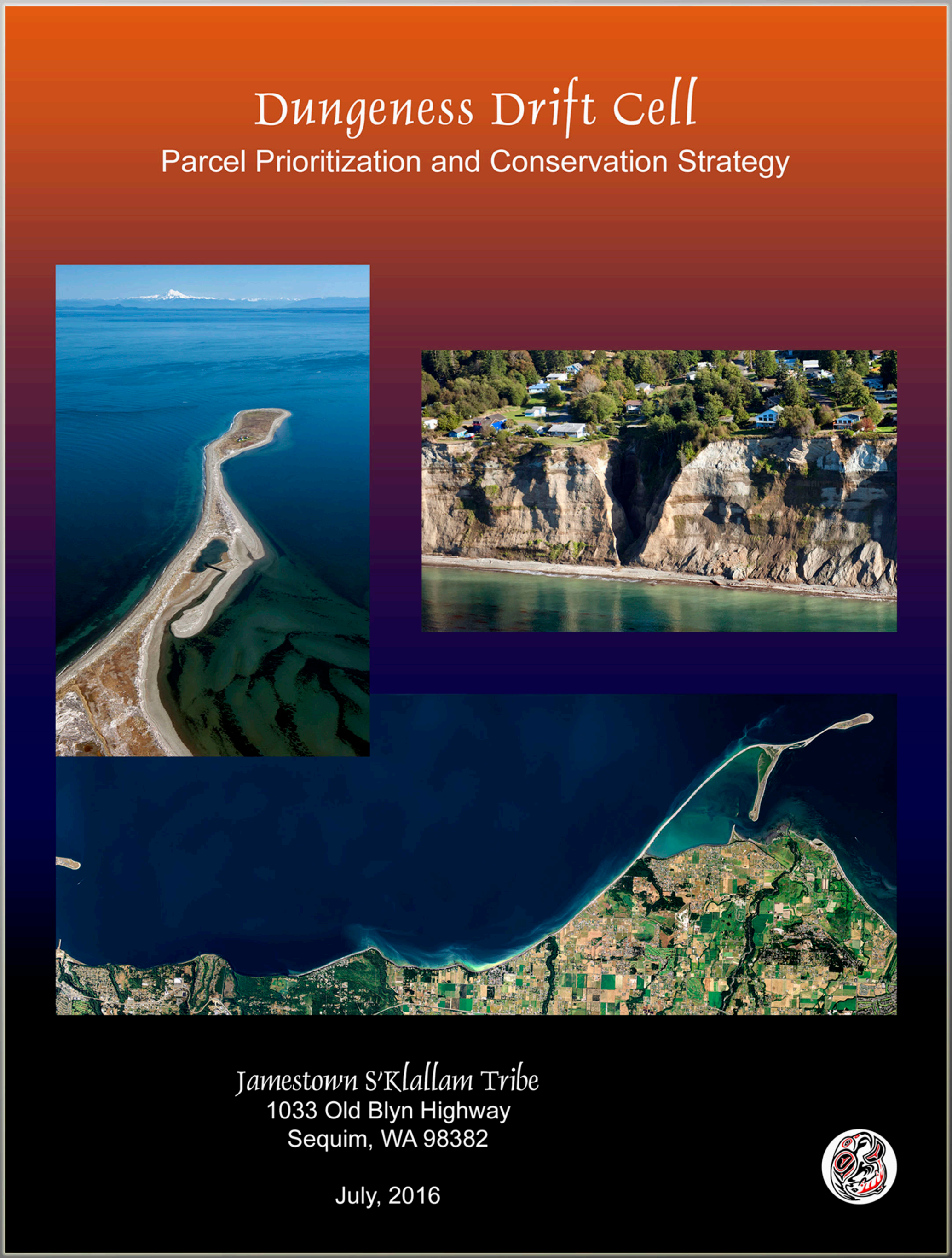


Dungeness Drift Cell

Parcel Prioritization and Conservation Strategy

Jamestown S'Klallam Tribe
1033 Old Blyn Highway
Sequim, WA 98382

July, 2016

Appendix G

Estimates of Feeder Bluff Recession Rates in the Dungeness Spit Drift Cell, Clallam County, Washington

Estimates of Feeder Bluff Recession Rates in the Dungeness Spit Drift Cell, Clallam County, Washington

Robert Knapp and Randy Johnson, Jamestown S'Klallam Tribe, July 2016

Contents

Introduction

Dungeness Spit, located on the north Olympic Peninsula in Clallam County, Washington [Figure 1), is a 5-mile long natural sand spit that curves gracefully from the base of a high bluff to a sandy point several miles offshore in the Strait of Juan de Fuca. A half mile from the end of the Spit stands the historic New Dungeness Lighthouse, built in 1857. The Spit is protected as a National Wildlife Refuge and is a major recreational destination for hiking, birding, wildlife watching, and other passive beach activities.

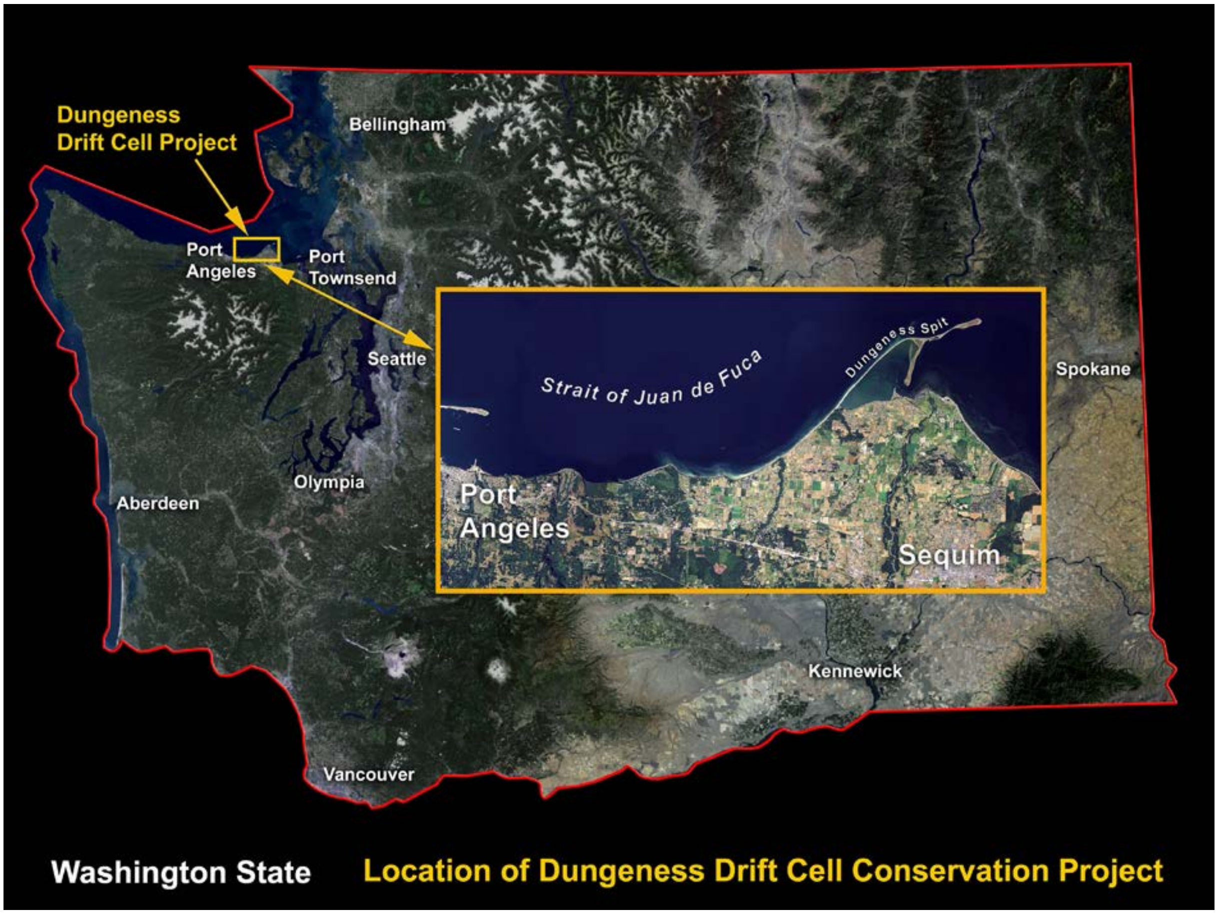


Figure 1: Olympic Peninsula

Dungeness Spit creates the 5.7-square mile Dungeness Bay, within which are two additional spits, Graveyard Spit, and Cline Spit. These two spits almost completely enclose Inner Dungeness Bay, which accounts for about one-third of the total size of the Bay. The portion of Dungeness Spit extending east beyond Graveyard Spit creates the larger Outer Bay (See Figure 2).

Together, the three spits protect the dynamic and habitat-rich estuary of the Dungeness River. Within Dungeness Bay there are marshes, eelgrass beds, tidal flats, and a small lagoon. These estuarine areas are important habitat for migratory and resident birds, wildlife, and fish, including endangered salmon and char. Dungeness Spit and the habitat within Dungeness Bay are of special importance to the Jamestown S'Klallam Tribe for their cultural and natural resource values.

