Can Dam Removal Restore Threatened Shorelines?

The Elwha Case Study

Mollie Holmberg[1,2]

Marine Sedimentary Processes Research Apprenticeship

[1]Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250

[2]Department of Biology, University of Washington, Seattle, WA 98195

Contact information:

Mollie Holmberg

Biology Department

Box 351800

Seattle, WA 98195-1800

mollieh@uw.edu

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Abstract

Dam construction on rivers like the Elwha River in Washington State reduces sediment supply to adjacent coastal systems and has often been linked to coastal erosion and threats to human infrastructure. With the removal of two dams on the Elwha River, it was hypothesized that chronic erosion of the surrounding coastline would slow or reverse. To test the impact of dam placement and removal on shoreline change, shoreline change was quantified by digitizing shoreline position using a 1908 survey map and four aerial photographs spanning 1939-2014. Anthropogenic and natural features related to shoreline change were identified using a combination of aerial photographs, remotely-sensed data and field surveys. Shoreline change analysis revealed retreat of the vegetation line east of the river mouth both before and during dam removal and areas of net accretion to the west. However, for ~1 km east of the river mouth during dam removal, new sediment accreted along the shoreline where vegetation retreated. Although this indicates that in some places movement of the vegetation line is not a reliable proxy for shoreline change, it also reveals that dam removal has not slowed erosion in all areas of the eastern coastline. Local wave regimes and the locations of abandoned river channels, levees, and shoreline armoring correlate spatially with calculated patterns of shoreline change. This suggests the importance of considering all of the potential geologic and anthropogenic influences when predicting shoreline responses to major disturbances such as dam removal.

1. Introduction

Shoreline change impacts a wide range of human infrastructure. Not only does a substantial fraction of the world's population live near the coasts (estimates vary from half of the world's population within 60 km of the coast (United Nations Environment Program) to less than a third within 100 km (Small and Nicholls, 2003)), but industry and transportation concentrated at the coasts often benefit people living farther inland. Around the Elwha River on the northern end of the Olympic Peninsula in Washington State, erosion has threatened homes, roads, and even a U.S. Coast Guard base placed along the shore (U.S. House of Representatives, 1973). Local and federal government agencies have installed shoreline armoring to protect this infrastructure against erosion (Shaffer et al., 2008). Engineered shoreline protections like this often require long-term maintenance and costly investments from communities and/or governments (Landry et al., 2003). For this reason, it is important to understand the processes influencing shoreline change to aid in the development of less costly solutions and help people predict future trends in shoreline change impacting human development.

Shoreline change can be driven by anthropogenic, meteorologic, or geologic processes occurring over time scales ranging from days to millennia. Over thousands of years, tectonic movement and isostatic rebound can shift shorelines by causing land to move upward or downward relative to sea level (Plafker, 1965; Gronewald and Duncan, 1965). Climate trends have similarly long-term effects. Currently, global climate change is driving relative sea-level rise in many places, moving shorelines inward and intensifying erosion (Leatherman et al., 2000). Climate also shapes shorelines on the decadal scale through global cycles like El Niño/La Niña and the Pacific Decadal

Oscillation that moves relative sea level and alter wave regimes (Rooney and Fletcher, 2005; Sallenger et al., 2002). Coastlines also advance and retreat over the course of a year due to the seasonal fluctuations in wave regimes (Pearre and Puleo, 2009). From moment to moment, waves shape shorelines through sediment transport, either moving it onshore and causing accretion or transporting it away via erosion (Komar and Inman, 1970). Human activities such as the construction of jetties and breakwaters often alter shorelines by interfering with the natural processes of wave-driven sediment movement (Nordstrom, 1994).

Dam construction shifts shorelines by trapping sediment upstream, preventing the transport of sediment to the coastal environment, often leading to downstream erosion. The popularity of hydropower as a “clean,” renewable, and often inexpensive energy source has led to dam-driven erosion on coastlines across the world (Anthony and Blivi, 1999; Frihy et al., 2008; Kowaleski et al, 2000; Poulos and Collins, 2002; Stanley and Warne, 1993). Many researchers have attributed erosion east of the Elwha River to dam construction in the early twentieth century (Schwartz and Johannessen, 1997; Warrick et al., 2009). Despite this interest in understanding the impacts of dam construction, no studies exist documenting the evolution of a coastline following dam removal.

In late 2011, the National Park Service began removing the Elwha and Glines Canyon dams on the Elwha River on the Olympic Peninsula of Washington State. This project is the largest intentional dam removal in U.S. history, providing a valuable opportunity to observe the reaction of shorelines following dam removal (NPS, 2014). Small, mountainous rivers such as the Elwha can be some of the most important sediment sources for coastal systems (Milliman and Syvitski, 1992), and construction of dams in

1910 and 1927 all but eliminated sediment supplied by the river to the coastal environment (Randle, 1996). Since private and government agencies had invested heavily in protecting local infrastructure against erosion, it was hoped that dam removal would slow or reverse erosion by restoring sediment supply to the shoreline (National Park Service, 1995).

This study examines shoreline change around the Elwha River delta prior to and during dam removal to gain a better understanding of how a shoreline responds to dam removal. Using maps and aerial photographs, shorelines were delineated around the Elwha River and rates of shoreline change were quantified from 1908 to 2011 (while the dams were in place) and 2011 to 2014 (during dam removal). This study also surveyed natural and anthropogenic features related to changes along this shoreline using a combination of RTK-DGPS (Real Time Kinematic-Differential Global Positioning System), aerial photographs, and elevation data collected with laser-based remote sensing technology (LiDAR). In this way, this study evaluates the relative importance of the dams in influencing shoreline change near the Elwha River.

2. Regional setting

A small mountainous river on the west coast of North America, the Elwha River drains an area of 831 km^2 on the northern end of the Olympic Peninsula in Washington State (Fig. 1). Over its 72-km length, the Elwha River cuts through a series of canyons and floodplains on its way to the Strait of Juan de Fuca. The Strait of Juan de Fuca connects the Salish Sea to the Pacific Ocean between Washington State and Vancouver Island. Northwesterly swell entering through the Strait of Juan de Fuca hits the coastline around the Elwha River mouth at an oblique angle, where it plays a key role in transporting sediment east along the shoreline (Galster and Schwartz, 1990).

