Chapter 5

Coastal Processes of the Elwha River Delta

By Jonathan A. Warrick, Andrew W. Stevens, Ian M. Miller, and Guy Gelfenbaum

Abstract

To understand the effects of increased sediment supply from dam removal on marine habitats around the Elwha River delta, a basic understanding of the region's coastal processes is necessary. This chapter provides a summary of the physical setting of the coast near the Elwha River delta, for the purpose of synthesizing the processes that move and disperse sediment discharged by the river. One fundamental property of this coastal setting is the difference between currents in the surfzone with those in the coastal waters offshore of the surfzone. Surfzone currents are largely dictated by the direction and size of waves, and the waves that attack the Elwha River delta predominantly come from Pacific Ocean swell from the west. This establishes surfzone currents and littoral sediment transport that are eastward along much of the delta. Offshore of the surfzone the currents are largely influenced by tidal circulation and the physical constraint to flow provided by the delta's headland. During both ebbing and flooding tides, the flow separates from the coast at the tip of the delta's headland, and this produces eddies on the downstream side of the headland. Immediately offshore of the Elwha River mouth, this creates a situation in which the coastal currents are directed toward the east much more frequently than toward the west. This suggests that Elwha River sediment will be more likely to move toward the east in the coastal system.

Introduction

Dam removal on the Elwha River will result in fundamental increases in sediment delivery to the Strait of Juan de Fuca (Strait). To understand and predict the effects of this increased sediment supply on marine habitats around the delta, a basic understanding of coastal processes is necessary. This chapter synthesizes information about the physical setting of the Elwha River delta to provide a general understanding of the coastal processes that will determine future changes to the coastal ecosystems in and around the Elwha River delta after dam removal.

Coastal Setting

The Elwha River discharges into the Strait of Juan de Fuca, a waterway between the Salish Sea and the Pacific Ocean (fig. 5.1). The Elwha River delta is sheltered from much, but not all, of the waves and swells from the Pacific Ocean, although it is exposed to the abundant and energetic exchange of water between the Salish Sea and the Pacific Ocean. This setting—sheltered from the ocean and yet exposed to strong tidal and estuarine circulation—is a defining feature of the Elwha River delta.

Another defining feature is the broad and shallow submarine delta that extends several kilometers offshore from the present shoreline (fig. 5.1*B*). The origins of this submarine delta are discussed in Warrick and others (2011, chapter 3, this report). This feature strongly influences the waves and coastal currents that act upon this section of coast. Acoustic, video, and physical sampling techniques have shown that the submarine delta seafloor is composed of coarse sand to boulders (Warrick and others, 2008). No fine-grained sediment has been deposited on the submarine delta, although deposits of fine-grained sediment are expected following dam removal (Warrick and others, 2008).

Another element of the Elwha River delta setting is the fundamental difference between processes and currents within the surfzone and within the coastal zone offshore of the surfzone (fig. 5.2). The fundamental difference between these zones is the relative importance of waves in dictating currents. Near the beach, breaking waves provide a dominant influence on currents (Komar, 1998). Waves in the surfzone are not only responsible for the back-and-forth motions of water as each wave passes, but also can drive currents along the beach when waves approach at an oblique angle (fig. 5.2). These wave-generated currents are the primary drivers of alongshore beach sediment movement in littoral cells (Komar, 1998).

Offshore from the surfzone, waves still impart substantial back-and-forth movements in the water-column and along the seafloor, but the currents primarily are driven by tidal, wind-generated, or other coastal currents. This may result in a situation, such as shown in figure 5.2, in which currents in the surfzone and the coastal zone are in opposing directions. This situation would cause differences in the transport directions of water and sediment in these zones. Although shear will not always be present between the surf- and coastal zones, transport within these zones will be produced by different, and largely independent, processes. For the Elwha River delta, the surfzone extends only several to tens of meters off of the shoreline depending on wave height and tidal stage. More information about these processes is available in the reviews of Nittrouer and Wright (1994) and Komar (1998).

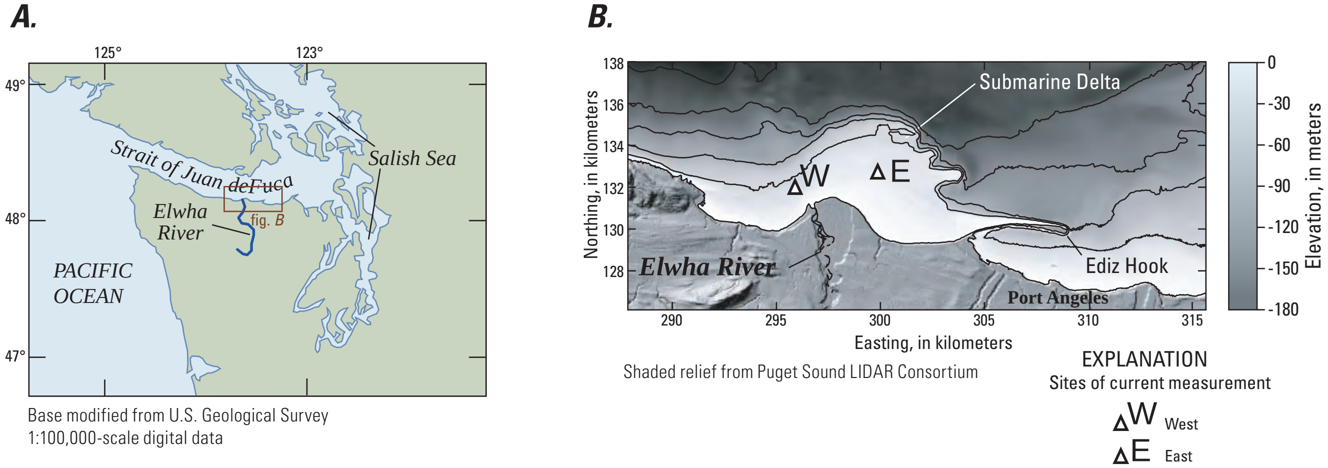


Figure 5.1. Elwha River and Strait of Juan de Fuca, near Port Angeles, Washington. (*A*) The Strait of Juan de Fuca is the primary waterway between the Salish Sea and the Pacific Ocean. (*B*) The local topography and bathymetry of the Elwha River delta.

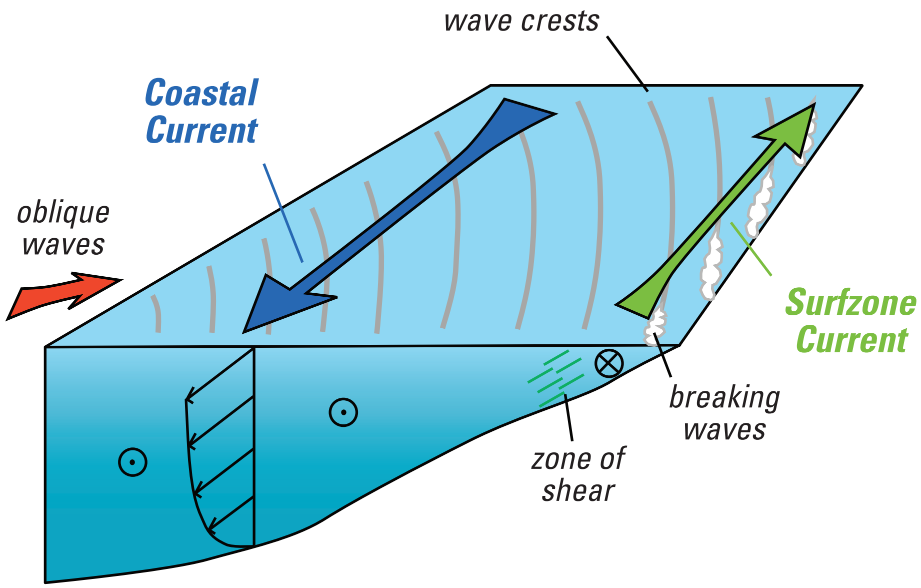


Figure 5.2. Schematic diagram showing alongshore currents of nearshore waters. Surfzone currents (green arrow) are caused by breaking waves when they have oblique approach angles. The coastal currents (blue arrow) offshore of the surfzone are influenced by tidal, wind-driven, or other regional currents and may or may not be in the same direction as the surfzone currents.

