Nearshore Substrate and Morphology Offshore of the Elwha River, Washington

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Abstract

The planned removal of two dams on the Elwha River, Washington, will likely increase river sediment flux to the coast, which may alter coastal habitats through sedimentation and turbidity. It is therefore important to characterize the current habitat conditions near the river mouth, so that future changes can be identified. Here we provide combined sonar and video mapping results of approximately 20 km^2 of seafloor offshore of the Elwha River collected with the purpose to characterize nearshore substrate type and distribution prior to dam removal. These combined data suggest that the nearshore of the western delta and Freshwater Bay are dominated by coarse sediment (sand, gravel, cobble, and boulders) and bedrock outcrops; no fine-grained sediment (mud or silt) was identified within the survey limits. The substrate is generally coarser in Freshwater Bay and on the western flank of the delta, where boulders and bedrock outcrops occur, than directly offshore and east of the river mouth. High variation in substrate was observed within much of the study area, however, and distinct boulder fields, gravel beds and sand waves were observed with spatial scales of 10-100 m. Gravel beds and sand waves suggest that sediment transport is active in the study area, presumably in response to tidal currents and waves. Both historic (1912) and recent (1989-2004) distributions of Bull Kelp (*Nereocystis sp.*) beds were preferentially located along the boulder and bedrock substrates of Freshwater Bay. Although kelp has also been mapped in areas dominated by gravel and sand substrate, it typically has smaller canopy areas and lower temporal persistence in these regions.

Introduction

The Elwha River drains the northern Olympic Peninsula of Washington and discharges water and sediment to the Strait of Juan de Fuca (Figure 1A). Two dams on the river have substantially reduced sediment transport in the lower river and to the strait for almost a century (Randle et al. 1996, Childers et al. 2000), and erosion of the beaches near the Elwha River mouth has been associated with this reduced sediment flux (Galster and Schwartz 1990).

The two dams of the Elwha River will be removed, sometime between 2010 and 2015, to restore the native anadromous fisheries and ecosystem (Duda et al. 2008 and references therein). During and following the removal of the two dams, sediment discharge from the river is predicted to increase by orders-of-magnitude (Randle et al. 1996, Childers et al. 2000), which is expected in turn to cause substantial geomorphic change in the downstream fluvial and coastal systems. Shoreline erosion will likely slow or reverse along the delta, and the additional sediment will alter the turbidity characteristics of coastal waters near the river mouth and change the grain-size characteristics of the beach and seabed (Stolnack et al. 2005). These coastal effects of the Elwha River restoration are expected to result in physical changes to coastal habitats and alteration of ecosystem productivity (Stolnack et al. 2005).

The goals of this study are to provide baseline seafloor substrate information about the nearshore of the Elwha River delta and to evaluate the relations between substrate type and habitat type. These data will be important to track changes—if and when they occur—in the Elwha nearshore. Prior to this study, there was little information documenting the types and distribution of seafloor types near the Elwha River mouth. More is known about the

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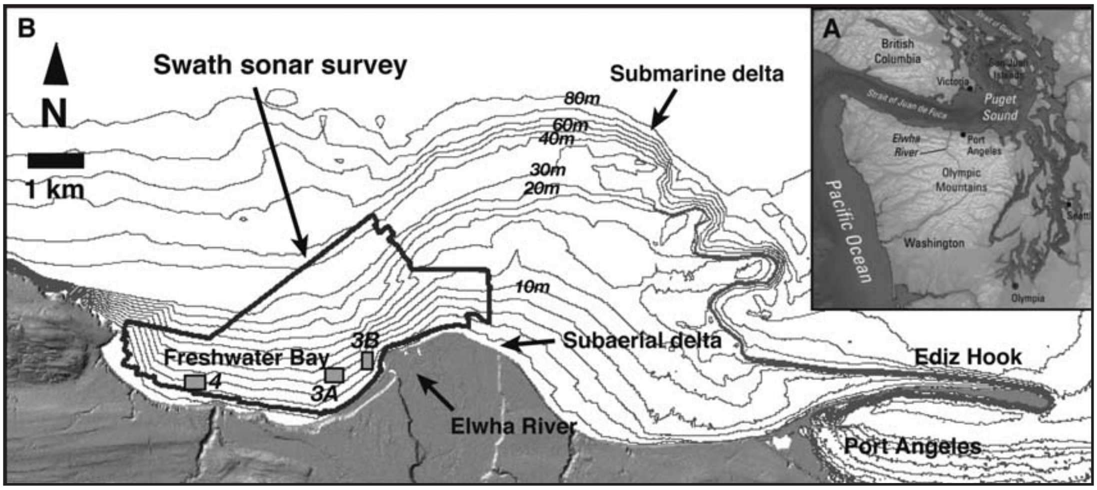

Figure 1. The Elwha River delta study area with the primary region of swath sonar data collection highlighted. Also shown are the locations of sonar imagery in Figures 3A, 3B and 4. Bathymetric data are based on NOAA navigational data.

nearshore habitats, especially the macroalgae communities (Seavey and Ging 1995, Shaffer 2000, Berry et al. 2005), which show seasonal variations with maximum growth in the summer. Our study was developed with the goal of filling fundamental information gaps about the seafloor substrate and its relations with macroalgae, and it is our intent that the data collected can be used to track changes in the future and to guide other habitat or seafloor sampling programs to specific seafloor types of interest. We combined sonar, video and grain-size observations to map the seafloor substrate and bathymetry, and focused this work offshore and west of the river mouth (Figure 1B). This study area was chosen because we understood that these regions may be both conducive and sensitive to changes in seafloor substrate, due to proximity to the river mouth and known kelp bed distributions (Berry et al. 2005). Seafloor changes may occur outside the limits of our study, especially east of the mapped region (Figure 1B), and additional information will be needed to characterize the seafloor of these areas.

