Pacific Ocean swell enters the SJF and hits these beaches at an oblique angle, generating an eastward longshore transport cell from the river mouth to Ediz Hook (Galster & Schwartz, 1990), a 4.8-km-long spit extending into the SJF from Port Angeles (east of the river mouth) (Fig. 2). Locally generated wind waves also play



**Figure 1.** Map of Western Washington, USA, including the study area, Elwha River, and NOAA buoys used to obtain wave data (Neah Bay #46087, Hein Bank #46088; ndbc.noaa.gov).



**Figure 2.** Map showing the study area, and identifying important features. The white star shows the location of the bottom tripod, and the red star shows the location of the NOAA tide station (#9444090; [tidesandcurrents.noaa.gov](https://tidesandcurrents.noaa.gov)).

an important role in sediment transport, especially during spring and summer when northwesterly winds blow down the long fetch of the SJF from the Pacific Ocean.

## *2.2 Chronology and beach form*

Two hydroelectric dams were constructed on the river: the Elwha Dam in 1913 at river kilometer 7.9, and the Glines Canyon Dam in 1927 at river kilometer 21.6. These dams effectively stopped most of the river sediment from reaching the Elwha littoral cell. As a result, these beaches have been chronically eroding at an average rate of about 0.6 m yr<sup>-1</sup> from 1939-2006, increasing to an average of 1.4 m yr<sup>-1</sup> from 1990-2006 (Warrick et al., 2009a). Lack of fine sediment input from the river has also resulted in a coarsening of the east beach, creating a dissipative low-tide cobble terrace with a shallow slope, and a narrow, reflective, and steeper-sloped foreshore composed of sand to gravel (Fig. 3; Warrick et al., 2009a). Generally, research in coarse and mixed beach dynamics is lacking compared to fine-grained beaches, especially over short timescales (e.g., Buscombe & Masselink, 2006). Thus, this dynamic beach offers a unique opportunity to study the effects and response of a sudden change in sediment input to the system.

In 1992, Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, inducing plans to fully remove both dams from the river in order to reestablish historically abundant salmon populations (Wunderlich et al., 1994). However, another result of this project is the renewed availability for the river to transport large volumes of sediment to its lower reaches, delta, and ultimately to the entire littoral cell. An estimated  $26 \times 10^6 \text{ m}^3$  of sediments had accumulated behind the two dams before they were removed (NPS, 2012). As of April 2013, the Elwha Dam has been completely removed,



**Figure 3.** Photograph of east beach looking northwest, with major features labeled. The Elwha River mouth is just out of the frame to the left (west).

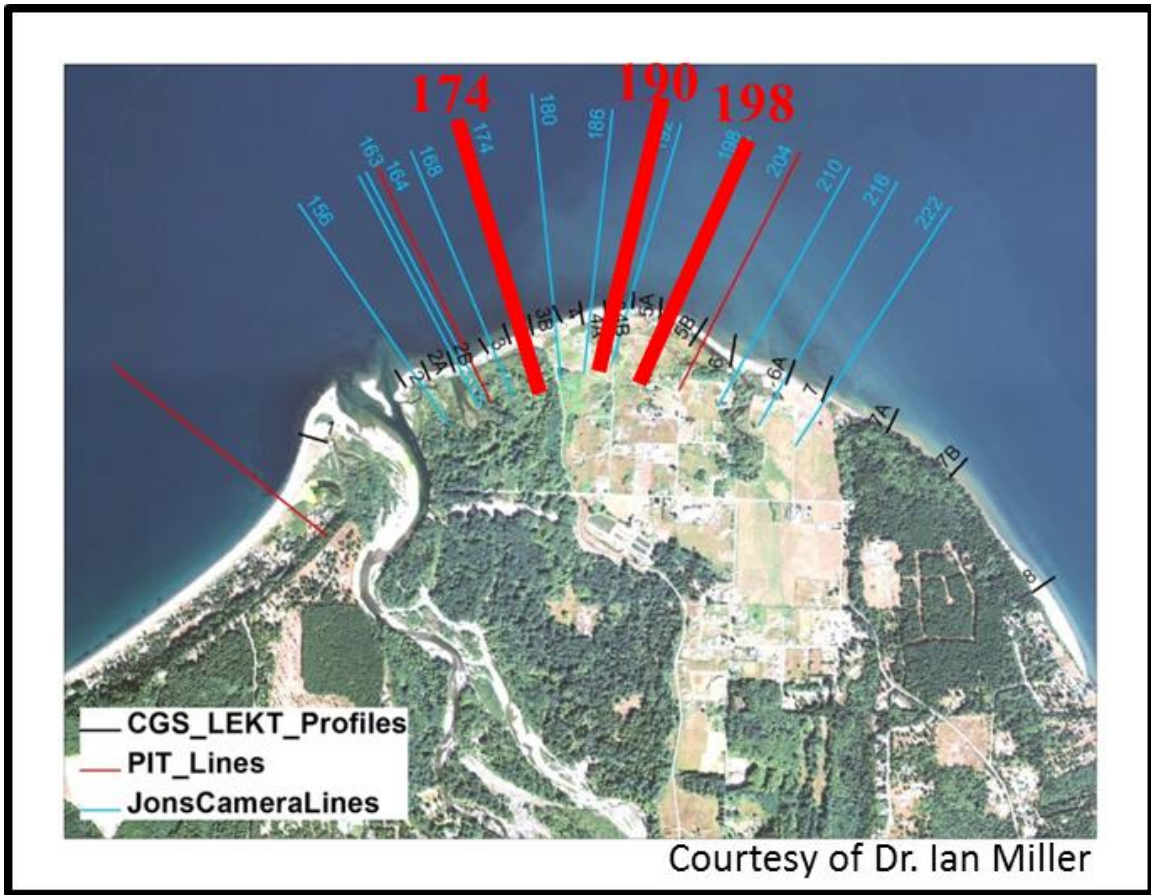
and the Glines Canyon Dam is scheduled to be completely removed in September 2013. Dramatic changes have already begun near the river mouth, however it is still unclear whether this sediment will be transported eastward and begin to slow or reverse beach erosion, and on what timescales this can be expected to occur.

### **3. Methods**

#### *3.1 Beach profiles*

Three transect lines running perpendicular to the shoreline were occupied on either 6 or 7 Mar (Lines 174, 190, and 198; Fig. 4). Lines started at or behind the high tide berm and ended at the water line at the time of the survey. Profile data was collected as per the RTK-DGPS method used by Miller et al. (2011), which has an estimated overall vertical accuracy of about  $\pm 20$  cm. Beach profiles were collected using a pole-mounted RTK-DGPS system, which was walked along each transect line to collect elevation points at  $\sim 1$  m increments. Data were then adjusted to the MLLW datum.

