

Appendix D: Sea Level Rise Analysis Details

A. Using the Sea Level Rise projections with the NOAA Sea Level Rise Viewer

Here we present a workflow for utilizing the probabilistic sea level rise projections with the NOAA Sea Level Rise (SLR) Viewer. This approach allows a community planner to either create sea level rise exposure maps for low-lying areas on the Strait of Juan de Fuca that are not mapped as part of this project (i.e. the Elwha or Dungeness River deltas, Diamond Point, Cape George), or explore particular areas or neighborhoods in greater detail.

1. Navigate to www.coast.noaa.gov/slr and use the +/- buttons to zoom to the area of interest.
2. Using Figure 18, select the community (Neah Bay/Port Angeles/Port Townsend) with a vertical land movement rate closest to that of your area of interest. After selecting this community, reference Table 4 to select a probability level and time horizon from the middle “sea level” column and find the appropriate magnitude of sea level rise. Round to the nearest whole foot.
3. Using the slide bar to the left of the screen to enter the sea level rise magnitude into the viewer.
4. Areas mapped in blue shades can be interpreted as areas vulnerable to changes in mean sea level.
5. Now select a flood magnitude from the right hand “coastal flood” column of the table that corresponds to the same time and probability level used in Step 2. Round to the nearest foot and enter in to the viewer using the slider.
6. Areas mapped in blue shades can be interpreted as areas vulnerable to annual extreme flooding.

As an example, here we map the Three Crabs Road area of the Dungeness River delta with water level at the contemporary MHHW level (Figure 1). Based on the location, this area is probably most similar to Port Townsend in terms of its vertical land movement, so the sea level rise projections for “Port Townsend” in Table 4 will be used. For this example, we map sea level at the 5% probability level for 2050, and extract a value of 1.2 feet from the Port Townsend section of the table, which is rounded to 1 foot.