Figure 2: Dungeness, Cline, Graveyard Spits mostly enclose the Inner Dungeness Bay, also called Dungeness Harbor. Dungeness Spit extends and continues to grow beyond Graveyard Spit, partially protecting the Outer Dungeness Bay. Imagery NAIP 2013.

Few visitors to Dungeness Spit realize that the high bluffs that form the shoreline extending 10.5 miles westward are an essential part of the geologic feature that culminates at the Spit. Eroding sand and gravel from the bluffs, swept alongshore by currents, wind, and waves, have created the Spit and continue to maintain it. Without the sediment eroded from the bluffs, Dungeness Spit would disappear, either gradually in the waves, or suddenly in a major storm.

The Spit acts as a barrier to waves generated by westerly winds and thereby protects homes and recreational developments that cluster along the shoreline several miles to the east and southeast. Without Dungeness Spit, the heavily developed bluffs bordering the sheltered Dungeness Bay would likely begin eroding at rates similar to those observed along the bluffs to the west that are open to the Strait. And without the Spit, the low-lying shorelines farther east– Rivers End and Three Crabs Road – would probably begin eroding at catastrophically high rates.

Within the Dungeness Wildlife Refuge federal laws protect Dungeness Bay and the Spit from development and incompatible uses. Outside the Refuge, various local, state, and federal regulations exist to conserve shorelines and protect fish habitat. These regulatory programs however are replete with exemptions that severely diminish their ability to ensure that the sediment sources for Dungeness Spit will be perpetually conserved.

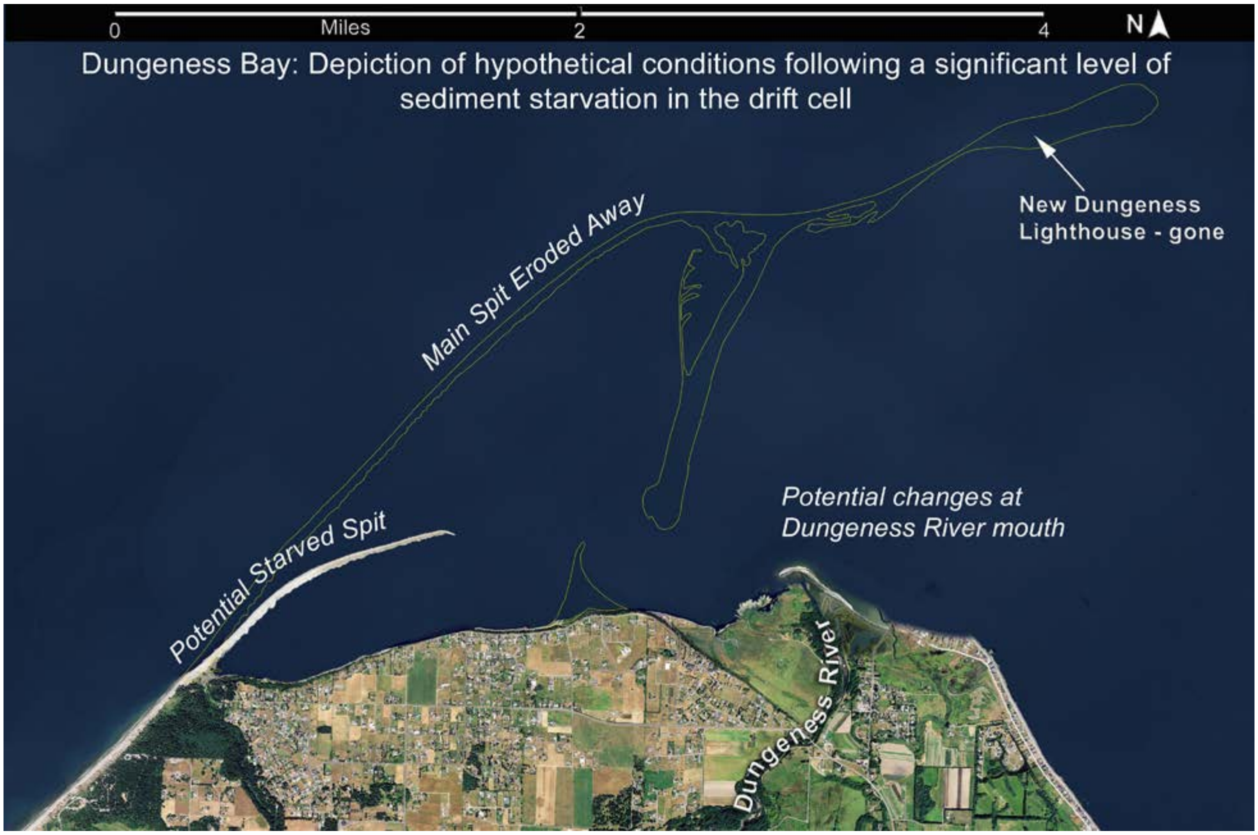


Figure 3: Hypothetical conditions at Dungeness Bay following significant sediment starvation in the drift cell. Imagery NAIP 2013.

As the shoreline west of Dungeness Spit has rapidly developed during the last several decades, the Jamestown S'Klallam Tribe has grown increasingly concerned that neither Federal, State nor the County land use regulations will prove sufficient to preserve the natural processes that created and maintain the Spit. The Tribe concluded that in order to protect this invaluable resource, it would be necessary to better understand Dungeness Spit's sediment source—the feeder bluffs—and how natural bluff erosion will likely affect the infrastructure – roads and buildings – that are closest to the bluffs. This was the genesis of the Dungeness Spit Drift Cell Feeder Bluff Recession Study. The goals of the study were the following:

- To estimate the rate of erosion (recession) of the bluffs that feed sediment to the Dungeness Spit.
- To assess the development close to the bluff.
- To inform long-range planning to protect the Spit and the life and property that depend on it.

Shoreline Processes

Shorelines formed by the deposition of sediment, such as sandy beaches and spits, are called *accretion shoreforms*. They are created by the action of wind, waves, and currents depositing (accreting) sediment in sufficient quantity to overcome the erosional forces working on the shoreline. When sufficient material is moved in one direction by longshore drift, and other conditions are right, an accretion shoreform will develop. Accretion shoreforms include wide, sandy beaches, barrier beaches, spits, tombolos (spit-like features connecting an island to the mainland), and cuspate forelands (triangle-shaped spits. All accretion shoreforms require a continuous supply of new material to replace materials that are washed away. Depending on the supply of sediment, an accretion shoreform may expand (get wider, longer, or higher), remain the same size and shape, or become smaller. If the sediment supply is insufficient for a period of years or decades, the shoreform will erode significantly and might eventually disappear.

Figure 4: Shoreforms.

The materials that make up accretion shoreforms - sand, gravel, and cobbles - come from two main sources: streams and bluffs. Streams carry sediment produced in their watersheds and deliver this material to a lake or sea. Shorelines, when eroded, often deliver significant amounts of sediment onto the beach. Both processes provide sediment sources for accretion shoreforms. Puget Sound has a large amount of the type of shoreline called “bluffs.” Bluffs along shorelines are often high and steep and are composed of materials that range from very hard and slow to erode, to loose and easily erodible. Bluffs that contribute significant amounts of sediment to accretion shoreforms are classified as *feeder bluffs* because as they erode they “feed” sediment to the shoreform.

Feeder bluffs erode, or recede landward, at rates often ranging from 0.25 to 3 feet per year. As it erodes, a bluff's slope may change. How steep the bluff face can become before the crest erodes depends largely on the composition of the bluff. Highly unstable materials tend to form low-angle slopes; in this case, the crest erodes at almost the same rate as the toe. At the other extreme, bedrock bluffs can support sea-caves and undercut slopes. The bluffs west of Dungeness Spit are somewhere in between these extremes. At some point, the slope becomes too steep for the bluff material to support itself, and the crest erodes. When caused by wind (saltation) and small slides on the bluff face, erosion can be fairly uniform from year to year. Occasionally large slides called *mass wasting events* occur and immediately deposit large amounts of bluff material onto the beach. These episodes can produce, in a single event, sediment quantities equal to several years of average annual erosion. Wind, precipitation, and wave action remove material from the face and toe of bluffs (Figure 3). Waves, especially during storms and high tides, work along the base or toe of the bluff and spread loose material over the beach, usually within days or weeks. Wind, waves, and tidal currents transport the sands and gravels along the beach. During any given storm event or moment in time, beach material may move in any direction. Over time however, the prevailing winds and waves will move material along the beach in a particular direction. This net movement of material is called *longshore transport* (net drift or littoral drift).***Insert photos of saltation, small slides and mass wasting***