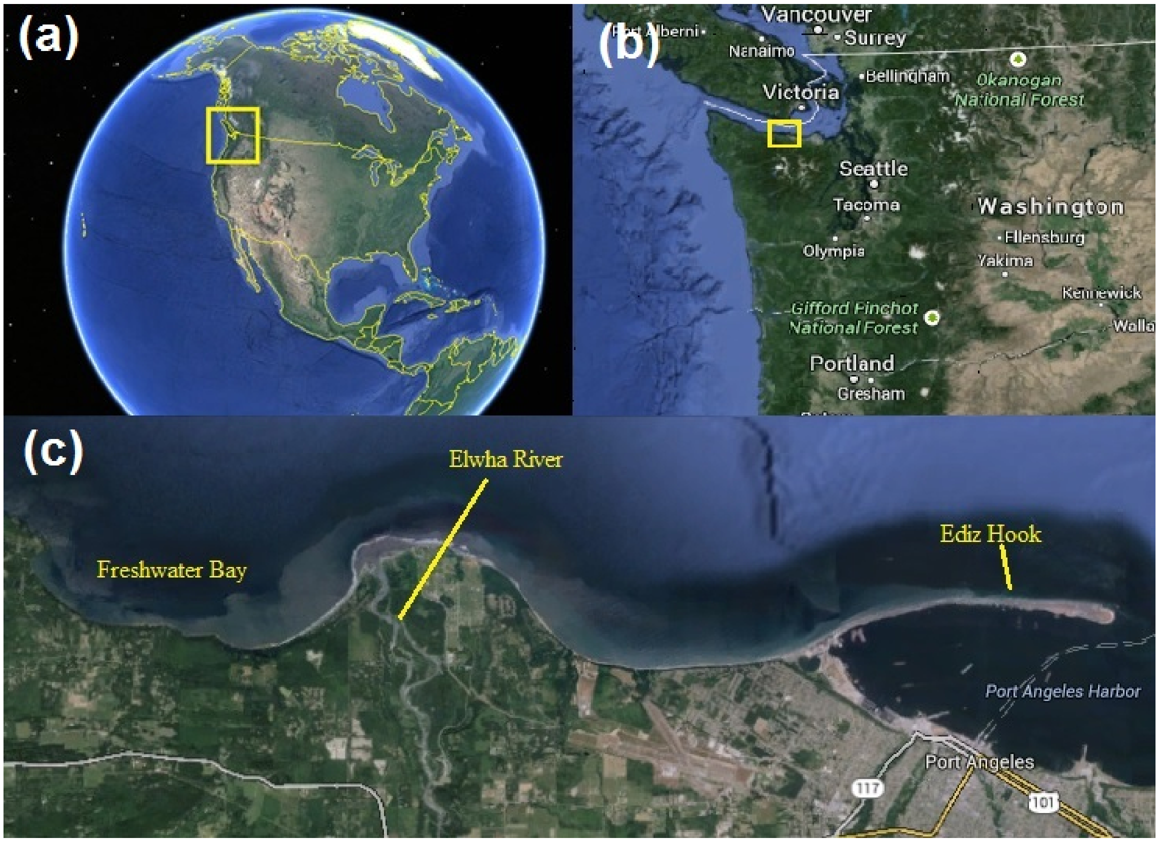

Figure 1. Situated on the northern end of the Olympic Peninsula in Washington State (a, b), the Elwha River is situated in a littoral cell extending from Freshwater Bay to the end of Ediz Hook (c). Basemap credit: Google Earth

Marine sedimentary rock dominates the upper Elwha Basin, with the Crescent Formation made of basalt farther downriver. During the most recent ice age, the Cordilleran ice sheet extended south across the Strait of Juan de Fuca to about 1150 m above present-day sea level in the Olympic Mountains, until its retreat about 15000 years ago. Alpine glaciers also extended down through the mountains. During glacial retreat, ice scoured the Elwha River basin and left thick deposits of till and outwash through most of the basin below the Crescent Formation (Tabor, 1987). The glacial history of this region and short reach of the river result in mixed grain size beaches (Shipman, 2008).

People have imposed impressive changes on the Elwha River channel, shoreline, and delta. The construction of the Elwha Dam in 1913 and Glines Canyon Dam in 1927 essentially eliminated sediment transport to the ocean. Armoring on coastal bluffs near the river mouth (Fig. 2) has also reduced shoreline erosion in some places. Since river transport and shoreline erosion have historically been the most important sediment sources for the littoral cell extending from Freshwater Bay to Ediz Hook (Fig. 1), there has been net sediment loss on the eastern shoreline where sediment once accumulated (USACE, 1971; Galster and Schwartz, 1990; Schwartz and Johanessen, 1997). People have also constructed flood-control levees (Fig. 2) and shifted the river channel in several places. These changes combined with natural channel meandering and avulsion have shaped the number and location of distributary channels on the delta. The Elwha River has had only a single distributary for most of recent history (Draut et al., 2008). Accounts from the Lower Elwha Klallam Tribe also suggest that dam construction led surrounding beach and seafloor areas to become dominated by much coarser-grained sediments than previously (Reavey, 2007). Since dam removal began in September 2011, finer-grained sediments have begun to cover coarse-grained habitats again (Miller, pers. comm.). The dam removal is expected to release 6-7 x 10^6 m^3 of sediment into the lower Elwha and surrounding coastal region by 2016 (Shaffer et al., 2008).

Figure 2. The Elwha River delta and surrounding coastline, extending from Freshwater Bay in the west to Ediz Hook in the east. Man-made modifications to the river channel, floodplain, and coast are also marked. Base map credit: Google Maps

Climate in this region varies between warm, dry summers and cool, wet winters. Although peak precipitation occurs between October and March, the quantity of this precipitation varies significantly over the length of the basin – more than anywhere else on the Olympic Peninsula. A rain shadow created by Mt. Olympus and the Bailey Range causes the river mouth to receive as little as 1,000 mm of precipitation annually while precipitation at Mt. Olympus reaches over six times that level (Duda et al., 2011).

The Elwha River estuary contains a wide mix of vegetation types. Dunegrass (*Leymus mollis*) is dominant along much of the shore, while riparian forest covers the majority of this area. The estuary also contains patches of riparian shrub, willow-alder forest, shrub-marsh transition, and emergent marsh (Shafroth et al., 2011).

3. Methods

3.1. Quantifying shoreline change

To measure shoreline change, aerial photographs were obtained from 9 dates between 1939 and 2014 (before and during dam removal). Aerial photographs for 1939-2011 had previously been orthorectified and geo-referenced by Josh Logan, USGS as described in Draut et al. (2008). Geo-referenced aerial photographs for 2012, 2013, and 2014 were developed through a novel remote sensing technology by Andy Ritchie, National Park Service (Ritchie, 2012). Five of these aerial photographs (shown in Table 1) were selected for use in shoreline change analysis because they represented key time points before and during dam removal. In these maps, the shoreline was digitized by using the high water level (HWL) visible at the vegetation line to estimate mean higher high water (MHHW). Aerial photographs were all viewed at a 1:3000 resolution while digitizing the shoreline. Shoreline digitization error was estimated by computing the average distance between the MHHW contour obtained from 2012 LiDAR data (http://pugetsoundlidar.ess.washington.edu/) and the shoreline digitized from a 2012 aerial photograph. It was assumed that shoreline digitization error would be the same for all aerial photographs digitized through the same method. The source, year, and error information are listed for each map used in shoreline change analysis in Table 1. Aerial photographs from 1956, 1965, and 2013 (not listed in Table 1) were also used to qualitatively evaluate the evolution of the river mouth and coastline.

A U.S. Coastal Survey chart from 1908 was also included in this shoreline change analysis. U.S. Coastal Survey charts, or “T-sheets,” document topographic and ecological information on coastal regions throughout the United States during the late 19th and early 20th century. For more information on the uses and accuracy of these T-sheets, see Collins et al. (2003). This map had previously been geo-referenced and converted from the Puget Sound Datum to NAD83 through the Puget Sound River History Project (http://riverhistory.ess.washington.edu/) as described in Todd et al. (2006). The ordinary high water level (OHWL) contour on this map was traced to digitize the 1908 shoreline. Since the OHWL is determined by marking the vegetation line, this contour should be comparable to the shorelines digitized by marking the vegetation line on aerial photographs (Shalowitz, 1964). Digitization error was estimated from the width of the OHWL contour line. For total error information, see Table 1.

Shoreline change was then quantified using end point rates in the Digital Shoreline Analysis System (DSAS) extension in ArcGIS along transects cast every 75 m (DSAS automates the casting of transects a specified distance apart). This analysis extended from ~6 km west of the river mouth to the base of Ediz Hook before dam removal and from ~1.3 km west of the river mouth to ~2 km east of the river mouth during dam removal (Figure 3).