Below we provide additional information about the nearshore study area and the pending dam removals, which is followed by a description of the methods, results and implications of our study.

Study Area

The Elwha River delta is represented by both a subaerial (above sea level) feature that protrudes approximately 2 km into the Strait of Juan de Fuca and a submarine (below sea level) feature that extends another 4 km from the shoreline (Figure 1). These subaerial and submarine features arose, starting at ~14,000 years before present (ybp) following the retreat of the continental ice sheet that filled Puget Sound and the Strait of Juan de Fuca (Dethier et al. 1995, Mosher and Hewitt 2004). Following ice retreat, relative sea level and sediment input from the river and coastal bluffs influenced the location and morphology of the Elwha River delta (Galster and Schwatrz 1990). Relative sea level was initially ~50 m higher than present immediately following the ice retreat (~12,500 ybp) and dropped to approximately -60 m by ~9900 ybp (Mosher and Hewitt 2004). This rapid decrease in relative sea level is largely attributed to isostatic rebound (Dethier et al. 1995). Relative sea level then gradually rose until 5500 ybp, after which it has remained relatively constant in the region (Mosher and Hewitt 2004). It is likely that the submarine portion of the Elwha River delta (Figure 1B) represents the extent of the Holocene delta at low sea stand (~9900 ybp), and that the subaerial delta had been migrating landward until relative sea-level stabilized approximately 5500 ybp (Galster and Schwatrz 1990, Mosher and Hewitt 2004). Evidence of eastward littoral transport is apparent in the subaerial spit, Ediz Hook, and two submarine spits on the eastern edge of the submarine delta (Figure 1B) formed during the transgression of relative sea level between 9900 and 5500 ybp (Galster and Schwatrz 1990, Mosher and Hewitt 2004).

Construction of the Elwha Dam in 1911 at approximately 8 km upstream of the river mouth eliminated the upper river sediment sources to the lower river and river mouth. Glines Canyon Dam was completed in 1927 at approximately 22 km from the river mouth, and combined these two structures captured over 15 million m^3 of river sediment during the 20th century (Childers et al. 2000). Erosion of the subaerial river mouth delta accelerated after dam construction and averaged 0.54 m/yr during 1939 to 1996 (Schwartz and Johannsessen 1997). Erosion has been greatest immediately adjacent to the river mouth (i.e., the western portion of the delta), where average rates exceeded 1.4 m/yr (Schwartz and Johannsessen 1997). Although large changes have been observed in the subaerial delta, it is not clear how the submarine portion of the delta responded to the reduced sediment loads.

Methods

We conducted nearshore mapping with a combination of sonar and underwater videoography in the coastal waters near the river mouth (Figure 1). Mapping was focused on the region immediately offshore of the river mouth and west into Freshwater Bay, due to the foreknowledge of the abundant macroalgae habitats in this region. Here we present a brief summary of the techniques utilized for this work, a complete explanation of the methods and raw data are available in a USGS Open-File Report (Cochrane et al. *In Press*).

The primary mapping instrument was an interferometric swath sonar operated from the research vessel (R/V) Karluk during 15-30 March 2005. These sample dates were chosen because they were early in the kelp growing season, which optimized water penetration and return of the acoustic signal and provided the best conditions for driving the boat. A total of 90-sonar transects covering approximately 20 km^2 of seafloor were collected during daily cruises from Port Angeles, and heavy seas prevented data collection during approximately a third of the planned cruise time. The 234-kHz interferometric sonar provided high-resolution images of both the intensity of sound reflected from the seafloor (backscatter) and seafloor depth calculated from the phase difference between reflections received by multiple receivers. Boat positioning was provided by a differential global positioning system (DGPS) and a high-resolution motion sensor that was used to correct for heave, pitch and roll of the R/V Karluk. Georeferenced backscatter and bathymetry grids were generated from the sonar output with horizontal resolutions of 0.25 and 1 m, respectively.

We obtained video imagery of the seafloor from the R/V Karluk using an obliquely viewing underwater video camera. Two parallel laser beams spaced 10 cm apart were mounted to the camera and oriented in the field-of-view to assist with sizing objects. Video transect locations were selected based on apparent geologic transitions and/or features from the sonar data. Video was characterized real-time every 30 sec from monitors on the R/V Karluk, and observations were recorded with DGPS positioning of the boat using the methods of Anderson et al. (*In Press*). Observations included the primary and secondary substrate grain-size (sand, gravel, cobble and boulder) and presence of benthic organisms and demersal fish. We use the Wentworth system of grain-size classification (McCave and Syvitski 1991), although gravel was defined broadly to include both granular and pebble sediment (i.e., 2 to 64 mm diameter sediment) due to the difficulty of distinguishing these particle sizes in the video data. A research diver from the Washington Department of Fish and Wildlife was on board during video operations to assist with fauna and flora identification. Nearly 9 hours of underwater video were collected in this manner along 18-transects.