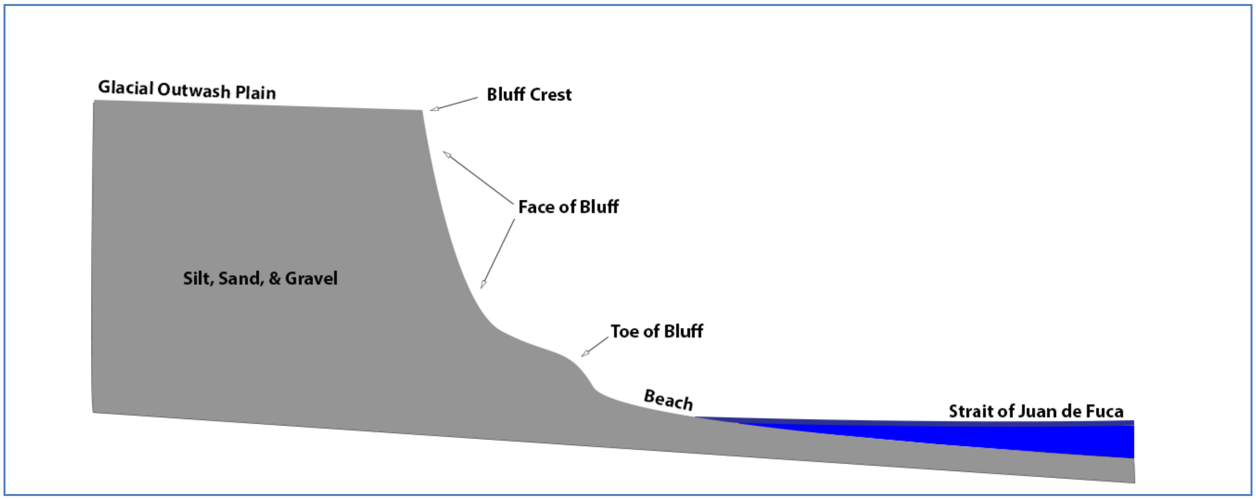


Figure 5: Simplified cross-section of a feeder bluff. Note: Natural feeder bluffs contain complexity not shown, including, but not limited to, slumps, benches, berms, and vegetation. For a more detailed beach cross section, see Figure 1 in Johannessen and MacLennan (2007).

A geologic unit composed of sediment sources – streams and/or feeder bluffs - and an accretion shoreform is called a *drift cell*. The bluffs west of Dungeness Spit are highly erodible, thick glacial deposits and they feed enormous quantities of sediment to Dungeness Spit. Thus, the Dungeness Spit Drift Cell consists of:

- the 10.5 mile bluff system extending east from the mouth of Lees Creek to the base of Dungeness Spit,

- a number of streams including Lees, Morse, Bagley, Siebert and McDonald Creeks and the Dungeness River, and
- Dungeness Spit itself.

The entire drift cell is 15.5 miles long (see Figure X). Because the bluff between Lees Creek and Morse Creek has been bulk-headed since 1915, and therefore has not contributed significant amounts of sediment to the beach in nearly a century, it is not included in the study. The streams are not included either, because they produce much less beach-sized sediment than the feeder bluffs and their sediment supply is not currently considered at-risk in any way. Hence, this study focuses on the 8.5 mile portion of feeder bluff complex extending east from the mouth of Morse Creek (Drift Cell Mile 13.5) to the base of Dungeness Spit (DCM 5).

Figure 6: Dungeness Spit Drift Cell with Drift Cell Miles (DCM's). Imagery NAIP 2013.

Although Dungeness Spit has been lengthening during the past century, it remains relatively narrow, low and fragile. During winter storms waves occasionally wash over the Spit, causing temporary gaps or breaches. Over several weeks or months the breach is repaired as longshore drift replaces the material that was washed away. However, if the amount of sediment delivered to the Spit decreases, breaches will become more common or even permanent. Over time, a reduced sediment supply would lead to a sediment-starved drift cell; the Spit could erode away, and Dungeness Bay would cease to exist. Without the protection of the Spit, the beaches and intertidal areas of Dungeness Bay would soon be scoured by large waves and tidal currents and be converted to deep water, as can be seen along other unprotected Strait of Juan de Fuca shorelines.

The sudden, large-scale erosion of nearby Ediz Hook following human impacts to its sediment supply (Appendix A), indicates the degree to which Dungeness Spit is vulnerable to sediment loss. Unlike Ediz Hook, which historically received approximately a third of its sediment supply from the Elwha River, Dungeness Spit receives only a very small portion of its sediment from the streams to the west—McDonald, Siebert, and Morse Creeks. Thus, the continued existence of Dungeness Spit, which protects critical wildlife and fish habitat, recreational resources, and human infrastructure (roads and houses), is dependent on both the natural erosion of an 8.5-mile stretch of feeder bluffs and uninterrupted longshore drift to deliver sediment to the Spit.

Erosion of a bluff face, which is often measured at the bluff crest, is called bluff retreat or *bluff recession*. Bluff recession is a natural process essential to the maintenance of diverse healthy shorelines of the Puget Sound. However, infrastructure placed near erodible bluffs can result in eventual loss of life and property, especially during rapid (episodic) bluff recession. People tend to build close to bluff crests because of the spectacular views, but doing so puts them and their infrastructure in the path of bluff recession.

The Dungeness Spit Drift Cell Complex contains feeder bluffs that are receding at various rates. The remainder of this report will focus on characterizing bluff recession in the drift cell, estimating recession rates, and assessing the infrastructure along the bluff crest. The goal is to better understand the characteristics of feeder bluff erosion and to inform a long-range planning process for protecting life, property, and the sediment source for the Dungeness Spit.

Study Area

The Dungeness Spit Feeder Bluff Complex (the study area) stretches for 10.5 miles west from the base of the Dungeness Spit to the mouth of Lees Creek. In order to facilitate bluff recession estimates, the bluff

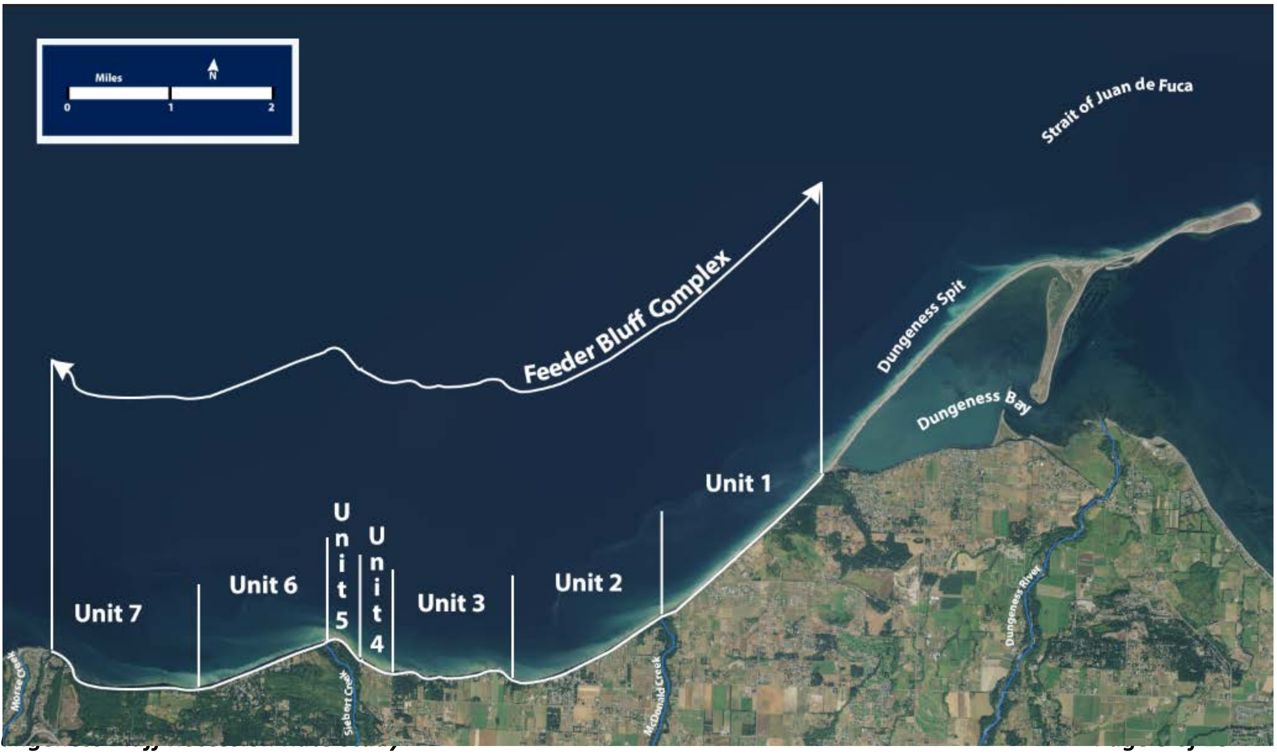


Figure7: Feeder Bluff Complex and analysis units (imagery source 2011 NAIP).

complex was systematically, but asymmetrically, subdivided into seven units, labeled 1 through 7 from east to west. The units range in length from 0.35 miles to 2.04 miles. Expert judgment was used to determine the starting and ending points for the units (see Figure 4).