Waves

The Strait of Juan de Fuca has an intermediate wave climate between the energetic outer coast exposed to the Pacific Ocean and the more placid conditions of the Salish Sea (Shipman, 2008), although few measurements of the wave conditions within the Strait of Juan de Fuca are available to corroborate this understanding. To better characterize waves, the U.S. Geological Survey (USGS) installed acoustic Doppler current profilers (ADCP) along the seafloor at two sites at about 10 m water depth, and sampled waves hourly between January 26 and May 2, 2006 (fig. 5.1*B*). Although limited in their duration, these measurements provide important information about the general wave conditions at the delta.

Waves heights at the Elwha River delta regularly exceeded 1 m and occasionally exceeded 2 m (fig. 5.3*A*). In contrast, waves of the outer coast of Washington exceeded 10 m during this same winter-to-spring season (Ruggiero and others, 2010). The wave heights at the Elwha River delta rose and fell rapidly in response to locally generated wind waves and swell from in the Pacific Ocean (fig. 5.3). Wave heights in excess of 1 m generally lasted for only a day or less (fig. 5.3), and wave heights were most commonly less than 0.5 m (fig. 5.4*A*).

The narrow shape of the Strait of Juan de Fuca causes waves to be focused into a narrow northwestern directional band. For example, more than 90 percent of the wave energy that approached the Elwha River delta during our observations came from the northwest (fig. 5.5). Warrick and others (2009a) provide further evidence that northwest wave directions dominate all seasons of the year.

The waves at the Elwha River delta also are derived from a combination of local wind-generated waves from the Strait and swell from the Pacific. Because of the shape and size of the Strait of Juan de Fuca, the Elwha River delta “fetch” (the distance over which wind can blow to generate waves) is about 70 km. One effect of this 70-km fetch is that waves generated within the Strait will be limited to periods of less than 8 seconds (Komar, 1998; U.S. Army Corps of Engineers, 2002). Waves with longer periods come from Pacific Ocean swell, where the fetch is much longer. Our records of waves at the Elwha River delta show combined influences from low period (4–8 seconds), locally generated wind waves and longer period (greater than 8 seconds) ocean swell (fig. 5.3*B*). The most common condition measured consisted of wave periods in excess of 8 seconds (fig. 5.4*B*), which indicates that Pacific Ocean swell dominate wave conditions more frequently than wind waves.

Because the waves at the Elwha River delta originate from the northwest direction, these waves break at oblique angles along much of the shoreline, and these obliquely breaking waves drive surfzone currents and littoral sediment transport. Observations of wave breaking angles have been obtained from airborne light detection and ranging, or “lidar,” of the ocean water surface, historical aerial photography of the beach, and numerical modeling of wave propagation in the Strait (fig. 5.6). Combined, these observations show that the northwest wave approach imparts normally aligned waves on the western side of the delta and oblique wave breaking angles on the eastern side (fig. 5.6). Thus, transport of littoral sediment should be negligible west of the river mouth and eastward on the eastern side of the river mouth. This conceptual model for littoral sediment transport is consistent with recent measurements of littoral sediment movement, which suggests that sediment can move more than 100 m/d along the east beach under the strongly oblique wave directions (see Miller and others, 2011, sidebar 5.1, this report).

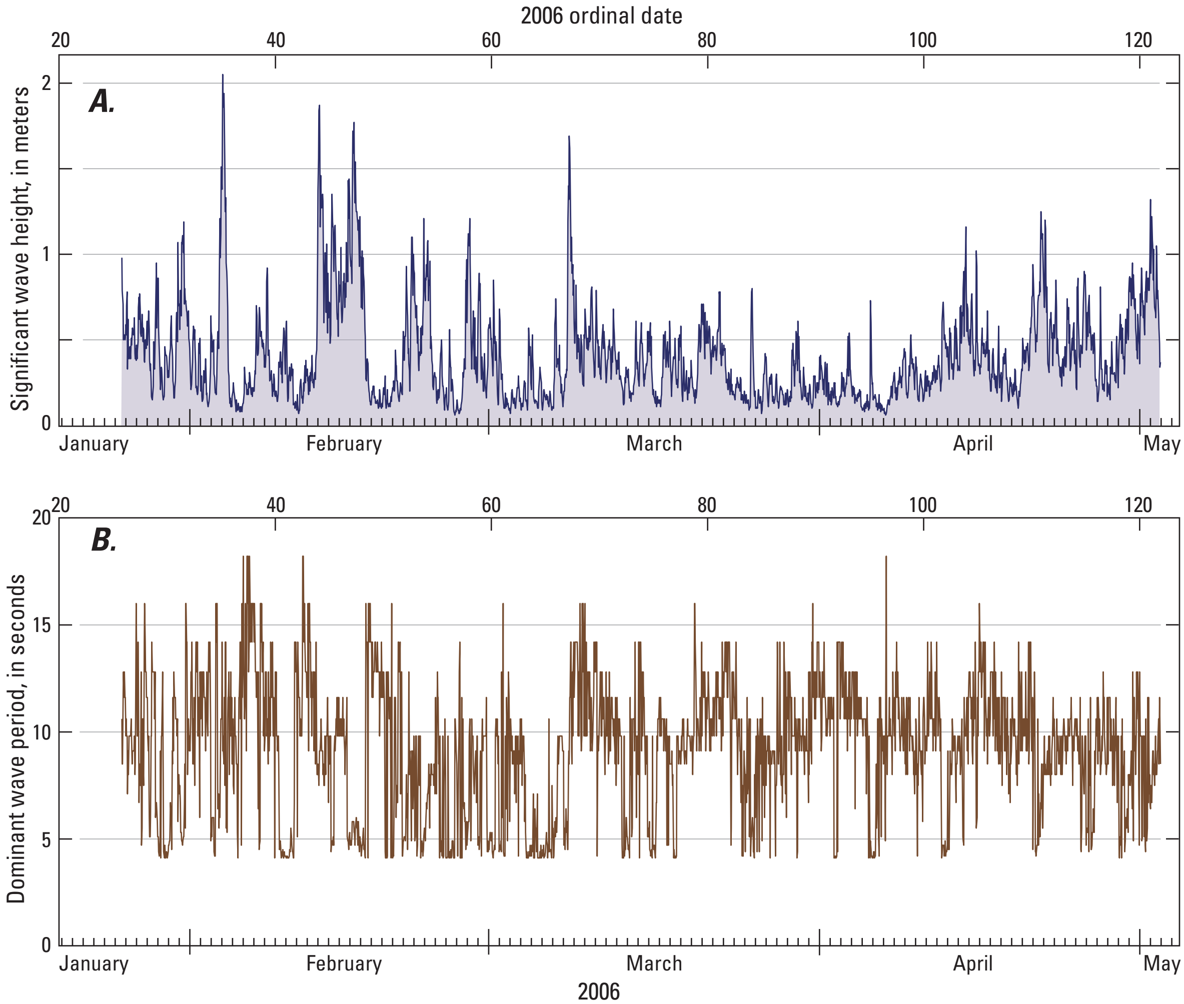


Figure 5.3. Wave height and wave period measurements from the western side (site W) of the Elwha River delta, Washington, during 2006.

