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Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

SANTA CRUZ

**HISTORICAL SHORELINE EVOLUTION AS A RESPONSE TO DAM PLACEMENT  
ON THE ELWHA RIVER, WASHINGTON**

A thesis submitted in partial satisfaction  
of the requirements for the degree of

MASTER OF SCIENCE

in

EARTH AND PLANETARY SCIENCES

By

**Bethany M. Nagid**

September 2015

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## **Abstract**

Bethany M. Nagid

Historical Shoreline Evolution as a Response to Dam Placement on the Elwha River,  
Washington

Morphological changes of the Elwha River delta shoreline in Washington are analyzed from 1870-2015, revealing year-by-year as well as location-based geomorphological evolution. Change in the Elwha shoreline prior to the placement of two dams is shown as accretion in two of three areas of the delta with overall change of up to ~20-30m. To the east of the Elwha River mouth, annualized erosion rates during the lifetime of the dams averaged ~1m/year, but increased in recent years, regularly exceeding 4m/year between 2009 and dam removal in 2012. Other areas showed no significant trends during the overall time period of dam-use, but exhibit a wide variety of year-to year changes. Shoreline changes following dam removal (2012-2015) have shown a wide variety of responses: (1) an accreted shoreline beyond the extent of any previous year (west of the Elwha mouth); (2) an accreted shoreline not yet returned to the spatial extent prior to dam placement (east of the Elwha mouth), and (3) an eroded shoreline beyond previous shore configurations (east of Point Angeles).

This survey of over 130 years of shoreline data at the Elwha delta is intended to identify differences in shoreline morphology during distinct periods of dam placement, use, and removal. The large-scale changes in shoreline morphology associated with dam placement and removal will be important processes to understand as traditionally dammed river ecosystems transition to dam removal in coming years.



## **Dedication and Acknowledgements**

I am incredibly grateful for all of the opportunities that this project has afforded, and equally appreciative of the people that have helped make this work possible. I would like to acknowledge my reading committee for their vital feedback in every step of this project, with a special thanks to Professor Gary Griggs and Dr. Jon Warrick. I am extremely thankful for Gary's willingness to set aside time from all of his commitments to provide feedback as a truly invaluable adviser to his students. I am also deeply appreciative of Jon's generous support through all stages of this project; I cannot thank him enough.

There are so many people that have contributed to the success of this project, and in particular, the acquisition and management of spatial data. I'd like to thank Randall McCoy of the Lower Elwha Klallam Tribe and Erik Lowe of the UCSC Center for Integrated Spatial Research for their ArcGIS expertise, Gay Hunter of the National Park Service for her assistance in searching park archives, Andrew Stevens, Guy Gelfenbaum, Amy East, and Josh Logan of the USGS Pacific Coastal and Marine Science Center for all of their input and for sharing valuable new data of the Elwha coastal zone, and finally, Jeff Duda of the USGS Western Fisheries Research Center and Ian Miller of Washington Sea Grant for allowing me the privilege of seeing the beauty of the Elwha and the Pacific Northwest in person.

Lastly, I owe an immense debt of gratitude to my friends and family, who have supported me through the joys of this project, as well as occasionally wanting to throw my computer out of a window. I would like to dedicate my Master's thesis to my parents, Susan and David, who have been beside me in every success of my life.

## **Introduction**

With a final controlled explosion on August 26<sup>th</sup>, 2014, the remaining concrete slabs of the Glines Canyon Dam of the Elwha River were reduced to rubble. After a storied past of ecological, geomorphological, and political oscillation, the Elwha River is able to flow unimpeded after over a century of impoundment by two dams. The morphological responses to what has been categorically deemed the largest dam removal project in the country to date (Duda et al 2008, Brenkman et al. 2012) and one of the largest ecological restoration projects as well (Hart et al. 2002), are not only inherently complex, but can also provide insight into the historical state of change of the Elwha. At its core, the Elwha River is never in a single, fixed, “natural state”, but is instead in a persistent state of change. Meander bends exaggerate by erosion at cut banks and accretion at point bars; sediment supply downriver fluctuates with season, rainfall, and many other conditions; and shoreline sediment is built up by the river, as well as transported alongshore by waves. Although the Elwha River dams were constructed during a period of little long-term connection between upstream activities (i.e. dam building) and downstream conditions (i.e. channel and shoreline morphology), changes in these systems after dam removal may allude to the river’s previous state, prior to dam construction. Additionally, the small amounts of accurate information about the coastal Elwha prior to dam construction may assist in describing a future trajectory of changes along the coastline.

The goals of the research described herein are two-fold; primarily to identify accurate historical data relating to the geomorphology of the Elwha Delta in an effort to track any trends appearing from pre-dam and dam-use periods, and secondly, to utilize

these details in an effort to describe a potential trajectory of future change along the Elwha coast given recent changes following dam removal.

Sediment supply to coastal areas from dammed rivers is understood to be persistently and significantly diminished. In a study of California dams and beaches, Willis and Griggs (2003) discuss the nearly 1:1 relationship between the percentage of a given river basin that has been impounded by dams, and the percent annual reduction in sediment discharge. The Elwha River fits well within this pattern with nearly 95% of the Elwha basin historically impounded by the Elwha and Glines Canyon Dams, which led to between 85 and 90% reduction in annual sediment discharge (Curran et al. 2009).

Originally developed to supply hydroelectric power for Port Angeles industry, construction on the 32m high Elwha Dam (often referred to as the Lower Elwha Dam or Lower Dam) began in 1910 and was operational by 1913. Further economic expansion led to the construction of a second, larger dam: the Glines Canyon Dam (64m high, thirteen kilometers upstream from the Elwha Dam), which was completed in 1927. Until removal in 2012, both dams also formed the reservoirs Lake Aldwell (Elwha Dam) and Lake Mills (Glines Canyon Dam).

Although the biological significance of the river as salmonid spawning habitat was apparent at the time of construction of the first dam (Nathan, 1921), an ultimately unsuccessful fish hatchery was used to leverage construction of the dams, which would eventually block over 70 km of salmonid habitat. Over the course of the Elwha's next 50 years, which included the enclosure of the Glines Canyon Dam within Olympic National Park in 1938, various groups, including the Lower Elwha Klallam Tribe, would file requests and

perform studies for dam removal, intending to allow the Elwha River system to once again flow unimpeded into the Strait of Juan de Fuca.

The river and surrounding ecosystem has been the subject of numerous studies regarding the health and changing nature of a dammed river system, most notably restoration of salmon habitat (Duda et al. 2011, Wunderlich et al. 1994) and coastal and channel changes associated with, among other factors, changing sediment supply (eg. Draut et al. 2008, East et al. 2015, Gelfenbaum et al. 2015, Warrick et al. 2009a,). Although these are only a few examples regarding prominent research on identifying geological and biological changes on the Elwha system, this particular research will focus primarily on changes of the coastline at the mouth of the Elwha River in response to placement and subsequent removal of the Elwha and Gilnes Canyon Dams.

The Elwha River, as of 2008, prior to dam removal, was estimated to be delivering between 2-10% of its pre-dam sediment supply to the coastal zone, and estimates of the volume of sediment impounded in Lakes Aldwell and Mills have slowly increased from 14 million m<sup>3</sup> (Curran et al. 2009) to 19 million m<sup>3</sup> (Bountry et al. 2010) and finally, to the current estimate of 21 ± 3 million m<sup>3</sup> (Magirl et al. 2014, Gelfenbaum et al. 2015) This categorical interpretation of sediment release from the two dams indicates the Elwha decommissioning has been the largest dam removal project in North America to-date. Sediment starvation to the coastline during times of dam placement is not a particularly new concept, but there are many intricacies to consider in understanding the Elwha delta shoreline. Along with wave climate changes and erosional patterns separate from dam interactions, coastal changes specifically due to dam placement have also been

underrepresented in current assessments of the Elwha, mainly owing to a general lack of adequate historical data.

Previous research relating to the coastal Elwha has primarily involved recent changes to the shoreline (i.e. the transition between dam placement and subsequent removal) and has largely taken the form of topographic, bathymetric, and grain-size surveys to establish the effects of the Elwha's massive sediment release (e.g. Gelfenbaum et al. 2015, Warrick et al. 2011). In an effort to characterize the shift in coastal sediment structure Warrick et al. (2009a) have presented an evaluation of Elwha morphology prior to dam removal, where a novel method of grain-size analysis has identified a coarsened low-tide terrace (mean grain size  $104\pm 44\text{mm}$ ) with respect to the foreshore (mean grain size  $28\pm 15\text{mm}$  and  $49\pm 22\text{mm}$  for the lower and upper foreshore, respectively). As thoroughly described in Warrick et al. (2009b), the "cobble cam" method involves the use of high-resolution photographs of small sediment-covered areas, autocorrelated to produce a low error grain size distribution quickly and efficiently. The beach morphology mode of a coarser low-tide terrace with respect to the foreshore has been shown to be relatively uncommon and, additionally, mixed grain beaches have been traditionally underrepresented in scientific literature (Mason and Coates 2001). The designation "mixed-beach" has also often specifically represented an area of a coarser, gravel foreshore with a finer, sandy low-tide terrace (Pontee et al. 2004). This particular configuration of grain sizes across the beach profile has been noted in two cases in the Puget Sound area in addition to the Elwha, both of which are located in areas of relatively rapid coastal erosion (Finlayson 2006, Warrick et al. 2009a). With the use of shoreline positions derived from digitally

orthorectified quadrangles (DOQs) from the Elwha region in 1939, 1990, and 2006, and an additional seven topographic shore surveys between 2004 and 2007, Warrick et al. (2009a) draw a similar conclusion for Elwha geomorphology: an accelerated erosion rate, with an average of ~0.8 m/year between 1939 and 1990, compared to ~1.4 m/year erosion between 1990 and 2006.

This research, although often utilizing similar methodologies as previously described for shoreline analyses, will expand on the variability of the Elwha shoreline over time by analyzing change during the period prior to 1927 (herein referred to as the “pre-dam period”) in addition to shorter time intervals between 1927 and 2012 (referred to as the “dam-use period”). These analyses may then be placed within the context of recent “post-dam” shoreline analysis (beyond 2012), in an effort to describe whether the Elwha may be exhibiting similar geomorphological patterns as prior to dam placement, or if a mode of beach morphology exists that is yet unseen in the Elwha’s history.

### **Study Area**

The Elwha River, located in northwestern Washington, flows from its source within Olympic National Park to its mouth on the Strait of Juan de Fuca, for a total distance of over 70 kilometers. The delta region of the Elwha sits to the west of the city of Port Angeles (figure 1), and although the entirety of the Elwha basin encompasses roughly 830 km<sup>2</sup>, the Elwha delta represents less than 5% of the Elwha basin area.