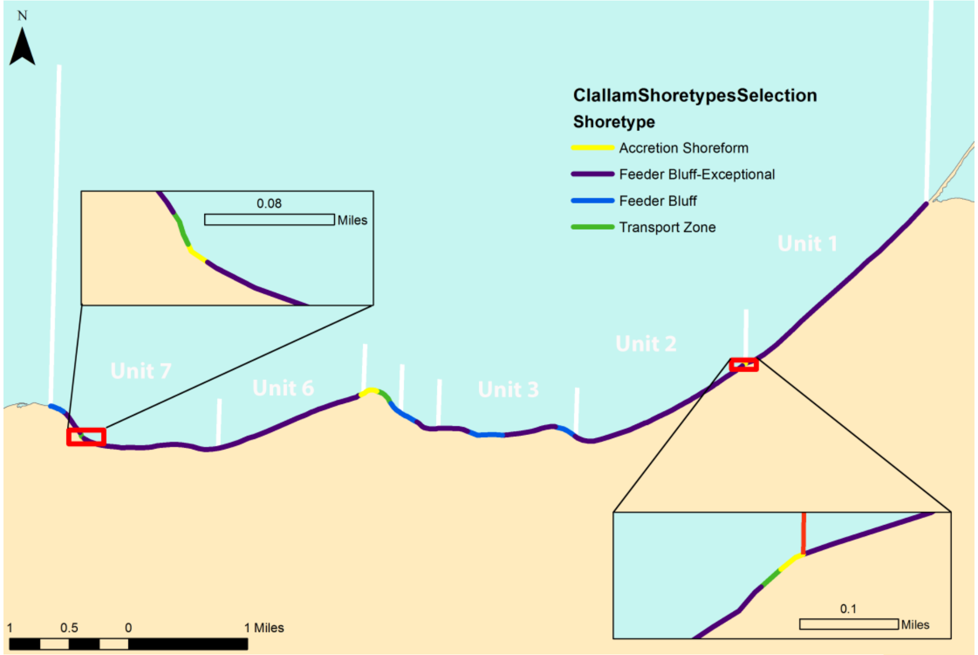


Figure 8: WA DNR Shoretype for study area.

The Dungeness Spit feeder bluffs are not uniform, but vary in numerous ways, including composition, height, average slope, amount of vegetation, aspect, and the shape of the bluff. One classification of shore structure is *shoretype*. Coastal Geological Services mapped the shoretypes for much of Puget Sound, including the study area (CGS 2012). Figure 5 depicts the shoretypes and units for the study area. Table 1 provides the approximate length and percentage of each shoretype within the complex. Feeder Bluff Exceptional is the dominant shoreform in the study area, accounting for almost 85%, while Accretion Shoreform and Transport Zone make up just over 5%. The Feeder Bluff Exceptional shoretype represents the most rapidly eroding bluffs (Johannessen and Chase 2006). As with all classification schemes, the classes impose simplicity that obscures the truly complex makeup of these natural shorelines. There is variability within all of the shoretypes (not all feeder bluffs are the same height, made of the same material, etc.). This is especially the case where there is a transition from one shoretype to another (for example, from feeder bluff to transport zone). Appendix B expands upon the analysis of the shoretypes in the study area

Table 1: Shoretypes statistics for study area

Shoretype	Miles	Percent
Accretion Shoreform (AS)	0.19	2.24%
Feeder Bluff (FB)	0.88	10.38%
FB-Exceptional (FBE)	7.17	84.54%
Transport Zone (TZ)	0.24	2.84%
Total	8.48	100.00%

Methods

The first step in this multiphase project was to estimate the recession rates of the feeder bluffs that supply sediment to the Dungeness Spit. There are currently several efforts underway to estimate the amount and volume of bluff erosion, and to estimate short-term recession rates; however, these studies will need to be repeated over a longer time frame to provide additional insight into the long-term recession rates. To precisely know the amount and long-term rates of bluff recession would require hundreds of careful measurements between surveyed control points and the bluff crest, collected over decades (preferably centuries). In the absence of accurate long-term measurements, there are a number of methods that have been used to approximate long-term bluff recession rates (NRC 1999). The method used in this study involves making distance measurements between the bluff crest and fixed reference locations on georeferenced aerial photographs (NRC 1999). For the purposes of this document, the term “reference location” is used instead of “control points,” to highlight the fact that the reference locations are not surveyed locations, just highly visible points on aerial photographs. Comparing the distance between bluff crest and reference locations using a time-series of aerial photographs makes it possible to estimate bluff recession rates (distance bluff crest recessed divided by time interval between photographs).

Georeferenced aerial photosets

The Jamestown S’Klallam Tribe acquired aerial photographs for the years 1956, 1976, 1997, 2008, and 2010 for the shoreline between Morse Creek and the base of Dungeness Spit. In this document, each group of photos for a given year will be referred to as a “photoset.” For example, the 1976 photoset was taken on the 8th of August, 1976. (Appendix C contains additional detail about photosets.) Individual 1956 and 1997 photographs were scanned using an Epson Expression 10000XL large-format professional grade graphic arts quality scanner. The other photosets were purchased as high-resolution electronic files from their photographic providers: the Washington Department of Transportation for the 1976 set and Bergman Photographic Services for the 2008 and 2010 sets. All photos were precisely georeferenced and brought into a Geographic Information System (GIS). The 2010 photoset was georeferenced against the National Agriculture Imagery Program (NAIP) 2009 orthographic aerial imagery (NAIP 2009). Because the NAIP imagery is lower resolution than the 2010 photoset, the 2010 photoset was used as a master and all other photosets were georeferenced to the 2010 photos.

Once all of the photos were georeferenced, each photoset was inspected to find suitable reference locations. Ideally, reference locations are clearly visible in at least one photo in all photosets, represent an object that can’t be easily moved, and are relatively near a section of bluff crest that is not obscured by vegetation, shadows, or photographic imperfection. Because air photos always distort ground-based features to some extent, reference locations close to the center of photographs and physically located closer to the ground were considered the best candidates, where they were available. The corners of structures, roads, driveways, and single trees make good reference points if they are clearly visible in most or all photosets. The early photos (1956, 1976) contain fewer structures and associated infrastructure than the more recent photos, while some structures visible in the early photos have been moved or torn down. All these constraints resulted in a limited set of reference locations.

> Note about photo selection: The photos in a photoset often overlap significantly, so a single reference point may be visible in two or more photos in the same photoset. In this case, the photo with the clearest and least distorted view of the reference point and bluff crest was selected to be used for the measurements. As mentioned above, there is often less distortion in the center of each photo; however, the number and location of available georeferencing control points (control points in this context differ from surveyed field locations and monuments) used during the photo georeferencing play a role in overall photo distortion. The analysis used expert opinion to weigh all of these factors when determining the best available photo to use for each measurement. Because the bluff-top areas along the feeder bluff complex are relatively flat, the distortion of ground features within the images is minimized but not eliminated. A detailed description of the georeferencing process is beyond the scope of this document; however, a number of books and publications are available on the topic.

The distance from a reference location to the bluff crest (roughly perpendicular to the bluff crest) is the key measure used in estimating rate and amount of bluff recession. Reference locations are at a premium in the study area and are not evenly spaced along the drift cell; thus, analysis units and subunits contain different quantity and quality of reference locations. This is a source of unmeasured variance in the estimates.

For each photoset a measurement between the reference location and the bluff crest was made on the most suitable photo. If the reference point and the bluff crest were clearly visible in each selected photo in each photoset, then five measurements would be made (1956, 1976, 1997, 2008, and 2010) at each reference location. It should be noted that the georeferenced photosets do not match precisely between years at each reference location because of variations in camera type, flight-platform elevation, location, pitch, yaw, and roll as well as variations in the georeferencing. To reduce the error associated with these differences, each measurement was made on only one image, where possible. Shading, sun angle, riparian vegetation, and changes in land cover and land use result in reference points and bluff crests not always visible in every photoset. These variations made some measurements more difficult or impossible. At sites and dates where the bluff crest was clearly visible but the reference location was not visible, distance from bluff crest to reference location was estimated using a reference line. Reference lines were created using the following methodology:

- Using the 2010 georeferenced photoset, the sixty-four reference locations were marked to produce a reference point GIS dataset. Note: Due to the previously mentioned differences between photos, the reference point may not fall exactly on the reference location when viewed on photos other than the photo used to create the points.
- Each reference point was used in the GIS to create a single reference line (GIS line dataset) parallel to the bluff crest and intersecting the reference point. The reference line was extended some distance in either direction away from the reference point.
- Viewing the reference line features in the GIS over the selected photo (where the reference location is missing), a distance was measured between the bluff crest and the reference line perpendicular to the reference line. In this case the reference line is a proxy for the reference location. While these measurements may be quite accurate, not

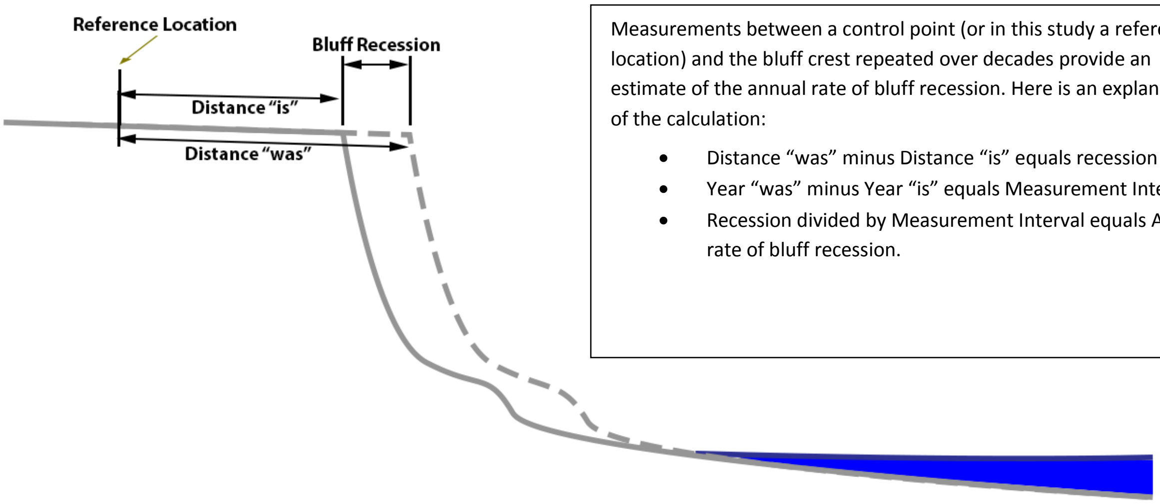
having a visible reference location creates a greater level of uncertainty and adds variance due to photo-to-photo georeferencing differences.