These transects were occupied again on three consecutive days from 12-14 Apr (besides Line 198 on 12 Apr, due to the quickly rising tide). For these surveys, a Lasermark automatic self-leveling rotary laser was set up on the foreshore, and a stadia rod with attached universal laser detector was used to collect beach elevation data at regular increments along each transect (1 m increments on the berm and foreshore, and 3-5 m increments on the cobble terrace). At the start of this study period, stakes were pounded into the sediment at the landward end of each transect, and their elevations were surveyed with the RTK-DGPS system. The elevation data from this study period was then adjusted to the MLLW datum by correlating the top elevations to those measured via



**Figure 4.** Aerial image of the Elwha River Delta showing regularly surveyed transect lines. Lines occupied in this study are highlighted in red.

RTK-DGPS. It can be assumed that these stakes were static through the three-day period, since the water level never reached close to their elevations, and they were pounded at least 20 cm into the ground.

### *3.2 Grain-size data*

Grain-size data along these transects was determined using the CobbleCam autocorrelation technique described by Warrick et al. (2009b) on digital photographs, and sieve analysis on physical samples in accordance with the Wentworth grain size scale. For CobbleCam, photographs were taken with a 12.1-megapixel Canon PowerShot oriented perpendicular to the beach, at the same intervals along each transect at which elevation points were taken. Rubin (2004) recommended that the camera be held a constant distance from the bed regardless of grain size. However, variable heights yielded more accurate results on these highly mixed beaches (i.e., closer to the bed to resolve small sand grains, and higher off the bed to include many large cobbles in the photo). All photos included a scale bar placed on the ground, which was used to correlate pixels with actual distance on the beach, and sticks and woody debris were removed from the photo area as much as was reasonably possible. An area of each photo was cropped to include as little debris as possible, and the mean grain size within each crop area was determined using CobbleCam scripts.

A total of thirteen physical samples of beach sediment were also obtained along the three transects on 13 and 14 Apr and analyzed in the lab. Samples were taken on the active foreshore and, in the case of Line 174, on the sand flat seaward of the cobble terrace. A 10 cm x 10 cm square was traced on the sediment and the top 1-2 cm was collected. Samples from the foreshore were then dried and dry-sieved from  $-4\phi$  to  $4\phi$  in

1 $\phi$  increments using a Ro-Tap sieve shaker for about ten minutes per sample. Samples from the sand flat were subsampled (~30 g) and wet-sieved at 4 $\phi$ . The sand fraction was dry-sieved by the same procedure as the dry beach samples, and the mud fraction was analyzed via the pipette method (UW, 1998). Grain-size statistics were calculated by Folk and Ward (1957) methods, using the GRADISTAT program (Blott, 2001).

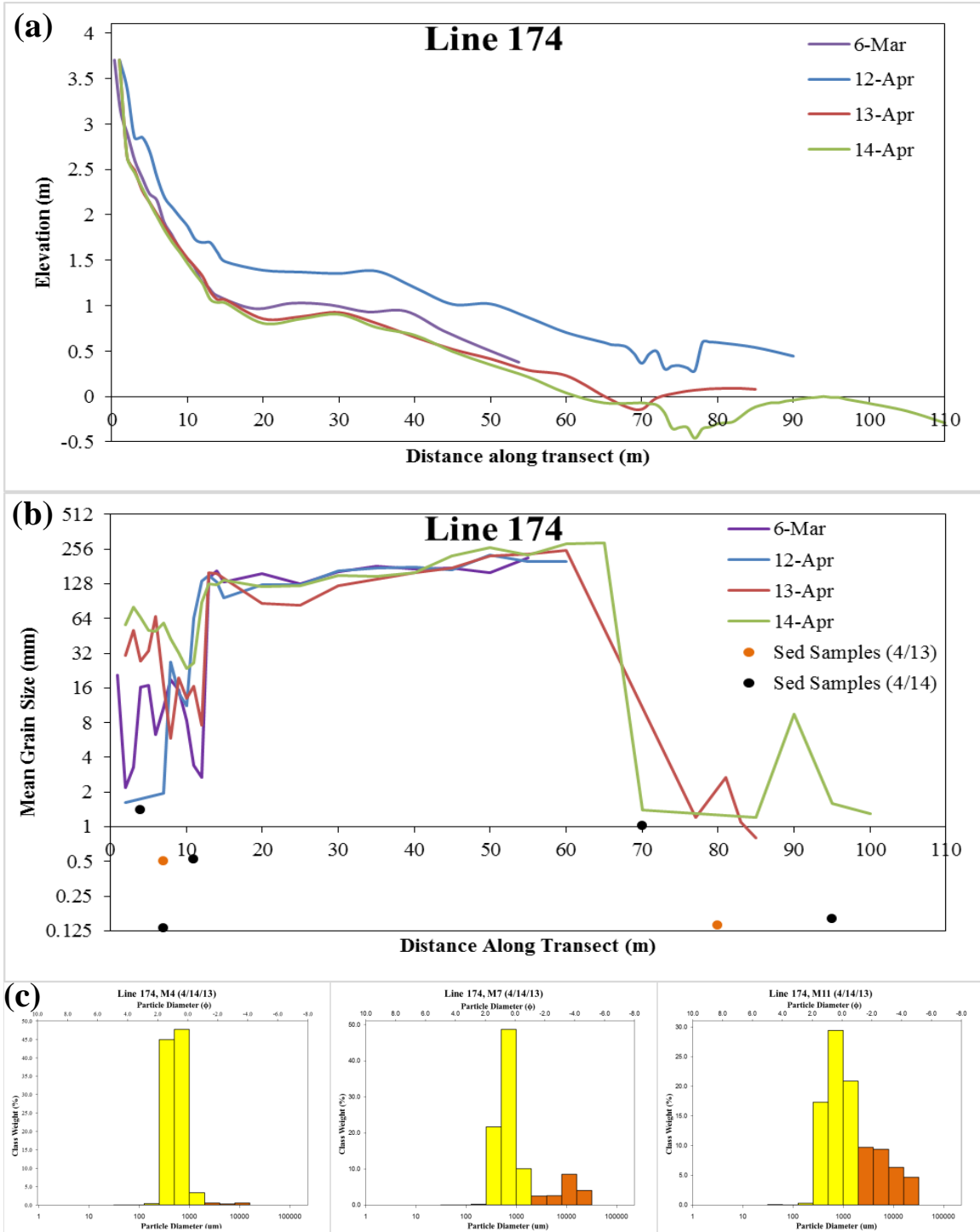
### *3.3 Waves and tides*

Wave data was obtained from a seabed-mounted tripod (Palinkas et al., 2010) deployed on the submarine delta near the river mouth (Fig. 2). Supplementary wave data was obtained from NOAA buoys at Neah Bay and Hein Bank (Stations #46087 and #46088; Fig. 1; ndbc.noaa.gov). Observed water level data was obtained from the NOAA tide station in Port Angeles, WA (#9444090; tidesandcurrents.noaa.gov).