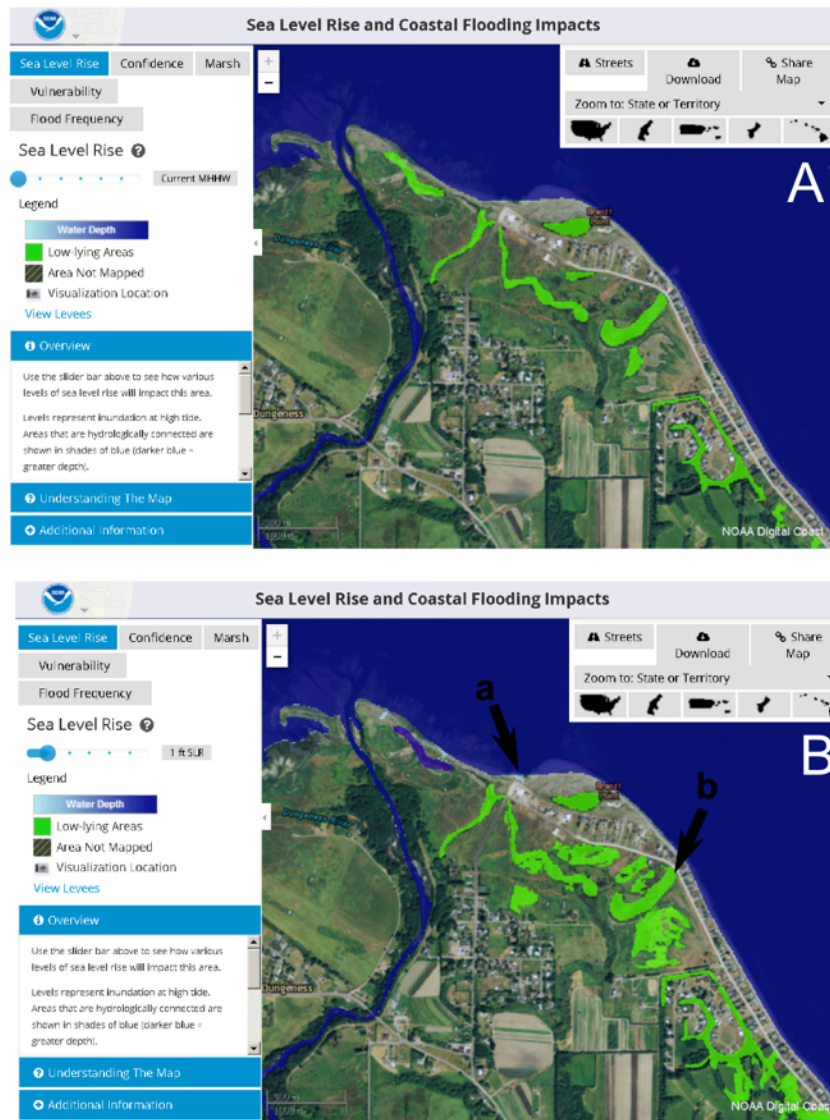


Figure 1. Example maps generated with the NOAA Sea Level Rise Viewer (<http://coast.noaa.gov/slr/>) for parts of the Dungeness River delta, Strait of Juan de Fuca. Panel A (top) shows the contemporary MHHW shoreline, with low-lying areas mapped in green, while Panel B (bottom) shows 1 foot of sea level rise. Arrow “a” shows small areas of new inundation, while “b” marks expanded low-lying areas.

The NOAA SLR Viewer simply raises sea level on top of the existing topography (i.e. it does not include estimates of erosion), and this first step suggests minor vulnerabilities to ~ 1 foot of mean sea level rise for this area (Figure 1B; disregarding any coastal erosion that may occur as a result of that sea level rise). Impacts suggested by this mapping example include some inundation, as well as expansion of “low-lying” areas, suggesting the possibility of some conversion of existing upland areas into marsh or estuarine habitat types.

To assess the annual flood risk at the same probability level (5%) and the same year (2050) a value of 3.8 feet is extracted from Table 4, which is rounded to 4 feet. The resulting map (Figure 2B) suggests that there is a reasonable chance (5% probability) that many developed parcels and

homesites could be impacted by coastal flooding by 2050 along this part of the Dungeness River delta. Comparing Figure 2B to Figure 2A, in which the contemporary annual extreme flood risk at the 5% probability level is mapped, suggests areas of new vulnerability to coastal flooding by 2050.