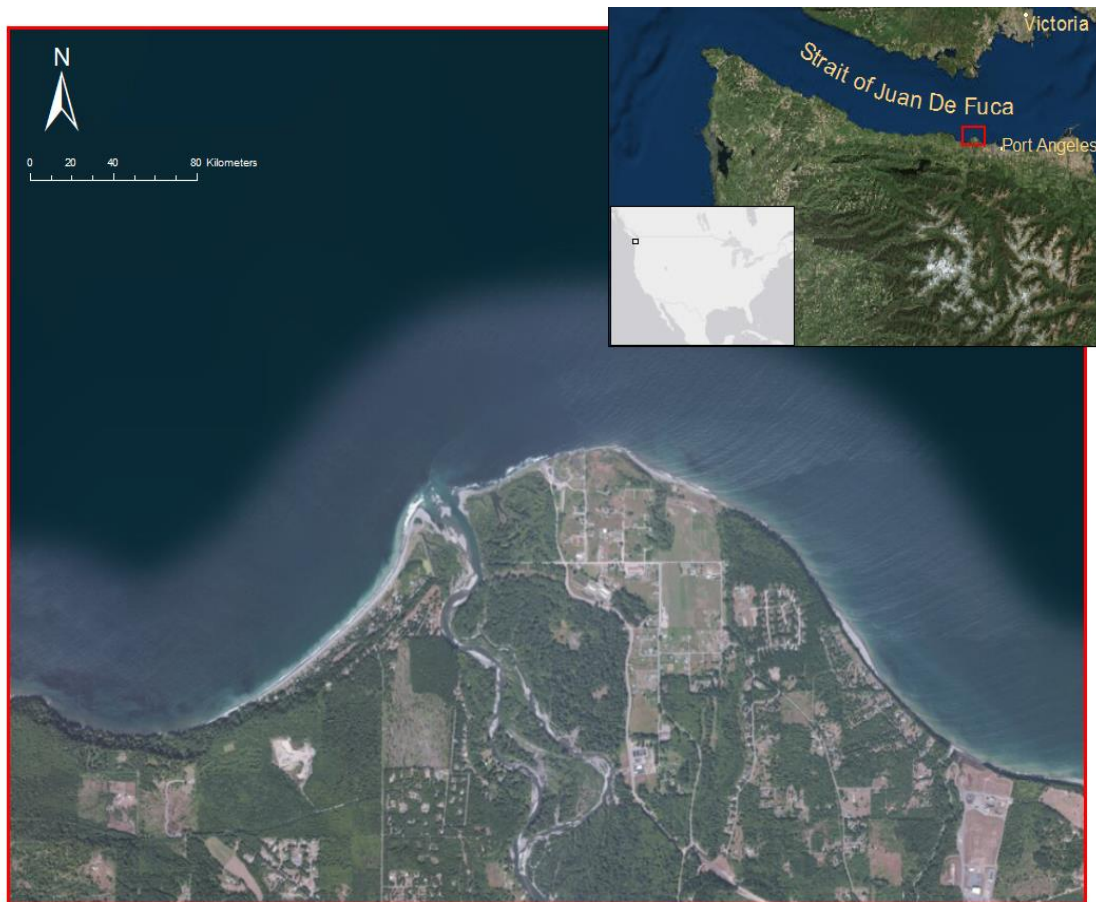


Figure 1: Location of the Elwha River delta in Washington State.

Downstream of the former Elwha Dam, at the end of the nearly 8km long stretch known as the “lower river”, the Elwha River discharges into the Strait of Juan De Fuca, with one, two, or three historical river channel outlets along the coast. These channel outlets have also, within recorded history, been located between the Northern-most point of land along the delta, at one point distinguished as “Point Angeles”, and the western side of the delta along Freshwater Bay (figure 2).

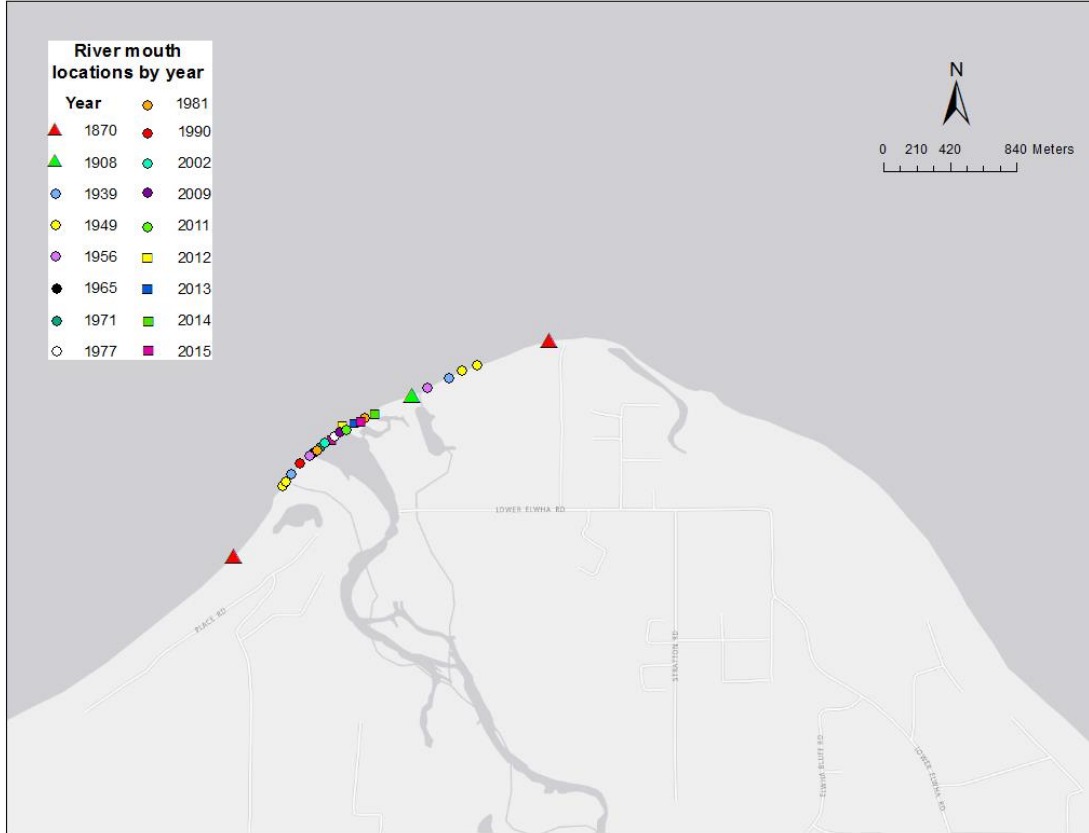


Figure 2: Variation in location of the Elwha River's dominant river channel outlet.

The Elwha River is considered to be anabranching, where, similar to braided channels, individual “threads” of the river separate from the main channel; but unlike braided river systems, these individual threads are morphologically stable and undergo predictable changes as single-channel systems would (Eaton et al. 2010). This categorization of river system also implies a maximum of three channels (in order to maintain overall stability), which is consistent with the maximum number of the channels at the mouth of the Elwha historically. The Elwha’s channels have merged upstream from the river mouth many times, but occasionally occur as distinct outlets of the river into the Strait of Juan de Fuca.



## **Materials and Methods**

Historical map data were collected from special map collections at the University of Washington, the Clallam County Historical Society, as well as individual contributions from the Port Angeles and Lower Elwha Klallam communities. Aerial photographs have been supplied by the USGS and the Lower Elwha Tribe, and were originally taken by a variety of government agencies, including the U.S. Army Corps of Engineers and the Washington Department of Natural Resources. All appended map imagery, aerial photographs, and digital datasets are summarized in table 1.

The greatest challenge in working with and properly analyzing historical map data is in accurately assessing and registering appropriate error. Sources of error that contribute to total error in determining shoreline position are primarily classified in two ways: (1) the positional (or registration) error, measuring how spatially accurate the intended (source) layer is registered to the destination layer; and (2) the digitization error, which represents how accurately the shoreline (represented as MHW) has been established.

Owing to the dynamic nature of shorelines and associated changes, identifying a specific spatial “line” as an identity of a land/water border is not only central to shoreline change analyses, but is often disregarded as a common source of error. Though many shore and beach features have been previously used to identify a shoreline, the two most commonly used indicators are the high water line (HWL) and, with increasing prevalence due to the use of geographic information systems (GIS) in shoreline analyses, the mean high water line (MHW).

Table 1: Map, aerial photograph, and digital data sets of the Elwha River coastal zone used in shoreline change analysis.

Month/Year	Type	Source	Scale	Total Error (for digital sets, DEM uncertainty)
09/1870	Plat Map	Department of the Interior, General Land Office	1:20,000	27.86
02/1908	Topographic T-Sheet	Department of Commerce and Labor, Coast and Geodetic Survey	1:20,000	26.71
08/1939	Aerial Photograph	US Army Corps of Engineers	1:36,000	22.64
01/1949	Survey Map	Metsker Atlas	1:20,000	27.24
11/1949	Survey Map	"Flood Control Project" B-5-49 (Unknown Origin)	1:20,000	26.44
08/1956	Aerial Photograph	Clallam County Assessor	1:12,000	27.38
05/1965	Aerial Photograph	Washington Department of Natural Resources	1:12,000	24.94
07/1971	Aerial Photograph	Washington Department of Natural Resources	1:12,000	26.06
08/1977	Aerial Photograph	Washington Department of Natural Resources	1:12,000	25.36
07/1981	Aerial Photograph	Washington Department of Natural Resources	1:12,000	27.18
07/1990	Aerial Photograph	Washington Department of Natural Resources	1:12,500	23.85
06/2002	Aerial Photograph	Washington Department of Natural Resources	1:12,000	29.36
08/2009	Digital Dataset	US Geological Survey	5m grid	0.13
08/2011	Digital Dataset	US Geological Survey	5m grid	0.13
05/2012	Digital Dataset	US Geological Survey	5m grid	0.13
08/2012	Digital Dataset	US Geological Survey	5m grid	0.13
03/2013	Digital Dataset	US Geological Survey	5m grid	0.13
09/2013	Digital Dataset	US Geological Survey	5m grid	0.13
04/2014	Digital Dataset	US Geological Survey	5m grid	0.13
09/2014	Digital Dataset	US Geological Survey	5m grid	0.13
01/2015	Digital Dataset	US Geological Survey	5m grid	0.13

Other shoreline indicator features include: wet/dry line (or runup maxima), vegetation line, storm/debris line, mean higher high water (MHHW), mean low water (MLW), and mean lower low water (MLLW), the last three of which (as well as MHW) are datum referenced (figure 3, from Warrick et al. 2009a). The two categories of shoreline estimates, proxy-based and datum-based shorelines, each have characteristics that are advantageous for shoreline analyses. For example, several proxy-based shoreline estimates, particularly the HWL, are fairly easily identified by a change in tone of sand color, left by the most recent high tide, which many researchers have used as a shoreline indicator due to the relative ease of approximating this line from aerial photography (Moore et al. 2006, Ruggiero and List 2309).