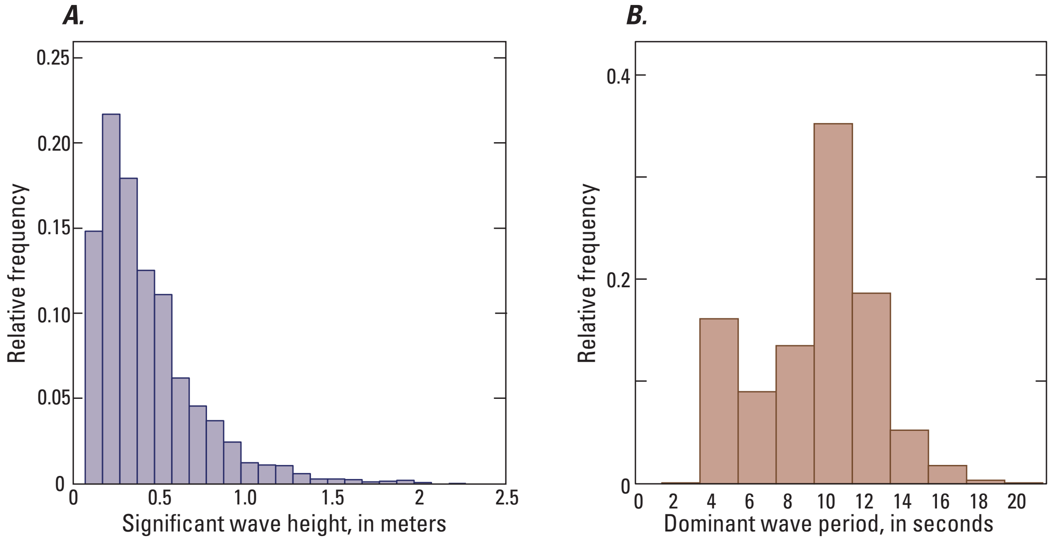


Figure 5.4. Histograms of significant wave height and dominant wave period from observations at the western side (site W) of the Elwha River delta, Washington. Waves generally are less than 1 meter with periods greater than 8 seconds, indicating Pacific Ocean origins. Location of site is shown in figure 5.1.

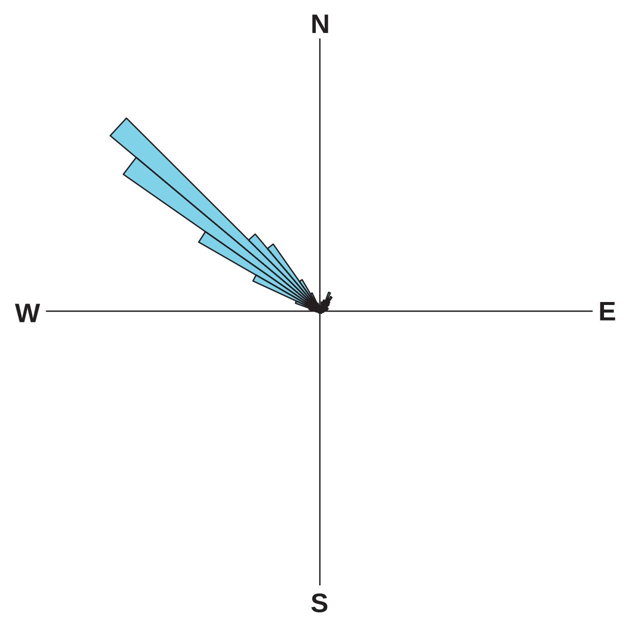


Figure 5.5. Rose diagram showing dominant wave direction from observations at the western side (site W) of the Elwha River delta, Washington. More than 90 percent of the observations were dominated by waves from the northwest, which is the direction of approach for waves generated in either the Pacific Ocean or the western Strait of Juan de Fuca.

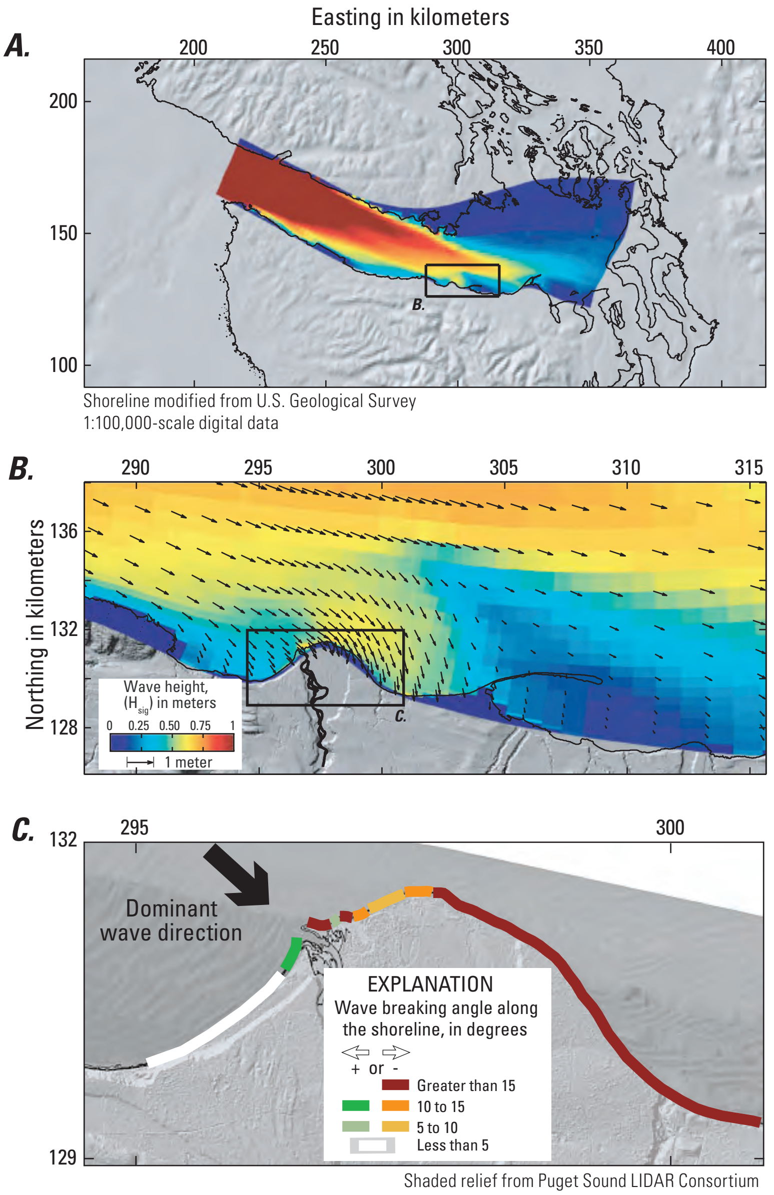


Figure 5.6. Wave patterns for the Strait of Juan de Fuca and Elwha River delta, Washington, from measurements and model simulation results. (*A*–*B*) The transformation of wave heights and directions in the Strait from 6 meter Pacific Ocean swell as predicted by the SWAN numerical model (after Gelfenbaum and others, 2009). Arrows in (*B*) show modeled wave directions. (*C*) Measurements of the angle of breaking waves along the Elwha River delta shoreline during northwest swell (black arrow) from lidar and aerial photographs (after Warrick and others, 2009).

