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Kayak Point Restoration Feasibility and Design

Phase 2 – Sea-Level Rise Assessment

Prepared for

Coastal Geological Services, Inc.

Prepared by

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1. EXECUTIVE SUMMARY

This report provides a summary of coastal processes, geomorphology, and the response of the Kayak Point shoreline to future sea-level rise. The key findings are summarized below:

- The medium[1] relative sea-level rise projections for this project are 0.5 feet by 2050 and 1.1 feet by 2100. The high sea-level rise projections are 1.8 feet by 2050 and 4.2 feet by 2100.
- Estimated shoreline retreat rates along the southern shoreline were as high as 1.4 ft/year prior to the construction of the bulkhead, although shoreline position has stabilized since its construction in the 1960/70s.
- Estimates of recent accretion rates (post-1965 to present) along the northern shoreline range from 0.3 to 0.6 ft/year. If these rates were extrapolated into the future, then the northern shoreline would accrete by approximately 10-25 feet by 2050 and 25-60 feet by 2100.
- The existing protective structures along the littoral cell and at Kayak Point have modified the natural bluff recession processes and sediment inputs by reducing bluff sediment at the structures and potentially accelerating erosion of the fronting and adjacent beaches along the southern shoreline.
- Predicted rates of future recession along the southern shoreline for both 2008-2050 and 2008-2100 without the bulkhead range from 0.3 ft/year (medium sea-level rise scenario) to 1.0 ft/year (high sea-level rise scenario), equating to a recession of between 10 and 40 feet by 2050, and 25 to 90 feet by 2100.
- On the southern side of the Point itself, predicted recession rates for both 2008-2050 and 2008-2100, without the bulkhead, are between 0.1 ft/year (medium sea-level rise scenario) and 0.4 ft/year (high sea-level rise scenario) resulting in a 5-15 foot recession by 2050 and a 10-40 foot recession by 2100.
- With the bulkhead in place, we expect erosion to concentrate below the bulkhead, causing a steep drop off, and increased overtopping. This scenario was not analyzed.
- It is expected that future accretion rates along the northern shoreline will decrease as future rates of sea-level rise increase. Under the medium sea-level rise scenario, depositional processes continue to outpace landward recession. Predicted accretion rates along the northern shoreline are approximately 5-25 feet by 2050 and 15-55 feet by 2100. Under the high sea-level rise scenario, landward recession outpaces depositional processes for the shoreline north of the pier. Here, predicted future shoreline recession is approximately 15-20 feet by 2050 and from 40-45 feet by 2100. South of the pier and north of the point, accretion is predicted to continue, with approximately 15-25 feet of accretion by 2050 and 25-55 feet by 2100.

[1] the ‘medium’ sea-level rise scenario is based on a review of global projections and consideration of local affects. The term medium is used even though it refers to the lowest relative sea-level rise used in this study.

- For the southern shoreline set back distances of at least 60 and 120 feet are recommended for park infrastructure, by 2050 and 2100, respectively. For the northern shoreline, north of the pier, set back distances of at least 40 and 80 feet are recommended for 2050 and 2100, respectively.

Potential Shoreline Movement by 2050 and 2100 Using Historic Extrapolation of Shoreline Change

	Southern Shoreline	**Point (south)**	**Northern Shoreline (south of pier)**	**Northern Shoreline (north of pier)**
Historic Extrapolation by 2050 (ft)*	N/A (bulkhead controlled)	N/A (bulkhead controlled)	+25	+10
Historic Extrapolation by 2100 (ft)*	N/A (bulkhead controlled)	N/A (bulkhead controlled)	+60	+25

*-ve values denote erosion +ve values denote accretion

Potential Shoreline Movement by 2050 for Medium and High Sea-Level Rise Scenarios

	Southern Shoreline		**Point (south)**		**Northern Shoreline (south of pier)**		**Northern Shoreline (north of pier)**	
Sea-level Rise Scenario	Med	High	Med	High	Med	High	Med	High
Position change in 2050 (ft)*	-10	-40	-5	-15	+25	+15	+5 to +10	-15 to -20

*-ve values denote erosion +ve values denote accretion

Potential Shoreline Movement by 2100 for Medium and High Sea-Level Rise Scenarios

	Southern Shoreline		**Point (south)**		**Northern Shoreline (south of pier)**		**Northern Shoreline (north of pier)**	
Sea-level Rise Scenario	Med	High	Med	High	Med	High	Med	High
Position change in 2100 (ft)*	-25	-95	-10	-40	+55	+25	+15	-40 to -45

*-ve values denote erosion +ve values denote accretion

Note that the medium sea-level rise scenario corresponds approximately to the historic sea-level rise rate and hence provides results for the northern shoreline similar to projecting historic rates forward.

2. PROJECT BACKGROUND

Coastal Geologic Services, Inc. (CGS) has been contracted by Snohomish County Surface Water Management (County) to provide restoration feasibility assessments and proposed restoration designs of the shore at Kayak Point Regional Park. The project is comprised of two phases. The first phase was completed in late 2007 and entailed geomorphic assessments used to support the development of three conceptual beach and backshore restoration designs (Coastal Geologic Services Inc. 2007). A final design would be selected and completed to a 30% and 100% stage in Phase 2.

Most recently CGS was asked by the County to amend Phase 2 to include an assessment of the potential implications of future sea-level rise (SLR) on the Park. The low elevation Park is the main study area for this sea-level rise assessment, with some analyses of the drift cell that extends approximately nine miles southeast towards Tulalip Bay. Philip Williams and Associates, Ltd. (PWA) was contracted by CGS to provide a summary of the coastal processes and geomorphology in the vicinity of Kayak Point Regional Park, with particular emphasis on the response of the shoreline to future sea-level rise.

3. SITE CONDITIONS

Kayak Point Regional Park is located in northern Puget Sound (approximately 48.136°N 122.367°W), along the eastern shore of Port Susan, in between the Snohomish and Stillaguamish River mouths. Kayak Point itself is a small accretionary salient (cuspate foreland or cuspate spit) with northwest-facing (northern) and southwest-facing (southern) beaches (see **Figure 1** and **Figure 2**). Cuspate shorelines typically form at the convergence of two littoral cells although the geomorphologic feature at Kayak Point is more likely due to strong northerly-directed sediment transport combined with a change in orientation of the shoreline from east-west to north-south (**Figure 2**). Examination of the 1884 T-Sheet for this area indicates that Kayak Point has been a fairly permanent, persistent feature over a relatively long geomorphic time scale (~125 years). Since the late 19th century, Kayak Point salient has migrated slowly northward in response to erosion on the south side and deposition on the north side (Johannessen and MacLennan 2007). This is due to the dominance of southerly storm waves in controlling the net sediment transport.

In order to protect the Park from erosion (in particular an access road immediately behind the shoreline), a sheet pile bulkhead was installed along the majority of the Kayak Point shoreline in the 1960s or 1970s. Currently, lowering of the beach profile has caused the top of the bulkhead to become exposed along approximately 270 feet of the southern shoreline (**Figure 3**). In addition, the bulkhead is so low that wave and debris overtopping occurs in most winters (CGS 2007), and the wall has much rust.

3.1 DATA COLLECTION

In order to characterize the existing geomorphic conditions and provide input for the technical analyses, CGS prepared a topographic (and nearshore bathymetry) map from a ground survey performed in April 2008. From this map, five shore-normal beach transects were cut to characterize the profile geometries along the northern and southern shorelines (**Figure 2**). These cross-sectional profiles (NB-N2, NB-N, and NB-S along the northern shoreline, and SB-W and SB-E along the southern shoreline) are presented in **Figure 4** through **Figure 8**.

3.2 GEOMORPHOLOGY OF KAYAK POINT

The Puget Sound coastline is characterized by narrow shore platforms notched into steep walls of the marine basins and channels of the Sound. Seaward of the limit of wave influence (the so-called 'closure depth') the profile drops steeply into deeper water (Finlayson 2006b). The beach at Kayak Point consists of a low-gradient low-tide terrace composed of sand and silt, and a steeper high-tide foreshore composed of coarse sand and gravel, with pebbles and occasional cobbles. This composite profile has a noticeable break of slope between the sand/gravel section and the lower terrace (see **Figure 4** through **Figure 8**) except at the point, where a steep beach slope continues into the subtidal. Hence, much of the low-tide beach is wave-dissipative with an abrupt change to reflective conditions around mean tide level (MTL).

These types of composite beaches occur in regimes with relatively large tidal range and a wide range of sediment sizes. The distribution of slopes and sediments implies sand transport in the lower intertidal and subtidal elevations and cross-shore sorting of sediments with coarser sediments transported upslope by waves.

Mixed sand and gravel beaches are common in Puget Sound where the effects of glaciations have provided an abundant sediment source for subsequent reworking by rising sea levels during the Holocene (last 10,000 years). Up drift (south) of the southern shoreline of Kayak Point the beach is backed by unconsolidated bluffs composed of glacial deposits. Here, the lower geologic units are composed of silt and fine sand, and sandy gravel outwash, overlain by generally fine-grained till (Gerstel in prep, Minard 1985). Erosion of these bluffs supplies sediment to the Kayak Point littoral cell. Slides and slumps are the predominant mechanism of bluff recession transferring the sediment to the upper beach. The coarser sands and pebbles are then transported alongshore by wave action and the fines are re-suspended and lost offshore through tidal processes or groundwater seepage through the beach face at low tide. Larger gravel and cobbles on the beach are less readily transported alongshore, but can be moved by larger storm waves during infrequent high-energy events.

The slope of the high-tide terrace at Kayak Point varies. At the Point (Transects NB-S and SB-W) the beach slope is relatively steep compared to the southern and northern shorelines (see **Figure 4** through **Figure 8**). This variability in beach slope is due to the accretion of the Point into very deep water, and is reflected by less beachface sand and a relatively high proportion of relatively coarse sediments.

3.3 LOCAL CLIMATE AND METEOROLOGY

The closest long-term wind gauge to Kayak Point is Smith Island (Station SISW1), owned and operated by the National Data Buoy Center (NDBC). Wind speed and direction measurements at Smith Island have been collected since 1984 and a wind rose for the 1984-2005 is shown in **Figure 9**. The predominant wind direction at Smith Island is between west-southwest and west with most of the extreme winds from the south-southeast and southeast. It is likely that winds at Kayak Point are funneled by the topography along the main axis of Port Susan so that the actual wind climatology at the site may deviate from the Smith Island gauge, with south-southeast and southeast winds likely more common. Examination of the wind speed time series indicates that winds in excess of 50 mph occur on an annual basis, although this speed was exceeded only 75 times (hourly 2-minute average) during the 20-year record. Over 90% of wind speed occurrences in excess of 50 mph were from the southeast or south-southeast. The maximum reported wind speed of 59 mph occurred on November 16, 1991. Note that a 2-minute average wind speed of 59 mph represents a much stronger wind event that a 1-minute average speed of 59 mph (USACE 2003).

3.4 RELATIVE SEA-LEVEL RISE

3.4.1 Historic Rates

IPCC (2007) estimated a global average sea-level rise over the 20th century of between 1.2 and 2.2 mm/yr with an average value of 1.7 mm/yr (0.56 ft/century). Between 1961 and 2003, the rate was estimated at 1.8 mm/yr (1.3-2.3 mm/yr or 0.43-0.75 ft/century) rising to 3.1 mm/yr (2.4-3.8 mm/yr or 0.79-1.25 ft/century) between 1993 and 2003. IPCC (2007) did not indicate whether the faster rate of 1993-2003 was due to decadal variability or was an increase in the long-term trend. Prior to 1993, these estimates are based on relative sea-level measured at tide gauges corrected for land movements from either tectonics or glacial rebound. The estimates post-1993 are based on satellite altimetry. For the purposes of this study an historic rate of 2.0 mm/yr is used.

3.4.2 Future Rates

As part of this study, a range of estimates of future relative sea-level rise at Kayak Point were developed based on a literature review (Coastal Geologic Services Inc. 2008) (Appendix A). The lower estimates use the medium-range projections of global sea-level rise and hence are called 'medium' projections or scenarios in this study. The medium relative sea-level rise projections used in this study are 0.5 feet by 2050 and 1.1 feet by 2100. The high projections used are 1.8 feet by 2050 and 4.2 feet by 2100. 'Low' estimates of relative sea-level rise were not considered, as the most recent global sea-level rise research suggests low rates are not likely. Note that the medium projections are approximately similar to the historic sea-level rise rates for 1993-2003.