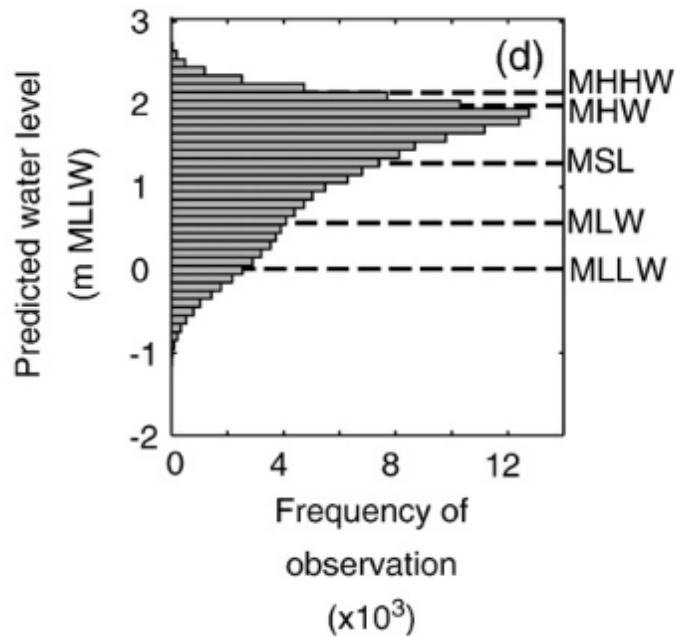


Figure 3 (from Warrick et al. 2009a): Various datum-based shoreline proxies for the Elwha coastline. MHW (used in this study) is equivalent to 1.926 MLLW.

Another advantage of high water line for use in historical analysis is that, due to the ease of identification in field surveys, HWL was primarily used as the shoreline extent in National Ocean Service (NOS) topographic sheets, or “T-sheets” (Moore et al. 2006) maintained by the U.S. Coast Survey in the early 1800s (the US Coast and Geodetic Survey [USCGS] beginning in 1878, and eventually reorganized and expanded to the National Oceanic and Atmospheric Administration [NOAA] in 1970). Datum-based shorelines, in contrast to the historical use of proxy-based (largely visual) shorelines, are derived from the along-shore position of specific elevation contours, often derived from LiDAR data and topographic surveys. The advantages of datum-based shorelines are that they vary primarily with long-term morphological changes (whereas proxy-based shorelines such as HWL are greatly subject to short-term variations), and identification of datum-based shorelines can additionally be automated with relative ease (and relatively low digitizing error) in a GIS, given data with sufficient accuracy. In some cases the horizontal offset between the MHW and HWL has been suggested to be as much as 52m (Ruggiero et al. 2003) for a beach profile along the coast of southern Washington State (low-slope, high wave energy), with an average offset of 30.6m, although other areas and coastal climates have produced varying results (e.g. 18.8m offset for a high-slope, lower energy coastline in Maryland and Virginia [Moore et al. 2006]).

The MHW line for the Elwha delta region is (and has previously been) digitized from aerial photography as the mid-point between the berm crest and low tide terrace shift, both of which constrain a maximum digitization error of 22m in establishing a MHW line (Warrick

et al. 2009 a/b). This digitization error is then combined with each layers' positional error in determining the total error of shoreline position.

For a given georeferenced image, the positional error is the average offset of control points between the source and destination layer, added to the root mean square error (RMS) of the destination layer, reported by the agency producing the image (USGS). All historical imagery was referenced to a 1990 DOQ. The RMS of the orthorectified (1990/1994) destination layers is 7m, to which each individual layer's georeferencing error was added, giving a positional error for each layer. Hapke and Reid's (2007), (included in Draut et al.'s [2008] report on spatial changes of the lower Elwha River channel) total error associated with shoreline position was calculated using the following equation:

$$E_{total} = \sqrt{E_{pos}^2 + E_{dig}^2} \quad (1)$$

Historical map data, along with aerial photographs were digitized as needed and analyzed in the Geographic Information System (GIS) software package ArcGIS (ESRI 2011).

Map and aerial photography imagery were added into a geographic information system (GIS), and were prepared for analysis using methods appropriate for each individual layer. The coordinate system for all layers is: State Plane, North American Datum (NAD) 1983, Continuously Operating Reference Station (CORS) 1996, Washington North (meters). Maps and aerial imagery have been georeferenced to 1990/1994 orthophotographs (aerial photos by R. McCoy, Lower Elwha Tribe), which have been the basis for registration for several other Elwha based studies (Draut et al. 2008, Warrick et al. 2009a). Control points were chosen primarily on the basis of known land corners appearing in historical maps and

surveys beginning in the mid-1800s. These land corners, in the region of the Elwha mouth, delineate sections 26, 27, 34, and 35 of Township 31, North Range 7 West, as well as subsequent land parcels. Additionally, Lower Elwha Road and Charles Road were used as control points for map imagery beginning with a 1925 Metsker's Atlas edition (although Lower Elwha Road may initially be present as early as a 1908 USCGS map). As with most spatial referencing, control points that are spread throughout an image will yield a more accurate registration, so when possible, identifiable points in corners of map imagery were used, in addition to supplementary points throughout the maps. Although many historical maps were identified and able to be digitized, many were disregarded; those remaining were used contingent on the following criteria: (1) the availability of functional control points (roads, land corners, and other unchanging features) or quantifiable image distances; (2) likelihood of original shoreline shape; and (3) completeness of image and adequate scale.

All digitized shoreline layers were appended into a single shoreline layer and, combined with a baseline and transect layer, were loaded into the Digital Shoreline Analysis System (DSAS), an ArcMap extension (Thieler et al. 2009). The baseline layer, which is used as a reference to which other shoreline layers are measured from, was created by buffering the on-shore side of the shoreline of a 2009 aerial image by 175m to ensure that it resided entirely on-shore of all other existing layers. The transect layer was created by adding a series of pre-existing transects (used for bathymetric and topographic surveys of current Elwha research), and extending them to the baseline layer (figure 4). These transects were chosen from pre-existing research (as opposed to DSAS' created transects, cast in user-definable increments) for their use in direct comparisons of current shoreline changes.

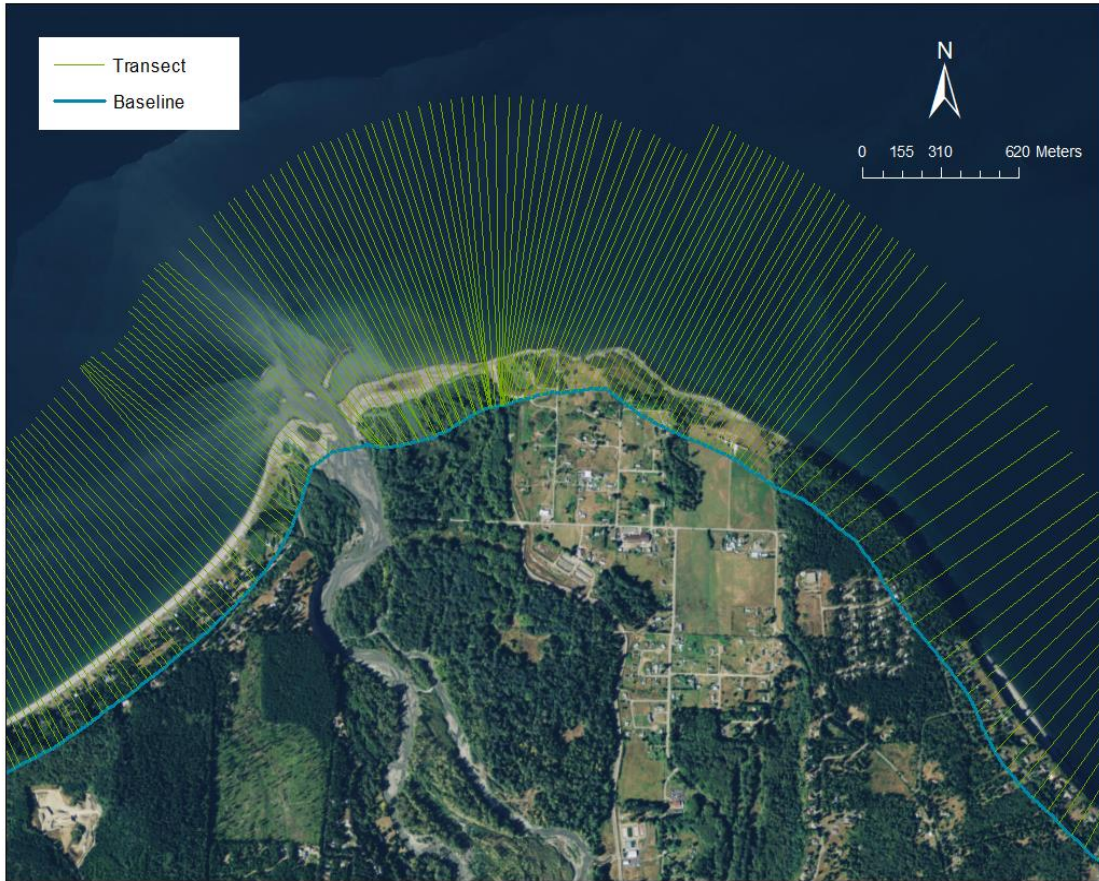


Figure 4: Baseline and transect layers used for digital shoreline analysis

DSAS allows for the operation of various measurements and statistics, including net shoreline movement (represented as the distance between two designated shorelines), end-point rate (rate of change between two specific shorelines), linear regression, and weighted linear regression, weighted by error. For each time interval used, end-point rate (EPR) was calculated and spatially displayed as measurable accretion, measurable erosion, or no measurable change. To be considered measurable, rate of change between any two timespans must exceed the error calculated by equation (2) (Hapke and Reid, 2007):

$$E_a = \frac{\sqrt{E_{total,1}^2 + E_{total,2}^2}}{t} \quad (2)$$

## Results

Figures 5 through 24 show either end-point rates (EPR) or net shoreline movement (NSM) between two successive map images, photographs, or digital data sets. End-point rates (EPR) calculated from each time interval are spatially represented at each applicable transect by scales in which negative values indicate erosion and positive values denote accretion. For recent coastal changes (less than a one-year change in time), net shoreline movement (NSM) is used in lieu of EPR, as it represents change over a smaller time frame, rather than representing an average change over a larger time scale.