Sidebar 5.1 Tracking the Movement of Cobble on the Elwha Beach

Ian M. Miller and Jonathan A. Warrick

It is challenging, and yet important, to measure and understand sediment transport rates and directions on a mixed grain-size beach like the one along the Elwha River delta. To directly measure these sediment movements, Radio Frequency Identifier (RFID) tags have been placed into native pebbles, cobbles, and small boulders, and their movements have been tracked over various sites, time scales, and wave conditions. RFID tags (fig. S5.1*A*) are small passive transponders used frequently in tracking fish and applied more recently to the study of bedload transport in rivers and beaches. The device contains a small chip and a capacitor, which will absorb energy transmitted by a nearby radio antenna and, using the power stored in the capacitor, transmit a unique numerical code back to the antenna. Small (23 mm long), durable glass encapsulated RFID tags were implanted directly into native beach clasts to create the tracers; the only evidence of the RFID tag is a small epoxy cap visible on the surface of the rock (fig. S5.1*B*). An easily carried mobile antenna was used to re-locate and identify individual clasts buried in the beach (fig. S5.1*C–D*).

Application of the RFID technique resulted in 80–100 percent recovery of the tracers placed on the beach. To the east of the Elwha River mouth, tracer trajectories indicate that there is consistent movement to the east (fig. S5.2). By contrast, tracer samples placed on the beach west of the river mouth moved in both alongshore directions (Miller and others, 2011). Wave height, and therefore the energy contained in the waves, seems to be the best predictor of the overall velocity of a sample of tracers on the beach over a 24 hour interval (fig. S5.2). The velocities of these tracer sediments also have been surprisingly high. During the 0.64 m wave heights of February 6-7, 2009, gravels and cobbles were measured moving more than 100 m during a tidal cycle (fig. S5.2*C*).

Figure S5.1. Methods used to track cobble movement on the beach with Radio Frequency Identifier (RFID) tagged clasts, Elwha River delta, Washington. (*A*) A single 23-millimeter long RFID tag. (*B*) A set of completed tracers ready for placement. The epoxy cap is barely visible on each tracer and is the only permanent indication of the RFID tag inside. (*C*) The mobile reader unit, with a hand-held antenna. The battery and unit are carried in a backpack. (*D*) A recovered clast (at the base of the orange stake) was buried approximately 25 centimeters.

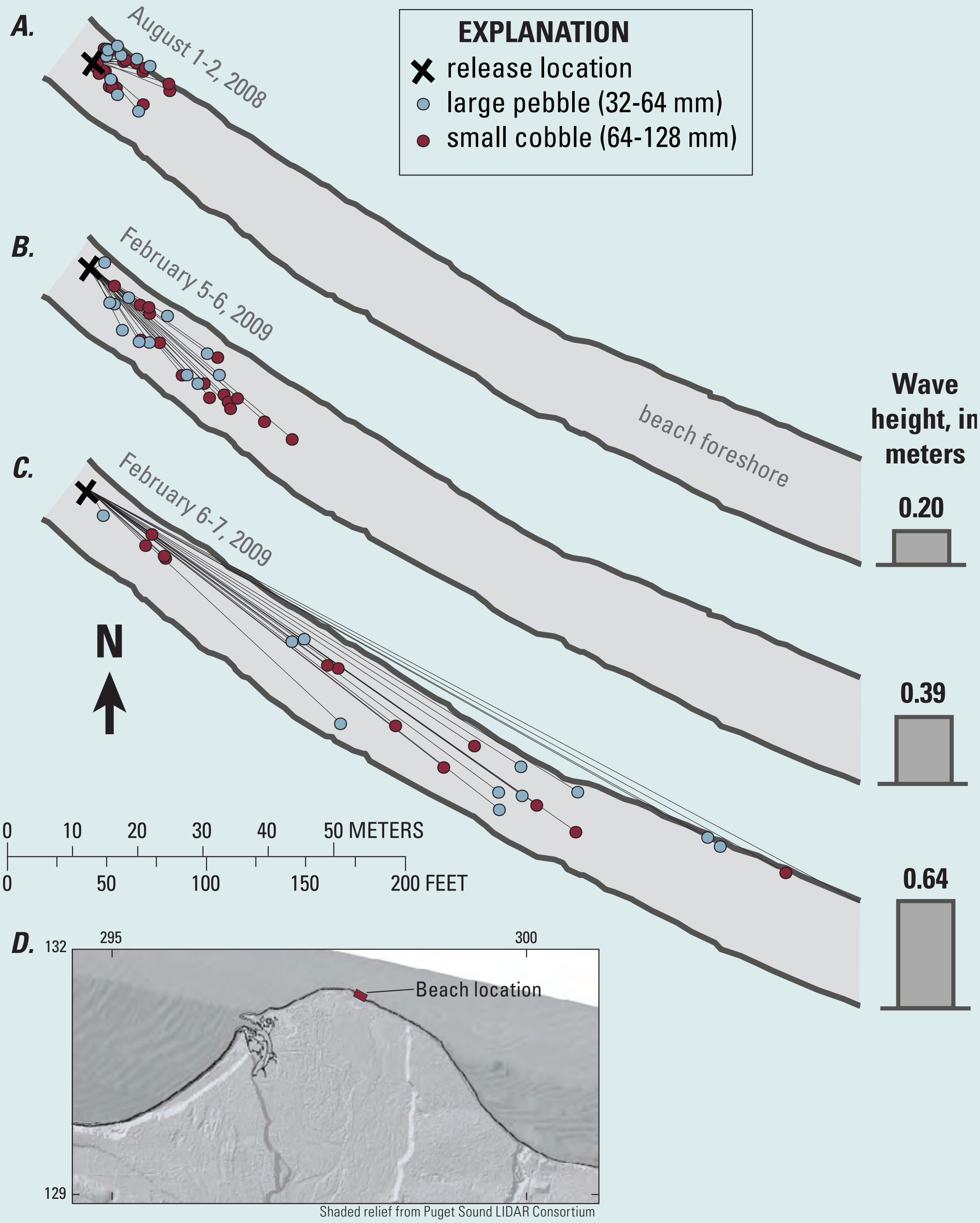


Figure S5.2. Diagrams and map showing examples of three 24-hour releases of the Radio Frequency Identifier tracers over a range of wave conditions, Elwha River delta, Washington. (*A*) August 1–2, 2008; (*B*) February 5–6, 2009; (*C*) February 6–7, 2009, (*D*) location of active foreshore and release site. Wave heights from visual estimates on August 1–2, 2008, and a pressure transducer located offshore of this site during the February 2009 measurements.

Tides and Water Levels

The water levels within and outside of the Elwha River delta dictate the estuarine flow in and out of the river mouth, the elevation of beach processes such as swash, and the potential for coastal flooding. These water levels respond to tidal and atmospheric conditions that can change greatly over the course of a day. The Strait of Juan de Fuca has a mixed, mesotidal regime (Mofjeld and Larsen, 1984; Finlayson, 2006). The "mixed" classification indicates that diurnal and semi-diurnal cycles in water levels (that is, cycles that occur approximately once and twice per day, respectively) influence the overall water level in approximately equal amounts. The "spring tidal range" is defined as the difference between the mean higher high water (MHHW) and the mean lower low water (MLLW), which are the multiple year averages of the higher high tide of each day and lower low tide of each day (Komar, 1998). The spring tidal range of the nearest tidal gauge in Port Angeles, Washington (National Oceanic and Atmospheric Administration station 9444090) is 2.15 m, which makes this region "mesotidal." The spring tidal range generally increases with distance into the Salish Sea, and the inner parts of the Puget Sound are macrotidal with spring tidal ranges greater than 4 m (Finlayson, 2006).

An example of water levels at nearby Port Angeles is shown in figure 5.7. These data reveal two important characteristics. First, the water levels reside at the higher elevations for longer intervals of time than the lower elevations (fig. 5.7). The low tides are fairly brief in time and have punctuated drops and rises. This is a common phenomenon within the Strait of Juan de Fuca and the Salish Sea, and results from the mixing of diurnal and semi-diurnal tidal components (Finlayson, 2006). Thus, the distribution of water levels at the Elwha River delta is skewed toward the higher elevations (fig. 5.8).