Error analysis was conducted by accounting for geo-referencing error and error in digitizing the shoreline as $E_{photo}=\surd(E_{ref}^2 + E_{shore}^2)$ (Table 1), and then combining the error from each individual photograph as $E_{total}=\frac{\sqrt{E_{photo1}^2+E_{photo2}^2}}{years\ between\ photos}$ (Draut et al., 2008). Total error (E_{total}) (Table 2) was calculated separately for each analysis (before dam removal, during dam removal, and before/during combined) since each analysis spanned a different length of time.

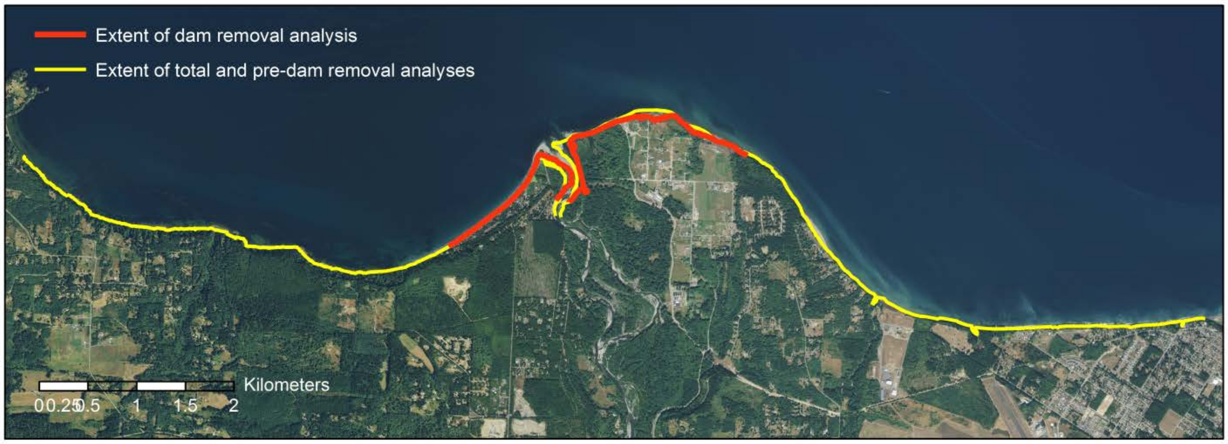

Figure 3. The shoreline extent used in shoreline change analysis for this study. Aerial photograph credit: U.S. Department of Agriculture

3.2. Evaluating impacts of anthropogenic and natural features

Shoreline change patterns were evaluated in light of historical changes to the lower Elwha River and surrounding shoreline. Anthropogenic and natural features related to shoreline evolution were identified on the aerial photographs and digitized. LiDAR data from 2012 were also used to identify river channels occupied in geologic time. Anthropogenic features digitized included a seawall, riprap, shoreline armoring east of the Elwha River mouth, and levees constructed on the lower river. Natural features of interest included biological features and geologic features related to shoreline change such as peat and tree stumps visible on present-day beaches and abandoned river channels. The identification and location of these features was aided through the examination of several maps (Warrick et al., 2009) and a survey of the eastern Elwha delta with Real-Time Kinematic Differential Global Positioning System (RTK-DGPS). RTK-DGPS was used to geo-locate features within a mile east of the river mouth along the shoreline. Evolution of the river mouth in historical time was assessed qualitatively by examining a General Land Office (GLO) survey map from 1872, the T-sheet from 1908, and aerial photographs spanning 1939-2014. The locations of these natural and anthropogenic features were then compared with patterns of shoreline change before and during dam removal.

Table 1. Source information and error for maps and aerial photographs used in calculating shoreline change

Year	**Source**	**Estimated Geo-referencing Error (m)**	**Shoreline Digitization Error (m)**	**Total Error (m)**
1908	Puget Sound River History Project, University of Washington	8	5	9.4
1939	Puget Sound River History Project, University of Washington	10.6	7.8	13.2
2000	Washington Dept. of Natural Resources; orthorectified by Josh Logan, USGS	13.0	7.8	15.2
2011	U.S. Department of Agriculture	5	7.8	9.3
2014	Andy Ritchie, National Park Service	1	7.8	7.9

4. Results

4.1. Quantifying shoreline change

Between 1908 and 2014, the coastline around the Elwha River accreted throughout Freshwater Bay and eroded over much of the river mouth and coastline just east of the river (Fig. 4a). Transects along this coastline were divided into three groups: those west of the river mouth, at the river mouth, and east of the river mouth (Table 2). When shoreline change was averaged within each of these regions, it was only statistically significant (i.e., the magnitude of the shoreline change was statistically greater than zero) at the river mouth and east of the delta (Table 2). Although shoreline change averaged across transects west of the river mouth was not statistically significant (Table 2), at some individual transects in Freshwater Bay the shoreline accreted up to 0.32 m/year over the past century (Fig. 4a). Overall, vegetation line retreat accelerated at the river mouth and east of the river mouth between 1908 and 2014 (Table 2).

Some of the greatest shoreline erosion occurred over a ~0.5 km stretch of coastline ~1.5 km east of the river mouth where total erosion was on the order of 50 to 100 m between 1908 and 2014 (Fig. 4a), most of which occurred after dam removal commenced (Fig. 4b, 4c). There has been relatively little shoreline change since the dam removals began outside of this stretch of coastline and the river mouth. Vegetation line retreat was the only statistically significant trend in quantified shoreline change observed during dam removal (Fig. 4c). However, the aerial photograph used to construct the 2014 shoreline does not extend to some of the areas east and west of the river mouth where significant shoreline change, including accretion, occurred prior to dam removal (Fig. 4). Also, although accretion is visible on aerial photographs of the delta after the start of dam removal (Fig. 7), this accretion was not captured in this analysis since the majority of the accretion occurred outside the vegetation line used to estimate shoreline.

Table 2. Average rate of shoreline change over different time periods and at different parts of the shoreline. Statistically significant rates of change (magnitude of rate > uncertainty) are shaded in gray.

	West of mouth	River mouth	East of mouth	Overall	Uncertainty
Pre-dam removal	0.0 m/yr	-0.4 m/yr	-0.3 m/yr	-0.2	0.2 m/yr
During dam removal	-1 m/yr	-15 m/yr	-5 m/yr	-4 m/yr	3 m/yr
Total	0.0 m/yr	-0.3 m/yr	-0.3 m/yr	-0.2 m/yr	0.1 m/yr