Additionally, figures 5, 25 and 26 show overall EPR changes during specified periods of damming (pre-dam, dam-use and post-dam, respectively).

Given the often high error in annualized rates of change, resulting from highly conservative estimates of overall shoreline error (table 1), many potential trends over short timescales become immeasurable. Figure 13 provides an example of how a relatively high annualized error leads to the removal of many spatial trends from significance. Thus, for the purpose of representing all available data, although the results identified here characterize all significant changes between any two given time periods, the attached appendix provides a comprehensive assessment of all changes for years where large amounts of data are removed by a high threshold of significance.

For recent shoreline changes (2012-2015), some MHW features do not represent a continuous shoreline, but rather accretion in shore-parallel bars (e.g. figure 22). Because these features may only represent temporary change, they were disregarded for the purposes of this analysis if they existed as an isolated feature, not connected to the main



body of the shoreline. However, because we cannot assume no change occurred in the area, these areas are represented as blank “no-data” areas.

In order to represent changes to the Elwha shoreline by area, average distance from each shoreline was calculated for a specific area (west of the river mouth, east of the river mouth, and the east delta region) (figure 27). These averages were compiled and regressed during the dam-use period (the pre-dam period only encompasses two dates and the post-dam period only represents three years of change). The results are summarized in figure 28. During the pre-dam period, each region saw either moderate accretion or no change. During the dam-use period, the east river mouth area was the only to see a significant erosive trend at  $p > 1.0 \times 10^{-3}$ . After dam removal, overall response varied by location, with the east and west river mouth areas seeing an overall accretion of shoreline sediment, and the eastern delta region seeing overall erosion.



Figure 5: Annualized shoreline change of the Elwha River at each transect between 1870 and 1908, additionally used as overall pre-dam analysis. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <1.02 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 6: Annualized shoreline change of the Elwha River at each transect between 1908 and 1939. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <1.13 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 7: Annualized shoreline change of the Elwha River at each transect between 1939 and January 1949. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <3.54 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESR).



Figure 8: Net shoreline change of the Elwha River at each transect between January 1949 and November 1949. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <37.96 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 9: Annualized shoreline change of the Elwha River at each transect between November 1949 and 1956. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <5.44 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 10: Annualized shoreline change of the Elwha River at each transect between 1956 and 1965. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <4.12 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 11: Annualized shoreline change of the Elwha River at each transect between 1965 and 1971. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <6.01 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 12: Annualized shoreline change of the Elwha River at each transect between 1971 and 1977. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <6.06 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 13: Annualized shoreline change of the Elwha River at each transect between 1977 and 1981. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <math>< 9.29</math> m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 14: Annualized shoreline change of the Elwha River at each transect between 1981 and 1990. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <4.02 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 15: Annualized shoreline change of the Elwha River at each transect between 1990 and 2002. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <3.15 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 16: Annualized shoreline change of the Elwha River at each transect between 2002 and 2009. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <4.19 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



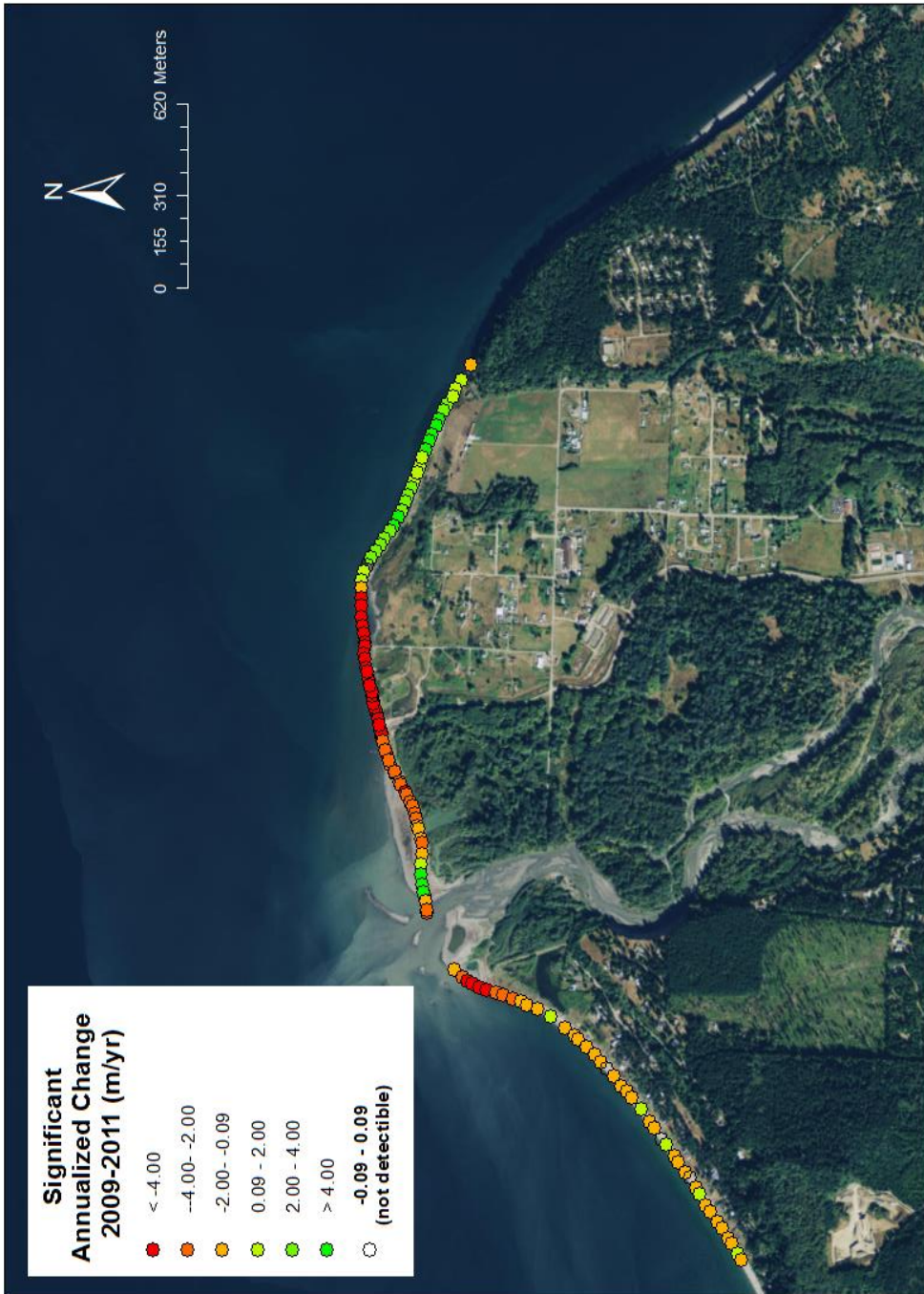


Figure 17: Annualized shoreline change of the Elwha River at each transect between 2009 and 2011. Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of  $<0.09$  m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).

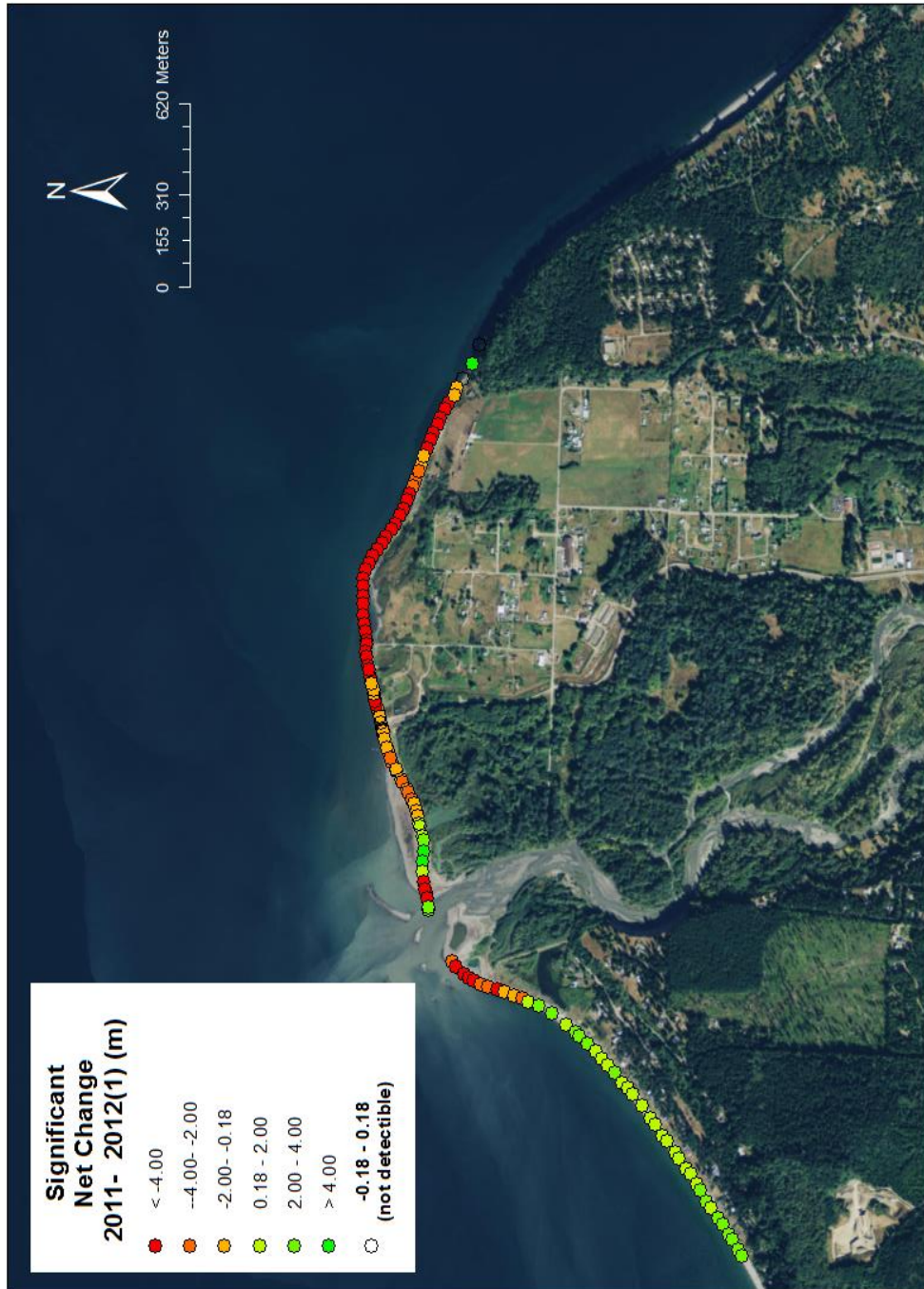


Figure 18: Net shoreline change of the Elwha River at each transect between 2011 and May 2012. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