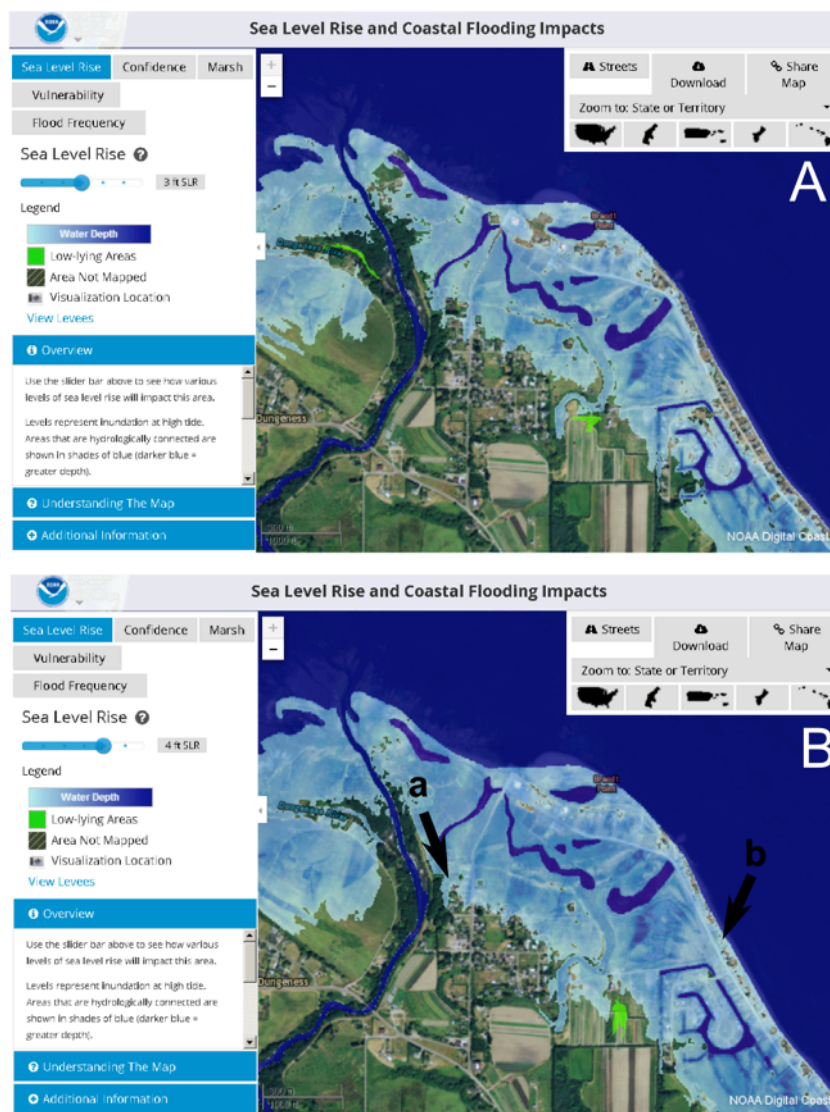


Figure 2. Example maps generated with the NOAA Sea Level Rise Viewer (<http://coast.noaa.gov/slr/>) for parts of the Dungeness River delta, Strait of Juan de Fuca. Panel A (top) shows the contemporary 5% annual extreme coastal flood level (3 feet relative to MHHW), while Panel B (bottom) shows the projected 5% annual extreme coastal flood level in 2050 (4 feet relative to the contemporary MHHW). Arrows “a” and “b” mark areas that these maps suggest may be newly exposed to coastal flooding by 2050.

B. A Comparison to other published sea level projections

In this section we compare the “base” (i.e. eustatic) sea level used in this assessment for the Strait of Juan de Fuca (derived from Kopp and others, 2014), to the global projections of Kopp and others (2014) in order to assess projected differences in sea level between regional and

global projections. We also compare the regional projections published here with two other frequently cited sea level rise assessments:

- Sea Level Rise in the Coastal Waters of Washington State, by Phil Mote, Alexander Petersen, Spencer Reeder, Hugh Shipman and Lara Whitely-Binder, published in 2008 and available at <http://cses.washington.edu/db/pdf/moteetalslr579.pdf>. The “Mote” projections, as they will be referred to below, were based on the global sea level rise projections of the IPCC’s 4th Assessment report, with minor modifications to account for regional dynamics. The “Mote” projections also use the full range of emissions scenarios as input to their sea level projections, incorporating the range of values as a loose estimate of the uncertainty in the projections.
- Sea-Level Rise for the Coasts of California, Oregon and Washington: Past, Present and Future, published by the National Academies of Science in 2012 and available at <http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington>. The “NAS” projections, as they will be referred to below, were based on the global sea level rise projections of the IPCC’s 4th Assessment report, but with an enhanced contribution from ice sheets based on extrapolating current melting rates, and with modifications to account for regional dynamics. In particular, the NAS projections for the coastal waters of the Pacific Northwest incorporate an estimate of a “sea-level” fingerprint effect due to the changing gravitational field of large ice sheets as they lose volume due to melting. The committee largely built their projections around the A1B emissions scenario, but included estimates associated with the B1 and A1F1 emissions scenarios. The committee also incorporated a quantitative estimate of uncertainty where possible.

Differences in regional projections

The Kopp and others (2014) projections that form the foundations of this assessment differ from both the Mote and NAS projections in a few fundamental ways. First, they provide the full distribution of possible sea levels in the region, and therefore provide the full range of possible sea level futures. The fully probabilistic nature of the sea level projections published here also allows other processes, like storm surge, which can be calculated in a probabilistic sense, to be mathematically integrated into the projections.