The second important characteristic is that water levels near Port Angeles can deviate from expected levels, especially during storm surges. Storm surges within the Strait of Juan de Fuca and the Salish Sea result from drops in atmospheric pressure as storms reside over the region, and these effects generally are greatest in winter (Finlayson, 2006). The net effect of storm surge is that water levels can be much higher than expected, and water level deviations of as much as 0.5 m (fig. 5.7) are common for the winter storms in the Strait (Finlayson, 2006).

Storm surges within the Strait of Juan de Fuca also occur during times of high winds, and therefore high waves, because the storms that cause surge also cause high winds. The combination of these conditions—storm surge and high waves—often results in substantial littoral sediment transport and coastal erosion during winter storms (Finlayson, 2006).

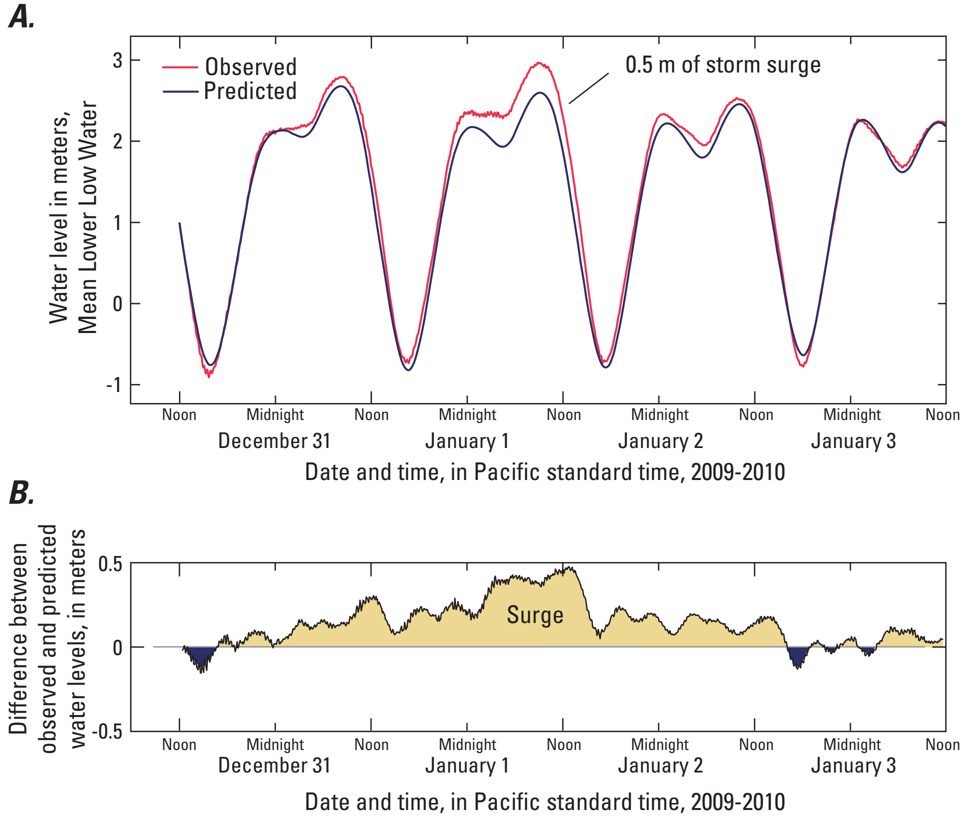


Figure 5.7. Water levels from the National Oceanic and Atmospheric Administration tidal gauge in Port Angeles, Washington (station 9444090) showing typical spring tidal range coupled with storm surge from the January 1, 2010, storm.

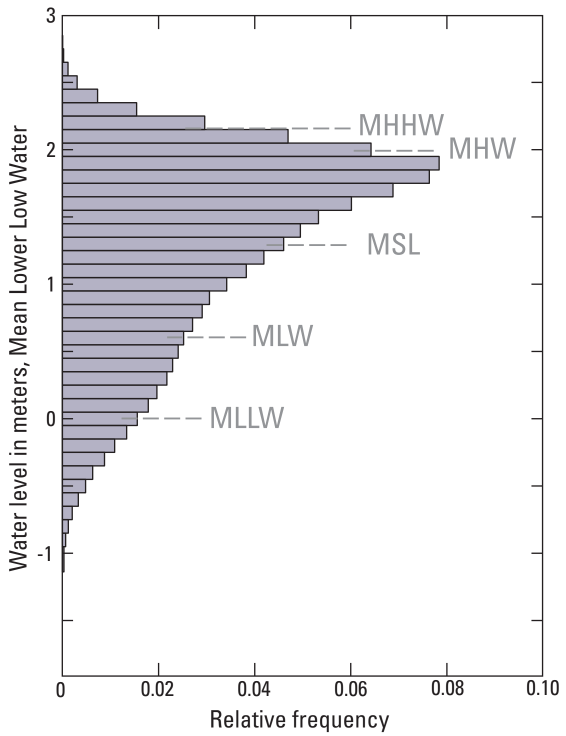


Figure 5.8. Relative frequency of water levels and tidal statistics at the National Oceanic and Atmospheric Administration tidal gauge in Port Angeles, Washington (station 9444090) showing distribution skewed toward high water levels. Data are from an 18.6 year tidal epoch.

Coastal Currents

The Strait of Juan de Fuca is the primary channel connecting the Salish Sea with the Pacific Ocean, and because of this physical setting the Strait serves as a conduit for tidal and estuarine exchange between these two water bodies. To provide the water necessary for the meso- to macrotidal conditions within the Salish Sea, strong tidal currents with speeds on the order of 100 cm/s flow in and out through the Strait daily (Holbrook and others, 1980). Much like the “mixed” diurnal and semi-diurnal characteristics of the water levels in the Strait, the strong tidal currents have diurnal and semi-diurnal components with somewhat more importance of the semi-diurnal (twice daily) cycling (Holbrook and others, 1980).

The large volume of river discharge that enters into the Salish Sea also dictates coastal currents in the Strait of Juan de Fuca. Freshwater discharged into the Salish Sea forms a freshened, buoyant layer along the upper 50 to 150 m of water depths in the Strait, and this freshened surface layer exits toward the Pacific Ocean at an average rate of about 10 cm/s (Holbrook and others, 1980; Thomson and others, 2007). Because this “estuarine” outflow of freshened water has strong vertical gradients in density (freshwater is less dense than seawater), it is characterized as a “baroclinic” flow. This flow of freshened water varies considerably over seasonal timescales, and is most intense during the spring freshet from snowmelt runoff (Masson and Cummins, 2004; Thomson and others, 2007).

To evaluate the effects of these coastal currents on circulation around the Elwha River delta, the USGS has conducted current meter measurements (fig. 5.1*B*) and developed a numerical circulation model described in Gelfenbaum and others (2009). These combined data show that the coastal currents near the Elwha River delta are strongly tidal (fig. 5.9). Most (about 90 percent) of the variance in the currents near the Elwha River delta can be explained by tidal ebbs and floods (Warrick and Stevens, 2011). These tidal currents have diurnal and semi-diurnal components, with slight dominance in the semidiurnal, or twice daily, cycling of currents.