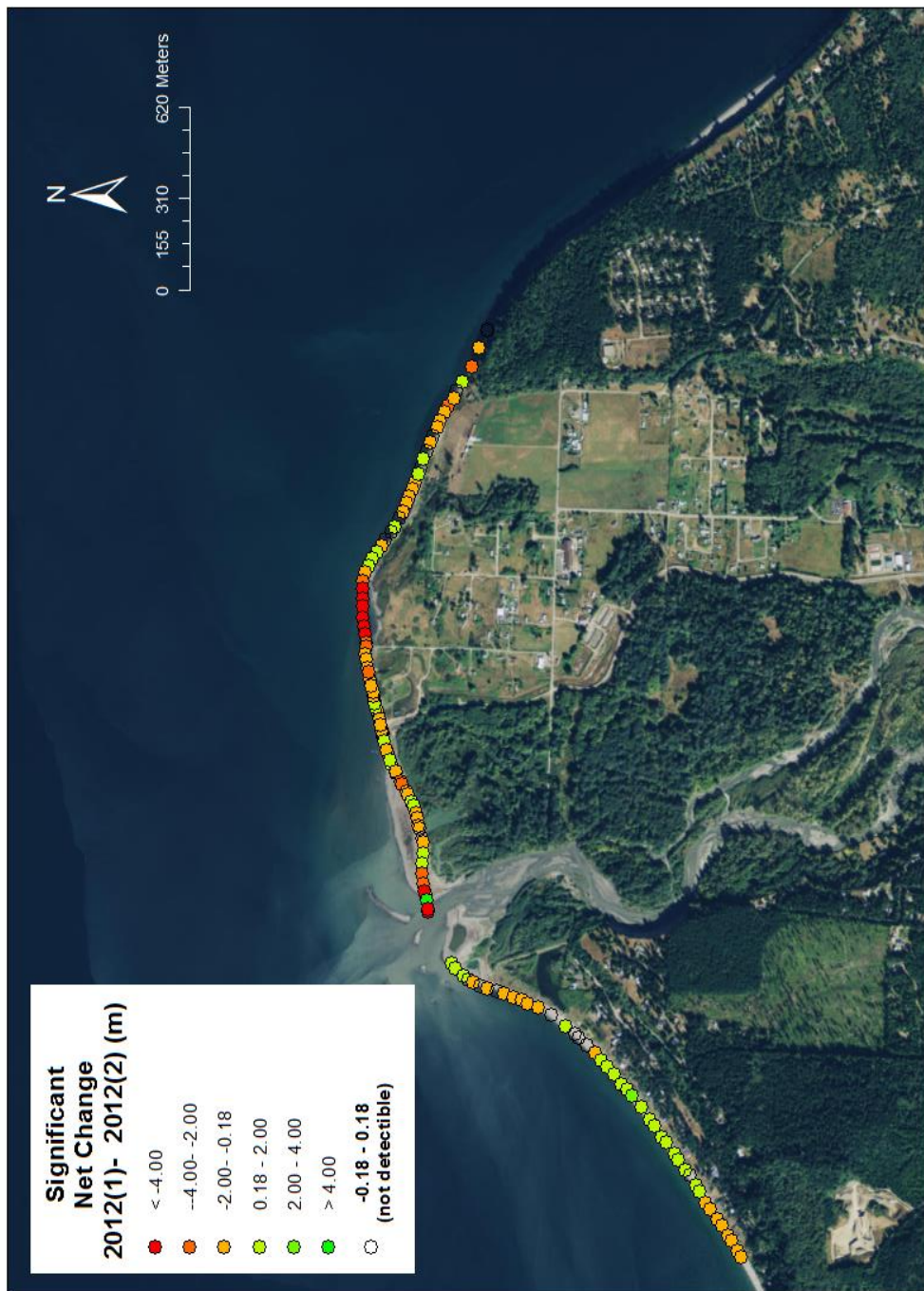


Figure 19: Net shoreline change of the Elwha River at each transect between May 2012 and August 2012. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



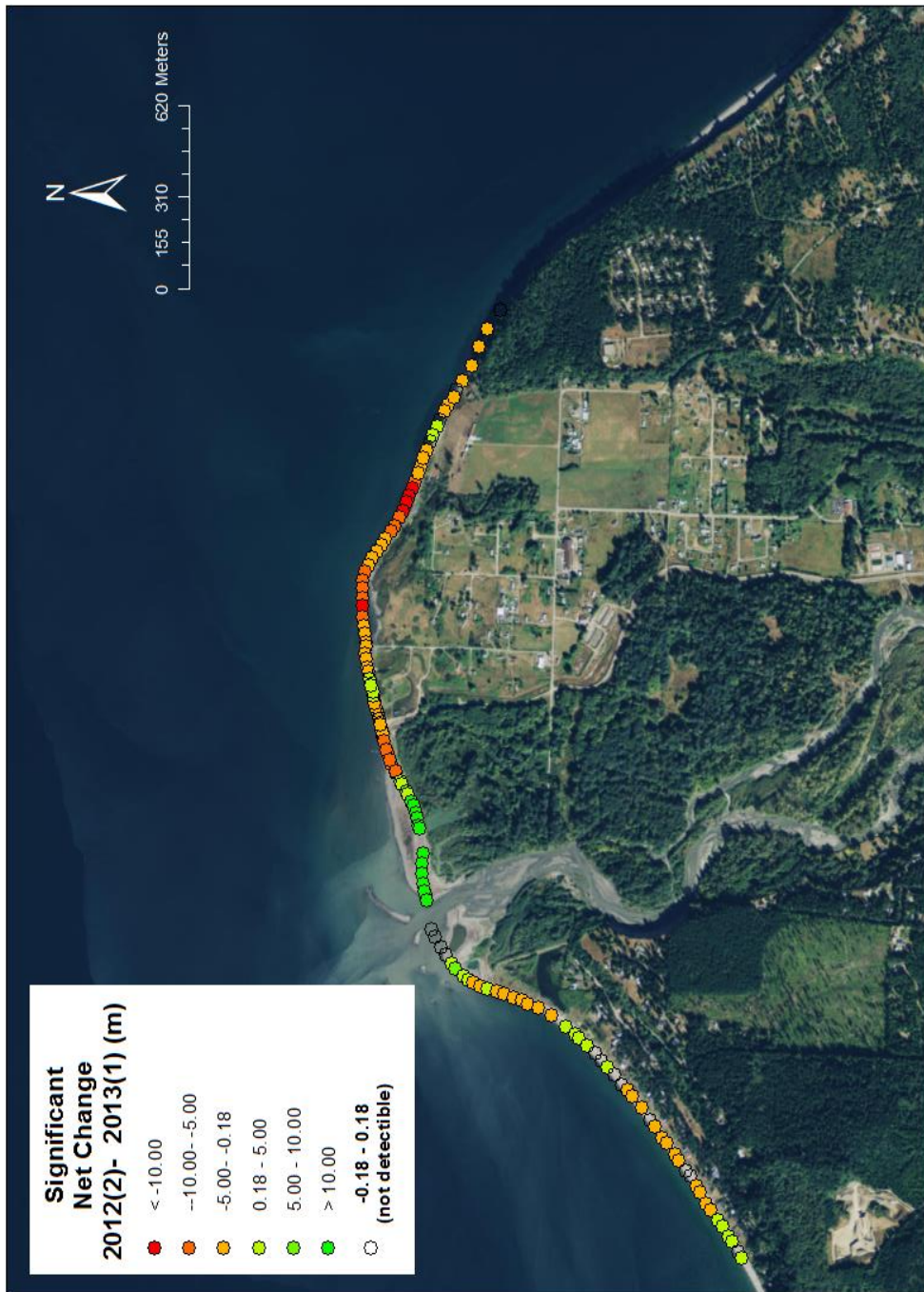


Figure 20: Net shoreline change of the Elwha River at each transect between August 2012 and March 2013. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 21: Net shoreline change of the Elwha River at each transect between March 2013 and September 2013. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 22: Net shoreline change of the Elwha River at each transect between September 2013 and April 2014. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESR).



Figure 23: Net shoreline change of the Elwha River at each transect between April 2014 and September 2014. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