Next, the dynamics of melting ice sheets are treated differently by Kopp and others (2014) than in the previous two assessments. In Kopp and others (2014), the distribution of the possible contribution of melting ice sheets to global sea level is comprised of both a new dynamic ice sheet model incorporated into the sea level rise projections of the IPCC’s 5th Assessment Report, as well as an analysis of expert opinion about possible future extremes in ice sheet dynamics given various climate change dynamics. By contrast, the NAS projections incorporated ice melt using an extrapolation-based technique that ascribed a higher confidence to ice melt contributing more to global sea level rise over the coming century. This is reflected, in particular, in the contrast between the NAS projections for the Pacific Northwest coastal waters under the A1F1 emissions scenario, as compared to the Kopp and others (2014) “base” projections used in this assessment, based on RCP 8.5 (Figure 3). In general, the NAS projections for the A1F1 emissions scenario only overlap with the Kopp and others (2014) projections at the very upper end of the Kopp probability distribution (and lower end of the NAS projections). This discrepancy between the two sets of projections, both based on very similar emissions

scenarios, is largely due to differences in the projected “likely” contributions to sea level by melting ice sheets.

By contrast, however, unlike the NAS projections, the very large range of possible sea level (i.e. at the edges of the distribution) in the Kopp and others (2014) projections reflect the possibility that the potential contribution to global sea level by melting ice sheets may be much larger than anticipated previously. In other words, the Kopp and others (2014) projections incorporates the possibility that sea level may be much higher than the median projection due to contributions from melting ice (in Antarctica in particular). A community may take this possibility into account in their planning by utilizing a sea level scenario at the upper edge of the distribution (i.e. at the 1 or 5th percentile level), especially for high value infrastructure projects.

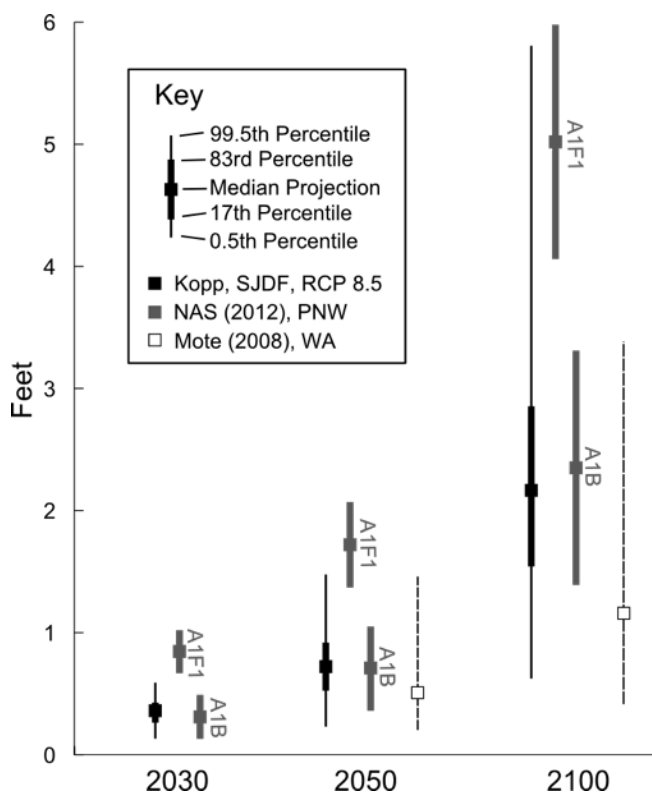


Figure 3. A comparison of sea level rise projections for 2030, 2050 and 2100 from Kopp and others (2014) for the Strait of Juan de Fuca for RCP 8.5, the National Academies of Science (2012) for A1B and A1F1 emission scenarios for the coastal waters of the Pacific Northwest, and the sea level rise assessment of Mote and others (2008) for the coastal waters of Washington State. The “Mote” projections did not include a formal quantification of uncertainty, so a dashed line is used here to indicate approximate ranges provided in their assessment.

In general, both the NAS projections, as well as the Kopp and others (2014) projections used in this assessment are both higher than the Mote projections (Figure 3). This is primarily due to the very conservative treatment of the potential contribution of melting ice sheets to global sea level rise incorporated into the IPCC’s 4th Assessment report, and integrated directly into the projections of Mote and others (2008).