The seafloor area mapped by the sonar was classified using a supervised maximum likelihood classification technique based on seven data layers of the sonar data: distance from boat track line, rugosity (or roughness) of the bathymetry, entropy and homogeneity of the backscatter at 1 m resolution, entropy and homogeneity of the backscatter at 0.25 m resolution, and the mean backscatter at 0.25 m resolution. Definitions and details of this classification can be found in Cochrane et al. (*In Press*). Supervisory signatures of each variable were generated for a series of fixed sites, and it was found that four dominant seafloor substrate classes could be distinguished by the classification technique: sand, mixed (i.e., gravel and cobble), hard (boulders and bedrock), and sand-waves (continuous bodies of sand with length scales of ~10 m). For this paper, the sand-waves—which represented less than 1% of the total mapped area—were combined with the sand class, which results in three substrate classes.

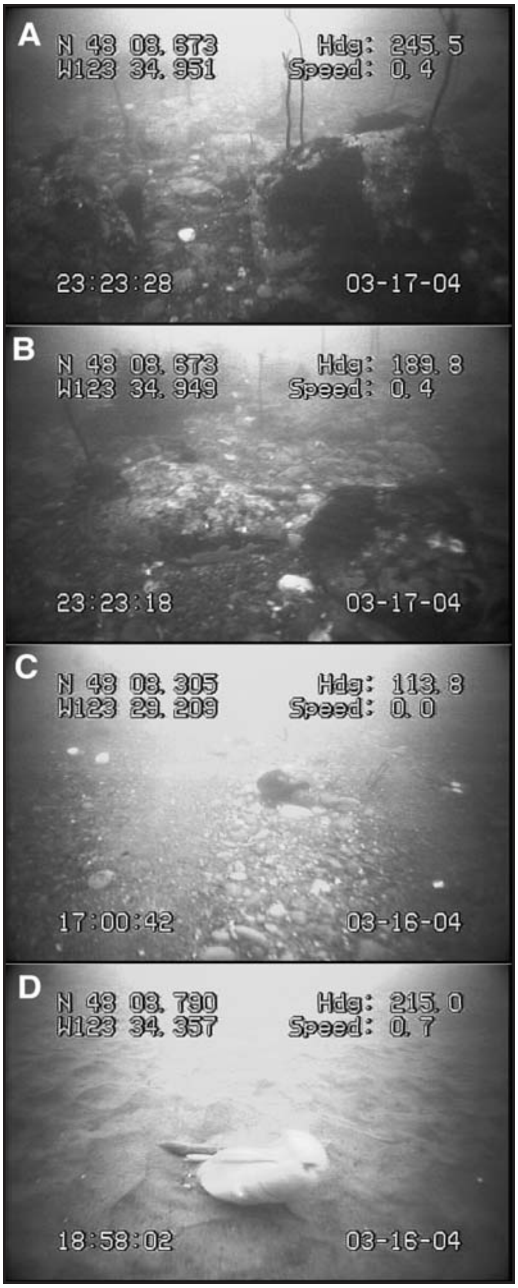

Figure 2. Example still imagery from the underwater video observations of seafloor with (A) and (B) boulders in excess of 1m diameter, (C) gravel with grain-sizes approximately 1-5 cm, (D) an Orange Seapen (*Ptilosarcus gurneyi*) in rippled sand.

An accuracy assessment across the supervised classification was conducted by comparing video observations with the classification results of the nearest classified pixel, and this resulted in an average 65% success across the classes (Cochrane et al. in press). This accuracy includes both the uncertainty of geopositioning of the video data, which was approximately 5 m, and the uncertainty of the classification technique. Broadening the spatial window for each video observation to allow for position uncertainty increased the accuracy assessment substantially, but this would also result in the majority of video observations linked to two or more substrate classes, thus making this kind of assessment biased toward successful classifications.

Results were plotted with topographic data provided by the Puget Sound LIDAR Consortium, which collected airborne light distance and ranging (LIDAR), also known as laser swath mapping, of the study area in 2001. Topography data are in the public domain and available at (http://pugetsound-lidar.ess.washington.edu/). Here we present these data as hillshaded slope maps of the terrestrial portion of the study area.

Lastly, the area of canopy-forming kelp bed areas were compared with the classification results to evaluate the relationship between substrate and habitat types. Canopy-forming kelp bed areas were obtained from the annual low-tide aerial photography surveys of the Washington State Department of Natural Resources, Nearshore Habitat Program, which has surveyed the outer coast and the Strait of Juan de Fuca since 1989 (Berry et al. 2005).