3.5 WATER LEVELS

3.5.1 Tidal Regime

Puget Sound experiences mixed semidiurnal tides, with two nearly equal high tides and two unequal low tides each day. In addition, the tides exhibit a strong spring-neap variability; spring tides exhibit the greatest difference between high and low tides while neap tides show a smaller than average range.

The closest tidal datum station to Kayak Point is located at Everett (ID# 9447659). However, the Everett station's datum is based on only two months of observation, and harmonic predictions for the station did not match the water level observations made during the site survey performed by CGS in April 2008. However, the recorded tidal elevation data for the NOAA tide gauge located at Seattle (ID# 9447130) closely matched the water level shots in time and elevation. Coupled with the similar over-water distance from Admiralty Inlet to Kayak Point and to the Seattle gauge, the Seattle gauge is assumed to accurately reflect tidal conditions at the Park. The NOAA tidal datums for the 1983-2001 epoch for the Seattle tide gauge are summarized in Table 1. The mean tidal range (defined as MHW minus MLW) is 7.66 feet and the diurnal range (defined as MHHW minus MLLW) is 11.36 feet.

Table 1. NOAA Tidal Datums for Seattle (ID# 9447130)

	MLLW (feet)
Highest observed water level (1/27/1983)	14.48
MHHW	11.36
MHW	10.49
MTL	6.66
MSL	6.64
MLW	2.83
MLLW	0

3.5.2 Extreme Water Levels

Finlayson (2006b) analyzed annual water level maxima at Seattle for 1902-2004 and determined a 100-year water level of 14.44 feet MLLW. This analysis suggests that the highest observed water level of 14.48 feet MLLW on January 27, 1983 roughly corresponds to a 100-year event. This is referred to as 'still water level' because it does not include setup and runup caused by waves incident to a particular shore. Also, wind setup can affect water levels locally, where there are shallow depths and embayments.

3.6 WAVE CLIMATE

Storm seas in sheltered waters are limited by the size and shape of the water body and any land masses that can alter wind and wave directions. For this analysis, average annual wind wave conditions were computed from the available wind data from January 1984 to December 2005 (**Figure 9**). Wind data from Smith Island and wave hindcasting methods from the Coastal Engineering Manual (CEM) (USACE 2003) were used to predict wave conditions offshore (deepwater waves) of Kayak Point. Wind data were separated into bins representing primary wind directions from the northeast to southeast and wind speeds ranging from 0 to 60 mph. Fetch lengths incident upon Kayak Point were computed at 1° increments and averaged at +/- 12° about the primary directions listed in Table 2. Table 2 shows the maximum predicted wave heights and wave periods calculated for the range of wind speeds and direction-specific fetch lengths over the period of record. These predictions assume a storm of sufficient duration to achieve 'fetch-limited' conditions. H_{m0} is the spectrally-based significant wave height and T_p is the wave period corresponding to the peak energy in the wave spectrum.

Table 2. Hindcast Wave Conditions at Kayak Point, 1984-2005

Wind Direction	Fetch Distance (miles)	Maximum Wind Speed (mph)	Maximum H_{m0} (ft)	Maximum T_p (sec)
NE	0.01	31	0.9	1.6
NNE	0.02	51	1.7	2.0
N	1.6	51	2.6	2.7
NNW	7.1	33	3.0	3.3
NW	6.1	32	2.7	3.2
WNW	5.2	44	3.7	3.5
W	3.6	43	3.9	3.4
WSW	2.8	54	3.7	3.3
SW	2.6	40	2.5	2.9
SSW	2.8	32	2.0	2.7
S	6.4	53	5.0	4.0
SSE	3.2	57	4.1	3.4
SE	0.37	59	2.1	2.1

Wind fetches to the northeast and southeast are limited by the proximity of the adjacent shoreline (Figure 1), and wave heights and periods from these directions are generally very small except during a few extreme events. In general, prevailing wind and waves are from the west or west-southwest while the predominant storm waves are from the south or south-southeast, where deepwater wave heights of up to five feet can be generated. Waves in deep water are not influenced by bottom topography. Once a wave propagates into shallow water it begins to feel the effects of the bottom and wave crests slow down, refract, and begin to shoal (i.e. waves crests grow in height and steepness until the point of breaking). In order to estimate potential alongshore sediment transport, the offshore wave heights presented in Table 2 were transformed into wave heights at the breaker zone using formulae in the CEM (USACE 1984; USACE 2003).

The orientation and shape of the cuspate shoreline at Kayak Point is consistent with the general wave dynamics in Port Susan. Winds from off-axis directions are likely funneled by the local topography to align with the northwest-southeast orientation of Port Susan. As a result, the wave climate is dominated by two opposing directions, and wave energy arrives either at strongly oblique angles or nearly parallel to the two shorelines of the Point. For example, prevailing northwest winds generate waves crests that approach the northern shoreline nearly shore parallel, but approach the southern shoreline at a very high angle of incidence. The opposite is true for southerly storm waves.

4. GEOMORPHIC CONCEPTUAL MODEL OF KAYAK POINT

4.1 SEDIMENT SUPPLY FROM BLUFFS

Sediment is supplied to the Kayak Point littoral cell primarily by erosion of the coastal bluffs (Coastal Geologic Services Inc. 2007; Keuler 1988). These bluffs (feeder bluffs or feeder bluffs exceptional) supply a mixture of sand, pebbles, and cobbles which are then reworked by waves and transported alongshore. The amount of sediment supplied by the bluffs has been impacted by shoreline armoring along the littoral cell (Coastal Geologic Services Inc. 2007). CGS field mapping revealed that approximately 26% of the drift cell shores were modified by anthropogenic structures and shoreline armoring. Roughly three-quarters of the modified shores functioned historically as feeder bluffs, providing large quantities of sediment to the drift cell. Prior to development, approximately 68% of the Kayak Point drift cell shoreline functioned as feeder bluffs, while currently feeder bluffs represent approximately 49%. The cumulative effect of this armoring is believed to be a reduction in sediment supply to the Kayak Point drift cell.

In order to quantify sediment supply to Kayak Point, our analysis assumes that erosion of feeder bluffs is the only significant source of sediment to the drift cell, ignoring potential other sources such as landslides occurring in gullies, and stream inputs. Using LiDAR data, 51 shore-normal transects were constructed by CGS at roughly equal intervals between Hermosa Point (roughly seven miles to the south) and Kayak Point. Those transects that crossed shorelines classified as feeder bluff or feeder bluff exceptional in the CGS classification of shore type (Coastal Geologic Services Inc. 2007) were selected. Transport zones were not considered as they comprised a very small proportion of the study area (453 feet), and much of that distance is not immediately backed by bluffs. A total of 17 transects were selected for comparison with T-Sheets mapped in 1884.

The LiDAR elevation data was used to identify the break in slope at the toe and top of the coastal bluff. At each transect, the bluff height was measured as the difference in elevation between the toe and top of the bluff. The horizontal distance between the bluff toe on the T-Sheet and LiDAR was then measured to determine the amount of recession that had taken place over the 122 year period. Assuming the bluff angle and height remained constant during this period, the height and erosion distance were multiplied to produce a cross-sectional area of eroded material (**Figure 10**). To estimate a volumetric yield from the bluffs, average cross-sectional areas were determined for each shore type and multiplied by the total length of shoreline in each classification (Table 3 and Table 4).

Table 3. Bluff Transect Properties (FB = Feeder bluff, FBE = Feeder bluff exceptional)

Transect	Bluff Height (ft)	Shore type	Erosion (ft)	Cross section (ft^2)	Erosion Rate (ft/yr)
0	102	FB	157	16,017	1.3
1	92	FB	112	10,247	0.9
3	115	FB	43	4,898	0.4
12	131	FB	69	9,042	0.6
14	180	FB	62	11,248	0.5
26	62	FB	36	2,250	0.3
30	148	FB	39	5,813	0.3
37	269	FB	36	9,709	0.3
44	217	FB	0.0	0.0	0.0
48	194	FB	43	8,256	0.4
			Mean	**7,750**	
9	203	FBE	79	16,017	0.6
18	213	FBE	26	5,597	0.2
34	256	FBE	75	19,310	0.6
			Mean	**13,640**	

In order to estimate the amount of coarser sediment that could potentially be transported in this drift cell, geologic maps of the cell were examined. Minard (1985) mapped much of the marine bluffs as Vashon advance outwash (derived from the most recent period of glacial advance through Snohomish County) with underlying transitional beds of clay and silt. Vashon till was also mapped in the upper sections of some bluffs. For the purposes of this study, the following assumptions were made concerning the composition of the bluff sediment. Approximately 50% of the sediment is assumed to be clay, silt, and very fine sand and transported offshore. A further 5% is comprised of large cobbles and boulders, large enough to remain effectively immobile. The remaining 45% of the sediment could be expected to be transported along the beach as part of the littoral cell. Therefore, of the 14,100 cy/year currently eroded from the bluffs, only 6,350 cy/year remains in the littoral cell transported by wave action (Table 4).

Table 4. Sediment Inputs by Shore Type

Shore type	Total Length (ft)	Average cross section area (ft^2)	Total Inputs (cy)	Annual Inputs (cy/yr)	Inputs x45%
FB	4,646	7,748	1,333,158	10,928	4918
FBE	768	13,641	388,241	3,182	1432
			Total	**14,110**	**6350**

4.2 POTENTIAL LONGSHORE SEDIMENT TRANSPORT AT KAYAK POINT

This section provides estimates of potential sediment transport rates for the northern and southern shorelines of Kayak Point. Longshore sand transport in the nearshore depends on the available quantity of littoral sediment and the potential for transport is most commonly correlated with the longshore component of wave energy flux or power (USACE 1984). Historically, the so-called 'CERC' formula adopted by the U.S. Army Corps of Engineers has been used to calculate potential longshore sediment transport rates. Recently, based on new research and field results, the Coastal Engineering Manual (CEM) (USACE 2003) has updated the CERC formula for littoral sand transport as follows:

$$Q_l = K\left[\frac{\rho\sqrt{g}}{16\kappa^{\frac{1}{2}}(\rho_s - \rho)(1-n)}\right]H_b^{\frac{5}{2}}\sin(2\alpha_b)$$

where Q_l is the potential sediment volume transport rate, K is an empirical proportionality coefficient, ρ is the density of water, ρ_s is the density of sediment, g is the acceleration due to gravity, κ is the breaker index (≈ 0.78), n is the in-place sediment porosity (≈ 0.4), H_b is the wave height at breaking and α_b is the angle of wave approach at breaking. For the purposes of this study, K was assumed to be 0.6, ρ was assumed to be 1.99 slugs/ft^3 (1025 kg/m^3) and ρ_s was assumed to be 3.73 slugs/ft^3 (1922 kg/m^3, representative of a sand/gravel mixture).

To calculate potential sediment transport rates for the northern and southern shorelines, a range of representative values for breaking wave heights, H_b, and corresponding angles with respect to the shoreline, α_b were required. Breaking wave conditions were iteratively calculated for each combination of hindcasted wave height, period, and incident wave direction using the following two equations from the CEM (USACE 2003):

$$H_b = H_l^{\frac{4}{5}}(C_{gl}\cos\alpha_l)^{\frac{2}{5}}\left[\frac{g}{\kappa} - \frac{H_b g^2 \sin^2(\alpha_l)}{\kappa^2 C_l^2}\right]^{-\frac{1}{5}}$$

$$\sin\alpha_b = \sqrt{\frac{gH_b}{\kappa}}\frac{\sin\alpha_l}{C_l}$$

where the C_{gl} is the offshore group wave celerity (speed), C_l is the offshore wave celerity and α_l is the offshore wave direction. Together with constant values for K, ρ, ρ_s, κ and n, values for H_b and α_b for each hindcasted combination of wave height, period and incident wave direction were then used to calculate potential sediment transport rates using the equation for Q_l.