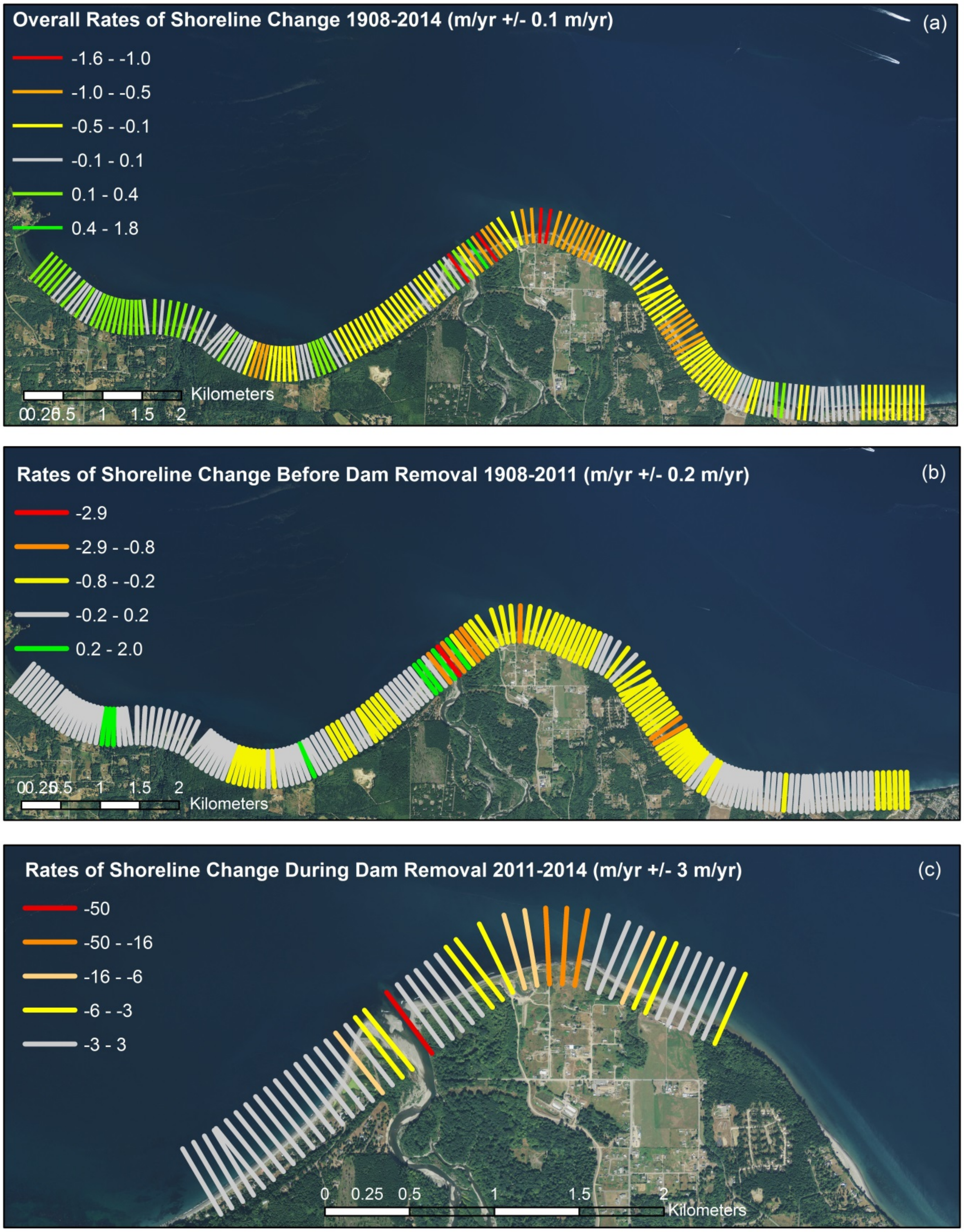

Figure 4. Rates of shoreline change for 1908-2014 (a), before dam removal (b), and during dam removal (c) in m/yr. Aerial photograph credit: U.S. Department of Agriculture

4.2. Anthropogenic features of interest

Anthropogenic features with potential to impact patterns of shoreline change were identified using an aerial photograph from March 2014 and a RTK-DGPS survey from April 2014 (Fig. 5). One levee was found ~50 m west of the 2014 river mouth and another ~500 m east. The remnants of ~ 650 m of riprap were identified between 15 and 50 m off the 2014 shoreline, ~1km east of the river mouth. Situated just behind and between two segments of the riprap was also a crumbling concrete seawall. The portion of the concrete seawall remaining intact (rather than scattered across the beach) is about 15 m seaward of the 2014 shoreline. Both intact and scattered portions of this seawall were recorded via RTK-DGPS. Finally, a wooden seawall about 165 m long was identified ~1.6 km east of the river mouth. This seawall remains intact and completely abuts the shoreline (Fig. 5).

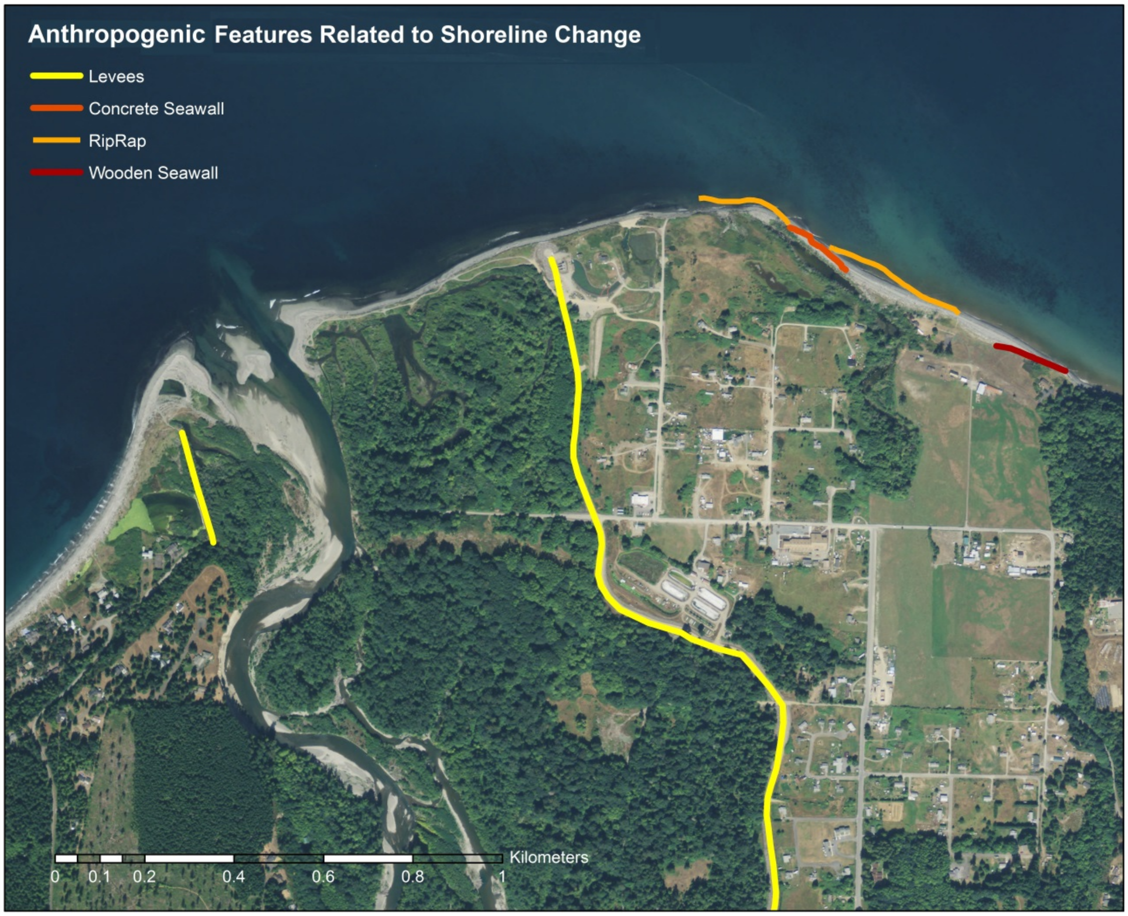

Figure 5. Anthropogenic features related to shoreline change. Aerial photograph credit: U.S. Department of Agriculture

4.3. Natural features related to shoreline change

Natural features of related to shoreline change were identified from LiDAR, aerial photographs, and an RTK-DGPS survey (Fig. 6). Peat and dead trees located via RTK-DGPS were found protruding from what is now coastal sediment (about 0.9 km and 1.2 km east of the 2014 river mouth, respectively). LiDAR data from 2012 were used to determine the extent of the floodplain and river-mouth locations prior to 1908. The river floodplain, marked on Fig. 6, is defined here as the low-lying region containing the river with bluffs to the east and west and contains just over 2 km of shoreline. Five river channels predating 1908 were identified, ranging between 0.9 and 1.9 km east of the 2014 river mouth, and two lagoons recorded using RTK-DGPS sit just north of these channels (Fig. 6).