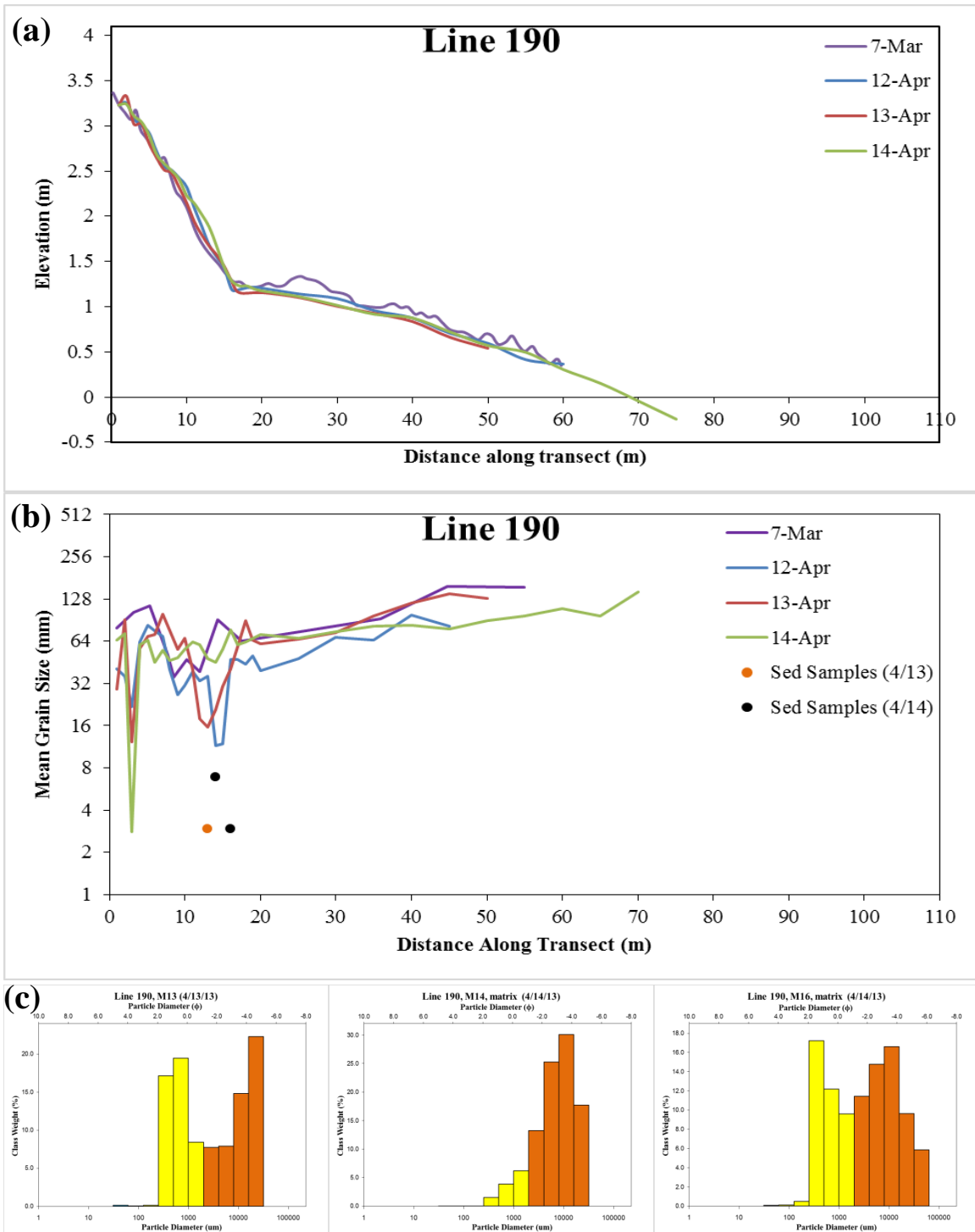
## **4. Results**

### *4.1 Beach profiles and observations of change*

Beach profiles extended from the high tide berm or backshore (3.3 to 3.7 m MLLW) to the water line at the time of the survey (-0.3 to 0.5 m MLLW). Profiles for Line 174 had steep elevation decreases (slope ~0.15) from the top of the profile (3.7 m MLLW) to the bottom of the foreshore (average elevation 1.3 m MLLW) (Fig. 5a), and a depression existed around meter 20 (herein labeled as M20). Elevations decreased seaward at a shallower slope of approximately 0.02 until reaching a runnel at the seaward end of exposed cobbles. There was then a small increase in elevation near the end of the profiles. Profiles for Line 190 had a steep foreshore (top elevation 3.2 m MLLW; average bottom elevation 1.2 m MLLW) with an average slope of 0.15 (Fig. 6a). A defined



**Figure 5.** Transect Line 174, east of the Elwha River mouth. Plotted are elevations relative to MLLW (a), mean grain size from CobbleCam analysis with locations and mean grain sizes of sediment samples (b), and selected grain-size distribution graphs from sediment sample analysis (c). For (c), yellow bars indicate sand fractions and orange bars indicate gravels.