To estimate yearly sediment transport rates, the calculated sediment transport values for each offshore wind-wave condition were multiplied by the percent occurrence of time per year that recorded wind speeds and directions from the Smith Island wind gauge generate each offshore wave condition. Annual potential longshore sediment transport rates for the northern and southern shorelines are shown in Table 5. Positive transport rates correspond to potential transport from east to west along the southern shoreline and from south to north along the northern shoreline.

Table 5. Potential Net Longshore Sand Transport Rates at Kayak

Wind Wave Direction	Southern Shoreline	Northern Shoreline
	Sediment Transport Rates (yd^3/year)	
NE	-	-20
NNE	-	-80
N	-	-2,020
NNW	-	-3,600
NW	-6,110	0
WNW	-17,860	53,830
W	-78,170	78,170
WSW	-26,410	53,610
SW	0	13,920
SSW	1,430	*
S	18,260	*
SSE	117,460	*
SE	10,980	*
Net Transport	20,000	194,000
Gross Transport	277,000	205,000

NB: Zero transport ('0' in table) results when waves approach the coast at an angle parallel to the shoreline (e.g. from the SW for the southern shoreline and from the NW for the northern shoreline). Wave angles greater than 90° from the shoreline ('-' in table) were excluded from the analysis. Positive values indicate south to north transport. *zero because of simplified refraction using Snells Law, actual transport is probably strongly to the north.

The estimates in Table 5 show similar gross transport rates along both shorelines and the potential for beach sediments to move from south to north, consistent with littoral drift cell mapping in the region (Coastal Geologic Services Inc. 2007; Keuler 1988). Since storm and erosion events are typically due to winds and waves from the south-southeast and southeast, the potential transport rates from these directions are greater than any other direction and the net transport potential is in a northerly direction.

The sediment transport potentials do not consider the wave climate from the east, wave refraction effects due to irregular offshore bathymetry, and transport as a result of tidal currents. It should be noted that the CERC equation is considered accurate to within +/- 50% (USACE 2003) and more valid for sand than for coarser sediments such as the coarse sands and gravels present on the upper beach at Kayak Point. These sediments will be transported at different rates than predicted by the formulae for sand beaches due to the steeper beach gradient, high hydraulic conductivity of the sediment, and differences in wave refraction and energy dissipation (Van Wellen and others 2000). The accuracy of the estimates is also limited by the use of simplified refraction analyses (Snell's law based on straight and parallel contours).

Overall, it is our judgment that a more detailed and accurate analysis would result in a stronger northward potential transport and a larger net rate northwards. The under prediction in northward transport is assumed due to (1) southerly fetches based on straight lines under predict actual fetches, and (2) Snells Law refraction has limited accuracy for a Point (where contours are not straight and parallel). Application of a 2-D grid based model of wave generation and transformation (e.g. SWAN) would provide better results.

In addition, actual transport rates can vary over time, can be quite different from long-term averages in any one year, and can be greatly affected by sediment supply. The calculated rates are potential, meaning that they are only possible with a high sediment input. As Puget Sound beaches are generally considered 'sediment starved' (Downing 1983; Finlayson 2006b; Johannessen and MacLennan 2007) smaller actual transport rates would be expected. This is supported by the small yield of beach-size sediment from the up drift feeder bluffs. Further, shoreline armoring, other erosion control measures, and development along the shore to the north and south of Kayak Point (Coastal Geologic Services Inc. 2007) have likely resulted in reduced littoral sediment supply that reduce actual sediment transport rates. Therefore, given these potential issues, the calculated rates represent the maximum potential sand transport rates, if an adequate supply were available, and can only be used to qualitatively assess the potential for gravel and cobble transport at the site.

5. SHORELINE RESPONSE AT KAYAK POINT

5.1 HISTORIC SHORELINE CHANGES

CGS (Coastal Geologic Services Inc. 2007) analyzed the historic change in the position of the logline at Kayak Point using aerial photos taken in 1947, 1955, 1965, 1974, 1984, and 2003. CGS recently updated that analysis based on survey data collected in April 2008. **Figure 11** shows the historic shoreline positions and the five transects analyzed in that report (**Figure 11**, transects A-E) (note these are different transects to those analyzed in this study, see **Figure 2**). Since 1965, the logline of the northern shoreline has shown an accretionary trend, building seawards at an average rate of 0.3-0.6 ft/year. Anecdotal evidence suggests historic erosion of the southern shoreline, although this trend is less evident in the logline analysis. This is probably due to the presence of the sheet pile bulkhead, which helps to hold the logline in a static position as sea level rises and the fronting beach erodes, although this trend is not consistent in either the MHW or toe of beach face analysis.

5.2 FUTURE SHORELINE CHANGES

While it is important to understand historic rates of erosion and current morphological processes, future erosion rates are important to engineering design and coastal planning. Predicting long-term geomorphic evolution, especially considering the effects of sea-level rise, is a difficult task. One way is to assume that historic rates can be projected linearly into the future; however, given the geologically short time period over which erosion rates have been measured, considerable uncertainty exists in these projections. More sophisticated projections can be developed through detailed wave and morphological modeling; however, these analyses are beyond the scope of this study.

The approach taken here to predict future shoreline response to sea-level rise is to project future shoreline positions forward, accounting for enhanced shoreline retreat due to accelerated sea-level rise. The approach assumes that the beach responds to sea-level rise by a landward and upwards translation of the beach profile (Bruun 1962; Bruun 1983). The magnitude of the translation depends on the profile geometry and the amount of sea-level rise. This simple model, generally known as the Bruun rule, has been widely applied to assess future shoreline response to sea-level rise:

$$R = S\frac{L}{P(B + h_c)}$$

where R is the predicted recession, S is relative sea-level rise, L is the length of the active profile, P is the fraction of upper beach material retained in the beach profile, B is the berm height, and h_c is the depth beyond which there is no wave influence (‘closure depth’). Based on wind-wave analysis and geomorphic interpretation of survey data at Kayak Point, the closure depth is estimated to be approximately -5 to -7 feet MLLW. Finlayson (2006a) examined very short-term beach profile changes at Cama Beach, Camano

Island, and observed profile changes down to approximately -3 feet MLLW. The deeper closure depth at Kayak Point is consistent with its greater degree of exposure to southerly storm waves.

While many studies and theoretical arguments have validated the Bruun rule qualitatively, there has been mixed success in applying the rule in site-specific studies (Cooper and Pilkey 2004; List and others 1997). More detailed longshore and cross-shore sediment transport models are often used (Hanson and Kraus 1989; Larson and Kraus 1989). The simplest form of these analyses use “equilibrium” or “typical” geometry and some form of the Bruun rule to obtain a first-order approximation of the anticipated shoreline response to sea-level rise.

Equilibrium shoreline theory indicates that the shape of the shore face (the profile generally coinciding with the surf and runup zones) is the result of the dissipation of incident wave energy, and the effects of the sediment type (primarily size) (Dean 1977; Dean 1991). Consequently, the shore profile is a shape in dynamic equilibrium, changing in response to changing waves and water levels but generally maintaining the same basic scales of overall slope, height and width. This assumption allows the relationship between sediment supply and shoreline position to be related, and the response to sea level to be estimated. The Bruun rule and associated methods assume that there is adequate sediment to build a new equilibrium shore at the higher sea level. The overall profile then shifts landward in general relation to the overall slope of the profile.

Future shoreline recession was estimated at five shore-normal transects cut from the topographic map. The Bruun-type recession was calculated using parameters derived from 2008 beach transects of Kayak Point collected by CGS (**Figure 2**).

5.3 FUTURE SHORELINE PROJECTIONS – NORTHERN SHORELINE

The approach adopted in this study is to assume that the future position of the northern shoreline will be the net result of (1) existing depositional trends projected into the future and (2) future Bruun-type recession due to accelerated sea-level rise. Thus, for the historically accreting northern shoreline, there exists a threshold rate of sea-level rise over which recession will overwhelm existing depositional processes. Along the northern shoreline of Kayak Point, littoral processes have built out the shoreline for at least the past 50 years, outpacing change due to rising sea levels. This observed historical accretion is assumed to equate to the net result of the depositional processes and Bruun-type recession over the past several decades:

[*Bruun recession*] + [*depositional littoral processes*] = [*net observed shoreline change*]

For the purposes of this study, a past rate of sea-level rise of 2 mm/yr was assumed from 1965 to 2003, for a cumulative sea-level rise of 0.25 feet. Table 6 shows the results of the historic calibration from 1965-2003 using the Bruun rule. The table shows the calculated Bruun recession rate and net observed shoreline accretion rate along each of the northern shoreline transects (**Figure 12**). The difference between the net observed accretion rate and the predicted Bruun recession rate over this time represents the ‘littoral rate’ due to depositional processes along the northern shoreline, which have outpaced the predicted Bruun-type recession due to sea-level rise.

Table 6. Historic Calibration of Shoreline Change for the Northern Shoreline (1965-2008)

Transect	Sea-level rise (ft)	Bruun Recession (ft)	Bruun Recession Rate (ft/yr)	Littoral Rate (ft/yr)	Net Observed Rate (ft/yr)
NB-N2	0.25	-5	-0.13	+0.40	+0.27
NB-N	0.25	-5	-0.12	+0.41	+0.29
NB-S	0.25	-2	-0.06	+0.69	+0.63

Note: The “net observed rate” is the rate of shoreline change along each transect and was determined by linear regression of the shoreline position time series from 1965-2008 (see Figure 12).

To predict future shoreline changes along the northern shoreline, we projected the historic ‘littoral rate’ and combined it with the anticipated Bruun recession for future sea-level rise to predict net future rates of shoreline change. Both the medium (0.5 feet by 2050 and 1.1 feet by 2100) and high (1.8 feet by 2050 and 4.2 feet by 2100) estimates of sea-level rise were used in the analysis. Tables 7-9 show the predicted shoreline response from 2008 to 2050, 2050 to 2100, and 2008 to 2100, respectively.

Table 7. Predicted Shoreline Change Along the Northern Shoreline (2008-2050)

Transect	Bruun Recession (ft)		Littoral Shoreline Change (ft)	Shoreline Change (ft)	
	Medium rise	High rise		Medium rise	High rise
NB-N2	-10	-36	17	7	-19
NB-N	-9	-33	17	8	-16
NB-S	-4	-16	29	25	13

Table 8. Predicted Shoreline Change Along the Northern Shoreline (2050-2100)

Transect	Bruun Recession (ft)		Littoral Shoreline Change (ft)	Shoreline Change (ft)	
	Medium rise	High rise		Medium rise	High rise
NB-N2	-12	-48	20	8	-28
NB-N	-11	-44	20	9	-24
NB-S	-5	-21	35	29	14

Table 9. Predicted Shoreline Change Along the Northern Shoreline (2008-2100)

Transect	Bruun Recession (ft)		Littoral Shoreline Change (ft)	Shoreline Change (ft)	
	Medium rise	High rise		Medium rise	High rise
NB-N2	-22	-84	37	15	-47
NB-N	-20	-77	37	17	-40
NB-S	-10	-36	64	54	27

The results indicate that under the medium sea-level rise scenario, accretion of the northern shoreline will continue over the next 50 to 100 years. The shoreline north of the pier (NB-N2 and NB-S) may build out as much as approximately 10 feet by 2050 and by approximately 15 feet by 2100 from its current location. Under the high scenario, landward recession in response to sea-level rise may exceed sediment supply, and the northern shoreline, north of the pier, may retreat from its current location as much as approximately 20 feet by 2050 and 50 feet by 2100.

The northern shoreline south of the pier (NB-S) has historically displayed a greater rate of accretion and a steeper profile that should continue to accrete in the future. The northern shoreline in the vicinity of the point may build out as much as approximately 15-25 feet by 2050 and by approximately 30-55 feet by 2100.

These projections are first order estimates with a large degree of uncertainty dependent on future rates of sea-level rise, changes in wave climate, and future sediment supply to the Kayak Point drift cell.

5.4 FUTURE SHORELINE PROJECTIONS – SOUTHERN SHORELINE

Future shoreline projections for the southern shoreline were conducted assuming the removal of the sheet pile bulkhead. The anticipated shoreline response with the bulkhead in place is discussed in Section 5.5. In any event, the low bulkhead shows signs of deterioration, and is overtopped during high water storms. Future shoreline positions were obtained assuming Bruun-type recession for 2050 and 2100 for the medium and high sea-level rise estimates. The results are shown in Table 10. See Section 5.2 above for a description of the Bruun methodology.