Using a combination of aerial photographs, a T-sheet from 1908, a GLO survey map from 1872, and RTK-DGPS, locations of the river mouth in historical time were also identified (Fig. 6). Lagoons present throughout the shoreline between these locations indicate locations of the river mouth in historical time. The easternmost Elwha distributary was recorded in 1872, about 900 m east of the 2014 river mouth, and based on the location of a lagoon in aerial photos, the westernmost extent of the river mouth appears to have been about 200 m southwest of its current location (Fig. 6). The westernmost former river mouth first appears in an aerial photo dated 1965, although it has already avulsed in this photo. Three distributaries appear in the Elwha map from 1872. However, both the T-sheet from 1908 and aerial photographs through 1956 show evidence of the Elwha River having two distributaries, and since 1965, the river appears to have been confined to a single channel (Fig. 7).

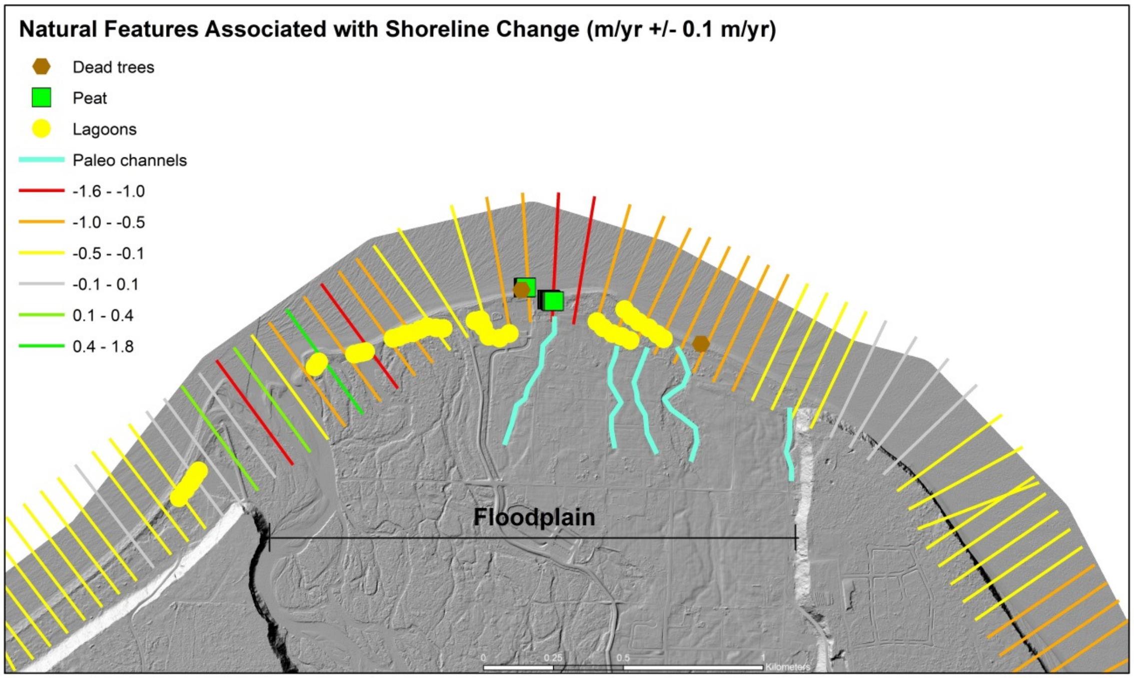

Figure 6. Natural features of interest and shoreline change transects for 1908-2014 overlain on LiDAR map from 2012. Base image is a 2012 hill-shaded bare earth LiDAR dataset from the Puget Sound LiDAR Consortium.

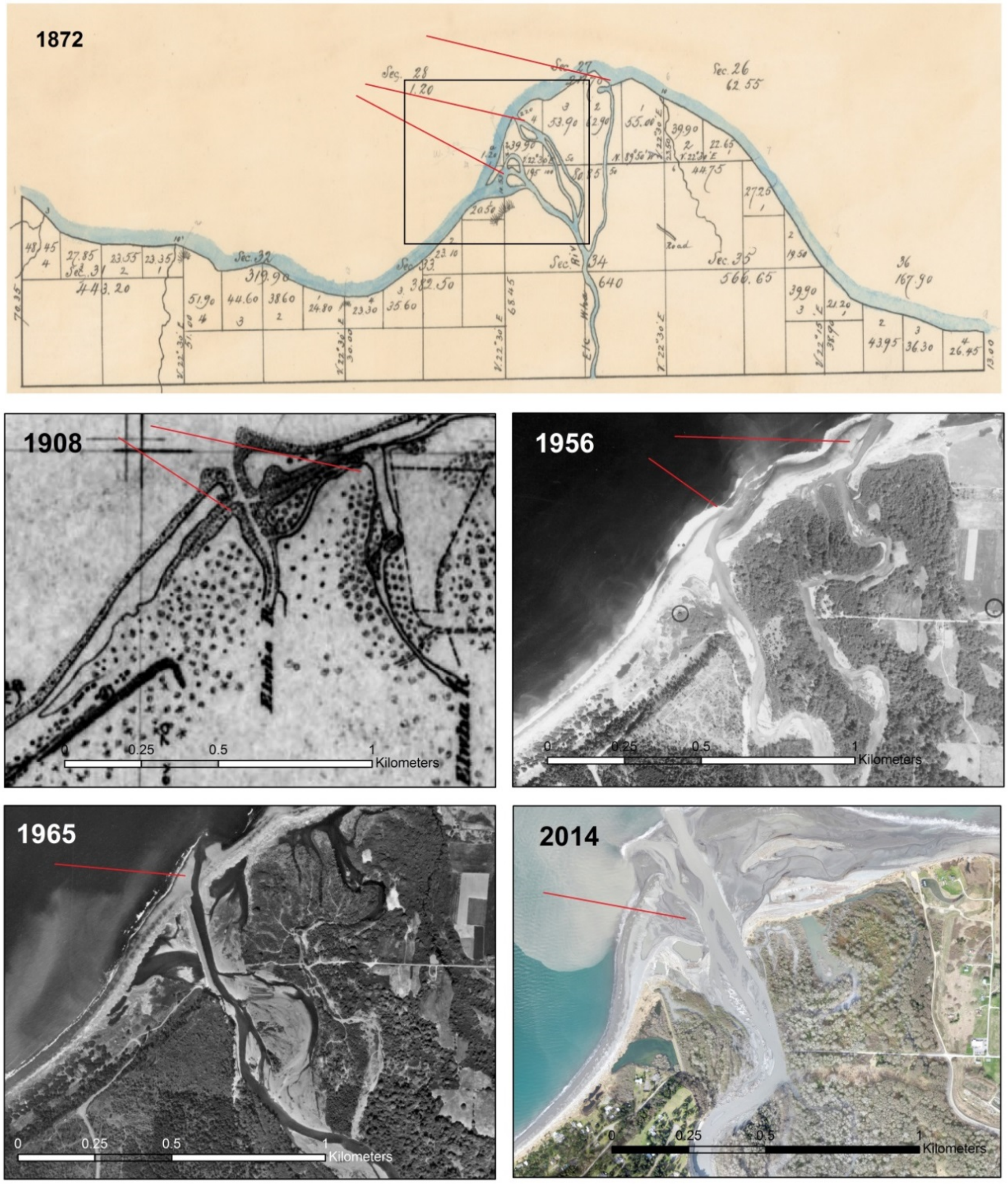

Figure 7. Time series of the Elwha River mouth. Approximate extent of four lower panels boxed in top panel. Note the three channels indicated in red in the 1872 map become two in the 1908 and 1956 panels and one channel in the 1965 and 2014 panels. 1872 map from the U.S. General Land Office. 1908 T-sheet provided by the Puget Sound River History Project. 1956 and 1965 aerial photographs from the

Washington Department of Natural Resources. 2014 aerial photograph from Andy Ritchie, National Park Service.