Differences between regional and global projections

The sea-level “finger-printing” effect is incorporated into the projections of Kopp and others (2014) as well as the NAS projections. This effect, due to the changing gravitational influence of shrinking ice sheets on the waters of the global ocean, is expected to reduce overall sea-level rise in the Pacific Northwest and the Strait of Juan de Fuca relative to global sea level (Figure 4).

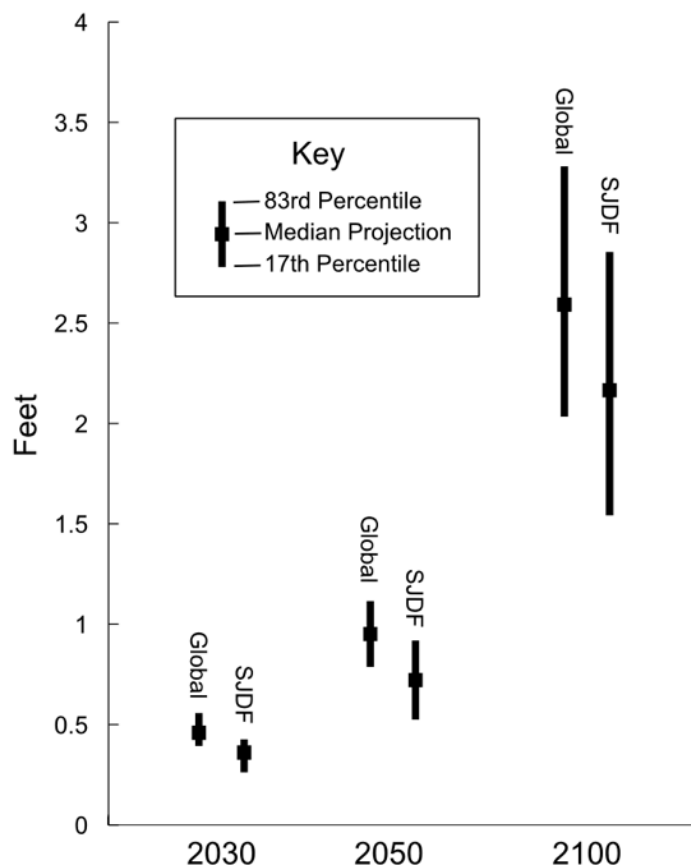


Figure 4. A comparison of the most likely ranges of global sea level rise and the projections for the Strait of Juan de Fuca (SJDF), derived from Kopp and others (2014) for 2030, 2050 and 2100.

C. Observed eustatic sea level for the Strait of Juan de Fuca

An estimate of observed “base” (or eustatic) sea level trends in the inland waters of Washington was derived by removing our project estimates of vertical land movement from time-series of average monthly water level from Friday Harbor, Neah Bay, Port Angeles, Port Townsend and Seattle (data from <http://tidesandcurrents.noaa.gov/>; shown in Figure 5, top panel). The resulting sea level time-series for each site were then averaged over the water year (October-to-October) in order to keep the winter of each year as a complete record, and fit with a regression line (Figure 5, bottom panel). The results suggest a “base” (or eustatic, irrespective of vertical movements of the land) sea level rise trend along the Strait of Juan de Fuca of 0.7 ± 0.3 mm/yr, which is equivalent to a rate of approximately 1.5 – 4 inches/century.