Results

Seafloor substrate as observed in the video transects varied between coarse sediment with boulders in excess of 1 m (Figure 2A,B) to gravel and sand (Figure 2C,D). Boulders were commonly observed in sets of at least a dozen, and in between the boulders within these fields lay cobble and gravel (Figure 2A,B). Kelp holdfasts were attached to the majority of boulders, apparently remnants from the previous summer's population (Figure 2A,B). Boundaries between the differing substrates were commonly sharp, often extending over less than 1 m (Figure 3A). Boulders were observed to lie immediately adjacent to bodies of sand and/or gravel, and both were observed to be continuous

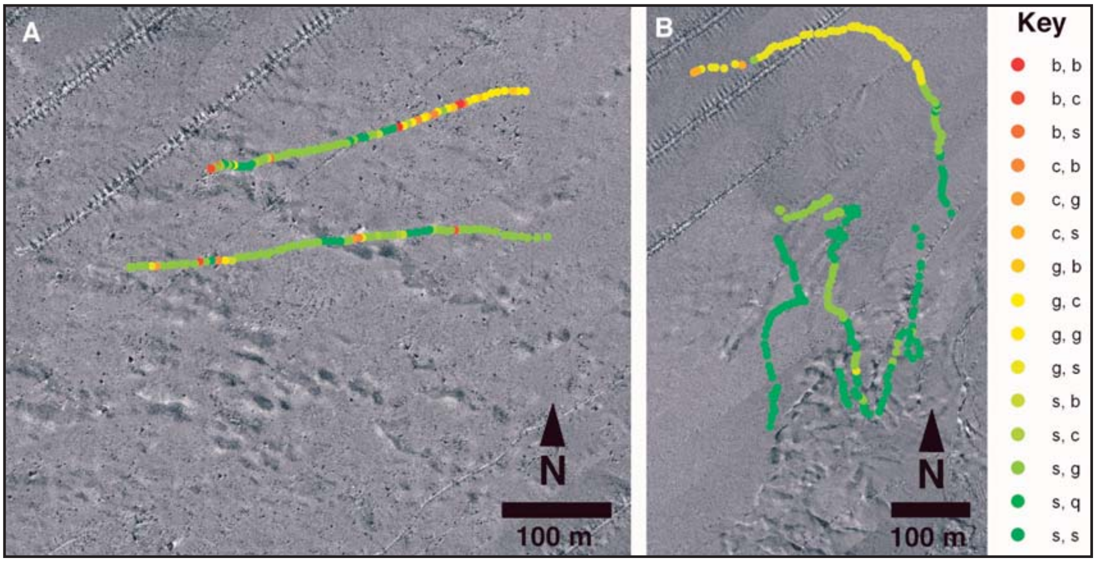

Figure 3. Example swath sonar backscatter imagery and video observation results from the seafloor west of the Elwha River mouth. Backscatter is shown as high backscatter in white and low backscatter in black. Color symbols are video observations keyed for primary and secondary substrate types (b – boulder, c – cobble, g – gravel, s – sand). The location of these images is shown in Figure 1B.

over at least 10's of m in the along-transect direction (e.g., Figure 3A).

High variation in substrate was also apparent in the sonar backscatter, where low backscatter patches with length scales on the order of 10 to 100 m (sand bodies) were immediately adjacent to large boulders, which could be identified in turn by a combined acoustic reflection and shadow (Figure 3A). Video observations suggest that the low backscatter patches were sand waves, whereas the combination of high acoustic reflection with acoustic shadow were boulders, some with diameters of several meters (Figure 3A). Nearer to the river mouth, a broad region of sand was observed in the backscatter and video data to extend at least 500 m alongshore (Figure 3B). Although not sampled by video, regions of Freshwater Bay were observed to have hard substrate with indications of bedding, which strongly suggest bedrock outcrops (Figure 4).

The examples highlighted above reveal that distinct seafloor substrate types existed in the study area, and that they could be identified relatively clearly in the combined video and sonar data. As detailed above, regions of combined video and sonar were used to derive a supervised classification chosen to represent: sand, mixed (gravel to cobble), hard (boulder to bedrock), and sand waves, although sand and sand waves have been combined into one class for the purpose of this report. Seafloor immediately below the research boat was not classified due to the unique backscatter signature obtained in this nadir direction (Figure 5).

The supervised classification resulted in the majority of the region being classified as mixed grain-size substrate, which suggests gravelly-to-cobbled sediments in most of the study area (Figure 5). Hard substrate was classified primarily west of the river mouth in Freshwater Bay (Figure 5). Areas that were qualitatively described as bedrock outcrops (e.g., Figure 4) were consistently classified as hard substrate. Little hard substrate was classified to the north and northwest of the river mouth, and observations of the raw backscatter data suggest that few if any boulders existed in this region. Sand substrate was mapped along the shoreline immediately southwest of the river mouth, within patches among the boulders, and mixed into the north-central portion of the surveyed area (Figure 5).

The bathymetric results provide new information about the study area seafloor and its morphology (Figure 6) and improve upon the relatively low resolution soundings existing previously for the region (gridded in Figure 1). The 5-10m