5. Discussion

5.1. Prehistoric and pre-dam influences

Knowing about the location of geologic features like prehistoric river channels and their potential impact on shoreline change matters because houses and roads occur throughout the shore and floodplain around the Elwha River. Attention has been given to the potential impacts of anthropogenic features on shoreline erosion around the Elwha with less discussion of how natural features might also impact shoreline change patterns that affect people (Duda et al., 2011; Warrick et al., 2009). Prior to dam construction, the Elwha River had multiple distributaries, with the mouth extending as far as 1.9 km east of its current location (Fig. 6). Places where these now-abandoned channels spill into the Strait of Juan de Fuca coincide with stretches of coastline that have seen some of the fastest erosion in the historical period (Fig. 8). Coastline within the river floodplain has also eroded on average 0.4 m/year between 1908 and 2014, while shoreline change averaged over all transects outside of the floodplain was not statistically significant over the same time period (Fig. 4a; Fig. 8). This suggests that the locations of floodplains and prehistoric channels can indicate places particularly vulnerable to shoreline change. Future work should investigate the extent to which these prehistoric features can be used to predict shoreline change around delta systems in general.

5.2. Coastal change around the dammed river

Feedback between natural and human processes has shaped shoreline change since the damming of the river. During this time period, significant shoreline erosion has occurred over much of the coast east of the Elwha River delta. Waves hitting the coast obliquely transport sediment east along the littoral cell extending from Freshwater Bay to Ediz Hook, and there has been speculation that reduced sediment discharge by the river after dam construction cut off sediment supply to areas east of the delta, leading to erosion (Duda et al., 2011; Warrick et al., 2009). Decreased sediment discharge may have a much lower impact on areas west of the mouth due to low net sediment transport rates (Miller et al., 2011). While the dams have been in place, areas west of the mouth have seen lower rates of erosion than areas to the east (Table 2; Figure 4b). This supports the hypothesis that dam construction contributed to erosion east of the Elwha River mouth.

However, Warrick et al. (2009) have also reported that some of the most oblique wave angles also occur along the stretch of coastline just east of the river mouth, with high rates of sediment transport (Miller et al., 2011). This part of the coastline has experienced some of the highest erosion rates (Fig. 4b). The correlation between wave dynamics, sediment transport rates, and shoreline erosion suggests that wave dynamics are an important driver of shoreline change here.

Sea-level trends in this area are also a potential contributor to observed shoreline changes. Increases to relative sea level have been frequently implicated in shoreline erosion (e.g., Camfield and Morang, 1996). At Port Angeles, NOAA data suggest no relative sea level rise between 1975 and 2006. However, during this time period sea level fluctuated by +/- 0.5 m, with major highs correlating with major El Nino events in 1982-

1983 and 1997-1998 (http://tidesandcurrents.noaa.gov/sltrends/). Since sea level variation can contribute to erosion (Ruggiero et al., 2005), this suggests that climatic variability may play a role in shoreline retreat near the Elwha.

In some of the most quickly eroding sections of coastline around the Elwha, the remnants of peat and dead trees protrude through sediment on the beach face (Figure 8). Aerial photographs confirm that these areas were populated by vegetation in historical time. This plant material is a stark indicator of how recently coastal marshes and forests have eroded into the Strait of Juan de Fuca. The erosion of these forest and marsh ecosystems also moves the water line closer to human habitations that once were set much further back from the shore.

As with prehistoric channels, the locations of river channels in historic time correspond well with where the shoreline has shifted the most dramatically (Fig. 8). The movement of the river mouth has been constrained by the construction of a levee to the west in 1964 and a levee to the east in 1985 (Fig. 5; Warrick et al., 2009). Since the location of the river mouth corresponds with where shoreline changes the most, this means that levee construction has also influenced patterns of shoreline erosion. Notably, peat is visible on the beach face along the most quickly eroding segment of shoreline (Fig. 8). Since marshes where this peat forms are associated with low-lying areas near water, this could further indicate the importance of former river beds in shoreline change patterns.

5.3. Coastal processes during dam removal

Despite increased sediment supply from the river (Curran et al., 2014), the vegetation line, used in this investigation as a proxy for shoreline position, at the Elwha River mouth and eastern coastline has continued to retreat at an accelerated pace since the onset of dam removal. Closer examination of aerial photographs from 2011-2014 reveals that this trend is only partially due to erosion. In fact, recent work has documented net accretion above the MHHW level ~200 m east of the river mouth (Dolan 2014; Mackaay 2014). The majority of erosion over this time period occurred between 2011 and 2013 (Fig. 9), likely prior to the accretion that began to appear in 2013. Recent accretion visible in aerial photographs at and near the river mouth remains unpopulated by vegetation (Fig. 10). In some places, accretion deposited between 2013 and 2014 has replaced vegetation (Fig. 9), suggesting that sediment is at times either accreting on top of coastal vegetation or scouring it away. For this reason, the methods used in our study to quantify shoreline change, estimating MHHW from the vegetation line, were unable to capture accretion during dam removal. Using the vegetation line as a proxy for MHHW may therefore fail to capture short-term accretion. Build-up of the sub-aerial delta observed in aerial photographs during dam removal suggests that with time, accretion of sediment could begin to extend the vegetated shoreline once more (Fig. 10).

However, accretion has not been observed farther than ~1 km east of the river mouth where our analysis detected accelerated shoreline erosion during dam removal (Fig. 4c). If shoreline erosion persists over this area during dam removal, it may become necessary to more closely examine features other than the dams as contributors to shoreline erosion. Increased wave heights in the NE Pacific Ocean (Allan and Komar, 2006), for example, may contribute to accelerated erosion along this stretch of shoreline, where (as previously mentioned) waves already hit the coast at highly oblique angles (Warrick et al., 2009). It is also possible that measuring shoreline change over a shorter time interval artificially increases the rate of shoreline change observed (Turcotte, 1997). However, this does not exclude the possibility that shoreline erosion may eventually slow or reverse as sediment continues to spill down from former dam reservoirs. Build-up of the subaerial delta below the high water line over the course of dam removal suggests that with time accretion of sediment from the river could begin to extend the vegetated shoreline once more (Fig. 10).

Anthropogenic features also mark the swift progress of shoreline erosion east of the delta since the onset of dam removal. One parking lot sign above the high water line in an aerial photo from 2000 was located >200 m offshore by 2014, well into the intertidal zone (Fig. 11). Riprap that once hugged the shoreline now lies 5-100 m offshore. Although it may still help attenuate wave energy approaching the shore, the riprap overlaps with some of the fastest-eroding segments of shoreline. Remnants of concrete seawall also lie scattered across the beach face east of the delta, up to 16 m off the 2014 shoreline. The concrete wall marks one of the few stretches of coastline just east of the delta where the shoreline has not changed significantly since the onset of dam removal (Fig. 12). Lagoons from prehistoric river channels lie just behind this concrete wall, and earlier analyses suggest these areas are particularly prone to erosion, implying that the concrete wall has been somewhat effective at slowing erosion. However, ongoing loss of these protective features and the shoreline behind them also suggests coastal armoring cannot be relied upon to protect inland human infrastructure without maintenance.