These observations also suggest that coastal currents do not flow in a simple, uniform manner around the delta, but rather the coastal currents generate eddies as they flow past the headland of the delta (fig. 5.10). The shape of the Elwha River delta causes the flow to separate near the tip of the delta headland during ebbing and flooding, which causes a return flow, or “eddy”, on the downstream side of delta (fig. 5.10). Warrick and Stevens (2011) determined that the headland-induced eddies are regular features in the coastal currents at the Elwha River delta during spring and neap tides. These eddies also explain why there is little agreement between currents measured at opposite sides of the delta even when differences in the orientation of the currents and in the timing of the tidal responses were considered (fig. 5.9; Warrick and Stevens, 2011).

One implication of these headland-induced eddies is that coastal currents near the shore on both sides of the delta are preferentially directed toward the delta tip. For example, the coastal waters immediate offshore of the river mouth are subject to currents that flow toward the northeast more frequently and at faster current speeds than those toward the opposite, or southwest, direction (fig. 5.10). In this situation, the waters discharged by the river are subject to northeast-directed currents, which strongly affect the location of the Elwha River plume and its ecological effects.

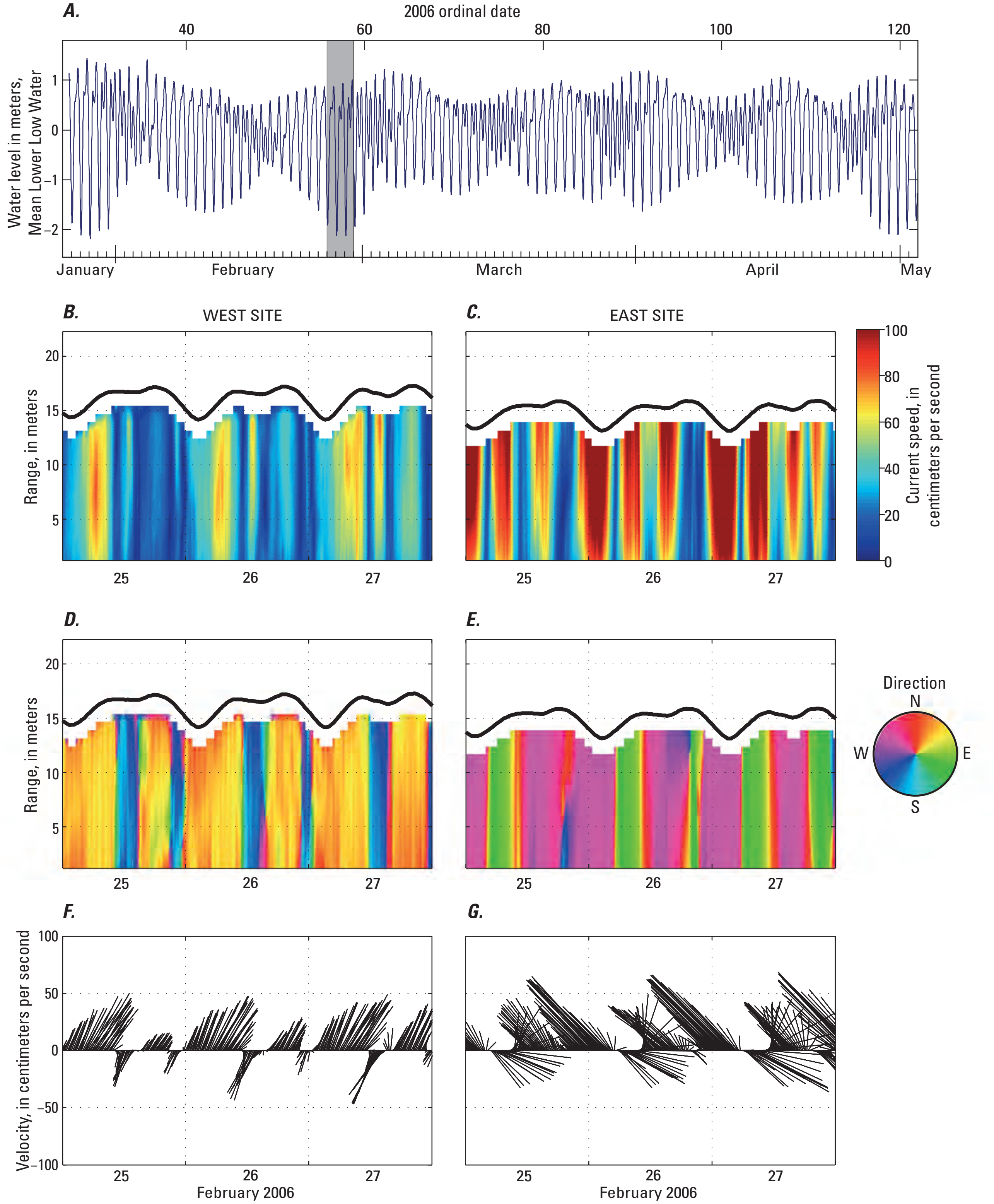
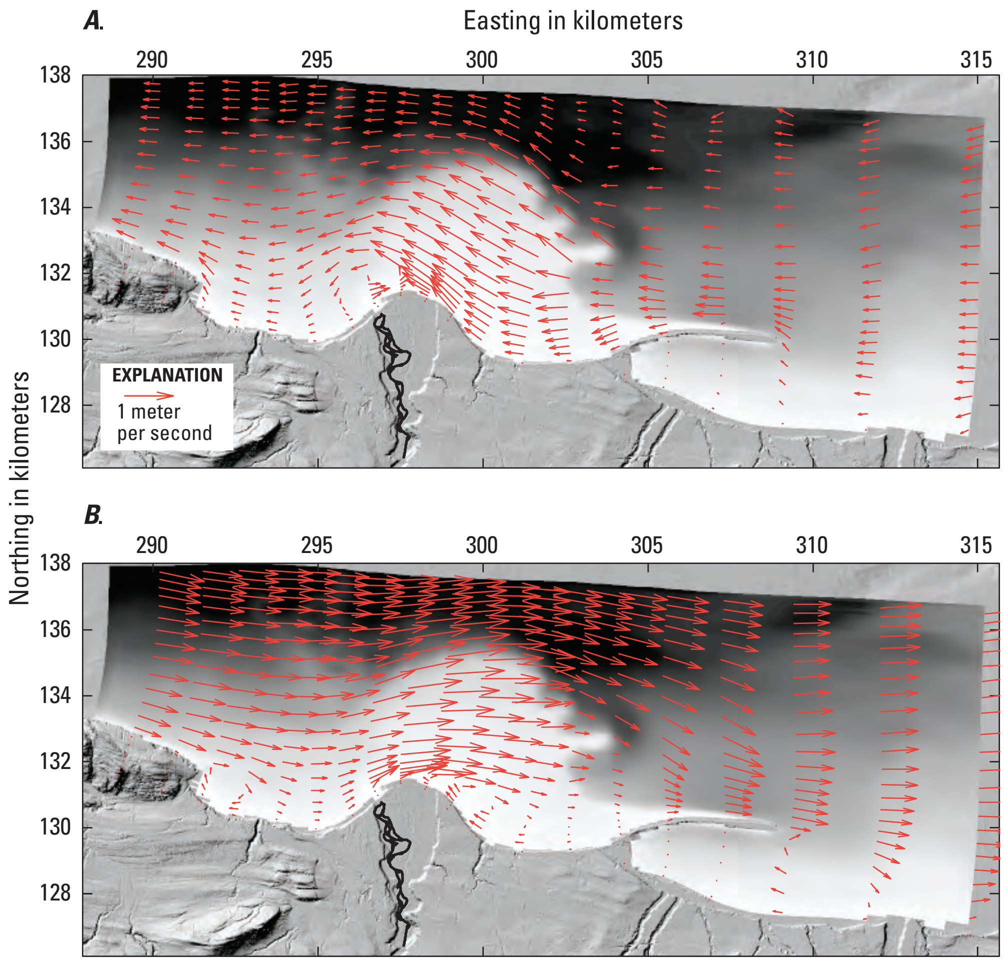


Figure 5.9. Coastal currents measured offshore of the Elwha River delta, Washington, at the West and East sites. (*A*) A four month tidal record and highlights, with a gray bar. (*B–G*) the 3-day records. Currents are shown as (*B, C*) depth-dependent speed, (*D, E*) depth-dependent direction, and (*F, G*) depth-averaged current. Although currents at both sites are strongly tidal, the magnitude, direction, and persistence of these tidal currents are not consistent.