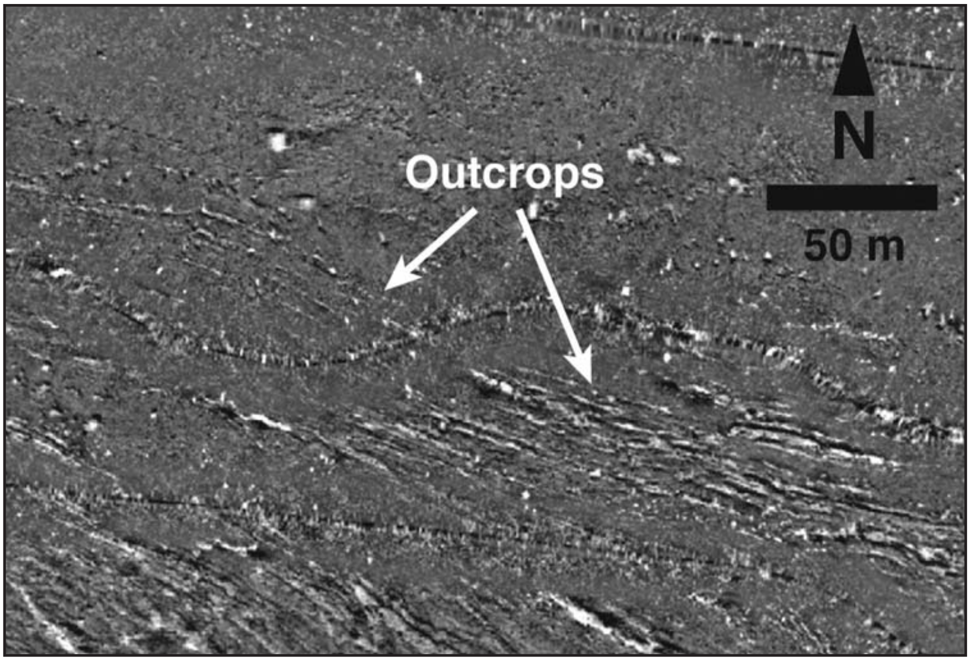

Figure 4. Example swath sonar backscatter imagery from the seafloor in Freshwater Bay showing apparent bedrock outcrops with an alongshore bedding direction. The location of this image is shown in Figure 1B.

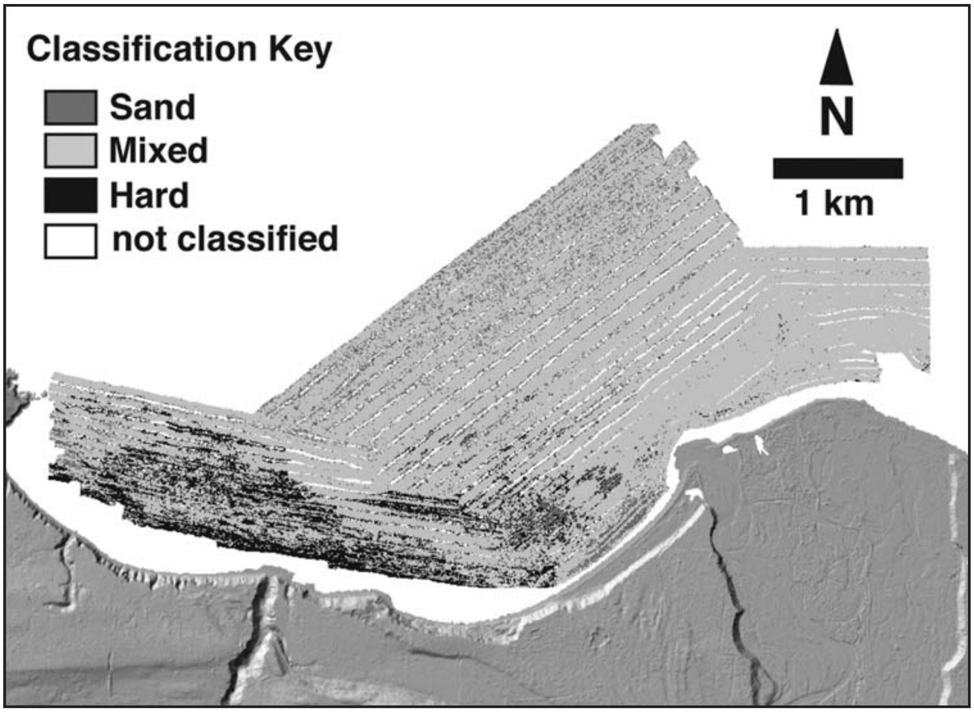

Figure 5. Results of the seafloor substrate supervised classification. Each 1 m pixel has been classified into one of three classes: sand, mixed, or hard, or it was not classified. Regions that were not classified typically lay directly under the track lines of the research vessel. Topographic data are also shown from the 2001 LIDAR survey.