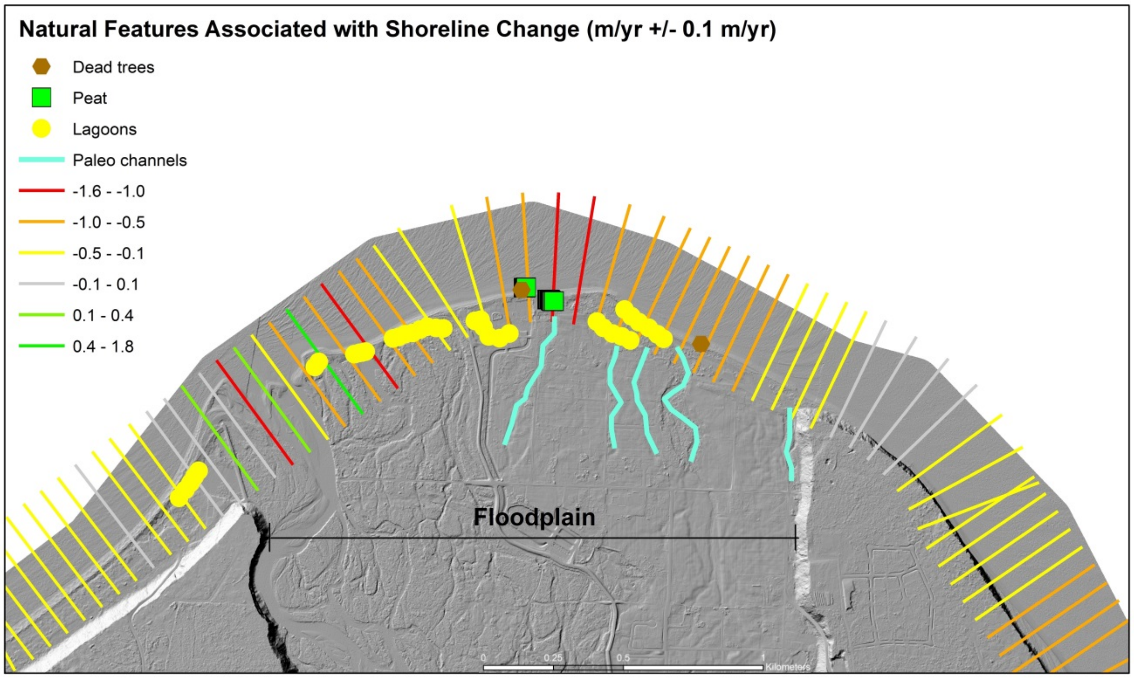

Figure 8. Rates of shoreline change overlain with natural features around the Elwha River delta. Rates of shoreline change are for 1908-2014. Base image is a 2012 hill-shaded bare earth LiDAR dataset from the Puget Sound LiDAR Consortium.

Figure 9. Shoreline evolution east of the river mouth during dam removal. The 2014 vegetation line is marked in red on all three panels. Note the shoreline region circled in blue where sediment resembling the accretion at the river mouth has deposited on top of vegetation between 2013 and 2014. Aerial photograph credits: U.S. Department of Agriculture (2011); Andy Ritchie, National Park Service (2013, 2014)

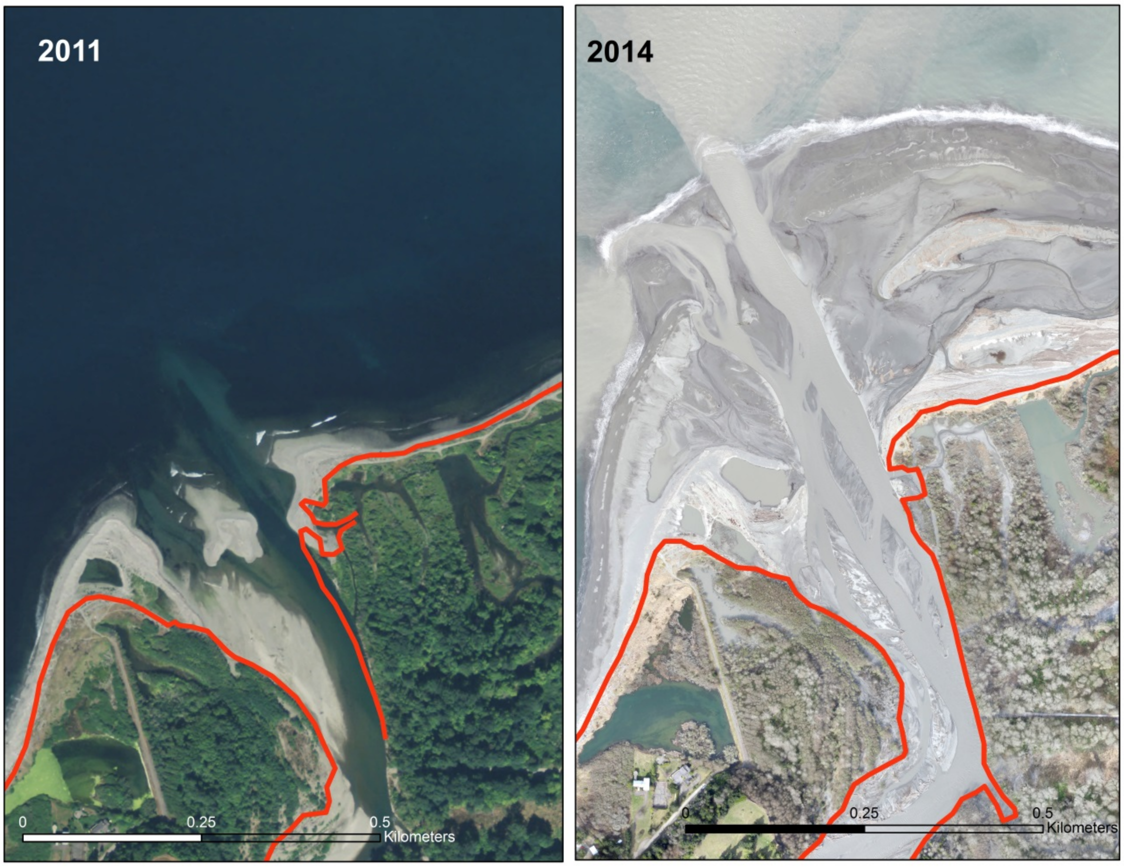

Figure 10. Aerial photos of the Elwha River delta near the beginning (2011) and near the end (2014) of dam removal. The estimated shorelines used for this analysis are shown in red. In the 2014 panel, note the accretion visible beyond the vegetated shoreline. Aerial photograph credits: U.S. Department of Agriculture (2011); Andy Ritchie, National Park Service (2014)