Table 10. Predicted Shoreline Change Along Southern Shoreline (2008-2100)

	Bruun Recession 2008-2050 (ft)		Bruun Recession 2050-2100 (ft)		Bruun Recession 2008-2100 (ft)	
Transect	Medium rise	High rise	Medium rise	High rise	Medium rise	High rise
SB-W	-5	-17	-6	-23	-11	-40
SB-E	-11	-40	-13	-54	-24	-94

The results indicate that under the medium sea-level rise scenario, and without a bulkhead in place, erosion of the southern shoreline will take place over the next 50 to 100 years. The shoreline may recede landward of its current location by up to approximately 5-10 feet by 2050 and by approximately 10-25 feet by 2100. Under the high sea-level rise scenario, landward recession may be as much as approximately 15-40 feet by 2050 and approximately 40-95 feet by 2100.

5.5 POTENTIAL IMPACTS OF RETAINING THE BULKHEAD

Due to the recent exposure of the bulkhead (**Figure 3**), it is likely that the southern beach will continue to lower if the bulkhead is retained and maintained. Our conceptual model shows that the sediment supply to Kayak Point from up drift sources is limited. The exposed bulkhead would lead to increases in wave reflection and scour during storm events. Continued lowering of the southern beach would position the bulkhead progressively lower in the active surf zone. By limiting the erosion of the land area behind the bulkhead, shoreline areas adjacent to the bulkhead will share a greater degree of erosional stress. Also, wave runup during storms will be progressively more severe, with increased overtopping volumes as the beach fronting the bulkhead steepens.

Overall, the performance of the existing bulkhead along the southern shoreline will degrade over time creating a situation that is unsustainable. The observed long-term erosion pattern will continue to persist and will likely worsen. Expected changes include: (1) a continued lowering of the beach profile in front of the bulkhead (there is insufficient sediment supply to maintain the beach profile), (2) an increase in measurable wave energy and currents near the bulkhead caused by storms from the south-southeast and southeast directions, and (3) increased wave overtopping and backshore flooding. Each of these changes will lead to an increase in the potential for erosion to occur in the vicinity of the bulkhead and for the Kayak Point Regional Park infrastructure to be damaged.

5.6 SET BACK DISTANCE FOR PARK INFRASTRUCTURE

The results of the shoreline translation analysis show that the southern shoreline without the bulkhead could potentially recede up to 40 feet by 2050 using the high sea-level rise scenario. In order to provide adequate buffer for park infrastructure for the next 42 years, we recommend that a set back distance of at least 60 feet (40 feet plus an additional 20 feet contingency buffer) is used along the southern shoreline. By 2100, the southern shoreline could move landward by up to 90 feet using a high sea-level rise scenario. In this case we recommend a set back distance of at least 120 feet (90 feet plus an additional 30 feet contingency buffer).

For the northern shoreline, the results indicate continued accretion south of the pier up to 2050 and 2100 (for the high sea-level rise scenario). North of the pier the shoreline could potentially recede up to 20 feet by 2050 using a high sea-level rise scenario. We recommend a set back distance of at least 40 feet (20 feet plus an additional 20 feet contingency). By 2100, 50 feet of recession could take place using a high sea-level rise scenario, and we recommend a set back distance of at least 80 feet (50 feet plus an additional 30 feet contingency).

6. LIST OF PREPARERS

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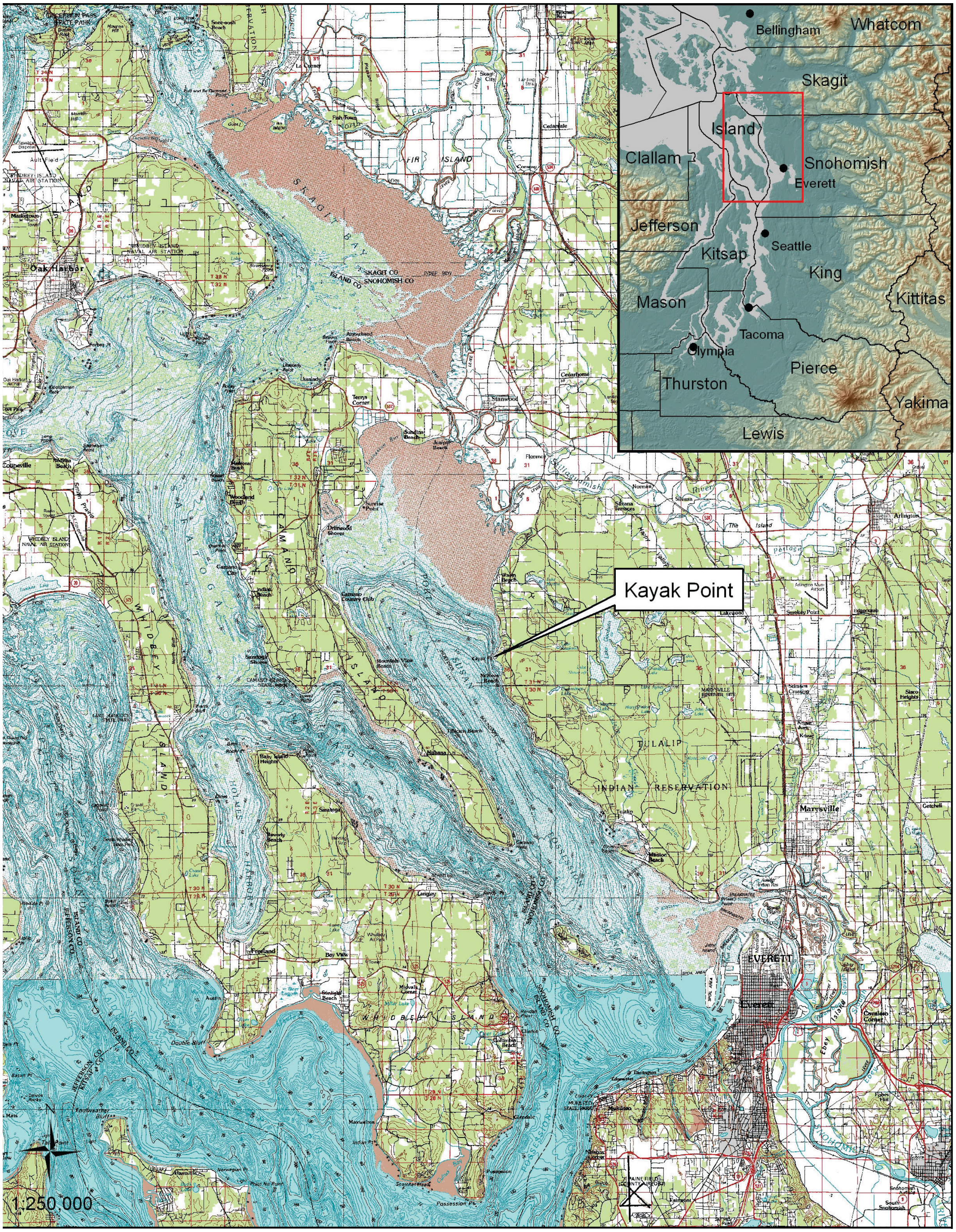
8. FIGURES



Source: Basemap from USGS 1:250,000 Port Townsend quarter quad. Puget Sound DEM courtesy Finlayson (2005) (provided by Coastal Geologic Services)

figure 1

Kayak Point Sea Level Rise Assessment

Location of Kayak Point Regional Park

PWA Ref. # 1937

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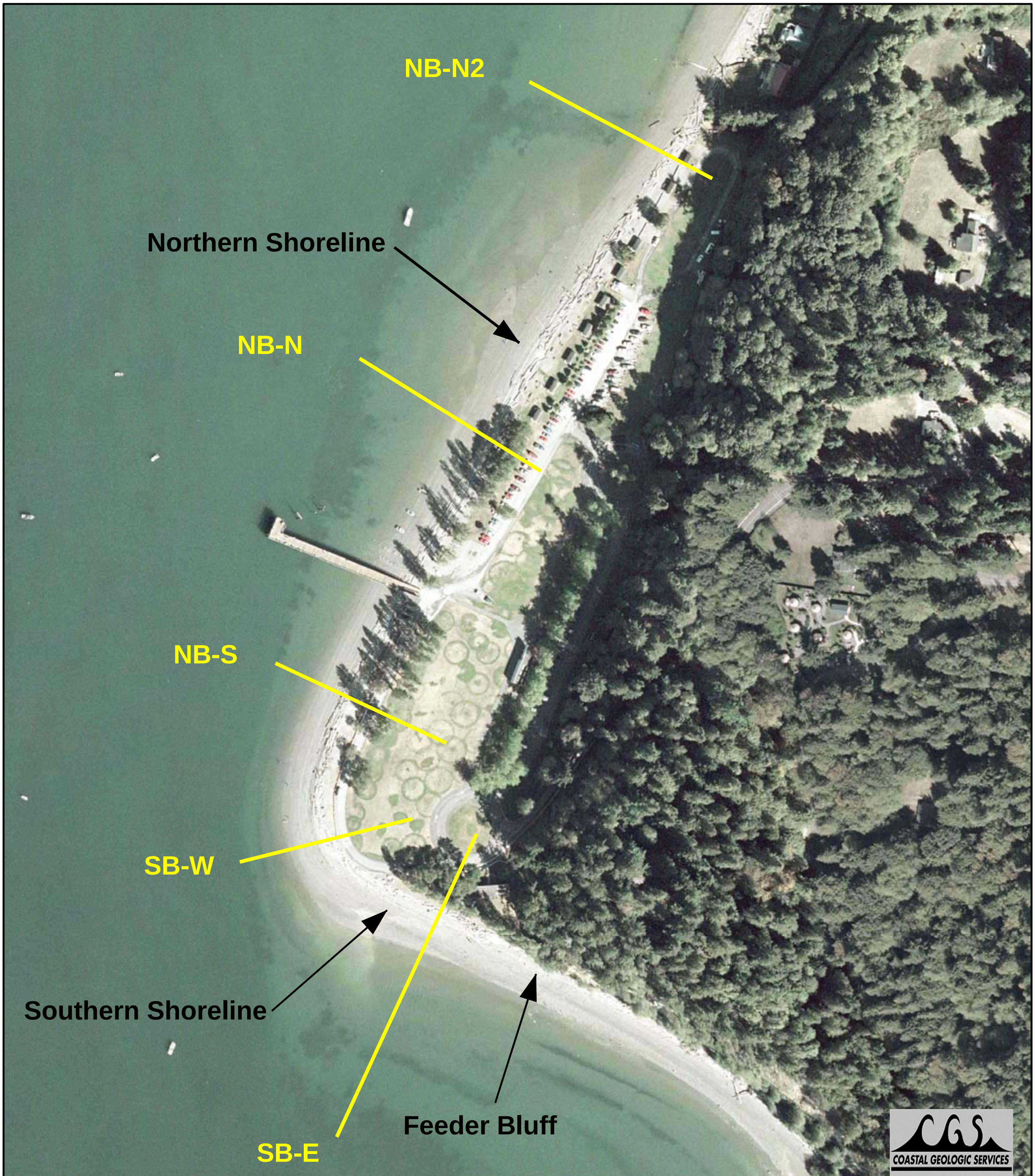

Source: Imagery acquired by Snohomish County (2003)