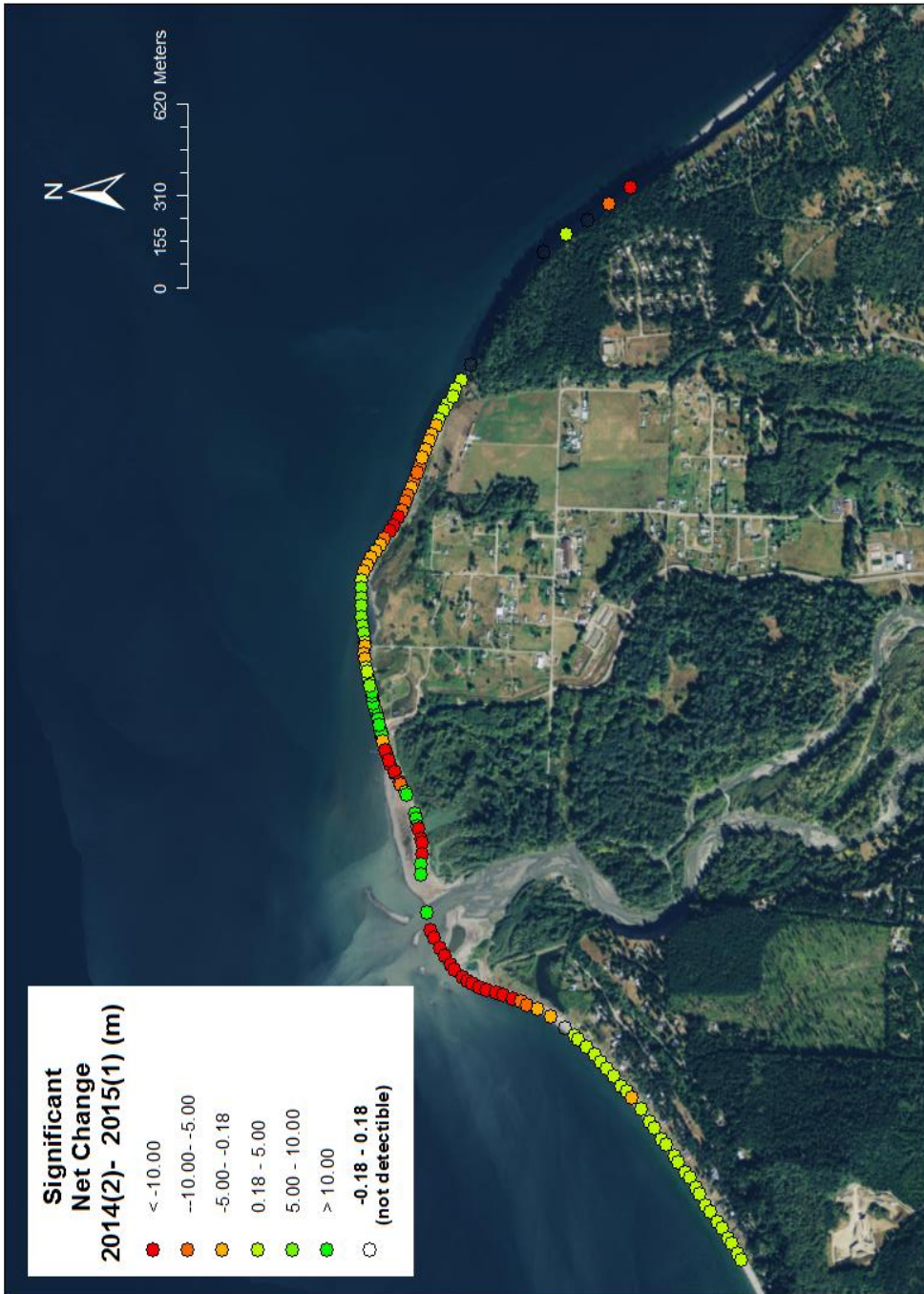


Figure 24: Net shoreline change of the Elwha River at each transect between September 2014 and January 2015. Shades of green represent accretion, and shades of red indicate erosion. Net changes of <0.18 m are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).



Figure 25: Overall annualized shoreline change during the “dam-use period” (1927-2012). Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <0.43 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).





Figure 26: Overall annualized shoreline change during the “post-dam period” (2012-2015). Shades of green represent accretion, and shades of red indicate erosion. Annualized rates of <0.06 m/year are considered immeasurable and are represented by colorless markings. Basemap image is of 2012 Elwha Delta (ESRI).

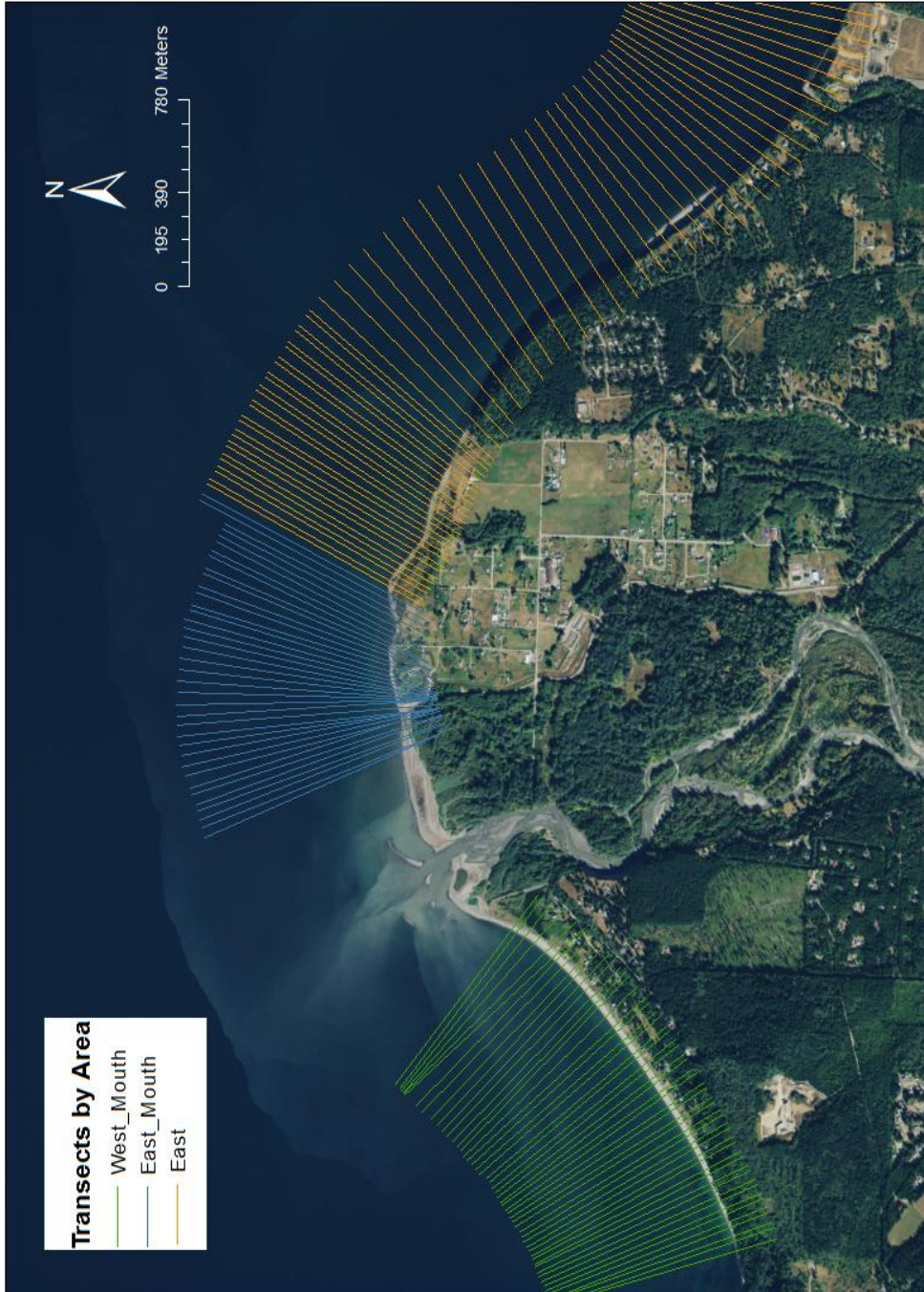


Figure 27: Transects by location. Uniquely colored transect areas denote different spatial locations. The area encompassing the river mouth was neglected for changes by area due to high variability in coastal change.



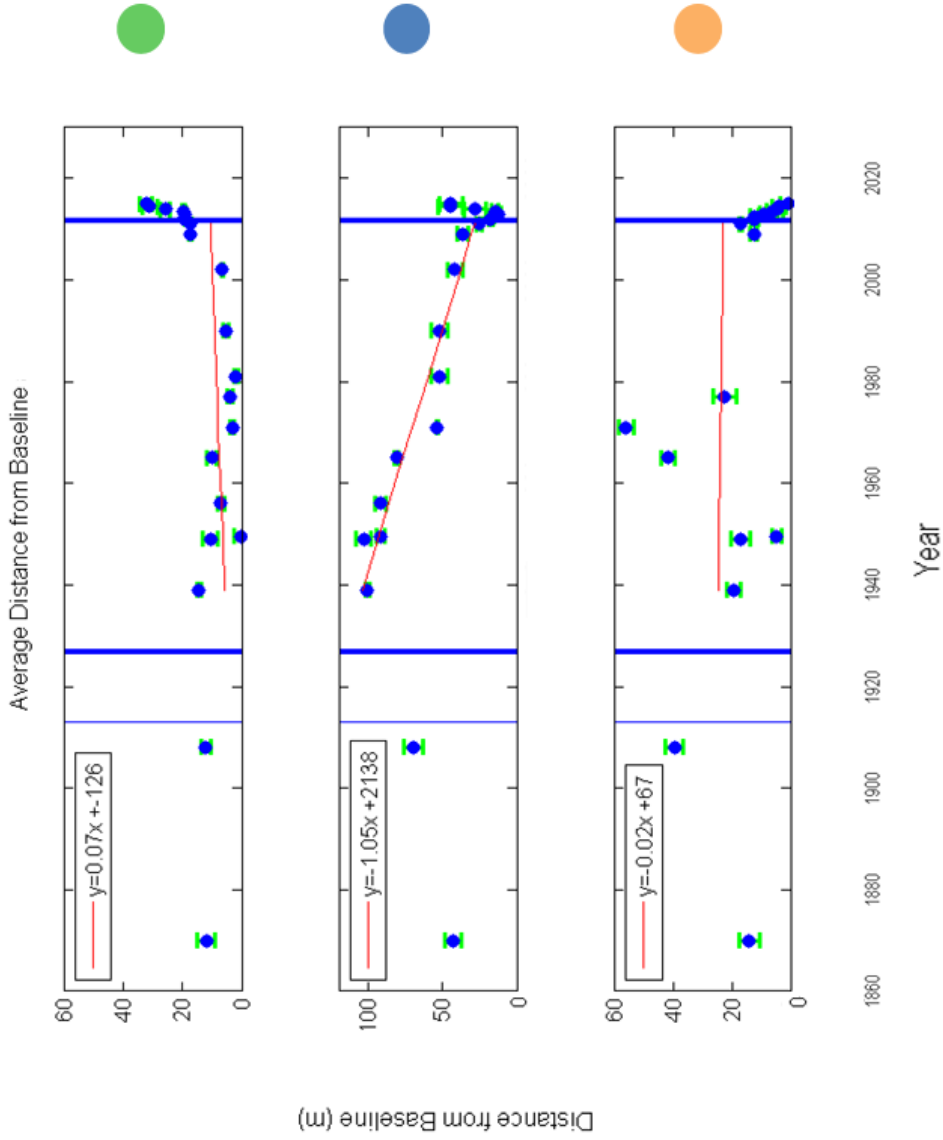


Figure 28: Average distance from baseline by area and by year. From top to bottom: west of the river mouth, east of the river mouth, and the east delta region. Blue lines indicate dam placement (1913 and 1927 for the Elwha and Glines Canyon Dams, respectively) and dam removal (2012). Standard error bars are represented in green.

## Discussion

This study was prepared in an effort to describe changes to the Elwha shoreline across multiple time-steps, and to identify patterns relating to current shoreline change and pre-dam morphology. Identifying the Elwha's previous states provides useful input in an ongoing narrative of describing the Elwha's current trajectory.