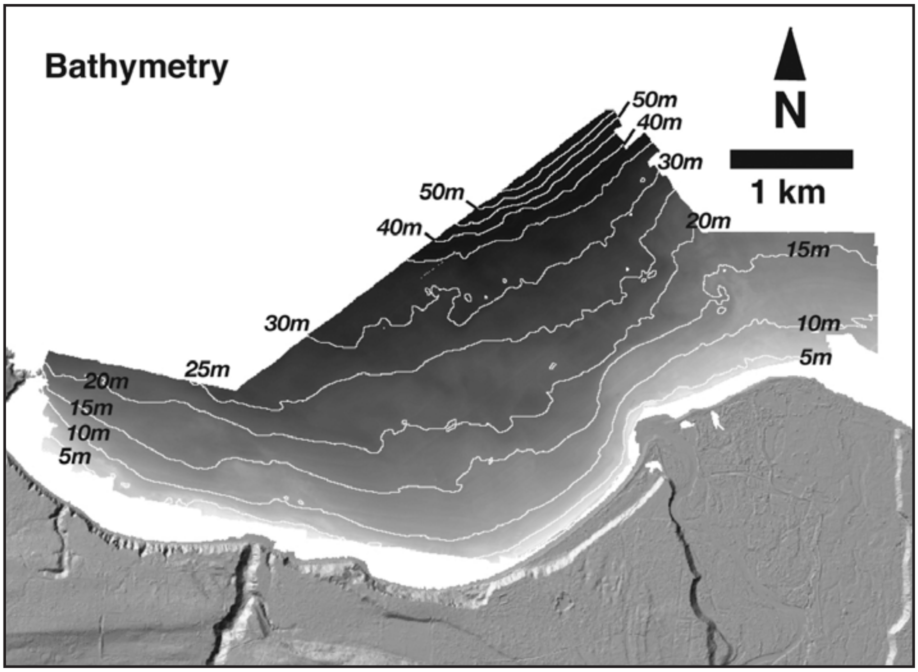

Figure 6. Results of the seafloor bathymetry mapping, which provides over ten thousand more soundings in the study area than previously available from NOAA navigational charts (shown in Figure 1B). Isobaths are shown at 5 m increments with white lines. Topographic data are also shown from the 2001 LIDAR survey.

bathymetric contours in the sandy region immediately to the southeast of the river mouth were smooth and parallel to shore (Figure 6), consistent with the smooth to rippled sandy seafloor observed in video imagery. A bulge in the 0-15 m isobaths is observed directly offshore of the present river mouth, and a steep river mouth bar is observed approximately 100 m offshore of the river. Bathymetry across this bar decreases by over 5 m—from 3 m to 8 m water depth—in approximately 50 m distance (Figure 6). The bathymetric contours for water depths of 15-30m were generally more complex in shape, suggesting that the majority of the seafloor in this depth range was not smooth, but rather had roughness on the scale of 10's of cm, apparently from the combined topographic influences of gravel to boulder substrate and irregular seafloor.

Comparison with Bull Kelp

Aerial mapping and historical observations suggest that the canopy-forming kelp in the study area is largely Bull Kelp (*Nereocystis luetkeana*). Mapping of the kelp in the early 20th century identified Bull Kelp only within the boundaries of Freshwater Bay (Rigg 1913). Recent mapping by Berry et al. (2005) has identified canopy-forming kelp in Freshwater Bay, which is consistent with Rigg (1913), but also northeast of the river mouth (Figure 7A); the Freshwater Bay kelp beds being larger and more persistent with time. Qualitative comparison of these results with the substrate classification (Figure 5) suggests that the persistent kelp beds were established on hard (boulder and bedrock) substrate in Freshwater Bay, whereas the less persistent kelp beds existed in mixed grain size (gravel to cobble) regions. Kelp beds were also observed only in water depths less than 15 m (Figure 7A).

Comparison of the 2005 substrate classification with the 2004 kelp maps—the year closest to the substrate mapping—suggests that kelp canopy areas from Berry et al. (2005) were consistently in shallow regions of hard substrate, whereas sandy regions did not have kelp (Figure 7B). A quantitative comparison was made using all substrate classification results in water depths less than 15 m (i.e., the observed offshore limit of kelp in