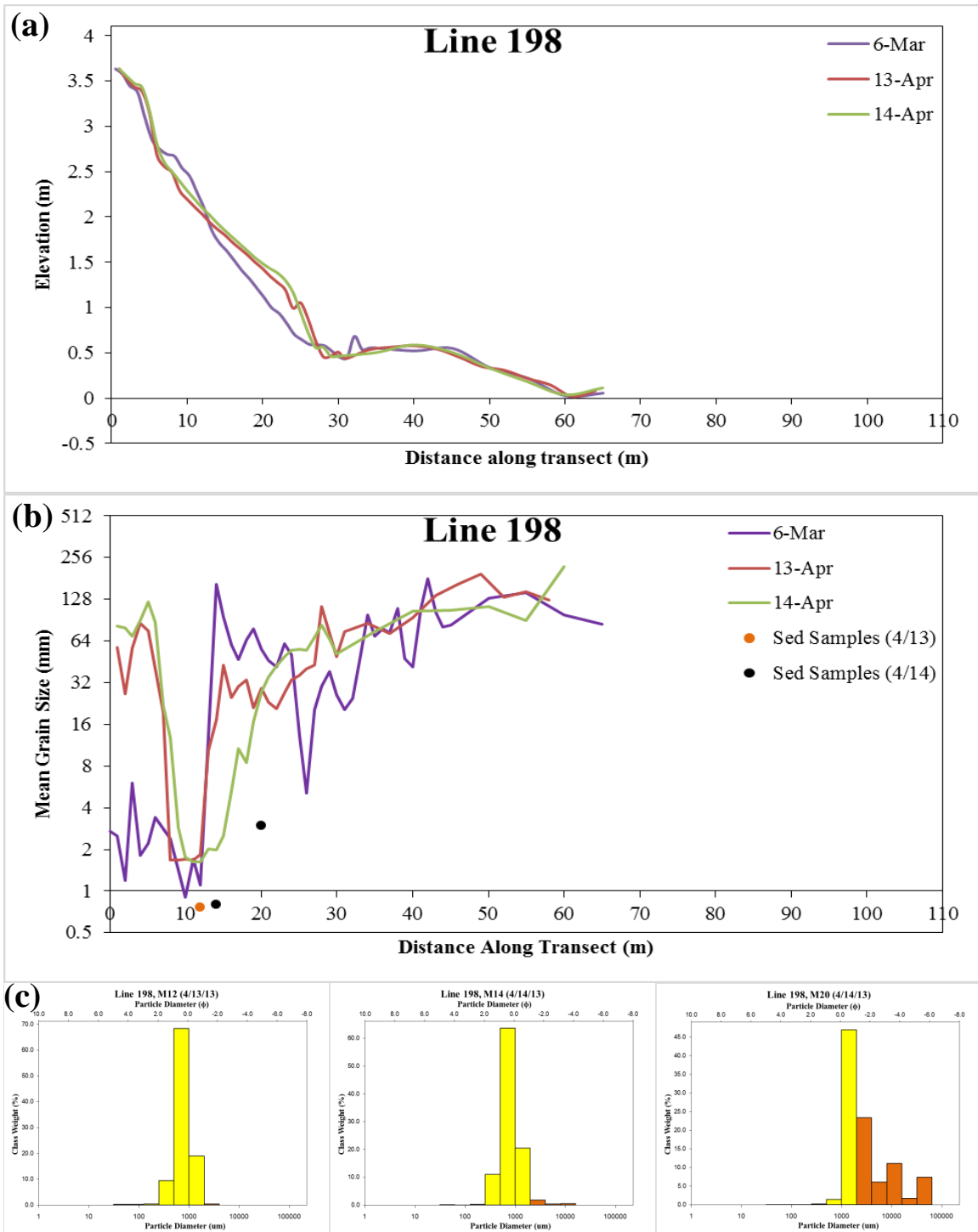
**Figure 6.** Transect Line 190, east of the Elwha River mouth. Plotted are elevations relative to MLLW (a), mean grain size from CobbleCam analysis with locations and mean grain sizes of sediment samples (b), and grain-size distribution graphs from sediment sample analysis (c). For (c), yellow bars indicate sand fractions and orange indicates gravels.

transition existed to the shallower-sloped terrace, which steadily decreased in elevation seaward. Profiles for Line 198 had a somewhat terraced foreshore (top elevation 3.6 m MLLW; average bottom elevation 0.6 m MLLW) with regions of differing slopes, followed by a defined transition to the low-tide terrace where there existed a depression (Fig. 7a). Past this depression, the profiles steadily decreased in elevation seaward.

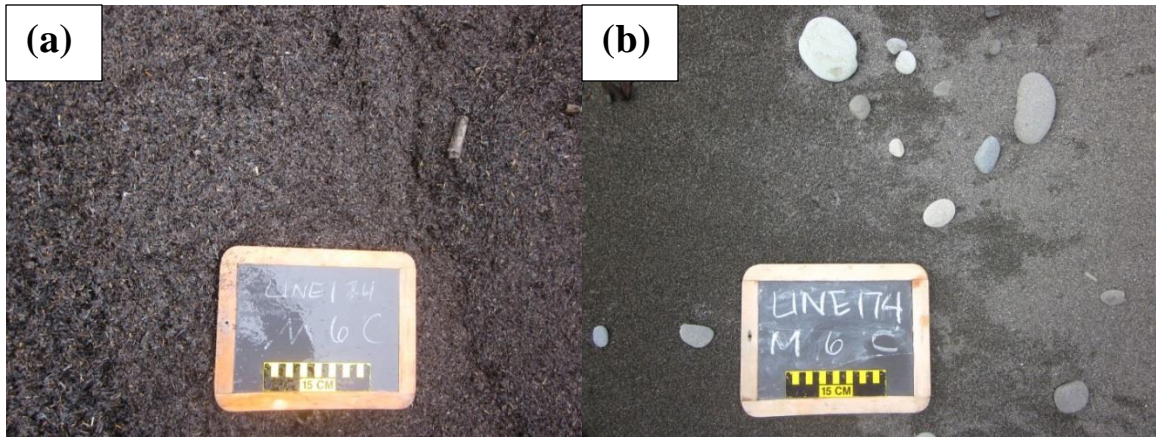
The most change in the profiles between the March and April study periods took place on the foreshore of Line 198 (Fig. 7a). Elevations on the upper foreshore decreased from 6 Mar to 13 Apr between M6 and M13, and elevations on the lower foreshore increased between M14 and M27. Maximum elevation changes were documented as -0.38 m at M9, and +0.41 m at M25.

Visual observations of beach zones and sediment size transitions along each transect revealed temporal changes. On Line 174, the slope break moved seaward from M11 on 12 Apr to M13 on 13 Apr, and then remained in the same position from 13 Apr to 14 Apr. On Line 190, this boundary moved landward, from M19 on 12 Apr, to M17 on 13 Apr, to M16 on 14 Apr. This boundary also moved landward on Line 198, from M28 on 13 Apr to M26 on 14 Apr. The sand flat at the seaward extent of Line 174 began at M59.5 on 12 Apr, and at M69 on 14 Apr. A runnel existed in this flat, which widened over the survey period, from 5 m wide on 12 Apr to 10 m wide on 14 Apr.

On 12 Apr, a shoreline-parallel berm composed of woody organic matter existed on top of beach sediment between M3 and M7 on Line 174 (Fig. 8a). Crude depth measurements of this berm at each meter along Line 174 provided an approximate cross-sectional area of  $0.625 \text{ m}^2$ . The next day on 13 Apr, this material was completely absent from Line 174 (Fig. 8b). From visual observations, this organic material extended



**Figure 7.** Transect Line 198, east of the Elwha River mouth. Plotted are elevations relative to MLLW (a), mean grain size from CobbleCam analysis with locations and mean grain sizes of sediment samples (b), and grain-size distribution graphs from sediment sample analysis (c). For (c), yellow bars indicate sand fractions and orange indicates gravels.



**Figure 8.** Digital photographs of the beach on Line 174 at M6, taken at the same location on 12 Apr (a) and 13 Apr (b).

hundreds of meters along the foreshore to the west of Line 174, and turned into a series of 8-12 separate berms closer to the river mouth. Some of these berms were at least 1 m deep and had runnel-like features between them that were filled in with organic material. This larger area of organic material persisted through the study period with no noticeable changes.

## *4.2 Grain size*

### *4.2.1 CobbleCam*

According to CobbleCam analysis, grain sizes on Line 174 ranged from sands to pebbles on the foreshore, with a sharp transition to cobbles on the low-tide terrace which coarsened seaward (Fig. 5b). Another sharp transition to fine sands occurred near the seaward extent of the transect. On Line 190, extremely variable grain sizes were observed on the berm and foreshore, transitioning to cobble-sized clasts on the low-tide terrace which coarsened seaward (Fig. 6b). On Line 198, grain sizes varied from sand to cobble across the foreshore, and transitioned to mostly cobble on the low-tide terrace, which coarsened seaward (Fig. 7b). The foreshore of Line 174 experienced coarsening on both short (12-14 Apr) and medium (6 Mar to 12 Apr) timescales (Table 1). The foreshores of Lines 190 and 198 fined on medium timescales (7 Mar-12 Apr for Line 190; 6 Mar-13 Apr for Line 198) and then showed coarsening trends during the April study period.