During the pre-dam period (-1927), shown here solely as the 1870-1908 time step, moderate accretion is shown in the Point Angeles region, with other, smaller areas of accretion in the east-delta and east-river mouth areas (figure 5). Additionally, during the 1908-1939 time-step (figure 6), which partially encompasses dam construction, the eastern river mouth area shows overall accretion on average, while the eastern delta region shows moderate overall erosion and the western river mouth remains relatively consistent. During this time, which encompassed a seventeen year span of intermittent dam construction (the Elwha Dam began in 1910, and the Glines Canyon Dam was completed in 1927), it is highly likely that large amounts of sediment were mobilized downstream as a byproduct of dam construction. The catastrophic blowout of the Elwha Dam in late 1912, as well as additional blasting used to rebuild the foundation of the dam would have mobilized additional large amounts of material that may account for some of the change observed during the 1908-1939 time step (figure 6, 28). Approximately sixteen tons of dynamite was used in the construction of the Elwha Dam (Mapes, 2013), although some portions were removed from the construction site, and additional portions were used in the repair process after the dam's blowout. It may be possible that the mobilization of large amounts of sediment during this time could have affected shoreline morphology downstream, but this effect

would be limited to the construction of the Elwha Dam, as the Glines Canyon, built later, was also constructed further upstream, and any large mobilized sediment would have been entrapped behind the Elwha Dam. It is difficult to quantify any effect blasting from dam construction may have had, mostly due to large differences in construction methods over the succeeding 100 years after the dams were originally placed. Thus, it is hard to constrain a particular pattern associated with pre-dam morphology directly attributable to dam placement given the lack of sufficient data during that time period. However, the scale of shoreline location with regard to other years (figure 28) may help in constraining shoreline position of the Elwha coast after sediment stabilizes from dam removal.

During the dam-use period, a similar spatial pattern emerges as with pre-dam shore configurations, where the western river mouth remains relatively constant in time, and the most pronounced changes occur along the eastern river mouth, between the Elwha mouth and Point Angeles. The eastern river mouth area is also the only area in which a significant trend is seen, and shows an average erosion rate of 1.05m/year during the 1939-2012 period. This pattern of a generally stable shoreline along the western side of the Elwha mouth, and a highly changed shoreline along the eastern mouth is consistent with previously described research (Warrick et al. 2009a) that points towards a highly eroded coastline along the eastern river mouth. This conclusion is further supported by Lower Elwha Klallam history along the Elwha coast in which habitat for shellfish, a valuable food source for many native peoples (Mapes, 2009), declined after the construction of the two Elwha River dams. This decline is most notably associated with a changing nearshore substrate, shifting from a sandy beach favorable to shellfish growth to the cobble

dominated low-tide terrace that persists today. The eastern river mouth exhibiting the dominant erosional pattern can be supported by the eastward littoral transport of sediment along the shoreline, heavily dominated (91%) by waves from the northwest (Warrick et al. 2009a).

Although regressing as significant, the erosional pattern along the eastern river mouth shown in figure 28 does not appear to show that a consistent, linear description of erosion fully represents the Elwha coastline and its variability during the dam-use period. As an example, the period between 1971 and 1990 showed very little change between successive years, and erosion rate increases after 1990, reaching one of the area's highest erosion rates between 2009 and dam removal in 2012. Short-term erosion rate also reaches a maximum between 1956 and 1971, supporting that perhaps neither linear, consistent erosion, nor increased erosion leading to dam removal may fully describe the pattern of erosion at the Elwha.

After dam removal, two of three areas (west and east mouths) show a marked accretion of average shoreline position, while the eastern delta region shows an erosional pattern. Average shoreline accretion of ~20m to the west of the river mouth is highly unusual, and is beyond the scope of any previous change for the region. Directly to the east of the river mouth, the extent of accretion is below the maximum average shoreline extent, which occurred in 1939, and is comparable with the average shoreline extent of 2002.

Based on the time intervals utilized in this study of the Elwha (long intervals prior to dam placement, somewhat shorter, but regular intervals during the dam-use period, and very short intervals immediately prior to and following dam removal), there may be an

inherent bias of shorter timescales overestimating the relative effect of sediment accumulation or erosion. The “Sadler Effect”, first quantified by Peter Sadler (1981), traditionally describes falling sediment accumulation rates with increasing time interval, which has since been described as a highly predictable relationship (e.g. Schumer and Jerolmack 2009). Recent work (e.g. Finnegan et al. 2014) has supported that the same may hold true for erosional patterns; increasing the timescale over which a particular system is observed increases the likelihood of observing a period of time (or multiple periods of time) without erosion. This effect implies that erosional estimates may categorically overestimate rates of erosion or accretion at the Elwha as they approach the present (most notably leading up to, and following, dam removal, where data from the Elwha is more numerous). In order to identify whether these data are time-dependent, the power-law relationship is observed by plotting magnitude of change against the time interval over which it is measured (figure 29).

The resulting power-law exponent of -0.927,  $R^2$  value of 0.242, and standard error of 0.579 combine to identify that the effect of time-dependence on these data cannot wholly be rejected. For this reason, the observations of magnitude of pre-dam and dam-period change listed in figure 28 are most relevant to discussing historical Elwha shorelines as a comparison against recent changes, rather than strict rate of change observations.

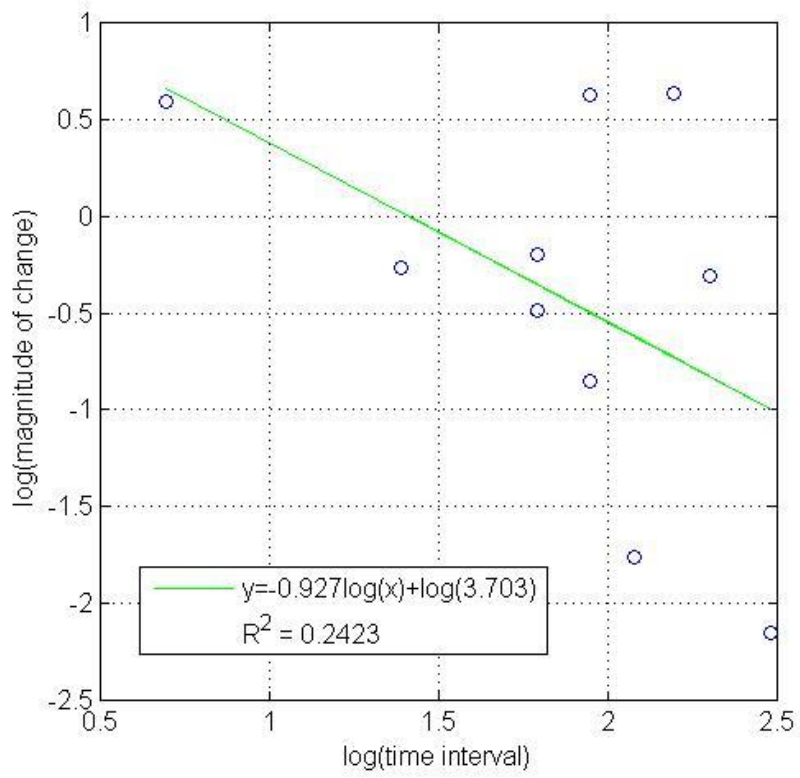


Figure 29: Power-law relationship of magnitude of change and time interval. Data points represent all averaged transect data for a given time interval

## Conclusions

Historical analysis of the Elwha shoreline has revealed compelling differences in shoreline morphology between 1870 and 2015 based on time period as well as coastal area. Annualized rates of change have varied from up to 6 m/year of erosion (predominantly to the east of the Elwha mouth, and during the period of time when the Elwha and Glines Canyon Dams were in use), to greater than 10m/year of accretion after dam removal (dominantly the eastern and western river mouth areas). Notable accretion of the Elwha coastline is seen prior to dam placement in both areas to the east of the river mouth, and significant erosion is seen during dam-use in one of these areas as well. All areas have shown prominent trends beyond dam removal, with the far eastern delta region showing a general erosive trend, and both areas surrounding the river mouth showing accretion.

Erosional rates of change during dam use are comparable with previous estimates at the Elwha, and current shoreline position has in some cases returned to or exceeded shoreline position prior to dam placement. As effects of dam removal continue, estimates of shoreline morphology during the late 1800s and early 1900s suggest that in some locations, coastal accretion may continue towards pre-dam conditions, while in other areas, the current post-dam trajectory may slow or reverse.

These trends can be used as a comparison point for other, similar, dam removal to understand the patterns associated with historical dam placement. Coastal studies regarding the effects of dam placement and removal will also become increasingly critical as more large-scale physical and biological restoration projects are proposed and initiated.