Quality Control

Measuring each of the 64 reference locations on all 5 photosets would result in 320 individual distance measurements across the drift complex. However, several factors reduced the number of actual usable values. In 24 instances a distance measurement was not made because of difficulties in determining the precise location of the bluff crest in a photoset, resulting in 296 individual distance measurements. After careful consideration of the quality of the data, distance values were used to estimate bluff recession only where both the reference location and the bluff crest were clearly visible. Photosets were georeferenced to a high degree of accuracy where possible. Some individual photos proved to be challenging to georeference because of a lack of suitable ground control points or the control points not being spread spatially across the photo. Expert judgment was also used to eliminate any distance values that were generated using photos where the quality of the georeferencing may have resulted in excess photo distortion. Following all quality control efforts, the final tally of distance locations that met the above criteria was 226.

The individual distance measurements alone are not significant; it is the change in distance over time (subtracting an older distance value from a more recent value at the same location) that provides an estimate of bluff recession (see Figure 6). Using all 5 photosets provides 10 possible time intervals. Comparing only the highest quality distance measurements for the 10 time intervals resulted in 314 individual bluff recession estimates across the bluff complex.

This report emphasizes the bluff recession averages for the longest time intervals where sufficient results were available and where the maximum annual rates of bluff recession were found. In general, the shorter the time interval between photosets, the greater likelihood of qualifying the effects of a larger episodic rapid recession event. Therefore, most of the maximum recession rates were found using the 2008 to 2010 photosets. The 1956 to 2010 time interval is the longest available; however, only 12 recession values met the quality control criteria, so these data are used only for recession estimates for the entire study area. The 1976 to 2010 interval was determined to provide the best available long-term bluff recession averages for individual units.



Measurements between a control point (or in this study a reference location) and the bluff crest repeated over decades provide an estimate of the annual rate of bluff recession. Here is an explanation of the calculation:

- Distance "was" minus Distance "is" equals recession
- Year "was" minus Year "is" equals Measurement Interval
- Recession divided by Measurement Interval equals Annual rate of bluff recession.

Figure 9: Explanation of bluff-recession-to-reference-location measurement.

> Note: The following is a simplified hypothetical example calculation to further illustrate the method used in this study. Assume the distance from a given reference location to the nearest point along the bluff crest was 100 feet (distance "was") in 1956 (year "was") and 50 feet (distance "is") in 1976 (year "is"); then the change in distance was 50 feet in 20 years. Dividing the change in distance (50 feet) by the measurement interval (20 years) yields 2.5 feet per year as the average annual recession rate. If a home was built in this area with a 100-foot setback from the bluff crest in 1976 and the average annual recession rate was accurate, then sometime before 2016 the home would need to be repositioned farther back from the bluff or else be removed.

Comments on precision and accuracy

While all of the methods used in this study were performed with care and the results were checked by a second analyst, the method did not include any replication of individual measurements. Acquiring, scanning, and georeferencing the aerial imagery is tedious, time consuming, and expensive. Finding an additional high quality photoset taken in the same timeframe to use to create replicate measures is unlikely, especially for the older time periods. Given these constraints, this study does not include estimates of either the precision or accuracy of individual distance measurements or of the bluff recession rates derived from the distance measures. There is however, replication across the drift cell and across most of the units. Please note the "N" (number of replicates) associated with each estimate in the tables and figures below. The results below are very suitable for long-term planning purposes.

Discussion and Results

The study results are grouped into bluff recession estimates for the entire feeder bluff complex and recession results for each analysis unit, and then followed up with analysis comparing the distance between the bluff crest and some existing structures. Where available, both long-term average rates of bluff recession and maximum rates are presented. Long-term average rates are important for some long-range planning processes, because the averages provide an estimate of recession rates over an extended time period. However, this does not tell the entire story. The maximum rate at a given location or area is also an important value, because it provides some indication of how fast bluff recession can take place over the short term.

NOTE: AVERAGES VS MAXIMUMS. Where bluff recession rates are characterized as “average”, these rates are the average of all the individual estimated recession rates measured within a unit or within the entire study area. Recession rates characterized as “maximum” are represented by a single site within each unit or within the entire study area. In each unit, only one measurement site represents the “maximum” rate, while the “average rate” includes the estimates from all the measurement sites.

Entire Feeder Bluff Complex, 1956 to 2010.

For the period 1956 to 2010 we estimated recession rates at a total of 12 individual sites within the entire feeder bluff complex. When combining all these estimates, the average rate of bluff recession was 0.97 feet per year. For this time period, the lowest recession rate measured at any site was 0.06 feet per year, while the highest rate measured at any site was 1.56 feet per year.

Entire Feeder Bluff Complex, 1976 to 2010.

For the period 1976 to 2010 we estimated recession rates at a total of 37 Individual sites within the entire feeder bluff complex. When combining all these estimates, the average rate of bluff recession was 1.00 feet per year. For this time period, the lowest recession rate measured at any site was 0.15 feet per year, while the highest rate measured at any site was 3.28 feet per year.

Maximum Rates.

Because much of the bluff recession along the drift cell complex is believed to occur episodically, especially during periods of high tides, high wave energy, and/or high rainfall events, a longer time interval of analysis tends to produce lower maximum recession rate estimates. For example, the most recent and shortest time interval was between the 2008 photoset (5/16/2008) and the 2010 photoset (3/6/2010), a period of 659 days or 1.81 years. This interval captures a publicized period of rapid bluff recession in Unit 2 near the Monterra community. According to reports (PDN 2010), over a 3-hour period on February 1, 2010, a 150-foot length of bluff receded 40 feet. This reported amount of recession appears to be exaggerated. Our study included several reference points near this area of rapid recession and one of these reference points provided the maximum recession rate (26.41 feet lost divided by 1.81 year = 14.59 ft /yr) for the study area. Given the reported rapid recession, it is possible that the bulk of the 26.41 feet was lost in this one event. It would be impractical to collect and analyze daily or even monthly aerial imagery; therefore, precise episodic recession rates are beyond the capability of this type of study. Over the last few years, the Tribe has collected imagery every year or two in order to make it easier to document the fluctuation in annual rates in the future. However, unless more high resolution historical aerial imagery becomes available for the study area, it will be difficult to get a clearer picture of the historical fluctuations in recession rates.

When compared to extreme episodic rates (possibly 26 ft. /day), the maximum rate measured for the period 1956 to 2010 is only 1.56 feet per year, although this is based on only 12 measurements along 8.5 miles of bluff. At the other end of the range, one area lost only 3 feet over the entire 54-year study period (this is approximately 0.66 inches per year). These maximum and minimum rates clearly show that recession rates vary across time and across the feeder bluff complex. For current and prospective owners of valuable infrastructure located near this bluff complex, the average erosion rate of approximately 1 foot per year may be less important than the rare, unpredictable, but large erosion event where tens of feet might be lost in a single day.

Temporal changes in bluff recession rates.

There is at least qualitative evidence that bluff recession rates are slowing over the study period. The average rate of bluff recession found between 1956 and 1976 was 1.21 feet per year (N=12), while average during the period 1976 to 1997 was estimated at 1.00 feet per year (N=36) and the notably shorter period 1997 to 2010 was estimated at 0.88 feet per year (N=52). The reason for this decrease in recession rates is unknown; it could be due to land use changes, or it might simply be an artifact of the measuring methodology. There are an increasing number of high quality reference locations and shorter time periods in the more recent photosets.

While no modeling of future bluff recession has been undertaken, some models predict more frequent and more severe storms in the study area because of global climate change. This combined with the predicted rise in relative sea level along the feeder bluff complex may result in an increase in bluff recession rates and greater frequency of large mass wasting events. These larger erosional events would likely be necessary to supply the increased sediment required to maintain Dungeness Spit during sea level rise. Although accurately predicting an increase in future bluff recession rates is not currently possible, recession will certainly continue and remain highly variable, both across the drift cell and over time.