An animation showing the simulated currents over one tidal cycle is available at http://pubs.usgs.gov/sir/2011/5120/

Figure 5.10. Coastal currents offshore of the Elwha River delta, Washington, from numerical simulations during (*A*) tidal ebbing and (*B*) tidal flooding. Note the tidal currents in excess of 1 meter per second and eddies on the downstream side of the deltaic headland.

Sidebar 5.2 Kelp-Mediated Sediment Transport

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Traditional models of sediment transport indicate that sediments will move in response to water flowing around the particle. In mixed sedimentary environments like the Elwha River delta coastal zone, however, larger clasts serve as substrate for kelps, and by doing so they make themselves easier to transport over large distances.

Numerous cases of kelp-mediated sediment transport were observed during surveys in the Elwha River coastal zone, where kelps have been attached to transported sediments of various sizes, including pebbles as small as a few centimeters to small boulders that are 40 cm or more in diameter (fig. S5.3). In some instances, the kelp-attached sediment was observed in motion due to high tidal or wave-induced currents. In other instances, trenches or disturbed sea-floor adjacent to a kelp-covered boulder were observed, indicating recent movement (fig. S5.3*B*). Windrows of kelp on the Elwha River delta beach were observed after big swells. Each kelp attached to a cobble clearly indicates that it recently was transported from deeper water (fig. S5.3*A*).

Two possible mechanisms may facilitate kelp-mediated clast transport: (1) the addition of drag as a result of the increased surface area of the kelp, or (2) the lift from buoyant kelps transmitted to the sediment through the kelp's holdfast. Non-buoyant understory kelps, such as *Cymathere triplicata* and *Pterygophora californica* are prolific in the Elwha River delta coastal zone, and have been observed attached to mobile sediments. Bull kelp (*Nereocystis leutkeana*) is one of a few buoyant species of kelp observed in the Elwha coastal zone, Bull kelps have been observed rafting cobbles above the seafloor along the Elwha coastal zone. The dominance of mixed grain substrate in the Elwha coastal zone, combined with the abundance of kelp species may, in fact, indicate that this kelp-mediated sediment transport plays an important role in transporting sediments and shaping coastal and littoral habitats.

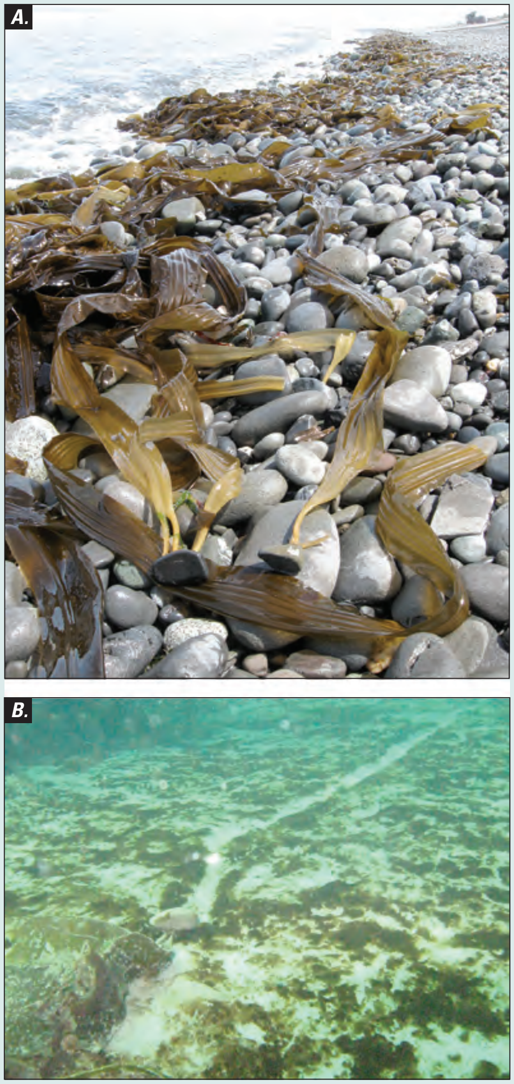


Figure S5.3. Examples of kelp-mediated clast movement from the Elwha River delta, Washington, coastal zone. (*A*) Numerous kelp-attached clasts litter the beach on June 21, 2009, about 250 meters east of the river mouth. Water level in this photograph is estimated to be 1.0 meter above Mean Lower Low Water (MLLW). The dominant kelp in these windrows is *Cymathere triplicata*, a common kelp at depths between -3.0 and -8.0 meters offshore of the delta. The two kelp-attached clasts in the near-field are estimated to be 5 centimeters along their long axes. (*B*) Active movement of an unidentified kelp attached to a cobble through algal debris at about -5.0 m MLLW depth offshore of the base of Ediz Hook on August 11, 2008. The clast under motion in this photograph is estimated to be 15 centimeters along the long axis. (Photographs taken by Ian Miller, University of California, Santa Cruz.)

Elwha River Coastal Plume

It is important to understand the patterns and dynamics of the coastal plume of suspended sediment from the Elwha River (fig. 5.11), because this plume will define the region of the coastal effects from dam removal. Numerous physical processes will influence this plume, however, which makes estimates complicated. For example, once turbid river waters reach the Strait, the freshwater of the river will be positively buoyant (that is, it will float), whereas suspended sediment particles will begin to sink toward the seafloor (Nittrouer and Wright, 1994; Hill and others, 2007). The rate of particle sinking will be related to the size, abundance, and chemistry of these particles, although for most river plume settings most of the fine sediment (silt and clay) will reside in the buoyant freshwater plume for an hour or more. Therefore, the buoyant plume can impart an initial and important transport direction and speed to the discharged sediment (Hill and others, 2007).

Repeat measurements of the position and characteristics of the Elwha River buoyant plume by Warrick and Stevens (2011) shows that the plume commonly hugs the eastern shoreline as it spreads toward the northeast, as shown in figure 5.11. The Elwha River plume is regularly directed toward the northeast because of the northeast-dominated currents that are offshore of the Elwha River mouth, which in turn are caused by eddies (fig. 5.10).

As the Elwha River discharges into the Strait, it freshens the upper 1–3 m of the coastal water column (fig. 5.12). The depth of the plume generally increases with the strength of the local current, because stronger currents mix the buoyant plume deeper (Warrick and Stevens, 2011). The rate of water discharge from the river mouth into the plume—especially during low river flow—also is a function of the tidal stage. Falling, or “ebbing,” tides export river water at higher rates as described more fully in Magirl and others (2011, chapter 4, this report).

Using this information about the coastal currents and buoyant river plume, the USGS has developed a numerical model that tracks the freshwater and suspended sediment discharged by the river (Gelfenbaum and others, 2009). Model simulation results indicate that suspended sediment discharged from the river should be dynamic and largely mimic the patterns of the buoyant plume (fig. 5.13). Because the buoyant plume is directed toward the east more frequently than toward the west, the suspended sediment effects of dam removal—including but not limited to water column turbidity and sedimentation on the seafloor—should be greatest and most persistent on the eastern side of the river mouth.

Figure 5.11. Aerial photograph of the plume discharging toward the northeast from the mouth of the Elwha River, Washington. (Photograph from the Washington State Department of Natural Resources, 1994.)