### *4.2.2 Physical samples*

Physical sediment samples were taken on the sand and gravel foreshore of each transect, and thus are only representative of change on the foreshore region. According to grain-size analyses, Line 174 coarsened seaward across the foreshore, and became more

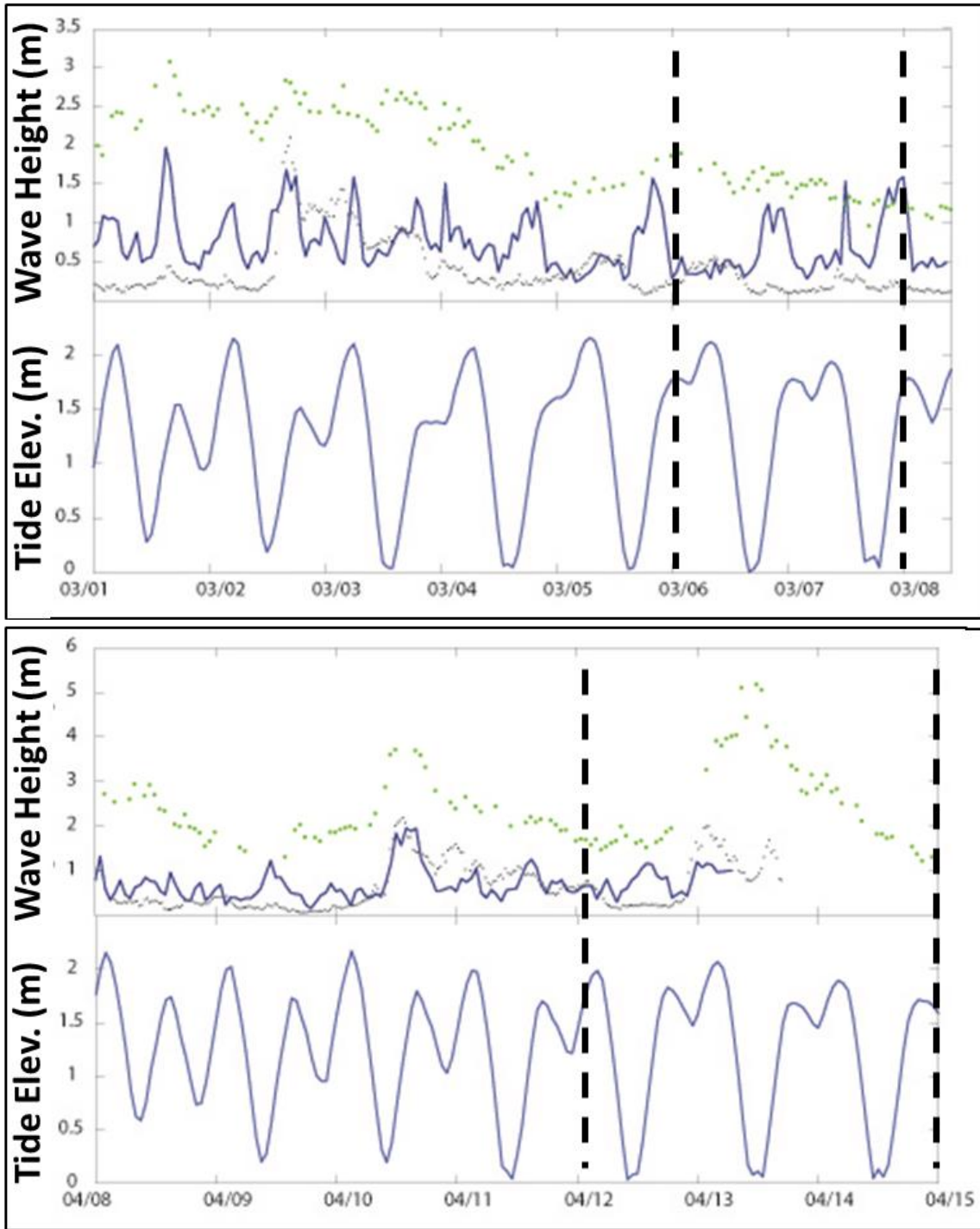
**Table 1.** Mean grain sizes in mm from CobbleCam analysis on all three transect lines. Values are averages over the entire foreshore on that specific day.

	<b>6 Mar</b>	<b>7 Mar</b>	<b>12 Apr</b>	<b>13 Apr</b>	<b>14 Apr</b>
<b>Line 174</b>	9.5	No data	11.2	26.3	48.5
<b>Line 190</b>	No data	40.6	26.4	36.2	53.9
<b>Line 198</b>	40.6	No data	No data	22.8	23.7

poorly sorted (Fig. 5c). On 14 Apr for example, M4 and M7 both consisted of ~50% coarse sand, yet M7 was 17.9% gravel while M4 was 1.4% gravel. Moreover, M7 coarsened from 13 Apr to 14 Apr from 99.4% to 82.1% sand, and shifted from moderately well sorted and symmetrical to poorly sorted and very coarse skewed. Samples from the sand flat on Line 174 consisted of mostly fine and very fine sand, with ~3% mud. These also displayed moderate sorting and symmetrical distributions. On Line 190, samples were poorly to very poorly sorted (Fig. 6c). Coarsening occurred from 13 Apr to 14 Apr, with mean grain size of 2.95 mm at M13 on 13 Apr, and 6.92 mm at M14 on 14 Apr. On Line 198, seaward coarsening was also observed (Fig. 7c). M12 and M14 consisted of 99.3% and 97.3% sands, respectively, and M20 consisted of 49.5% sands and 50.5% gravels. Samples also transitioned from moderately well sorted at M12 and M14 to poorly sorted at M20.

#### *4.3 Waves and tides*

Spring tides and moderate wave heights were observed during the study periods (Fig. 9). High tide elevations exceeded 2.1 m MLLW on 6 Mar, and exceeded 2.0 m MLLW on 13 Apr. Tidal ranges exceeded 2.1 m on 6 Mar, and exceeded 2.0 m every day of the April study period. During the two-day March study period, significant wave height (SWH) at Neah Bay peaked at 1.89 m at approximately 09:00 on 6 Mar, and SWH at Hein Bank peaked at 0.56 m at approximately 16:00 on 6 Mar. Tripod data indicates a maximum SWH on the submarine Elwha Delta of approximately 1.5 m. During the three-day April study period, SWH at Neah Bay peaked at 5.18 m at approximately 19:00 on 13 Apr, and SWH at Hein Bank peaked at 2.0 m at approximately 09:00 on 13 Apr.