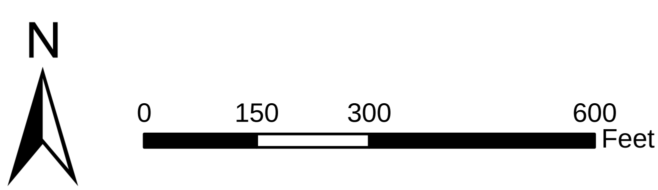

figure 2

Kayak Point Sea Level Rise Assessment

Kayak Point Site Map

PWA Ref# - 1937

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figure 3

Kayak Point Sea Level Rise Assessment

Exposed Bulkhead

PWA

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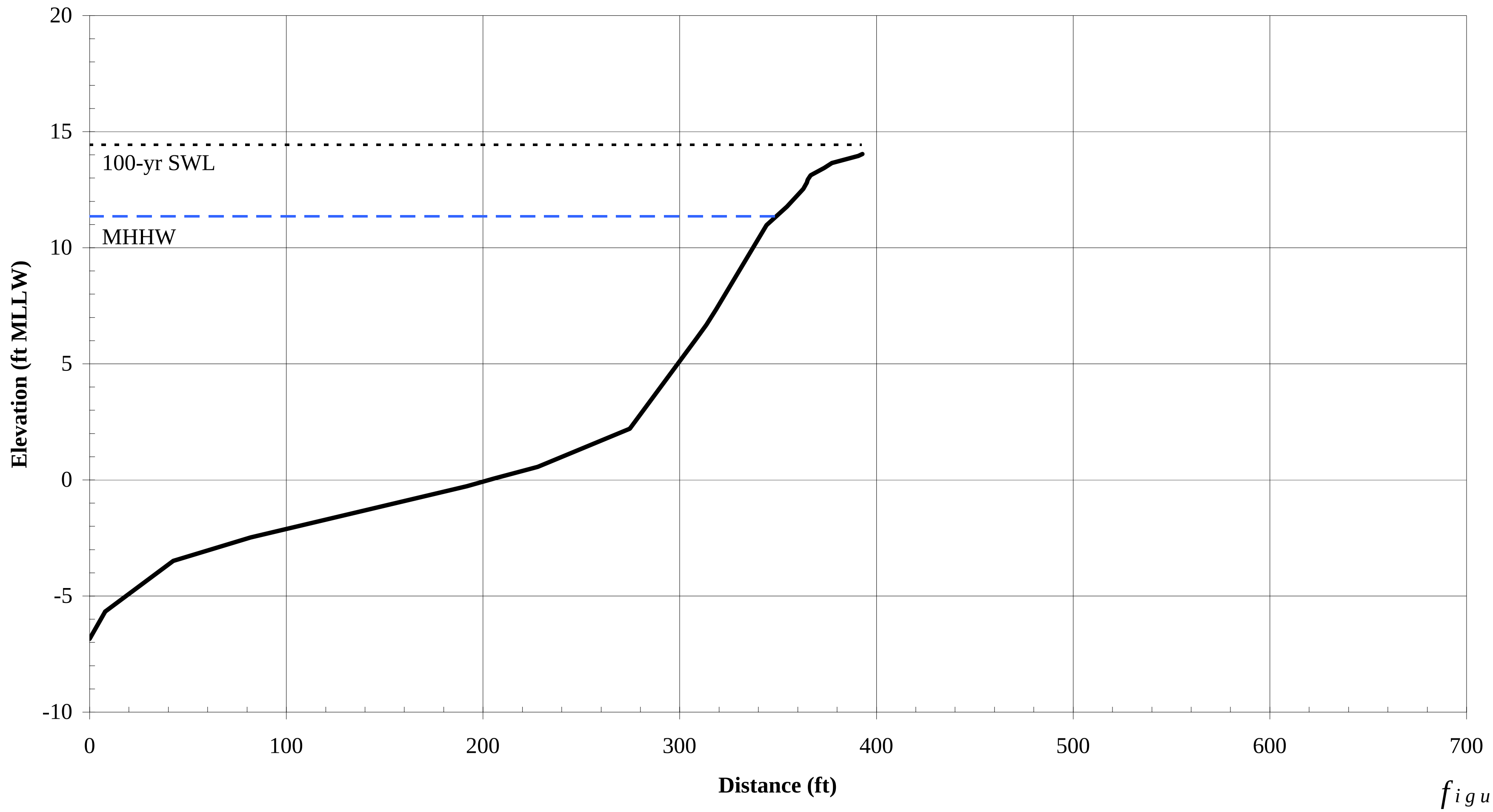

figure 4

Notes: Transect cut from DTM developed from CGS spot elevations surveyed Spring 2008.
Survey data collected in NAVD88 and converted to MLLW using conversion of 2.15 ft.
MHHW = 11.36 ft MLLW (NOAA Seattle, WA #9447130)
100-yr SWL = 14.44 ft MLLW (Finlayson 2006)

Kayak Point Sea Level Rise Assessment

Survey Transect NB-N2

PWA Ref# 1937

PWA

Figure 4 to 8_Kayak_Point_Transects.xls / Figure 4

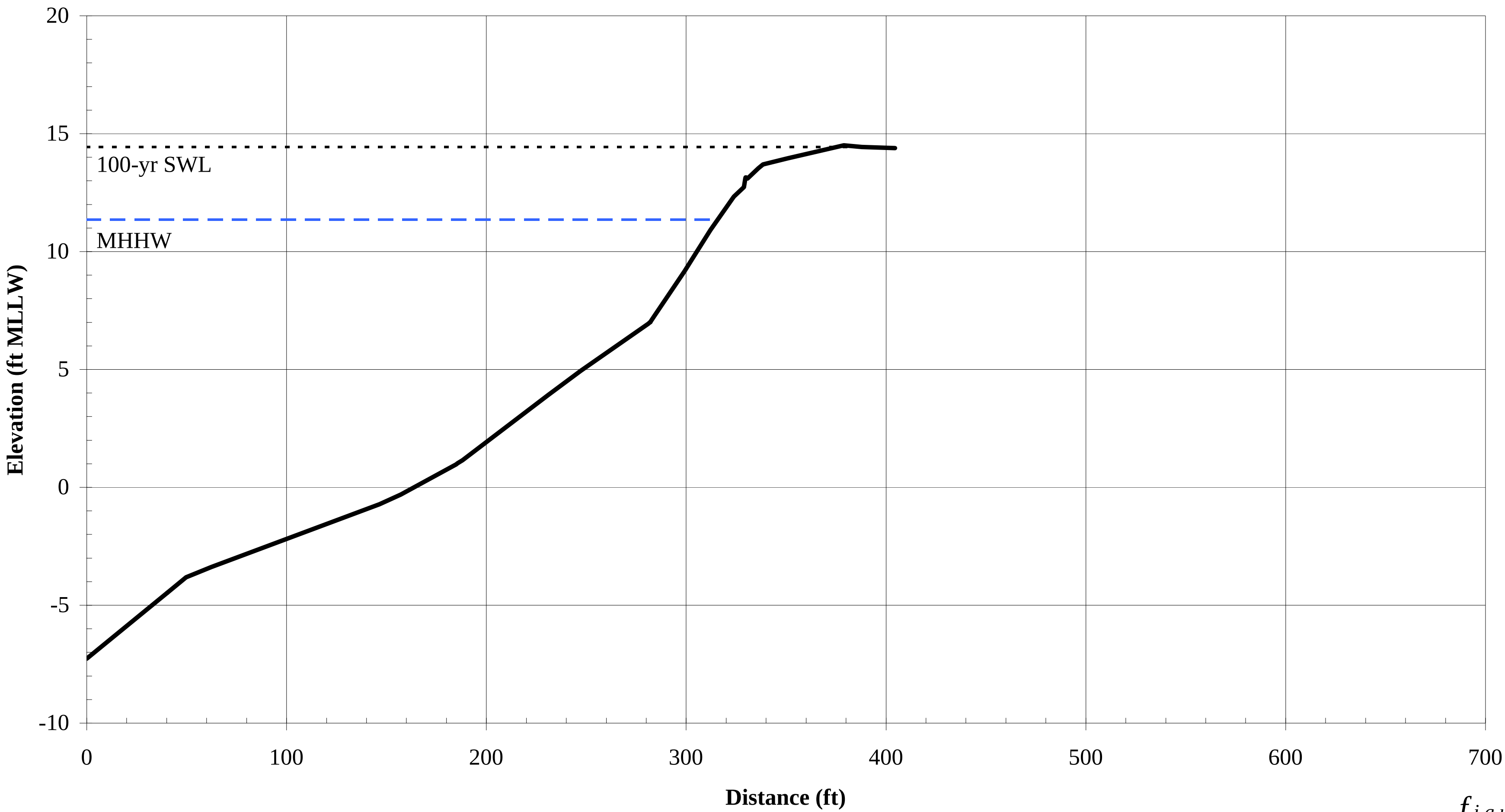

figure 5

Notes: Transect cut from DTM developed from CGS spot elevations surveyed Spring 2008.
Survey data collected in NAVD88 and converted to MLLW using conversion of 2.15 ft.
MHHW = 11.36 ft MLLW (NOAA Seattle, WA #9447130)
100-yr SWL = 14.44 ft MLLW (Finlayson 2006)

Kayak Point Sea Level Rise Assessment

Survey Transect NB-N

PWA Ref# 1937

PWA

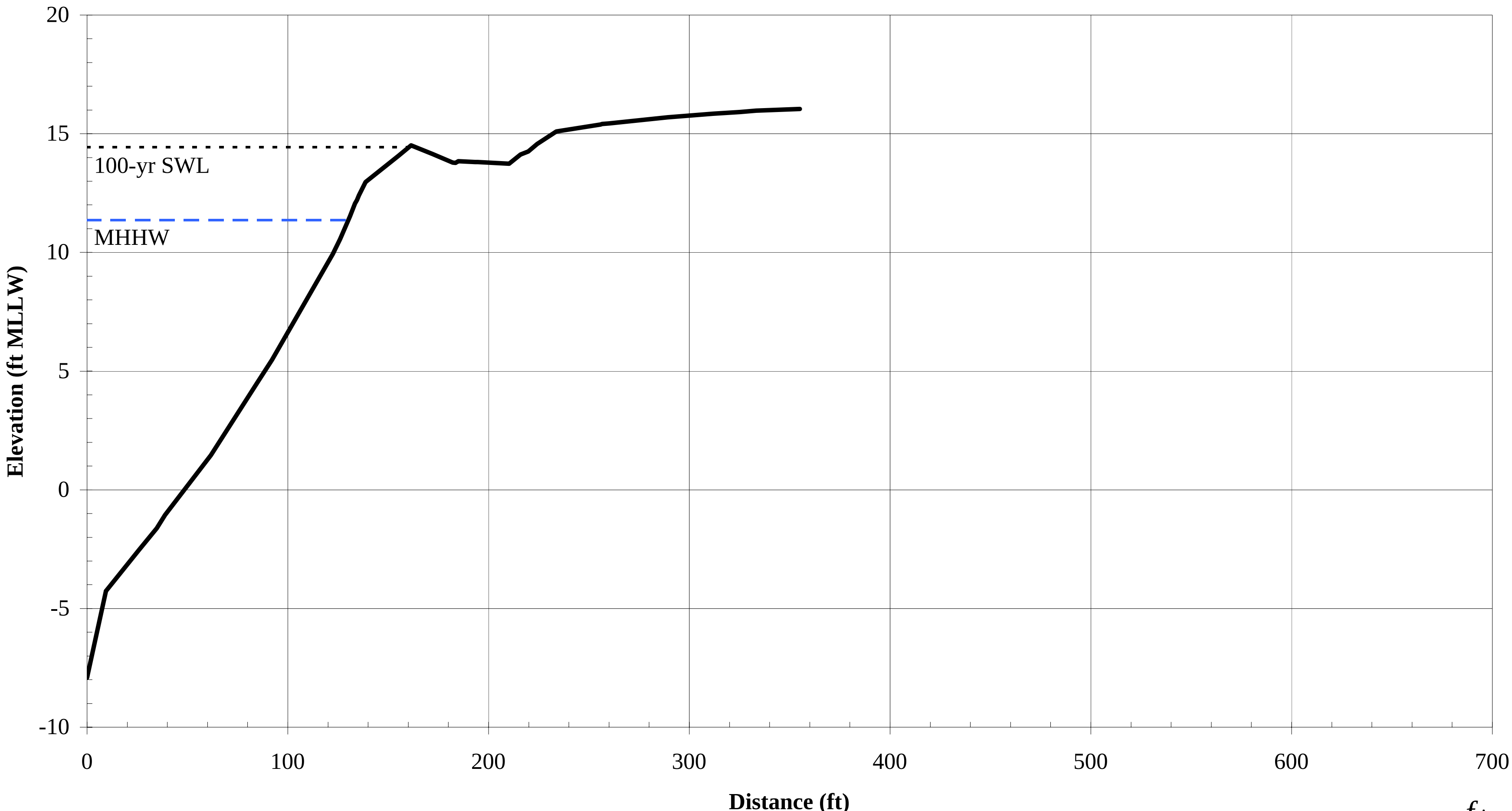

figure 6

Notes: Transect cut from DTM developed from CGS spot elevations surveyed Spring 2008.
Survey data collected in NAVD88 and converted to MLLW using conversion of 2.15 ft.
MHHW = 11.36 ft MLLW (NOAA Seattle, WA #9447130)
100-yr SWL = 14.44 ft MLLW (Finlayson 2006)