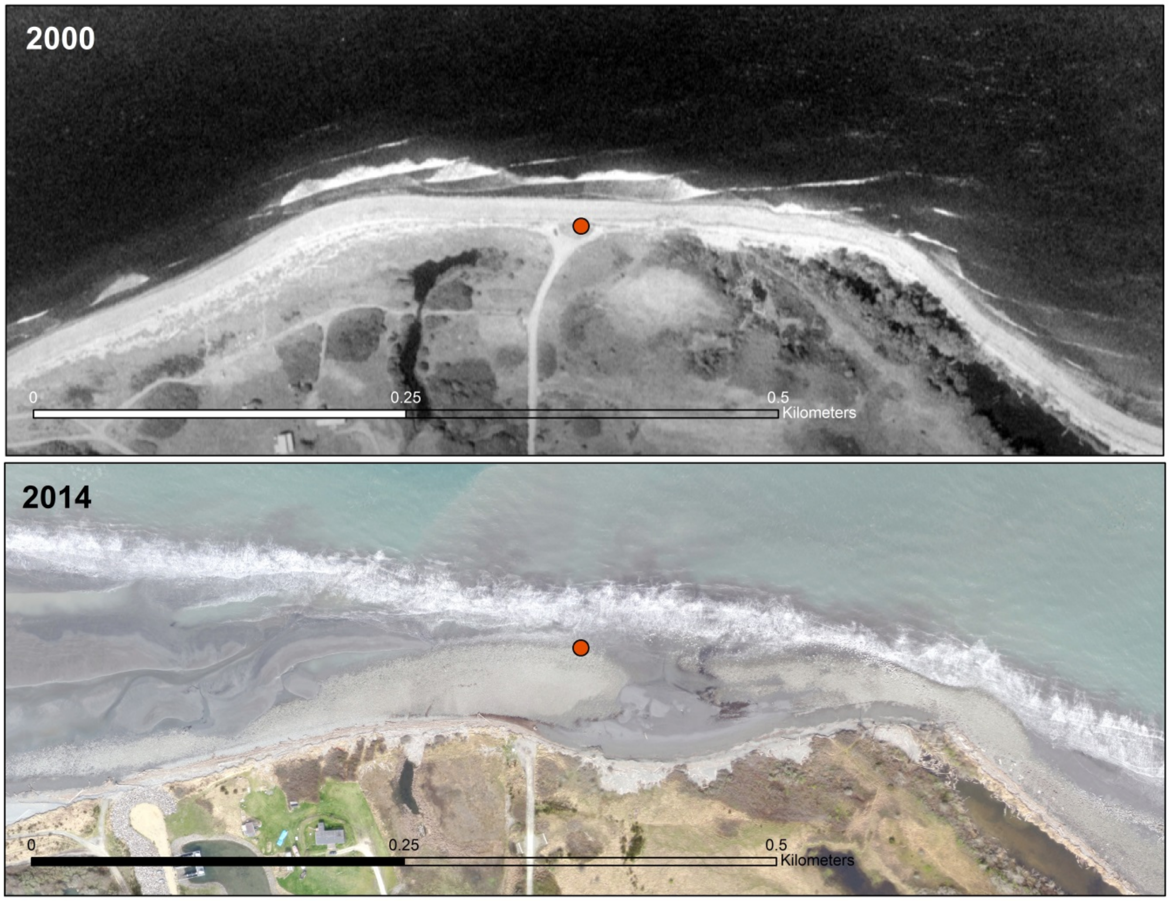

Figure 11. Changing shoreline position relative to a parking lot sign east of the Elwha River delta 2000-2014. The location of the parking lot sign is marked in red. Aerial photograph credit: Washington Department of Natural Resources (2000); Andy Ritchie, National Park Service (2014)

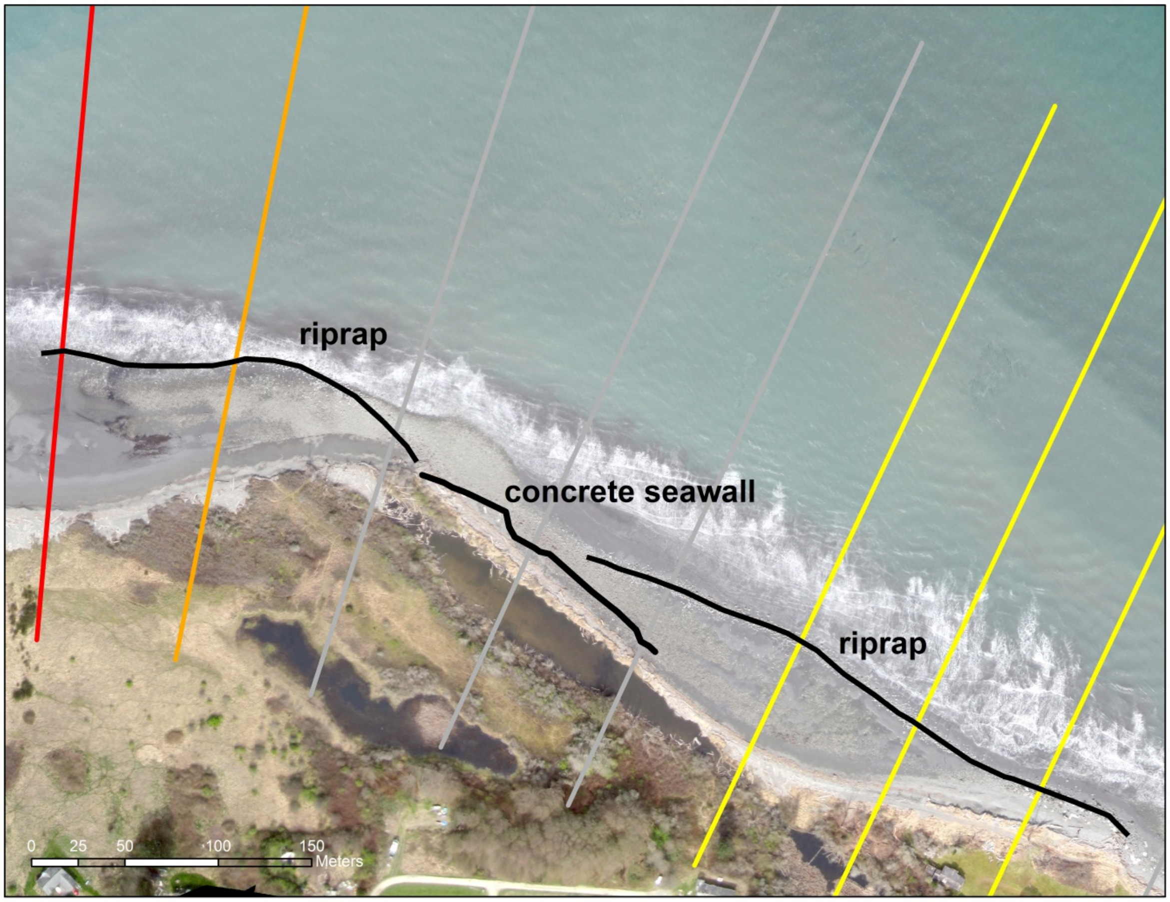

Figure 12. Anthropogenic shoreline armoring overlain with shoreline change transects for 2011-2014. Red transects indicate shoreline with the highest erosion rates (-29 m/yr), with orange representing rates from -16 to -11 m/yr and yellow signifying -6 to -3 m/yr. Gray transects indicate areas without statistically significant change. Aerial photograph credit: Andy Ritchie, National Park Service

6. Conclusions

Prior to dam removal, patterns of shoreline change were consistent with the hypothesis that dam construction contributed to erosion. Over the past century, erosion has been most pronounced at the river mouth. Levees on either side of the river mouth concentrate erosion over the stretch of shoreline between them. Erosion has also been pronounced over much of the shoreline between the river mouth and Ediz Hook. However, the evidence presented here also suggests that climatic variability, wave patterns, and past locations of the river mouth may contribute to shoreline erosion. Riprap and seawalls have had limited effectiveness at slowing this retreat. Along coastline more than ~1 km east of the river mouth, there has not been a slowing or reversal of shoreline erosion since dam removal commenced. If current trends persist, dam removal may not reduce erosion between the river mouth and Ediz Hook as has been hoped. However, sediment has accreted between ~1 km east and ~0.25 km west of the river mouth (even though the vegetation line has retreated here over this period). Future work will need to evaluate shoreline change in the decades following dam removal to determine the effectiveness of this strategy for shoreline restoration.

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