Drift Unit Recession Rates

Bluff recession rates averaged across the entire complex obscure the variability of these rates at any given location. To better understand the spatial variability, the feeder bluff complex is divided into 7 smaller analysis units. During the period 1976 to 2010, Unit 2 (McDonald Creek to Monterra) had the highest average recession rate (2.03 ft/yr) and maximum recession rate (3.28 ft/yr). The maximum value across all the time intervals (14.59 ft/yr also occurred in Unit 2 during the period 2008 to 2010. The lowest 1976 to 2010 rate was 0.15 ft/yr at Green Point, the sole measurement site in Unit 5. Since Unit 5 has only one reference location, no average or maximum is provided. Figure 7 shows all average and maximum values for each analysis unit for the time period 1976 to 2010.

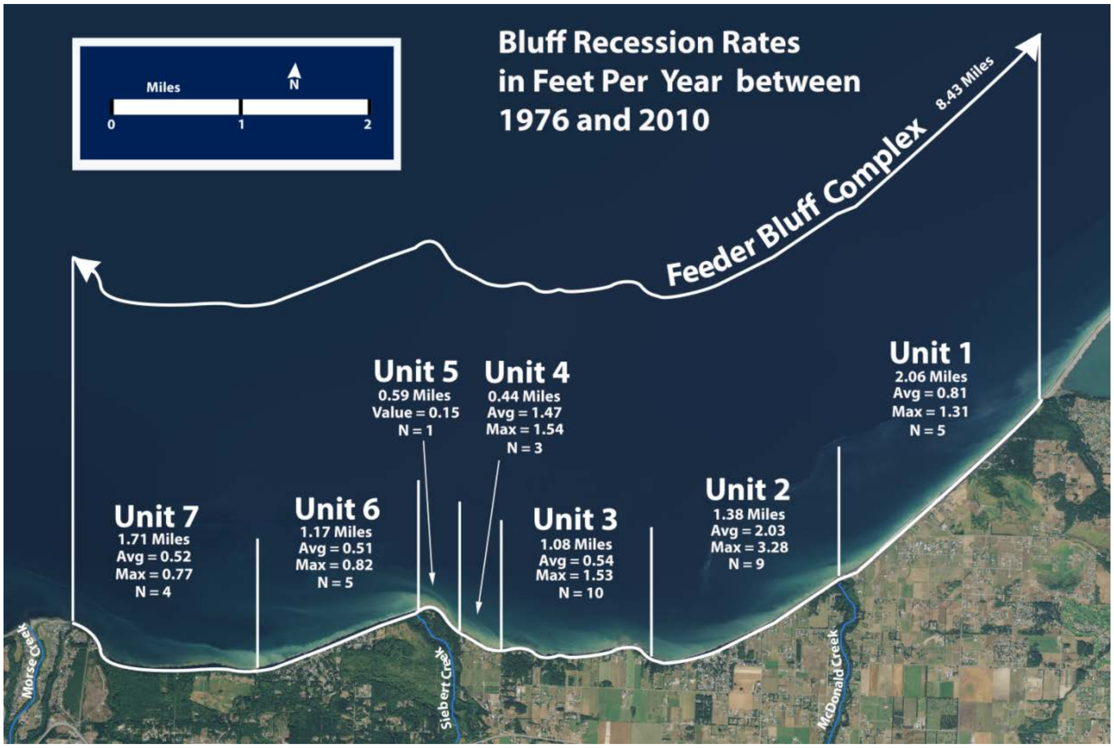


Figure 10: Bluff recession averages and maximum values for each analysis unit. Avg = the average annual rate of bluff recession for all the reference locations within the Unit. Max = the annual rate of bluff recession at the reference location with the highest rate of bluff recession within the Unit. N = the number of reference sites within the Unit. See Appendix D for discussion of shoreline length estimates.

Unit	Location	Length (miles)	Avg. Recession Rate of all reference locations in Unit (feet per year)	Recession Rate at reference location with highest recession rate within Unit (feet per year)	No. of Ref Sites	Time Period of Measurements
1	Dungeness Spit to Mariner's Point (DCM 5.1 to 7.2)	2.06	0.81	1.31	5	1976 to 2010
2	Osborn Road (McDonald Creek) to Monterra(DCM 7.2 to 8.6)	1.38	2.03	3.28	9	1976 to 2010
3	Calbert Road to Finn Hall Road (DCM 8.6 to 9.7)	1.08	0.54	1.53	10	1976 to 2010
4	Wildflower Lane to Gerkhe Road (DCM 9.7 to 10.2)	0.44	1.47	1.54	3	1976 to 2010
5	Green Point (DCM 10.2 to	0.59	0.15	0.15	1	1976 to 2010

	10.8)					
6	The Bluffs and west (DCM 10.8 to 12.0)	1.17	0.51	0.82	5	1976 to 2010
7	Gasman Road to Buchanan Drive (DCM 12.0 to 13.7)	1.71	0.52	0.77	4	1976 to 2010
All	Dungeness Spit to Buchanan Drive (DCM 5.1 to 13.7)	8.48	1.00	3.28	37	1976 to 2010
All	Dungeness Spit to Buchanan Drive(DCM 5.1 to 13.7)	8.48	0.97			1956 to 2010
All	Dungeness Spit to Buchanan Drive(DCM 5.1 to 13.7)	8.48	1.21		12	1956 to 1976
All	Dungeness Spit to Buchanan Drive(DCM 5.1 to 13.7)	8.48	0.88		52	1997 to 2010

Parcel Analysis

What can these bluff recession rates tell us about individual parcels and structures built along the bluff? For this part of the analysis, the bluff complex-wide, 1976-to-2010 average recession rate of 1 foot per year is compared to the distance between the 2012 bluff crest (available from high resolution elevation data) and structures built along the bluff. For this analysis, only the primary structure (home/business) was included. Structures that were clearly identifiable as barns, storage sheds, etc. were not considered “primary” structures and not included in the analysis.

Six primary structures are located within 10 feet of the bluff crest. Assuming a long-term average recession rate of 1 foot per year, in 10 years or less these 6 structures will likely be undermined. A single large erosion episode could cause any of these structures to fall off the bluff. An additional 11 primary structures are located between 10 and 25 feet of the 2012 bluff crest. With one documented erosion episode exceeding 26 feet, these 11 structures appear to have little or no safety margin.

The historical air photographs used to develop our bluff recession rates capture several examples of structures being moved back from the approaching bluff crest. Figure 8 shows one example where a structure was moved away from the bluff crest. It also provides an example of the temporal variability of bluff recession rates. In this location, between 1956 and 2010 the long-term average bluff recession rate was 1.52 feet per year; however, between 1956 and 1976 the rate was 0.74 feet per year, between 1976 and 1997 the rate was 2.51, and, finally, between 1997 and 2010 the rate was 1.17.

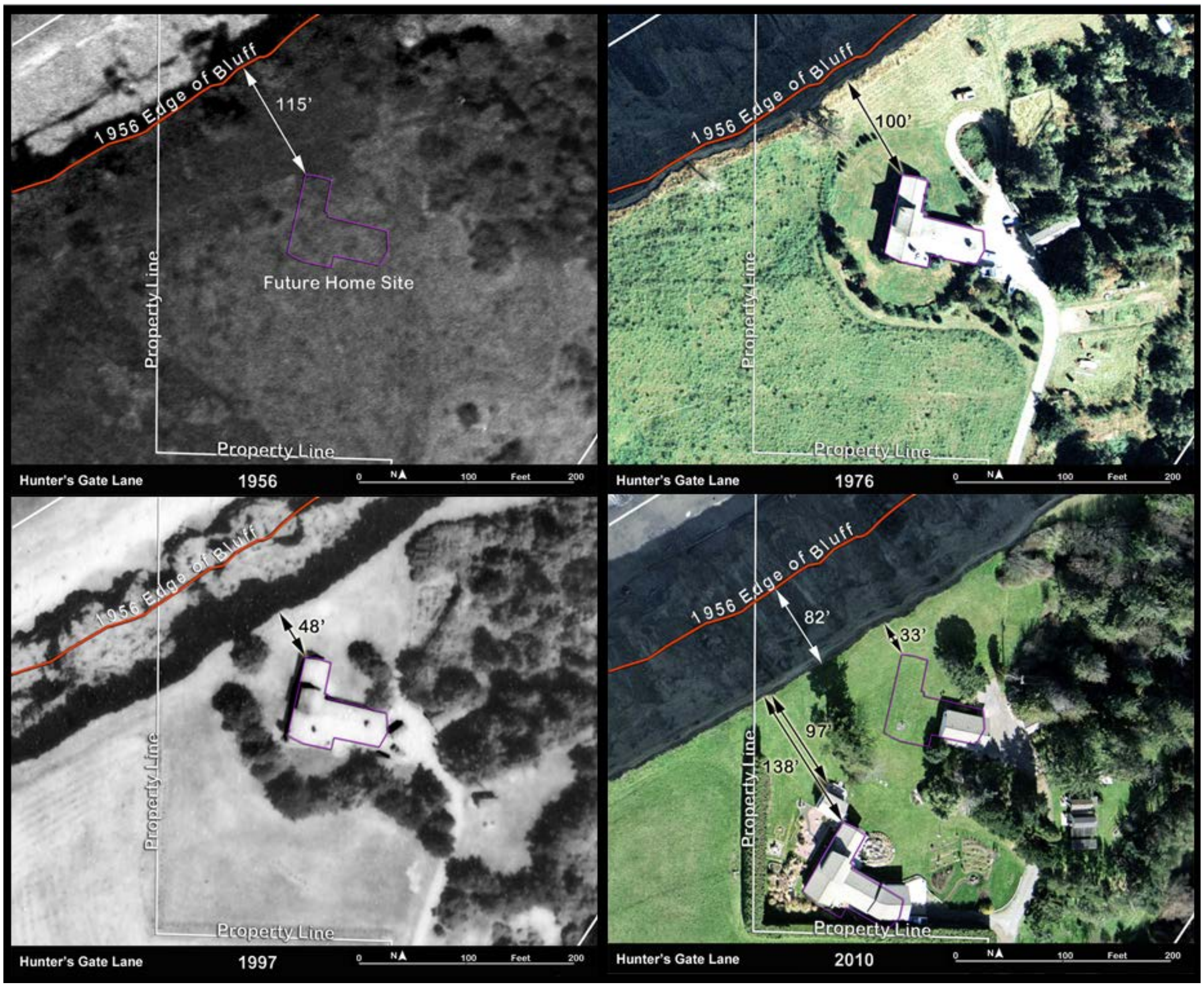


Figure 11: Bluff crest recession results in structure relocation at Hunter's Gate Lane.