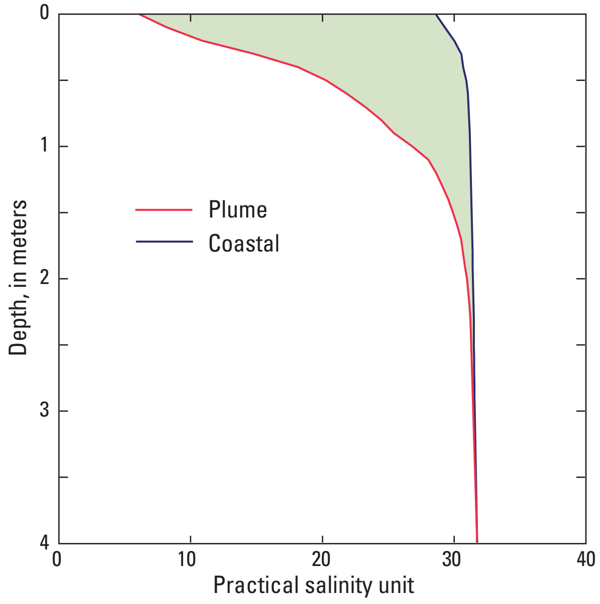
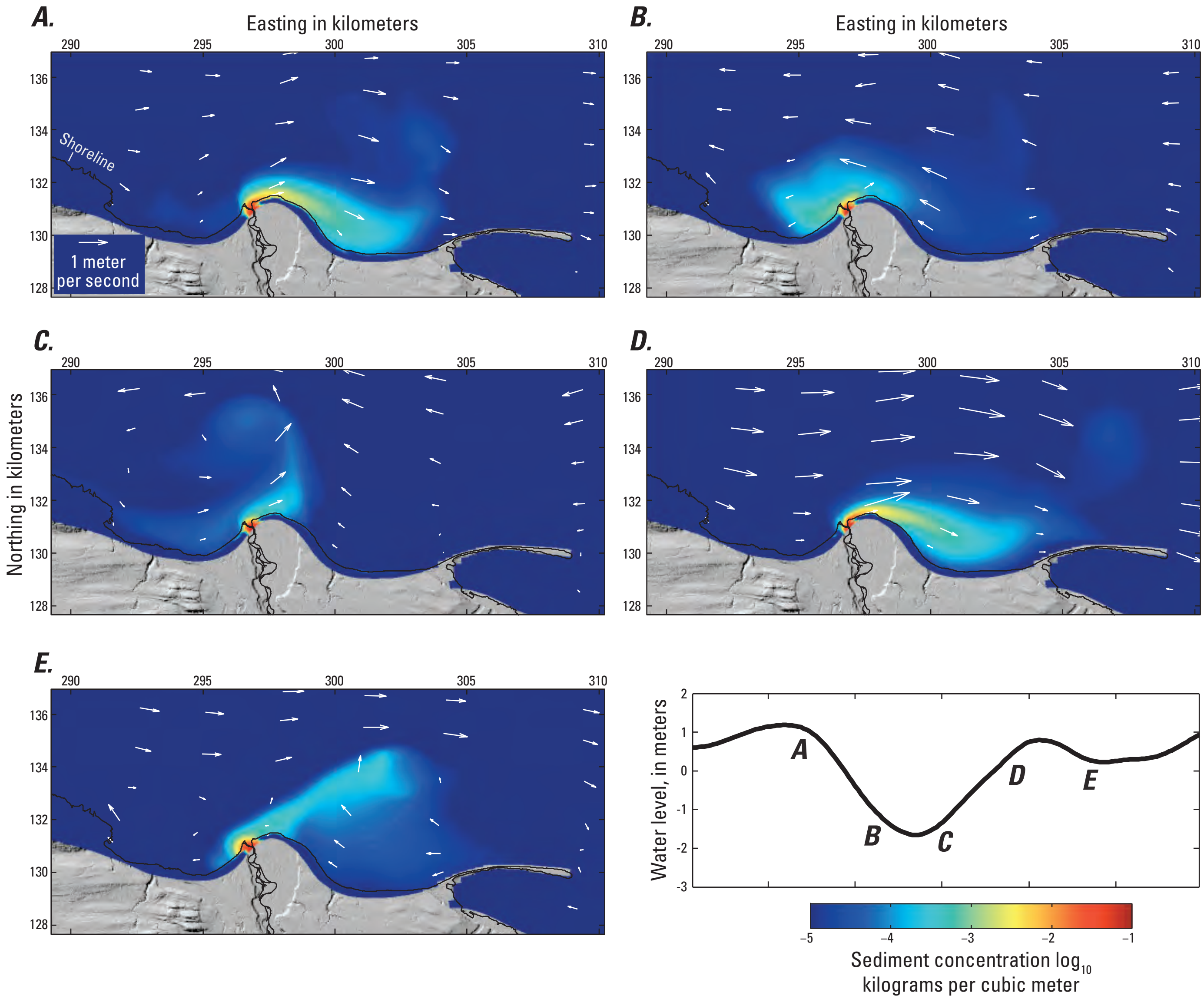


Figure 5.12. Salinity inside the buoyant plume (plume) and in coastal waters directly outside the plume (coastal), Elwha River, Washington. Measurements were taken at 1800 Pacific Standard Time on June 9, 2007, at about 0.5 kilometers offshore of the river mouth. The freshening of the upper 1.5 meters of water from the river water is shaded green. (After Warrick and Stevens, 2011.)



An animation showing the simulated sediment concentrations over one tidal cycle is available at http://pubs.usgs.gov/sir/2011/5120/

Figure 5.13. Evolution of coastal turbidity from the discharge of suspended sediment from the Elwha River, Washington, as determined by model simulation results (after Gelfenbaum and others, 2009). Arrows indicate depth-averaged flow direction and magnitude.

Summary

The coastal zone of the Elwha River delta is strongly influenced by waves from the Pacific Ocean and currents that respond to the exchange of water between the ocean and the Salish Sea. The shape and morphology of the submarine delta and shoreline also have substantial effects on how these waves and currents vary within this coastal system. Waves approach largely from the northwest, which results in oblique breaking wave directions along much of the shoreline. These oblique wave breaking angles will move littoral sediment from the river mouth toward the east. The coastal currents are largely tidal, but these currents also induce eddies at the tip of the delta that influence dominant current directions. The coastal currents immediately offshore of the river mouth are directed toward the east more frequently than to the west, which influences the direction of transport for suspended river sediment discharged by the river.

Because of these patterns, most of the sediment introduced from dam removal likely will be transported toward the eastern side of the river mouth. It is, perhaps, no coincidence that since the dams were emplaced, the eastern beach is the region of greatest coastal erosion (see Warrick and others, 2011, chapter 3, this report). This does not mean that no significant effects may occur from the river sediment toward the west of the river mouth. In fact, there are occasions during which coastal currents offshore of the river mouth are either negligible or toward the west. During these conditions, the Elwha River plume is expected to spread westward toward Freshwater Bay. If a high sediment discharge occurs during a westward spreading plume, fine sediment will be deposited in Freshwater Bay.

Although there is a good understanding of the basic physical conditions of the Elwha River delta nearshore and coastal zones, these conditions and processes have not been fully integrated into a predictive sediment transport model for the post-dam removal conditions. During the post-dam removal phase there will be a unique opportunity to measure the direction and magnitude of transport from this massive release of sediment. These observations can be used to develop, test, and improve analytical capabilities, so that future projects can benefit from these insights. Development and implementation of a strong coastal monitoring program during the post-dam removal phase and coordination of these observations with numerical modeling efforts can help in understanding the marine effects of dam removal.

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