Kayak Point Sea Level Rise Assessment

Survey Transect NB-S

PWA Ref# 1937

PWA

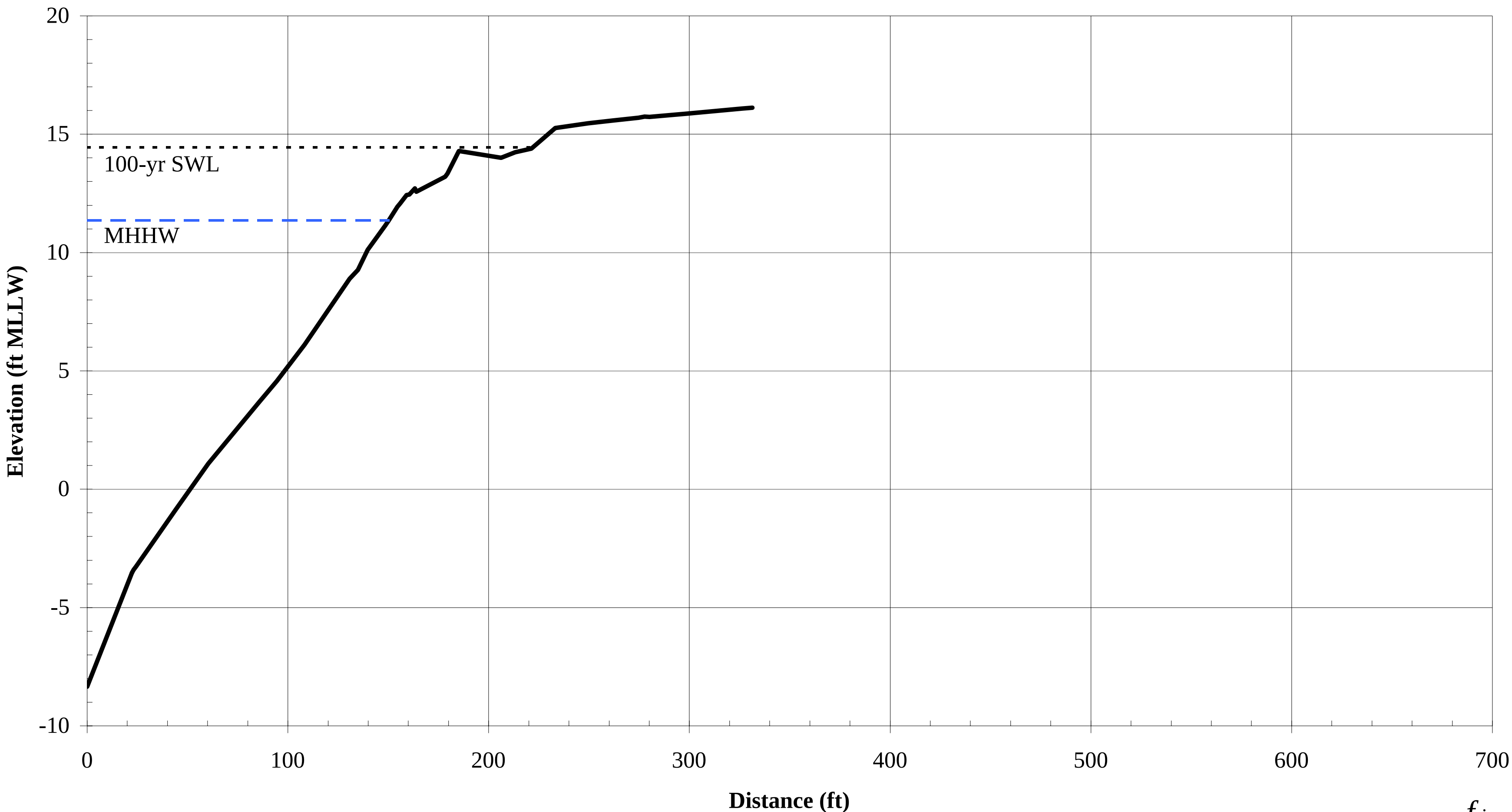

figure 7

Notes: Transect cut from DTM developed from CGS spot elevations surveyed Spring 2008.
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100-yr SWL = 14.44 ft MLLW (Finlayson 2006)

Kayak Point Sea Level Rise Assessment

Survey Transect SB-W

PWA Ref# 1937

PWA

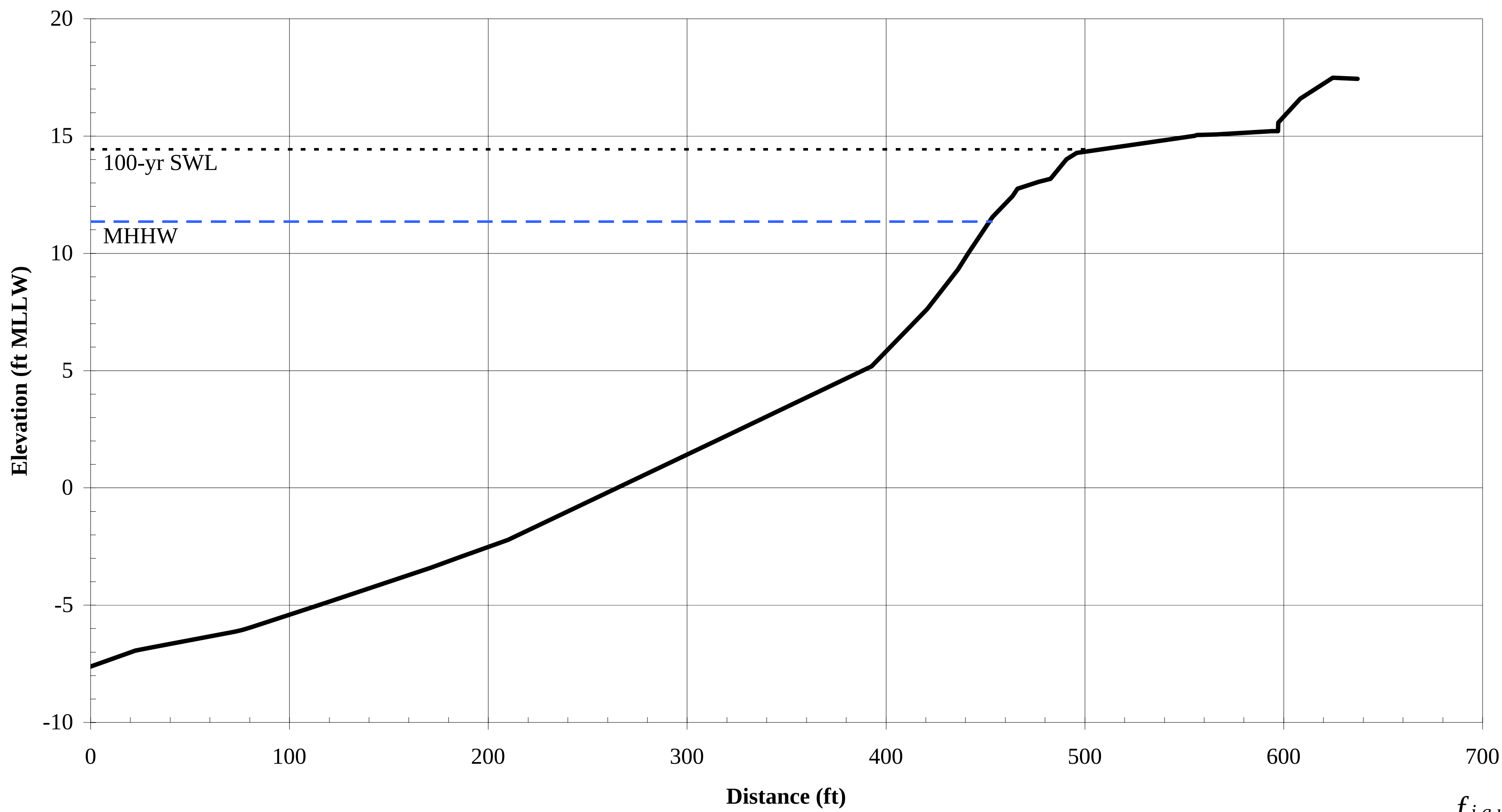


figure 8

Notes: Transcect cut from DTM developed from CGS spot elevations surveyed Spring 2008.
Survey data collected in NAVD88 and converted to MLLW using conversion of 2.15 ft.
MHHW = 11.36 ft MLLW (NOAA Seattle, WA #9447130)
100-yr SWL = 14.44 ft MLLW (Finlayson 2006)