**Figure 9.** Significant wave height and tide elevation at the Elwha Delta for time windows including the sampling periods. Tides are from the Port Angeles tide station (#9444090; tidesandcurrents.noaa.gov), solid line is significant wave height (SWH) from the bottom tripod located on the submarine delta, green points are SWH from the Neah Bay buoy (#46087; ndbc.noaa.gov), and black points are SWH from the Hein Bank buoy (#46088; ndbc.noaa.gov). Tripod was retrieved in the morning on 13 Apr, so data collection ended.

Tripod data indicates a maximum SWH of approximately 1.25 m before the tripod was retrieved for refurbishment the morning of 13 Apr.

## **5. Discussion**

### *5.1 Relationship between wave energy and short-term beach changes*

Measureable changes occurred on the beaches east of the Elwha River mouth during the April study period. Data suggests that moderate wave heights and spring tides at the delta played a role in the disappearance of the organic matter berm on Line 174 (Fig. 8). An erosional bank exists at the top of Line 174 that is ~1 m tall and nearly vertical. Thus, conditions could have been such that this bank acted as a natural seawall, reflecting and amplifying wave energy at the shoreline during high tide and transporting the woody debris elsewhere.

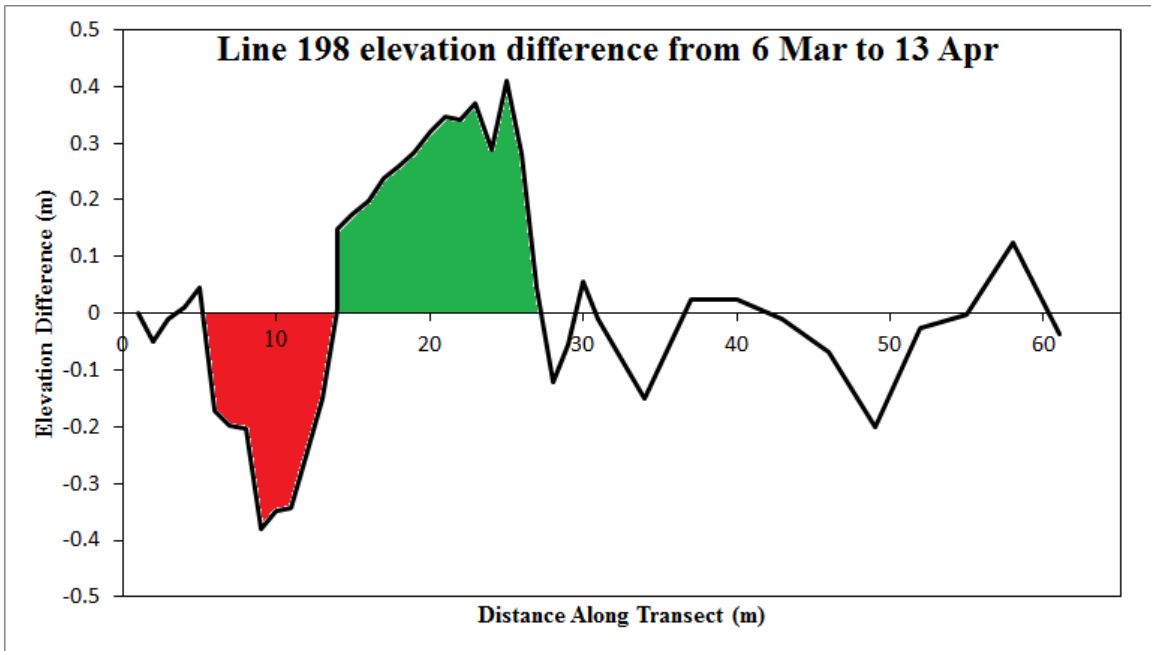
Storm waves and high tides (Fig. 9) also help to explain the migration of the slope break on all three transects during the April study period. Large waves breaking on the foreshore are capable of mobilizing sediment to depths in the bed exceeding 30 cm on these beaches, and have been shown to be most effective on the lower foreshore (Miller & Warrick, 2012). Anfuso and Ruiz (2004) also found that sediment activation was greatest on the lower foreshore. Thus, it is reasonable that foreshore widths changed by up to 2 m over a single day. This reinforces the idea that single wave events are capable of causing significant changes on beaches over day-to-day timescales (Martins et al., 2010). It is uncertain whether longshore sediment transport was occurring during the study period, but material was clearly being moved cross-shore. However, the mechanisms that led to a widening of the foreshore (i.e., slope break moving seaward) on

Line 174 and a narrowing of the foreshore (i.e., slope break moving landward) on Lines 190 and 198 are less certain. A possible explanation is the orientation of different lines to the dominant incoming wave angle (Fig. 4). The beach at Line 174 lies closer to the river mouth and is slightly more west-facing than Lines 190 and 198, so waves may have affected these sections of beach differently (Miller et al., 2011). However, repeated short-term study of these different transects is required in order to formulate a conclusion regarding variable wave dynamics and sediment transport.

## *5.2 Sediment distributions*

### *5.2.1 Sediment movement on Line 198*

Approximately 0.4 m of elevation change was documented at two different regions of the foreshore of Line 198 between March and April (Fig. 7a, 10). This is an interesting result, because it speaks contrary to the idea of large waves and tides depositing sediment higher up the beach and eroding inland. Since this change occurred over a 38-day span between sampling periods, it is uncertain whether it was slowly changing throughout this period or quickly changing during a single wave event. However, it provides additional evidence that the foreshore is very active, and different sections of beach can change in different ways, even if they are proximal to each other. It should be noted that the two colored regions in Figure 10 denote the only significant regions of change. Any smaller fluctuations in elevation seaward of the accretion area (i.e., on the cobble terrace) should be treated as data noise, as evidenced by the documented lack of change on the cobble terrace over many past years (Warrick et al., 2009b).



**Figure 10.** Elevation difference along Line 198 between 6 Mar and 13 Apr, found by subtracting March elevations from April elevations. Red region represents erosion from the foreshore over this time period, and green represents accretion. Other smaller variations are assumed to be data noise (see Section 5.2.1).