## Appendix

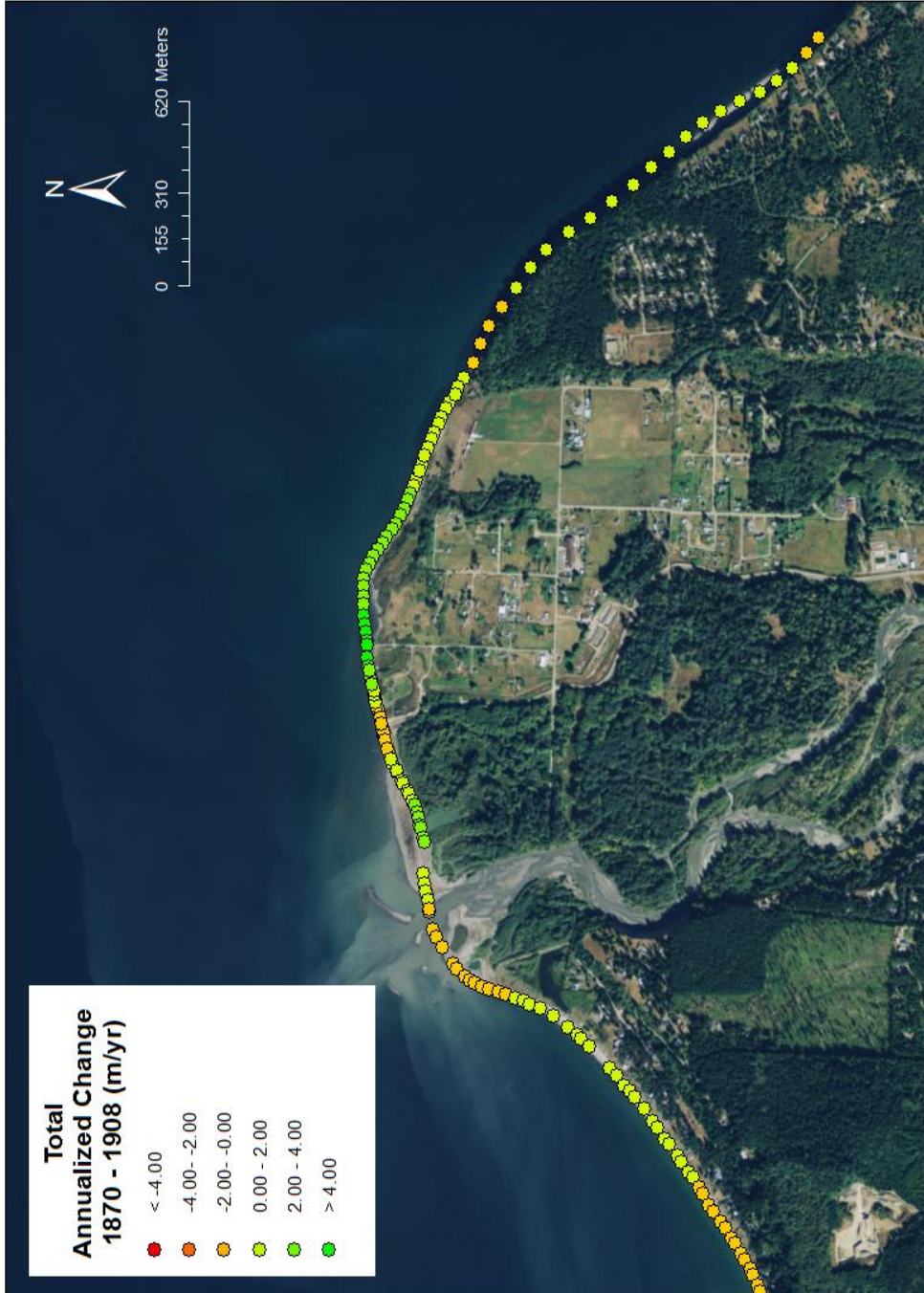


Figure A1: Overall annualized shoreline change of the Elwha River at each transect between 1870 and 1908. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI).





Figure A2: Overall annualized shoreline change of the Elwha River at each transect between 1908 and 1939. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)

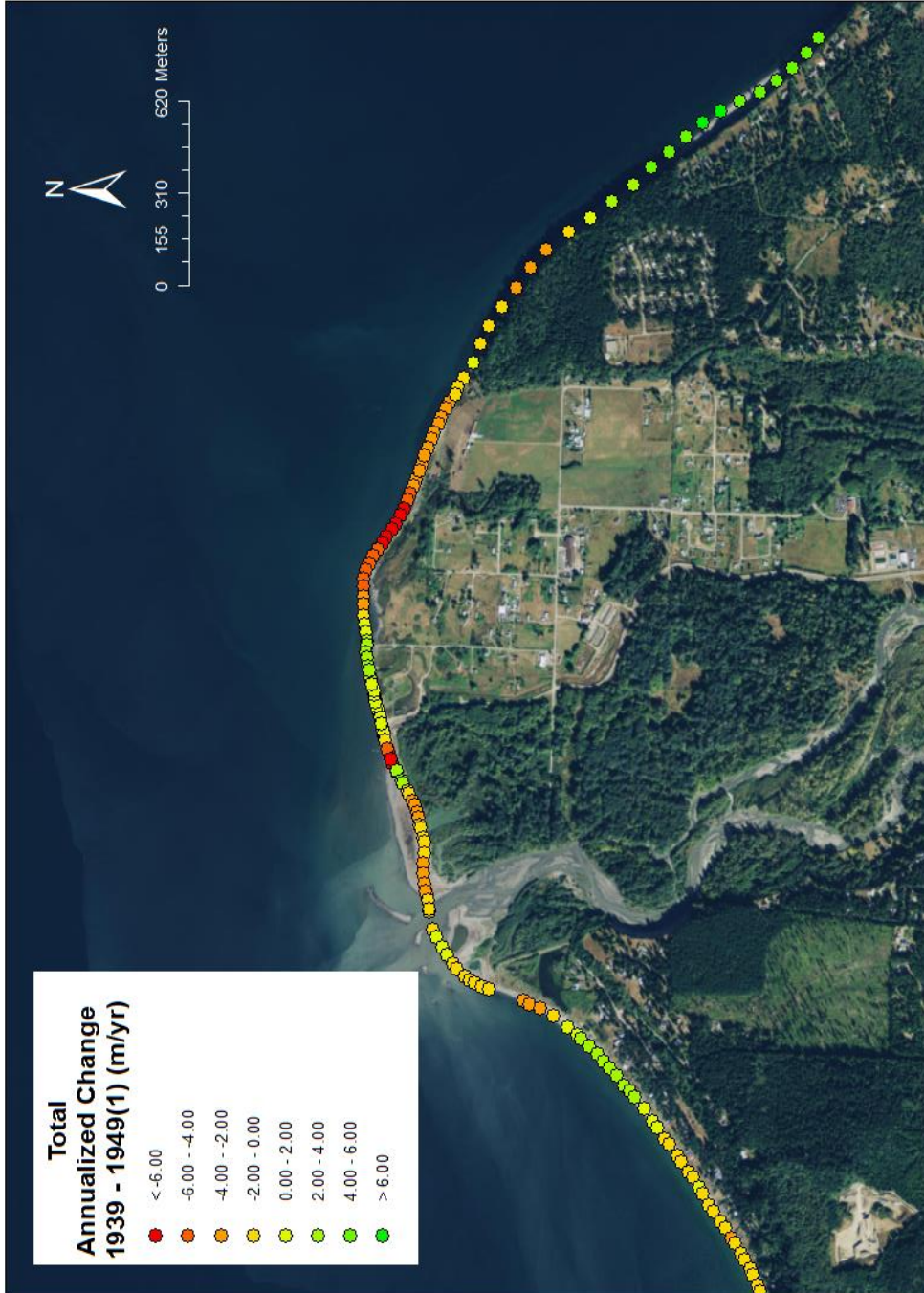


Figure A3: Overall annualized shoreline change of the Elwha River at each transect between 1939 and 1949. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI).

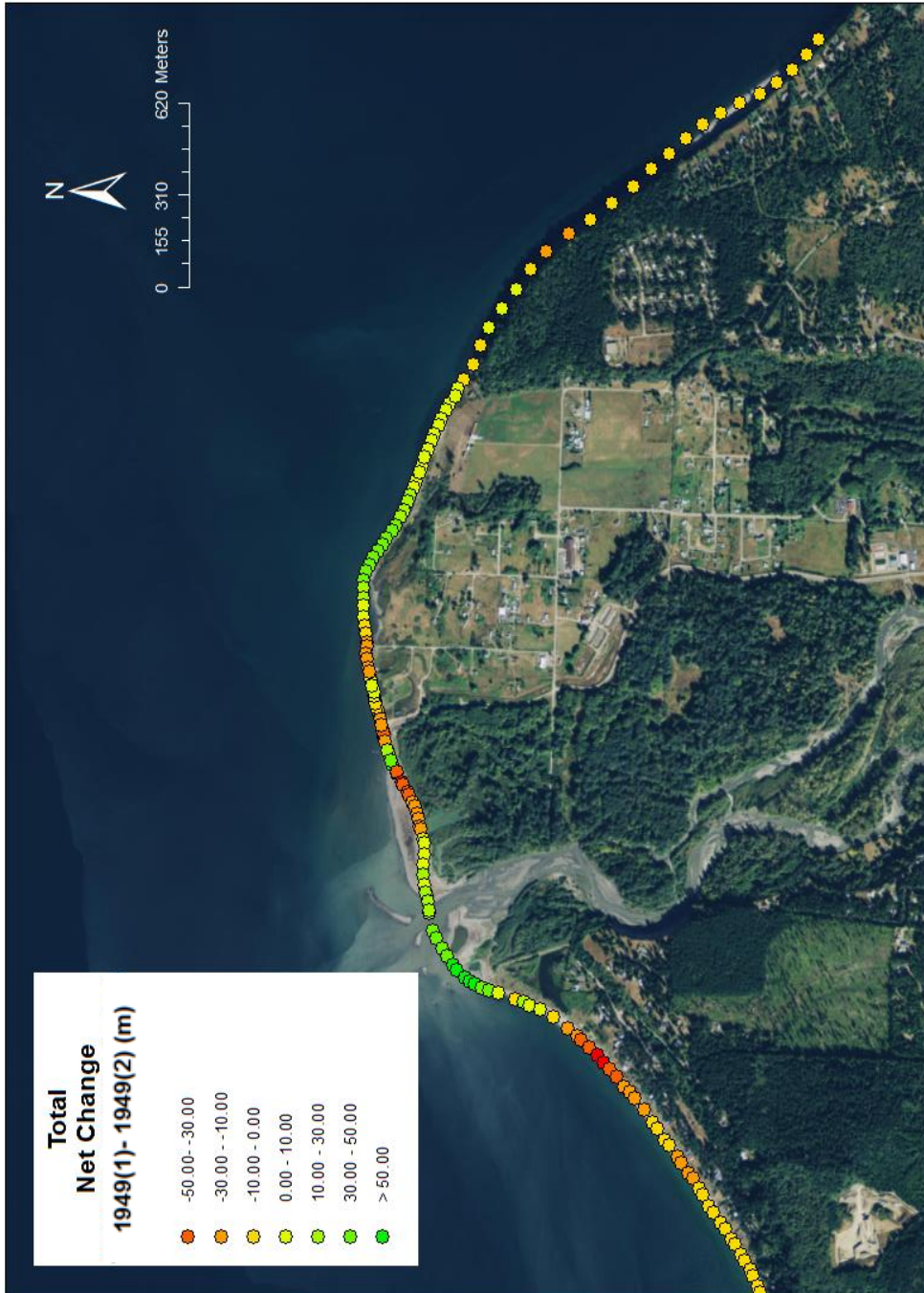


Figure A4: Overall net shoreline change of the Elwha River at each transect between 1949(1) and 1949(2). Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI).





Figure A5: Overall annualized shoreline change of the Elwha River at each transect between 1949(2) and 1956. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI).



Figure A6: Overall annualized shoreline change of the Elwha River at each transect between 1956 and 1965. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI).



Figure A7: Overall annualized shoreline change of the Elwha River at each transect between 1965 and 1971. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)





Figure A8: Overall annualized shoreline change of the Elwha River at each transect between 1971 and 1977. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)



Figure A9: Overall annualized shoreline change of the Elwha River at each transect between 1977 and 1981. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)



Figure A10: Overall annualized shoreline change of the Elwha River at each transect between 1981 and 1990. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)





Figure A11: Overall annualized shoreline change of the Elwha River at each transect between 1990 and 2002. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)



Figure A12: Overall annualized shoreline change of the Elwha River at each transect between 2002 and 2009. Shades of green represent accretion, and shades of red indicate erosion. Basemap image is of 2012 Elwha Delta (ESRI)

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