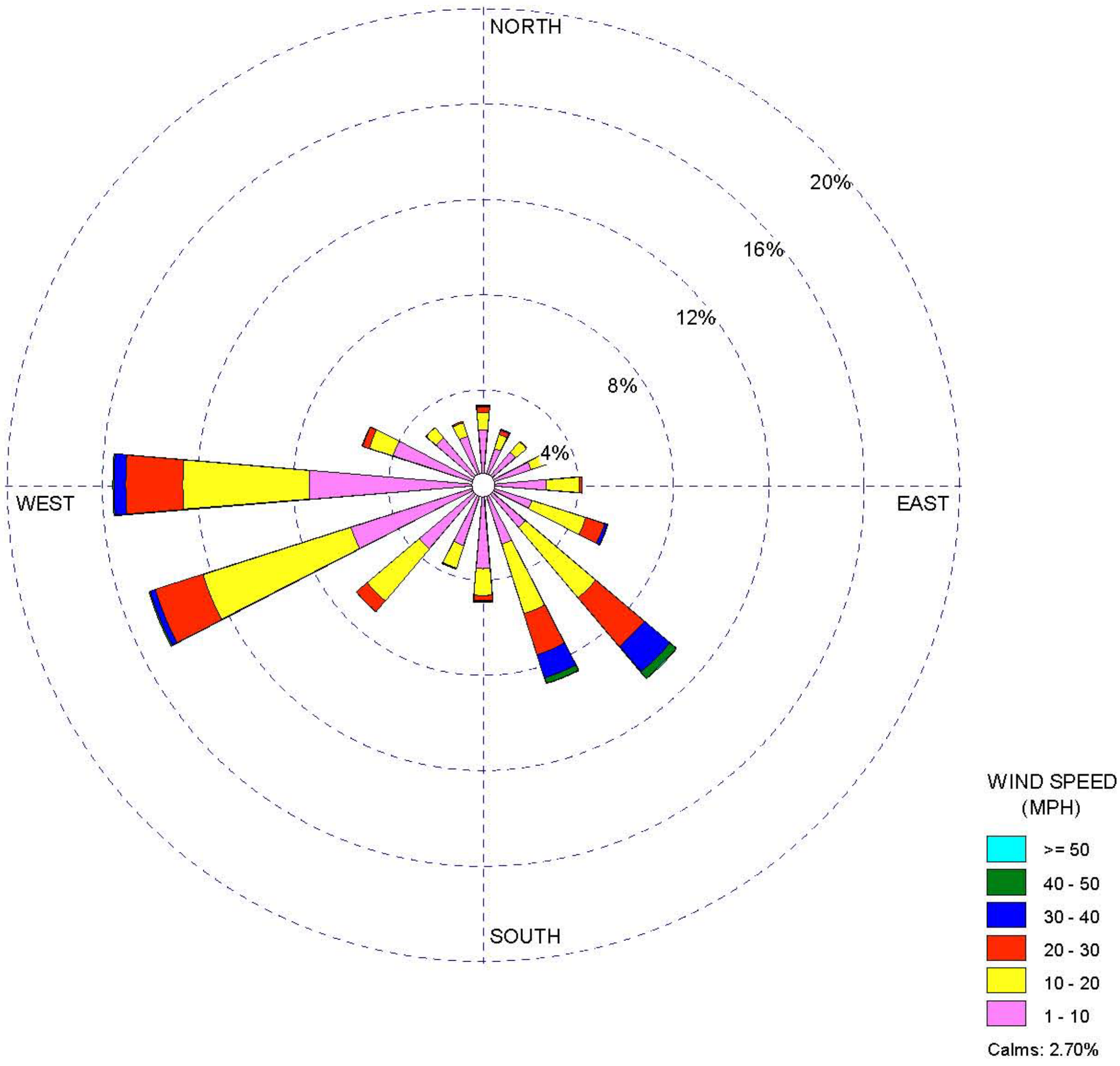
Kayak Point Sea Level Rise Assessment

Survey Transect SB-E

PWA Ref# 1937

PWA

Figure 4 to 8_Kayak_Point_Transects.xls / Figure 8



Source: NDBC Buoy SISW1 from 1984-2005

figure 9
Kayak Point Sea Level Rise Assessment

Smith Island Wind Rose

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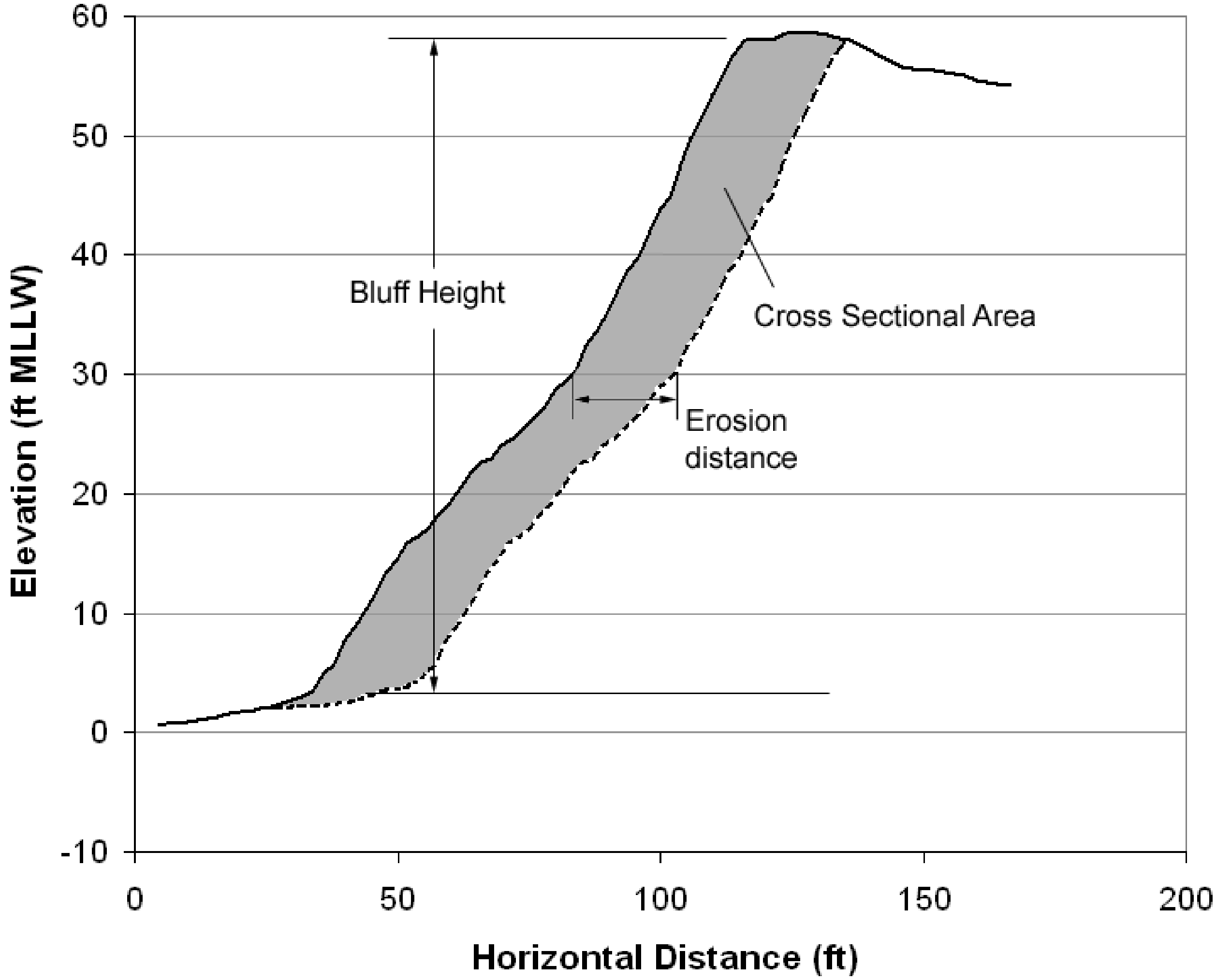


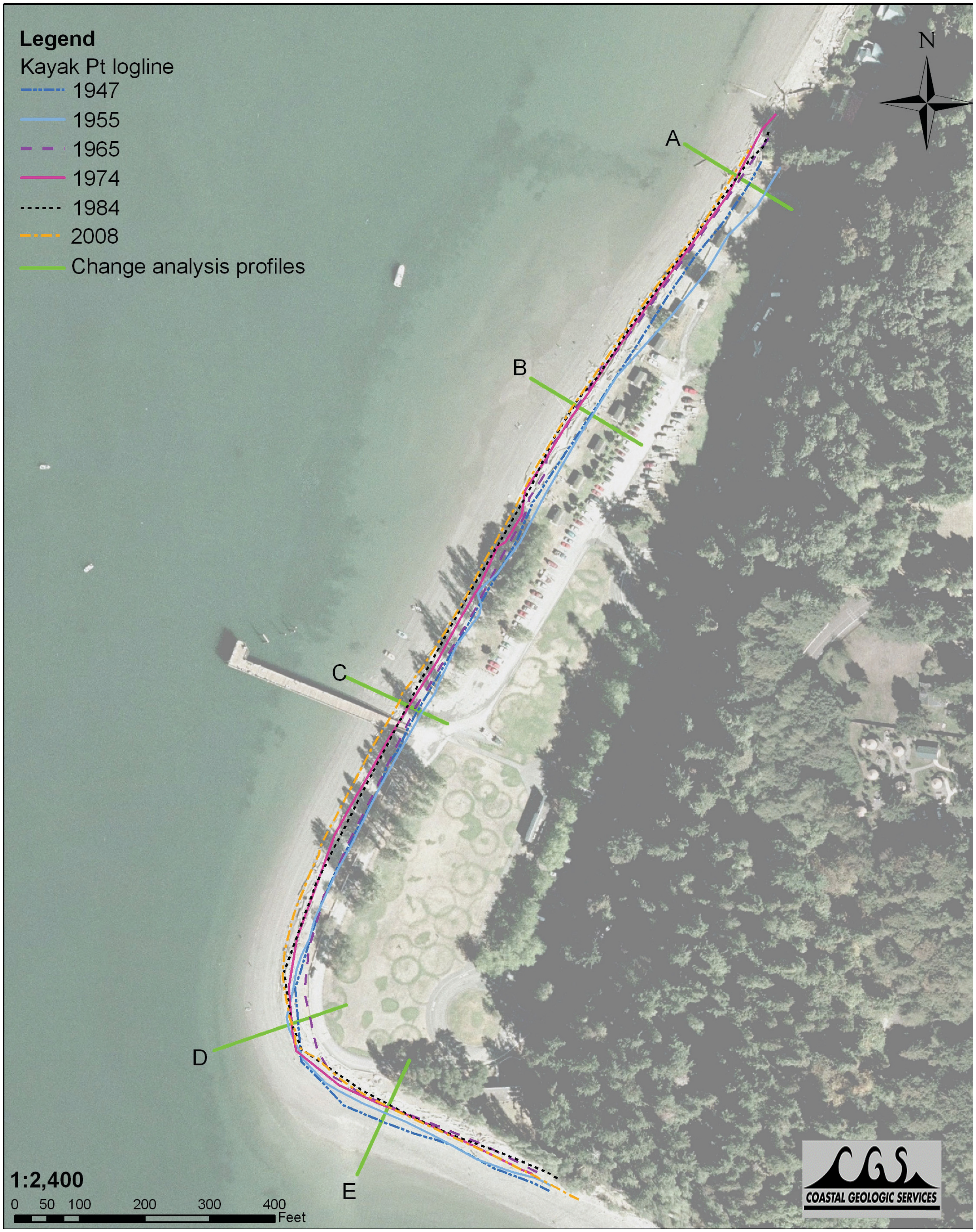
Source: Image provided courtesy of Coastal Geologic Services, Inc.

figure *10*

Kayak Point Sea Level Rise Assessment

Sample Bluff Transect

PWA Ref# 1937



Source: Imagery acquired by Snohomish County (provided by Coastal Geologic Services)

figure 11

Kayak Point Sea Level Rise Assessment

Shore Change Analysis Using the Logline

PWA Ref. # 1937

PWA

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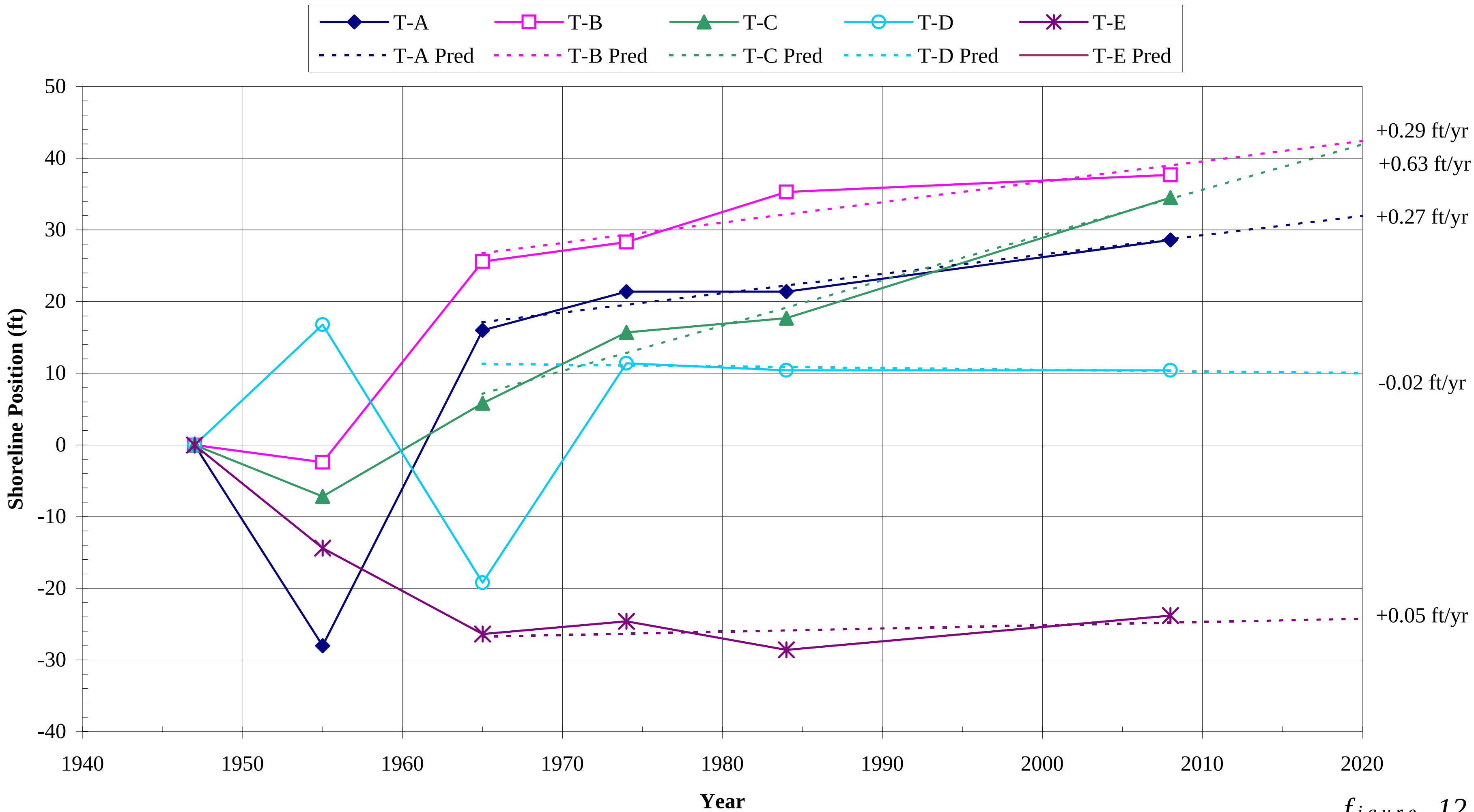

figure 12

Notes: North Beach Transects: A-C, South Beach Transect: E, Point Transect: D. See Figure 12 for transect locations. Shoreline positions based on logline analysis.
Source: Coastal Geologic Services (2008)

Kayak Point Sea Level Rise Assessment

Kayak Point Rates of Shoreline Change

PWA Ref# 1937

PWA

1937_Shoreline_Analysis_v2.xls / Shoreline Positions Pred fig v2

APPENDIX A

Kayak Point Restoration Feasibility and Design Technical Memorandum: Sea Level Rise Projections

Kayak Point Restoration Feasibility and Design
Technical Memorandum: Sea Level Rise Projections

Prepared for: Snohomish County Surface Water Management and Parks

Prepared by: Andrea MacLennan, MS and
Jim Johannessen, Licensed Engineering Geologist, MS

June 23, 2008

Introduction and Overview

Coastal Geologic Services, Inc (CGS) was contracted by Snohomish County Surface Water Management to provide restoration feasibility assessments and proposed restoration designs of the shore of Kayak Point County Park. Most recently CGS was asked by the County to include an assessment of the potential implications that sea level rise (SLR) will have on the Park. The low elevation portion of the Park is the study area for this portion of work, with some analysis of the drift cell that extends approximately 9 miles southeast towards Tulalip Bay. In this memo several recent global SLR projections are reviewed and the appropriate projections to use for analysis of the Park's shore are defined as a preliminary step for the larger restoration design analysis portion of this study.