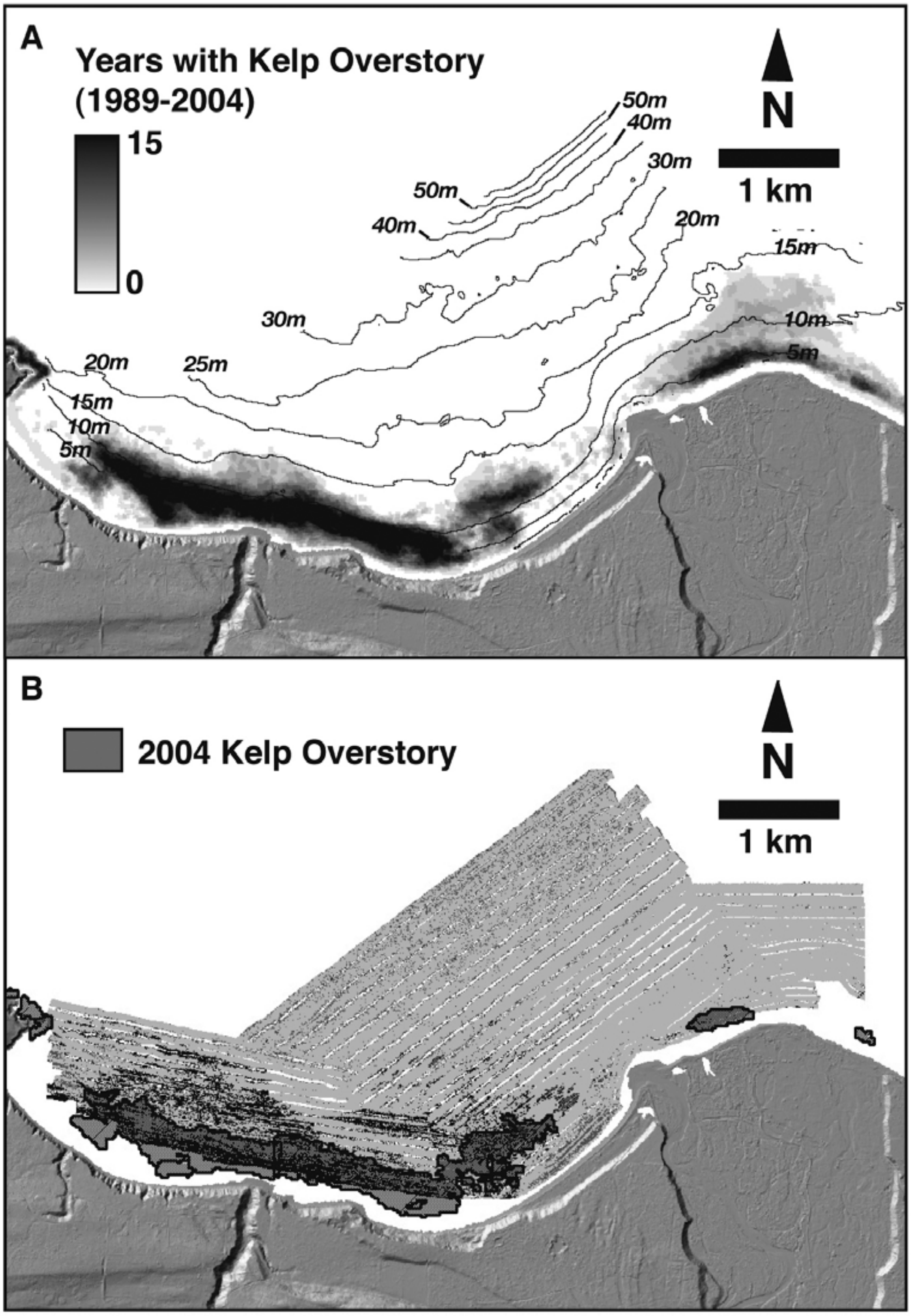

Figure 7. Kelp overstory distributions from Berry et al. (2005). (A) The number of years that overstory kelp was observed during the 1989-2004 annual surveys. (B) Comparison of the 2004 observations of kelp overstory with the seafloor substrate classification from Figure 5. Topographic data are also shown from the 2001 LIDAR survey.

TABLE 1. Seafloor and kelp bed distribution characteristics for mapped seafloor <15 m deep during 2004-2005 near the Elwha River.

Substrate Class	Seafloor Area (km^2)	% Substrate with kelp beds
Sand	0.12	23
Mixed	0.53	18
Hard	0.43	58

the study area) and the 2004 kelp maps (Figure 7B). It was shown that 58% of the hard substrate within 15 m water depth had kelp, whereas 23% and 18% of the sand and mixed grain-size substrate, respectively, had kelp beds (Table 1). The majority of the kelp growing in sand could be attributed to the sand waves occurring within the boulder fields (e.g., Figure 3A). We did not observe kelp holdfasts within the sand waves during video observations, and it is not clear whether the kelp observed over sand was actually anchored within the sand or on adjacent coarser materials. In summary, hard substrate, as identified by our mapping and classification methods, was 2.5 to 3.2 times more likely to have kelp beds than the other mapped substrate types.

Discussion

The results presented above have been integrated and simplified into a substrate type and morphology map for the western Elwha River delta (Figure 8). In general, the entire mapped area was observed to have sand-to-boulder grain sizes or bedrock outcrops. Thus, most of the region can be characterized as having coarse grain sizes (i.e., sand to boulder), with significant differences in the amount of the largest rocks. Differences in boulder abundance were evaluated by counting visible boulders in the raw backscatter data in seafloor areas of 100 m^2 (many boulders) to 10,000 m^2 (few boulders), which resulted in average boulder abundances of 1 to >10,000 boulders/km^2. These differences are