Using the maximum rate of 26 feet per year as seen during the winter of 2010, any structure within 25 feet of the bluff top could be undermined in a single episode. As more is learned about bluff recession in general and the Dungeness Spit feeder bluff complex specifically, it may be possible to provide much more detailed analysis of bluff erosion and recession and the potential for structure undermining. In the interim, Clallam County's planning division uses 75 years as its long-range planning horizon. Assuming the conservative 1 foot per year recession rate, a minimum of 78 structures will become unsafe and need to be removed, moved, or watched carefully over the next 75 years.

Within Unit 1, the closest structure is 37 feet from the bluff crest. The average rate of annual recession for Unit 1 is between 0.43 foot per year and 1.31ft/year, giving this structure between 28 and 86 years before it may be undermined. The closest structures in Unit 2 are in the area of the rapid recession event of February 2010. This recent bluff recession may provide some local and temporary protection from future recession by providing additional material at the toe of the bluff (see debris fan in Figure 9). However, if the long-term average rate were to remain steady for Unit 2, many of the structures in

Figure 9 could be in danger in 10 to 20 years. Units 4, 6, and 7 have at least one structure within 5 feet of the bluff crest. These structures are likely to be in jeopardy within the next decade.

Figure 12: 2010 Aerial images showing the recent rapid recession in the Monterra area of Unit 2. Note the fan shaped debris flow. Additional images of structures close to the bluff crest are provided in Appendix E.

As a further long-term planning exercise, estimates of the number of existing structures that may need to be moved in 150 years or 300 years are provided. To simplify the analysis, a 1 foot per year recession rate is used again. Within the next 150 years, a total of 129 primary structures must be moved and within 300 years 154 structures would need to be moved.

Conclusions

Dungeness Spit and its magnificent resources can persist only as long as the Spit's sediment supply remains uninterrupted. Conserving this sediment supply requires that the natural processes of bluff erosion and longshore drift be allowed to continue without human interference. Our calculated bluff recession rates, ranging from 0.06 to 14.59 feet per year, provide baseline information for predicting the time when existing structures will become unsafe. More importantly, these rates also provide a basis for planning sustainable, prudent development that protects human investments and safety—on the bluffs and the developed shoreline east of the Spit—while conserving irreplaceable natural resources at

Dungeness Spit and Dungeness Bay. Although the effects of climate change and sea level rise cannot be accurately predicted at this time, they will probably increase the rate of bluff recession, possibly by a significant amount.

Private property owners, local, state, and federal governments and affected Indian tribes should collaborate to develop measures for protecting life and property along the bluffs of the Dungeness Spit Drift Cell, while conserving Dungeness Spit's essential sediment supply. Recommended measures include:

- Provide incentives to conserve natural bluff habitats and to keep or move structures away from the bluff crest.
- Purchase and removing at-risk structures.
- Purchase bluff conservation easements.
- Establish adequate regulatory setbacks and buffers for all new development. We recommend a minimum buffer of 150 feet from the bluff crest. This distance should be increased if bluff recession rates are observed to increase, either from sea level rise or more frequent extreme weather events.
- Establish regulatory prohibitions against shoreline armoring and the construction of structures that would interrupt or halt longshore sediment transport within the Dungeness Spit Drift Cell.

These are some of the measures we view as necessary to protect the multitude of human and natural resource values that depend on the continued existence of the Dungeness Spit and the natural processes that maintain it.

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Appendix A: Ediz Hook—A Cautionary Tale

Ediz Hook, a sand and gravel spit that created the bay and harbor of the City of Port Angeles, was 3.4 miles long when first described by European-American settlers in the 19th century. Sediment coming from the Elwha River and erosion of feeder bluffs located between the Elwha River mouth and the Hook created and maintained the spit until the early 20th century. Then human impacts began to reduce Ediz Hook's sediment supply. First, the construction of two dams on the Elwha River blocked sand and gravel moving down from the Olympic Mountains. Soon thereafter, in 1930, a major bulkhead—2,400-feet long—was constructed near the base of the feeder bluffs to protect a stretch of the Port Angeles industrial waterline that had been buried along the shoreline. The waterline bulkhead caused bluff erosion to decline dramatically, from 3.6 feet per year to less than one foot per year. With the reduction in the supply of river and bluff sediment, the Ediz Hook began to "starve" —to erode away in the storms and winds without sufficient sediment to replenish it. Only seven years after the feeder bluffs were armored, the City of Port Angeles, in fear of losing the harbor, built its first major shore defense project on Ediz Hook—7,000 feet of log-crib bulkhead.

In 1945, work to save the Hook entered a phase of furious activity, with projects by the Coast Guard (1,350 feet of riprap bulkhead and 6 timber groins built in 1945-46), Crown Zellerbach Corporation (1,900 feet of pile, timber and riprap bulkhead in 1946-47 and 1,800 feet of riprap bulkhead in 1949), and the City, Coast Guard, and various industries (4,000 feet of timber and riprap bulkhead in 1951). Only 21 years after the construction of bulkheads along a portion of the Hook's feeder bluffs, it had become necessary to armor virtually the Hook's entire outer shoreline to prevent it from eroding away.

Despite this monumental amount of shoreline armoring, Ediz Hook continued to erode seaward of the bulkheads, causing bulkhead failure and the need for incessant maintenance of the shoreline defense works. By 1961 the entire outer shoreline of Ediz Hook had been riprapped and was being maintained annually. This maintenance is now performed by the U.S. Army Corps of Engineers, at an estimated cost of $500,000 to $1,000,000 for 2011 alone. The Ediz Hook case history clearly illustrates the swift, catastrophic consequences of armoring feeder bluffs that support important shoreline features.

Appendix B: Description of the Analysis Reaches (Units).

In order to facilitate bluff recession estimates, the bluff complex was systematically, but asymmetrically, subdivided into seven units (labeled 1 through 7 from east to west). The units range in length from 0.35 miles to 2.04 miles. Expert judgment was used to determine the starting and ending points for the units (see Table A-1).

Table A-1: length of each analysis unit is miles and percent of total bluff complex length (8.48 miles)

Unit	Miles	Pct. of Complex
1	2.04	24.07%
2	1.61	18.97%
3	1.20	14.16%
4	0.35	4.17%
5	0.40	4.77%
6	1.31	15.48%
7	1.56	18.37%
Total	8.48	100%

Coastal Geological Services (CGS) delineated the shoretype of the marine shoreline of the county. Shoretype is a categorical representation of the geological shoreform. CGS has used the same process for much of the shoreline of Puget Sound. The shoretype categories are shown in Table A-2.

Table A-2: Shoretype code and descriptions (note: study area includes only Feeder Bluff, Feeder Bluff Exceptional, and small amounts of Transport Zone and Accretion Shoreform.

Shoretype Code	Shoretype Description
FBE	Feeder Bluff Exceptional
FB	Feeder Bluff
FB-TS	Feeder Bluff Talus
TZ	Transport Zone
AS	Accretion Shoreform
MOD	Modified
NAD	No Appreciable Drift

The Dungeness Spit Drift Cell Complex includes only Feeder Bluff, Feeder Bluff Exceptional, Transport Zone, and Accretion Shoreform. Unit 1 is entirely the shoreform Feeder Bluff Exceptional, while all the other Units are a mix of shoretypes. Only Unit 5 does not have Feeder Bluff Exceptional. The lengths of each shoretype in each unit and the percentages are shown in Table A-3.

Table A-3: Analysis of the shoretype for each unit. Includes Unit number, Shoretype, miles of each shoretype in the unit, and the percentage of the length of the unit shoreline composed of each shoretype.