Medium and high range projections were selected for use as part of the sea level rise assessment of Kayak Point. It should be recognized that the SLR projections recommended here incorporate a higher estimate of sea level rise to intentionally (conservatively) measure the risk to the Kayak Point study area. This was justified due to very recent publications on this topic and to ensure that the range of potential implications that sea level rise may have on Kayak Point Park and not underestimated, as this would likely lead to degradation of the very resources that are proposed to be restored.

The medium SLR projection for this project is 0.15 m (0.5 ft) by 2050, and 0.34 m (1.1 ft) by 2100. The high-impact, low-probability projection is 0.55 m (1.8 ft) by 2050 and 1.28 m (4.2 ft) by 2100. Further explanations of the assumptions that lead to the selection of these projections are included in this memo.

Global Sea Level Rise Projections

Recent projections of global SLR for 2100 reported in the United Nations' Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (2007) ranged from 18 - 38 cm (7-15") for the lowest emissions scenarios to 26 - 59 cm for their higher emissions scenarios. However, over the course of the past year and a half, there have been major advances in the science of sea level rise, which have led to considerable criticism of the 2007 IPCC SLR projections. Their projections are now thought to be too low, and the approach used to derive the projections has been accused of being flawed. The Delta Risk Management Strategy (DRMS, Duffy 2007) for the Sacramento-San Joaquin Delta area in California planning effort and CALFED, which is a collaboration "among 25 state and federal agencies working to improve California's water supply and the ecological health of the San Francisco Bay/Sacramento-San Joaquin River Delta", argued that the modeled projections of the IPCC were too low and provided the following reasons:

- A linear extrapolation of historical rates of sea-level rise would be higher than the low end of the IPCC (2007) projections. The IPCC (2007) historic rates of 1.8 mm/yr and 3.1 mm/yr would equate to 0.2 m and 0.34 m, respectively, of sea level rise over the period 1990 - 2100. The low end of the IPCC (2007) range (0.18 m) would therefore require a deceleration of global sea-level rise. This is unlikely based on the likelihood of increased greenhouse gas emissions and the potential for accelerated melting of the Greenland ice sheet.

- The IPCC (2007) models under-predict historic sea-level rise. The sum of the modeled individual contributions to sea-level rise (thermal expansion, glaciers and ice caps, Greenland and Antarctic ice sheets) is lower than the observed sea level rise from tide gauges. It is possible that the models may also under-predict future sea-level rise.

- The IPCC (2007) projections exclude significant contributions from the potential accelerated future melting (by dynamical ice loss) of the Greenland ice sheet. Evidence suggests that significant melting is already underway (Cazenave 2006), and Overpeck et al. (2006) showed that sea levels during the last interglacial were several meters higher than today due to extensive melting of ice sheets on land.

Melting of the ice sheets of Greenland and Antarctica has the potential to raise sea level up to 70 m and is one of the largest potential threats of future climate change (Overpeck et al. 2006). Numerous studies have recently demonstrated that the mass balance (input from snowfall versus losses due to melting or detachment) of these ice sheets is shifting more towards rapid loss, most likely in response to warming of the atmosphere and oceans (Shepherd and Wingham 2007, Ringnot and Kanagaratnam 2006, Kerr 2006). For example Greenland's contribution to sea level rise increased from 0.23 (+/- 0.08) mm/yr in 1996 to 0.57 (+/- 0.1) mm/yr in 2005 (Ringnot and Kanagaratnam 2006). Recent research has shown that ice sheet flow is accelerating the rate of ice loss on Antarctica and Greenland due to meltwater lubrication or the removal of buttressing ice shelves and that the combination of these ice sheet dynamics may add as much as 1 m (39 in) to sea level rise by 2100 (Hansen et al. 2007). Meier et al. (2007) reported that the disintegration of glaciers and ice sheet wastage constitutes a substantial and accelerating cause of global sea level rise, which may result in an additional 0.1 - 0.25 m of SLR by 2100. It is anticipated that at least 60% of the eustatic, new water component of SLR will be derived from glaciers and ice caps (GIC) and that these dynamic changes will likely increase with further warming (Meier et al. 2007).

Other recent publications report contrasting SLR projections to those reported by the IPCC (2007). Horton et al. (2008) projected a 0.54 - 0.89 m SLR rise by 2100, using a different approach based on ground surface temperature changes, though this estimate also does not account for accelerating ice sheet melt. Rahmstorf (2007) used a linear empirical relationship (similar to the approach taken for predicting tides), which resulted in higher rates of SLR and global mean surface temperature for the 20th century relative to pre-industrial threshold to predict full range increases of 0.5 - 1.4 m during the 21st century (3.5 mm/yr). Rahmstorf's more liberal projections might also under-estimate because they do not account for Greenland ice loss.

Rahmstorf's (2007) projections were adopted by the Delta Risk Management Strategy for planning.

During a recent presentation at the European Geoscience Conference, Svetlana Jevrejeva, with the Proudman Oceanographic Laboratory in Liverpool, UK, projected a 1.5 m global rise in SLR by 2100 (which apparently incorporates ice sheet dynamic models). Unfortunately the peer-reviewed publication was not yet available at the time that this memo was compiled. Another group of researchers from the University of Buffalo expressed that if the IPCC models had accounted for data documenting the ice dynamics in Greenland, SLR projections could be twice as high as current projections (University of Buffalo 2008).

Relative Sea Level Rise for the Puget Sound Basin

Local or relative sea level rise is the result of the combined effects of global (eustatic) SLR and local factors such as vertical land deformation (e.g. tectonic movement, isostatic rebound) and seasonal ocean elevation changes due to atmospheric circulation effects (Mote et al. 2008). Based on current research Mote et al. (2008) projected that local SLR in the Puget Sound will closely match global SLR:

> "Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, a low-probability high-impact estimate of local SLR for the Puget Sound Basin is 55 cm (22") by 2050 and 128 cm (50") by 2100. This integrates 10 cm (4") of subsidence by 2050 and 20 cm (8") by 2100 based on Verdonck (2006) vertical land deformation rates for Puget Sound."

Local land level changes can occur as a result of crustal deformations (associated with tectonic movement, and isostatic rebound) or subsidence from sediment compaction (such as in deltas). The Puget Sound region is located along the western extent of the North American continental plate, beneath which the Juan de Fuca oceanic plate is subducting. The subduction processes produce uplift in the northwestern end of the state, subsidence in the central coast and smaller movement throughout the rest of the State (Verdonck 2006). Exact measures of the rates of vertical land movement (VLM) have been contrasting over recent years (Mote et al. 2008). Some of the least consistent measures have occurred within the Puget Sound basin, though the area encompassing the Kayak Point study area has consistently had low VLM measures on the order of 0-1 mm/yr (Verdonck 2006, Holdahl et al 1989).

Local atmospheric circulation effects relative sea level rise in the Puget Sound region on a seasonal and inter-annual time scale, due to the predominant southerly winds, resulting in wind-driven enhancement of sea levels, combined with the earth's rotation pushing water onshore (Mote et al. 2008). These processes are more pronounced during El Nino events. The processes been explored more thoroughly along the outer coast of Washington, but have resulted in mean wintertime sea level being roughly 20" higher than summer sea level on the Washington coast and within estuaries (Ruggierio et al. 2005). This effect has not been measured within the more protected shores of the Puget Sound basin; however a similar effect likely occurs however at a smaller scale.

Kayak Point SLR Projections

Considering the low lying nature of the site and the immediately adjacent infrastructure (road), it seems appropriate to apply conservative SLR estimates (from a risk management perspective) that integrate the most current local and global SLR projections. Therefore, for the intent of this study the higher SLR projections outlined by Mote et al. (2008) for the Puget Sound region were recommended for application (Table 1).

The highest SLR projection recommended for application is Mote et al.'s (2008) low-probability, higher-impact scenario of 0.55 m of SLR by 2050 and 1.28 m by 2100. This projection was calculated by starting with the IPCC's A1FI 95% value of 59 cm by 2100, then including an additional 0.34 m to allow for increase cryospheric contributions (ice sheet melt), 15 cm by 2100 and 7 cm for 2050 from atmospheric contributions, and 10 - 20 cm (2050, 2100 respectively) for VLM.

Table 1. Medium and high SLR projections for the Puget Sound basin for two different planning horizons (2050, 2100) for the Kayak Point study area based on IPCC and the higher range of SLR projections outlined by Mote et al. (2008). SLR (sea level rise) predictions are uncertain and are projections are therefore of unknown accuracy.

Component	Medium SLR Projection		High SLR Projection	
	2050	2100	2050	2100
IPCC SLR projection	0.15 m (0.5 ft)	0.34 m (1.1 ft)	0.38 m (1.3 ft)	0.59 m (1.9 ft)
Ice sheet contributions	0 m	0 m	0 m	0.34 m (1.1 ft)
Atmospheric contribution	0 m	0 m	0.07 m (0.2 ft)	0.15 m (0.5 ft)
Vertical land movement (subsidence)	0 m	0 m	0.10 m (0.3 ft)	0.20 m (0.7 ft)
Total SLR	0.15 m (0.5 ft)	0.34 m (1.1 ft)	0.55 m (1.8 ft)	1.28 m (4.2 ft)

The medium SLR projections were also derived directly from Mote et al. (2008). The medium SLR estimates range from 0.15 m (0.5 ft) for 2050 and 0.34 m (1.1 ft) for 2100. Mote et al. calculated these values by averaging the six central values from the six IPCC scenarios (34 cm or 13"). No additional cryogenic or atmospheric contributions were included, nor were contributions resulting from VLM.

Mote et al. (2008) were likely overly cautious about integrating the uncertainty of new research on ice sheet dynamics. It may be appropriate to augment these projections if and when peer-reviewed publications better documenting the SLR contribution from ice sheet dynamics become available; however we declined to incorporate those numbers at this time as it seemed premature considering the recent publication of Mote et al., the general lack of consensus regarding SLR ice sheet contributions, and the high level of uncertainty associated with the speculative projections of ice sheet projections.

Uncertainty

Mote et al. (2008) explained that their calculations did not entail quantifying probabilities, and were not uniformly appropriate, nor were they intended for use at specific locations. Therefore they stated that these projections should be used for advisory purposes and not for on-the-ground predictions. It must also be noted that SLR (sea level rise) predictions are uncertain and are prone to error due to the large number of uncertainties and are therefore of unknown accuracy. Additionally, is should be recognize that the rate of global SLR is expected to increase over time (the curve is concave upward or accelerating), and the uncertainty of most sea level projections are largely focused on when it is going to occur rather than how much (Mote et al. 2008, CALFED ISB 2007).

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