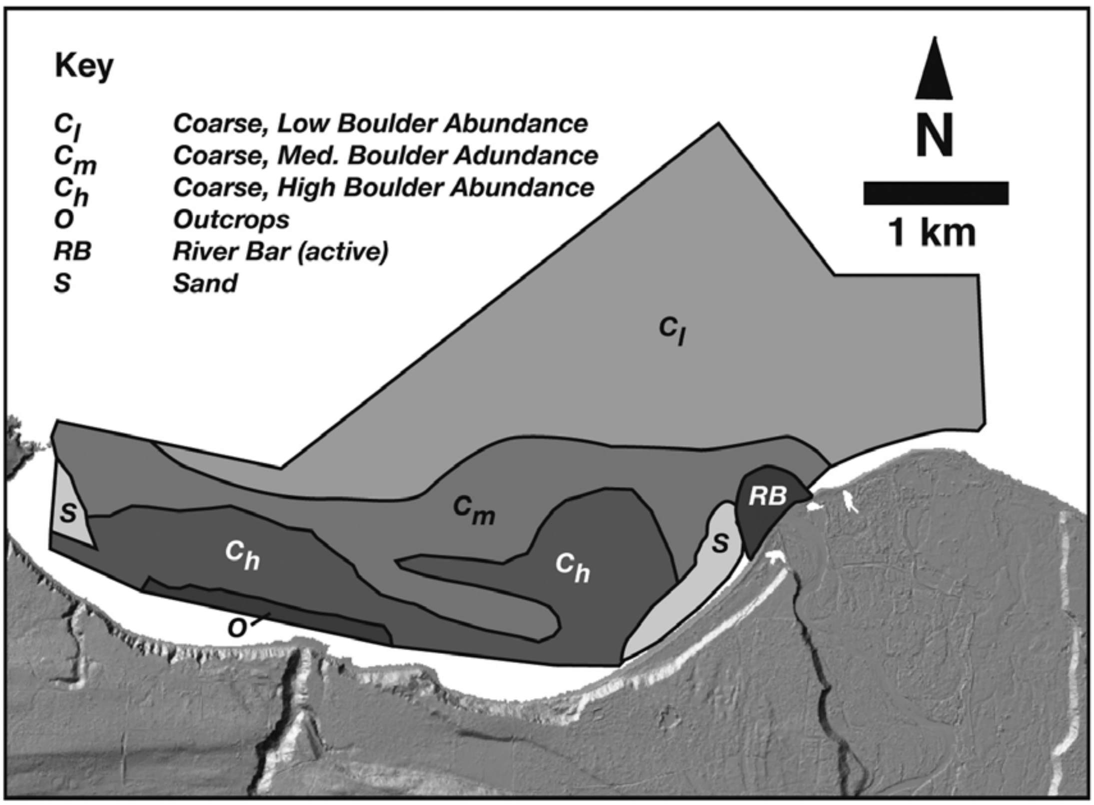

Figure 8. Interpretation of the seafloor substrate types in the study area from the combined data collection techniques. Information regarding each substrate grouping is given in the text. Topographic data are also shown from the 2001 LIDAR survey.

characterized by three levels of boulder abundance for the coarse (C) sediment: low (l), medium (m) and high (h), which are equivalent to average boulder abundances of <10 boulders/km^2, 10-10,000 boulders/km^2, and >10,000 boulders/km^2, respectively (Figure 8). The region west of the river mouth generally has many more boulders than the region north and east of the river mouth (Figure 8). This may be due in part to different parent materials for each of these regions, the western portion being derived from sea cliff contributions of glacial till and sedimentary bedrock, resulting in large lag boulders, and the northern region derived primarily of Elwha River alluvium, consisting largely of sand to cobble grain sizes. There is also decreasing boulder abundance with depth, which may be due to boulder burial by sand and gravel with time or differences in parent material.

Two broad regions (>200 m) were dominated by sand, one along the beach immediately southwest of the river mouth and the other on the far western side of Freshwater Bay (Figure 8). The eastern sand body lies immediately adjacent to the active river mouth bar and offshore of a region in which the littoral sediment has accumulated to a distance greater than 200 m from the sea cliff (as shown by the LIDAR data; Figure 8). We note that Seavey and Ging (1995) similarly observed sand in this region during 16 scuba dive transects in 0-10 m water depth. These submarine and subaerial characteristics are consistent with a region that has had net accumulation sediment during the high-stand in relative sea-level ca. 5000 ybp (e.g., Galster and Schwartz 1990). This portion of shoreline also is the most perpendicular to the predominant northwest swell and winds in the Strait of Juan de Fuca (Figure 1A), which should result in the lower alongshore littoral drift than the remaining shoreline, conditions conducive to sediment convergence.

Sand is also observed in narrow (~10 m) shore-normal bodies (Figure 3A) throughout the coarse sediment class with the highest boulder abundance (C_h; Figure 8). It is not known whether these sand bodies are mobile, and if they are, whether they may bury other substrate as they move. It is unlikely that the sand bodies would bury exposed boulders, because the sand bodies—as observed by video—did not appear to have relief (and thus a presumed thickness) greater than approximately 10 cm, and boulders were observed in the backscatter data to protrude from some sand bodies.

There is clearly at least 2 km of bedrock outcropping in the central Freshwater Bay within water depths < 10 m (Figure 8), which was distinguished by the linear bedding that dominated this region. This region forms the center of the broad Bull Kelp beds in Freshwater Bay (Figure 7A), and is therefore a likely location of relative high ecological productivity and diversity. Seavey and Ging (1995) conducted four dives in this region and reported observations of boulders, bedrock and hardpan (no definitions of these substrate types were given), and noted that these substrate types had "dense" communities of brown algae.

Although it is valuable to describe the seafloor features identified by our data, it is also important to discuss what the data did not show. Mud, which is defined by the combined silt and clay grain-size fractions (i.e., all sediment less than 0.063 mm), will absorb much of the sonar signal thereby producing a very low characteristic sonar backscatter. Regions of such low backscatter were not observed in the sonar results, and mud was not observed in any of the video observations, which implies that fine-grained sediment does not dominate the seafloor in any portion of the study area. One hypothesis to explain this may be that the potential to transport fine-grained sediment from currents and waves exceeds the sediment input rate from the river. Fine-grained sediment may or may not have accumulated previously in the region before dam construction, but if it did accumulate the upper portions of these deposits have likely been winnowed leaving only the coarser sediment (sand and gravel). Further geological investigations, especially subsurface sampling, will be needed to evaluate the impacts of the dams on fine sediment distributions.

Conclusion

The pending dam removals should increase the sediment input rates to the Elwha River nearshore for decades. The results presented here do not allow for accurate predictions of where this sediment will go, but they do provide valuable information about the types and distributions of seafloor characteristics prior to dam removal—data critical for describing future changes. We observed a diversity in seafloor substrate types, all within coarse (sand to boulder) grain sizes, and the variation in substrate appears to be consistent with patterns of parent material and littoral transport. Observations were also consistent with scuba dive transects from Seavey and Ging (1995), suggesting that the seafloor has not changed substantially during the decade between these surveys. Subsequent study of the sediment transport from the river and the effects of this sediment on nearshore habitat and ecosystems should consider the types and diversity of nearshore seafloor observed in this study.

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