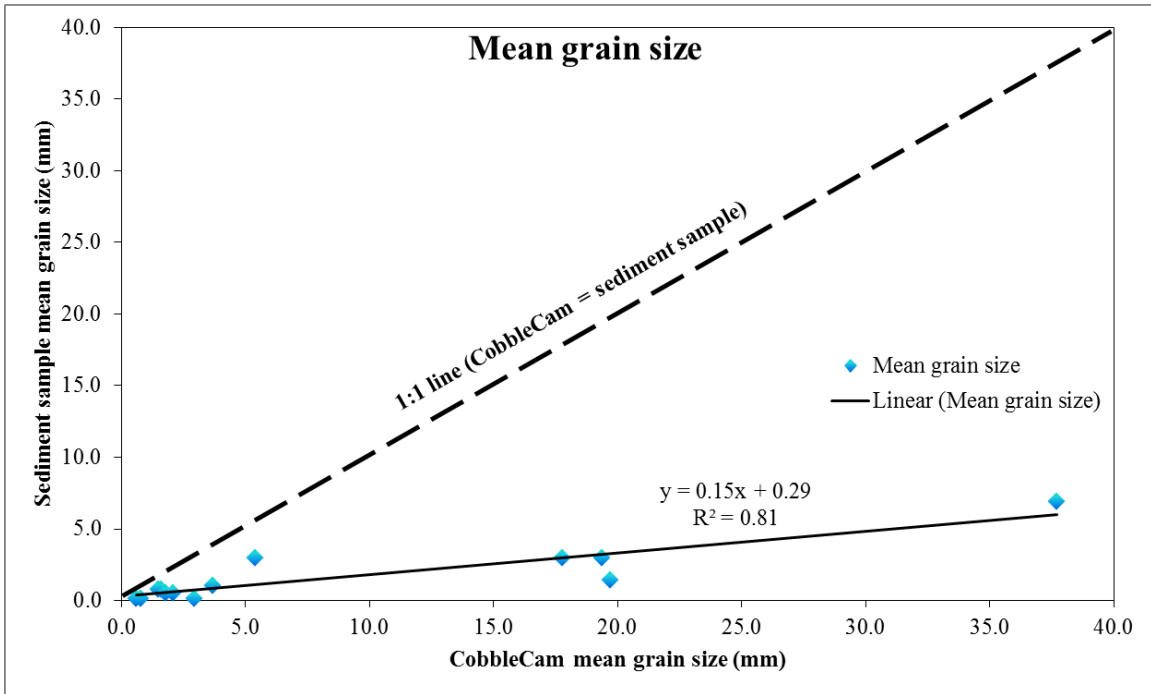
### *5.2.2 Spatial and temporal coarsening*

Results indicate spatial coarsening trends from the berm to the bottom of the foreshore on Lines 174 and 198 (Figs. 5c, 7c). This implies that breaking waves move finer sediments and deposit them in a higher region of the beach. The presence of a coarse low-tide terrace and the fining of sediments landward across the beach are anomalous characteristics, as most research on coarse beaches shows finer sediments on low-tide terraces (e.g., Miles & Russell, 2004). This is an important point, because the vast majority of new sand and gravel from the Elwha has been accumulating either right at the river mouth or on the nearshore submarine delta (Miller, 2013). Thus, if large volumes of this sediment migrate into the downdrift intertidal region in coming years, some will likely be transported onto the foreshore where it may prograde the beach seaward, acting to slow or reverse beach erosion. Between the March and April study periods, signs of beach profile change were the downslope movement of sediment on the foreshore of Line 198 (Fig. 7a), and the migration of slope breaks. However, it is unknown how these short-term variations will translate to longer-term changes as a result of dam removal. Continual dedicated study of these processes is a requirement if we are to understand these changes and the likelihood of Elwha dam removal to reverse chronic erosion.

### *5.3 Evaluation of CobbleCam technique and sources of error*

#### *5.3.1 Correlation between methods of grain-size analysis*

CobbleCam and sediment sample analysis revealed the same coarsening trends, both spatially (down the foreshore) and temporally (through the April study period). However, mean grain sizes from CobbleCam were always higher than those from



**Figure 11.** Mean grain size correlation between CobbleCam photographs and sediment samples.

sediment samples, sometimes by an order of magnitude. Mean grain sizes from both methods were plotted against each other, revealing a relationship ( $R^2=0.81$ ; Fig. 11). However, CobbleCam overestimated grain sizes in every case. This implies that CobbleCam was a good indicator of relative mean grain size for finer-grained regions, but a poor indicator of absolute size. In coarse-grained regions however, visual observations of photographs affirmed that CobbleCam seemed to accurately estimate mean grain size. Statistical comparison of CobbleCam to other techniques for coarse-grained substrates (i.e., pebble counts; Wolman, 1954) would be a useful direction for future studies. This would further validate the use of CobbleCam to characterize the cobble terrace at the Elwha beaches.

### *5.3.2 Depth in the beach*

CobbleCam can only evaluate the surficial grains on the bed since they are visible in photographs, whereas sediment samples were taken to 1-2 cm depth. This inevitably leads to CobbleCam bias towards overestimation of grain sizes. Previous studies note that larger grains on mixed beaches tend to be found closer to the surface since smaller grains fill in the space between them (a process called kinetic sieving; Buscombe & Masselink, 2006). This would result in a coarser surficial layer underlain by finer sediment. CobbleCam would see more gravel, while sediment samples would have more sand content and thus smaller mean grain sizes.

### *5.3.3 Sand sizes*

The CobbleCam method always overestimated mean grain sizes in sandy regions, because small sand grains of similar color have poorly defined edges in photographs. Mean grain sizes of foreshore sands were between 1 and 2 mm (very coarse sand) as

calculated by CobbleCam, but sieve analysis of sediment samples revealed that most of the sands on the foreshore were medium to coarse sand (0.25 to 1 mm). However, there existed a relationship between the two methods, as described in Section 5.3.1. Warrick et al. (2009b) describe in their methods that any grains smaller than about 1-2 mm could not be resolved, and were assigned to an arbitrary grain size of ~0.6 mm. This inability to collect detailed data for sand is an important factor on the mixed foreshores at the Elwha. If CobbleCam cannot reliably resolve individual sand grains, estimated mean grain sizes will be consistently too large, thus reducing the ability to see small variations in grain size in the data. A macro lens and smaller ground scale could be used to shoot photos closer to the bed, which would likely improve this issue. However, this method variation was not investigated in this study.

#### *5.3.4 Wet vs. dry surfaces*

Some grain-size estimates from this study show evidence of inaccuracy resulting from partially wetted areas in CobbleCam crop regions. In a few images, water and/or organic matter between cobbles on the low-tide terrace was covering smaller clasts. Mean grain sizes from these images were too large because smaller clasts were not on the surface, and areas of water or organic matter may have been treated as single clasts. Areas of patchy wetness on foreshore sand also led to overestimates of mean grain size. This may be because wet areas have less defined grain edges when compared to dry areas, so the wet regions may have been treated as single large grains. Warrick et al. (2009b) investigated this issue and found similar results.

### *5.3.5 Other sources of error*

The presence of sticks, plant material (as was sometimes present on the berm or backshore), and other woody debris in the crop area likely skewed results in some images. A few images had other issues that have been documented as affecting results, including rain drop spots on otherwise dry cobbles, oblique sunlight angle causing shadows, and blurry photographs (Rubin, 2004; Warrick et al., 2009b). About 15% of the images from this study were only somewhat compromised, and were left in the analysis for the purpose of having a more complete data set. However, some were very compromised and were not included, such as images near or on the wood wrack line, or those where a majority of the crop area was submerged in water.