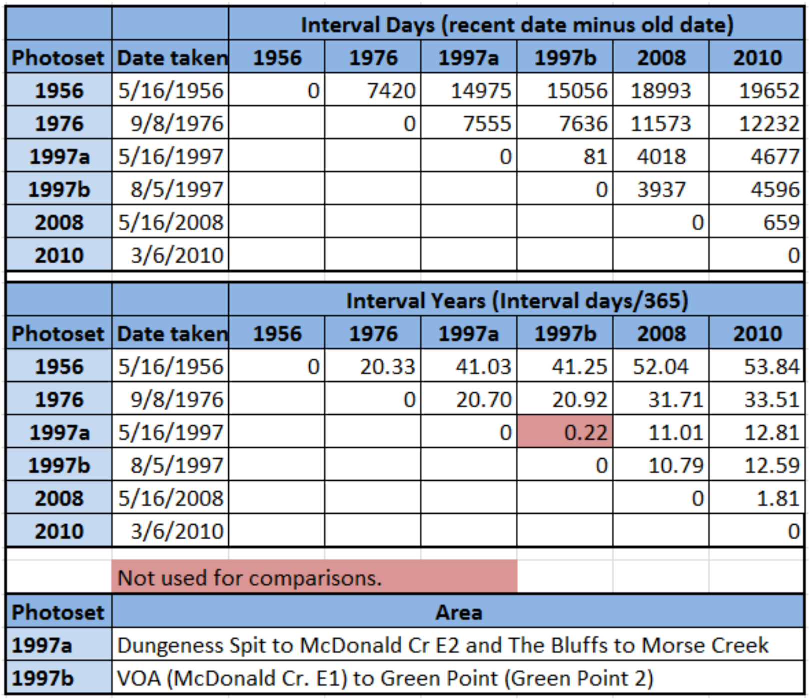
Unit	Shoretype	Miles	Percent of Unit
1	Feeder Bluff Exceptional	2.04	100.00%
2	Accretion Shoreform	0.02	1.05%
	Feeder Bluff Exceptional	1.58	97.94%
	Transport Zone	0.02	1.01%
3	Feeder Bluff	0.49	40.69%
	Feeder Bluff Exceptional	0.71	59.31%
4	Feeder Bluff	0.16	44.46%
	Feeder Bluff Exceptional	0.20	55.54%
5	Accretion Shoreform	0.12	30.21%
	Feeder Bluff	0.12	28.85%
	Transport Zone	0.17	40.95%
6	Accretion Shoreform	0.02	1.78%
	Feeder Bluff Exceptional	1.27	96.47%
	Transport Zone	0.02	1.75%
7	Accretion Shoreform	0.03	1.77%
	Feeder Bluff	0.12	7.56%
	Feeder Bluff Exceptional	1.38	88.36%
	Transport Zone	0.04	2.32%

Appendix C: Photosets.

The Jamestown S’Klallam Tribe’s Natural Resources Department acquired six sets of photographic prints taken by various organizations between May 1956 and March 2010. Each photograph was scanned into high quality digital format and carefully georeferenced in a geographic information system. The source and method of acquisition varied (Table B-1).

Table B-1: Photoset source information.

Photoset	Source	Acquisition Method	Date taken
1956	**Clallam Co. Assessor**	**Loan**	**5/16/1956**
1976	**WSDOT**	**Purchase**	**9/8/1976**
1997a	**WDNR**	**Purchase**	**5/16/1997**
1997b	**WDNR**	**Purchase**	**8/5/1997**
2008	**Bergman/JSKT**	**Purchase**	**5/16/2008**
2010	**Bergman/JSKT**	**Purchase**	**3/6/2010**



		Interval Days (recent date minus old date)					
Photoset	**Date taken**	**1956**	**1976**	**1997a**	**1997b**	**2008**	**2010**
1956	5/16/1956	0	7420	14975	15056	18993	19652
1976	9/8/1976		0	7555	7636	11573	12232
1997a	5/16/1997			0	81	4018	4677
1997b	8/5/1997				0	3937	4596
2008	5/16/2008					0	659
2010	3/6/2010						0

		Interval Years (Interval days/365)					
Photoset	**Date taken**	**1956**	**1976**	**1997a**	**1997b**	**2008**	**2010**
1956	5/16/1956	0	20.33	41.03	41.25	52.04	53.84
1976	9/8/1976		0	20.70	20.92	31.71	33.51
1997a	5/16/1997			0	0.22	11.01	12.81
1997b	8/5/1997				0	10.79	12.59
2008	5/16/2008					0	1.81
2010	3/6/2010						0

Not used for comparisons.

Photoset	Area
1997a	Dungeness Spit to McDonald Cr E2 and The Bluffs to Morse Creek
1997b	VOA (McDonald Cr. E1) to Green Point (Green Point 2)

Table B-2: Number of days and years between photosets

Photosets were each flown/taken in a single day; however, the day of the year varied (Figure B-1). Three of the photosets were taken on May 16 of the respective year, while the 2010 photoset was taken in early March and the 1976 and 1997b photosets were taken in late summer. When calculating annual bluff recession, the differences in the time of year the photoset was taken were accounted for by calculating the number of days between photosets (Table B-2). The number of days between photosets divided by 365 provides the fractional number of years between photosets. To produce the estimates of annual bluff recession, the change in distance between the two photosets (e.g. 1976 to 2010) from the bluff crest to the reference point was divided by “Interval Years” (1976 to 2010 = 33.51 years) and if, for example, the change in distance was 51.33 feet, then 51.33ft/33.51years=1.53 feet per year. A photoset covering the entire study area was not available for the 1990s; the best available photo record was compiled using two photosets, 1997a and 1997b. Photoset 1997a was taken May 16, while the 1997b photoset was not taken until August 5. The 1997 photosets' spatial extent covers differing parts of the complex with minimal overlap; these were not used to compare changes between spring and fall 1997.

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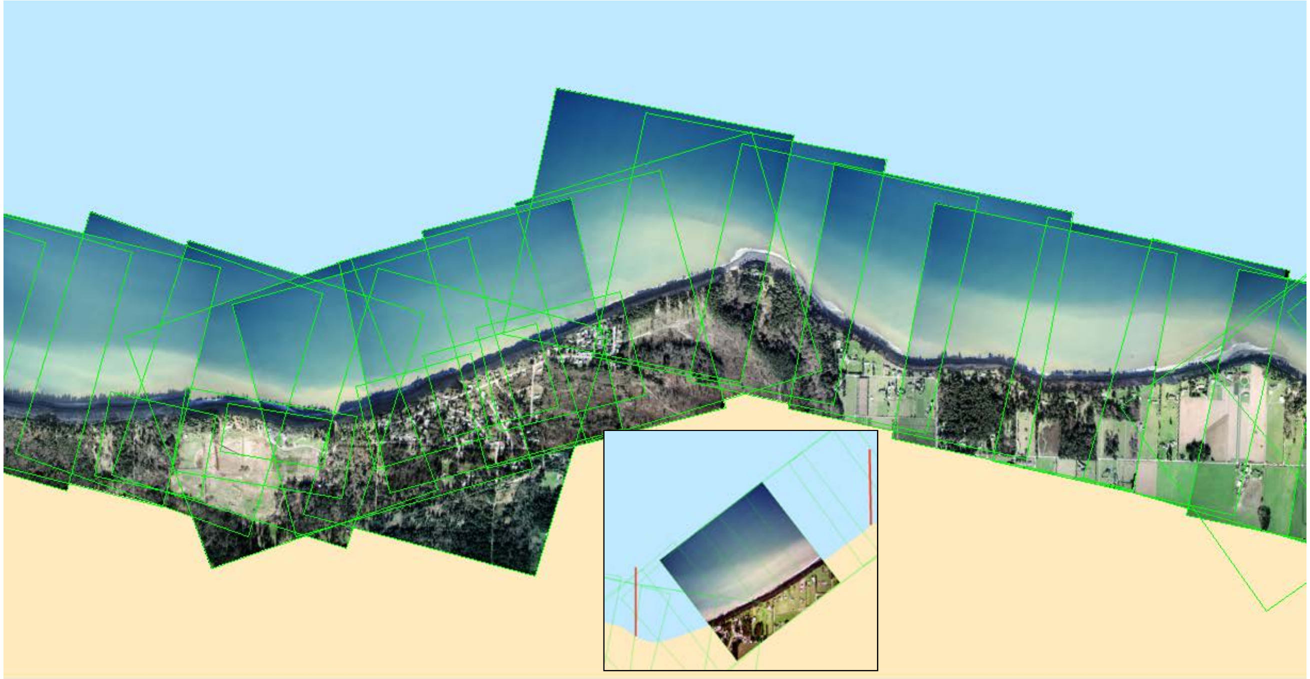

Figure B-1: Example of photoset (2010) overlap and spatial distribution. The inset shows the size of an individual image.

Appendix D: Measuring Linear Natural Features.

Natural features like shorelines and streams are often represented on maps as line features. The advent of computerized GIS made determining the length of these representative features trivial. However, getting an accurate measurement of the actual length of a river or shoreline in essentially impossible. Natural linear features are best represented mathematically by fractals. For both natural shorelines and fractals, the more you "zoom in," the more complexity is revealed. This phenomenon is called the "Coastline Paradox" (http://mathworld.wolfram.com/CoastlineParadox.html), which, crudely stated, is that the length of a coastline, shoreline, or river depends on the method and scale of the measurement. In this document, the lengths of shoreline segments were derived from GIS using the DNR Shorezone [szline] dataset.