In general, it is difficult to obtain good quality images for CobbleCam analysis on these beaches because they are dynamic, especially on the foreshore and closer to the river mouth. Large quantities of woody debris are being exported from the river and collecting on the beaches in addition to sediment, foreshores are eroding landward into regions with live plant material, and abundant sticks and logs lie in and above the wrack line. In addition, much of the width of the beach cannot be accessed except for a couple hours at low spring tides, and weather conditions are not always favorable. As a result, it is difficult to improve upon the CobbleCam method on these beaches. As long as sticks and debris are removed from the photo area to a reasonable degree and sandy areas are disturbed as little as possible, this method should prove satisfactory.

## 6. Conclusion

This study found that measurable changes occurred on the Elwha beaches during the large wave and tidal conditions observed, and over monthly and daily timescales.

Namely:

- A berm of organic woody material disappeared from Line 174 overnight.
- Over daily timescales, slope breaks moved by up to 2 m, the landward edge of the sand flat on Line 174 moved seaward by 10 m, and foreshore coarsening was observed on Lines 174 and 190.
- Spatial coarsening seaward along the foreshore was documented on Lines 174 and 198.
- On Line 198 between March and April, sediment eroded from the upper foreshore and accreted on the lower foreshore.

These results demonstrate that change is possible on day-to-day timescales. Long-term monitoring is crucial to continually broaden our understanding of these processes, and draw connections between short- and long-term changes as new sediment continues to be exported by the river.

This study also found that CobbleCam analysis provided a good estimate of relative mean grain sizes, but always overestimated absolute sizes when compared to physical sediment samples. This was due to many reasons, including non-sediment material in CobbleCam crop areas, small sand grains that could not be resolved, wet or disturbed sand, and/or sediment samples being taken to some depth in the bed. A conclusion that can be drawn from this is that digital analysis provides a faster and easier

means to attain grain-size data as compared to sampling and manual sieving, yet it has potential for more sources of error.

### **Acknowledgements**

The author sincerely thanks Andrea Ogston and Emily Eidam for providing continued invaluable advice and guidance throughout the research and writing processes. Ian Miller provided knowledge of the research topics, and gave his time and assistance with field methods and data processing. Matt Beirne of the Lower Elwha Klallam Tribe provided permissions to access private property on the beaches. Brianna Sweeney assisted with data collection in the field and processing of CobbleCam images. Katie Boldt and Tianna Simmons also assisted with data collection in the field. Benjamin Reynolds, Brianna Sweeney, Tianna Simmons, Trevor Harrison, Campbell Glass, and Riane Young contributed useful advice, peer edits of this manuscript, and moral support, and assisted with processing physical sediment samples. Lastly, the author thanks the Henry and Holly Wendt Endowment and the University of Washington Provost for financial support of Friday Harbor Labs research apprenticeships, and the staff of Friday Harbor Labs for providing a great research environment and quality food.

## References

- Anfuso, G., Ruiz, N., 2004. Morphodynamics of a mesotidal, exposed, low tide terrace beach (Faro, southern Portugal). *Ciencias Marinas*, 30(4), 575-584.
- Anthony, E., Blivi, A., 1999. Morphosedimentary evolution of a delta-sourced, drift-aligned sand barrier-lagoon complex, western Bight of Benin. *Marine Geology*, 158(1-4), 161-176.
- Blott, S., Pye, K., 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26(11), 1237-1248.
- Buscombe, D., Masselink, G., 2006. Concepts in gravel beach dynamics. *Earth-Science Reviews*, 79(1-2), 33-52.
- Cannon, G.A., ed. 1978. Circulation in the Strait of Juan de Fuca: some recent oceanographic observations. NOAA Technical Report ERL 399-PMEL 29, Seattle, WA.
- Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27, 3–26.
- Galster, R.W., Schwartz, M.L., 1990. Ediz Hook — a case history of coastal erosion and rehabilitation. *Journal of Coastal Research*, Special Issue no. 6, 103-113.
- Hinderer, M., 2012. From gullies to mountain belts: A review of sediment budgets at various scales. *Sedimentary Geology*, 280, 21-59.
- Kloehn, K.K., Beechie, T.J., Morley, S.A., Coe, H.J., Duda, J.J., 2008. Influence of dams on river-floodplain dynamics in the Elwha River, Washington. *Northwest Science*, 82, 224-235.

- Martins, C.C., de Mahiques, M.M., Alveirinho Dias, J.M., 2010. Daily morphological changes determined by high-energy events on an embayed beach: a qualitative model. *Earth Surface Processes and Landforms*, 35(4), 487-495.
- Miles, J., Russell, P., 2004. Dynamics of a reflective beach with a low tide terrace. *Continental Shelf Research*, 24(11), 1219-1247.
- Miller, I.M., 2013. The Coast Nerd Gazette. Accessed 6/3/2013 from [coastnerd.blogspot.com](http://coastnerd.blogspot.com).
- Miller, I.M., Warrick, J.A., 2012. Measuring sediment transport and bed disturbance with tracers on a mixed beach. *Marine Geology*, 299-302, 1-17.
- Miller, I.M., Warrick, J.A., Morgan, C., 2011. Observations of coarse sediment movements on the mixed beach of the Elwha Delta, Washington. *Marine Geology*, 282(3-4), 201-214.
- National Park Service, 2012. Sediment monitoring reveals long-hidden secret. Accessed 5/8/2013 from [www.nps.gov](http://www.nps.gov).
- Palinkas, C.M., Ogston, A.S., Nittrouer, C.A., 2010. Observations of event-scale sedimentary dynamics with an instrumented bottom-boundary-layer tripod. *Marine Geology*, 274(1-4), 151-164.
- Rubin, D., 2004. A simple autocorrelation algorithm for determining grain size from digital images of sediment. *Journal of Sedimentary Research*, 74(1), 160-165.
- Shaffer, J.A., Crain, P., Winter, B., McHenry, M.L., Lear, C., Randle, T.J., 2008. Nearshore restoration of the Elwha River through removal of the Elwha and Glines Canyon dams: An overview. *Northwest Science*, 82, 48-58.
- University of Washington, 1998. *Sediment Analysis Lab Manual*, Seattle.

- Warrick, J.A., George, D.A., Gelfenbaum, G., Ruggiero, P., Kaminsky, G.M., Beirne, M.,  
2009a. Beach morphology and change along the mixed grain-size delta of the  
dammed Elwha River, Washington. *Geomorphology*, 111(3-4), 136-148.
- Warrick, J.A., Rubin, D.M., Ruggiero, P., Harney, J.N., Draut, A.E., Buscombe, D.,  
2009b. Cobble cam: grain-size measurements of sand to boulder from digital  
photographs and autocorrelation analyses. *Earth Surface Processes and  
Landforms*, 34(13), 1811-1821.
- Wolman, M.G., 1954. A method of sampling coarse river-bed material. *Transactions,  
American Geophysical Union*, 35(6), 951–956.
- Wunderlich, R., Winter, B., Meyer, J., 1994. Restoration of the Elwha River Ecosystem.  
*Fisheries*, 19, 11-19.