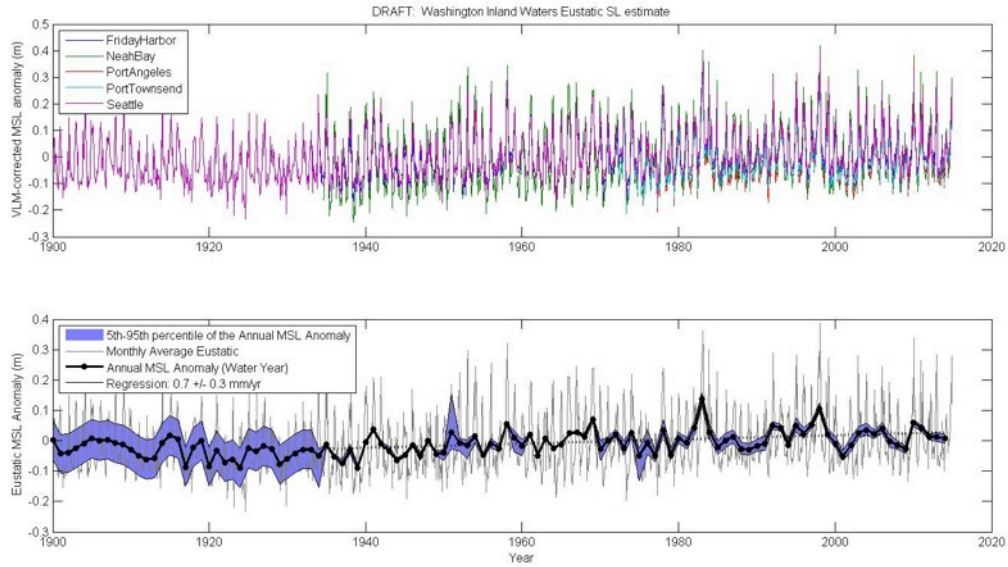


Figure 5. Monthly water level time-series from five tide stations in the inland waters of Washington, with our project estimates of vertical land movement removed (top panel). The monthly eustatic sea level estimates were averaged over the water year, providing an estimate of a local eustatic sea level time-series for the inland waters of Washington (bottom panel).

Comparing this estimate of the observed “base” (or eustatic) sea level in the inland waters of Washington state to the probabilistic projections of Kopp and others (2014; Figure 6) illustrates the importance of sea level variability in the coastal waters of Washington, especially associated with events like El Niño-Southern Oscillations (ENSOs).

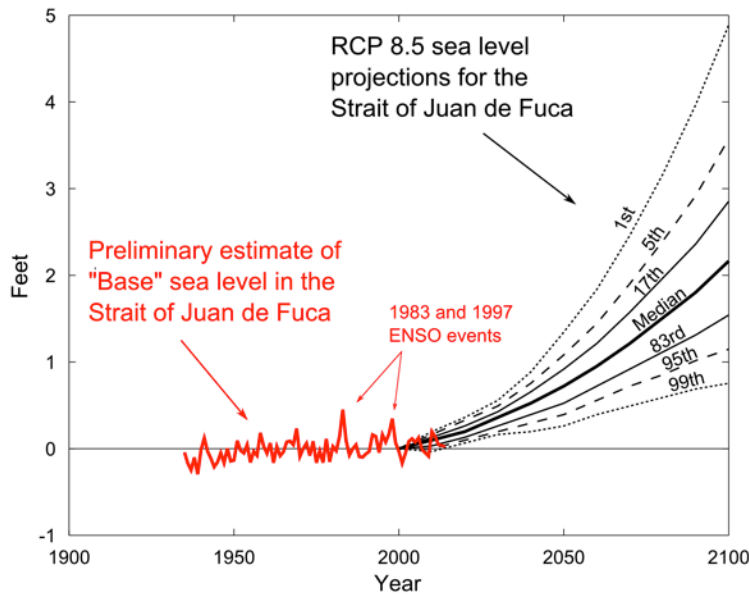


Figure 6. Observed “base” (i.e. eustatic) annually-averaged sea level in the inland waters of Washington State (red line), plotted with probabilistic sea level projections for the Strait of Juan de Fuca, based on Kopp and others (2014).

D. Sea level rise and bluff erosion

Coastal bluff erosion is influenced by a variety of processes, including surface and groundwater run-off, the geology or sedimentology of the bluff material, and marine erosion facilitated by elevated water levels and waves. Climate change is expected to influence bluff erosion rates in a variety of ways, including changing precipitation patterns, elevated sea level, and potentially changing patterns of storminess or wave magnitude. In general, though, the interplay of the various processes leading to coastal bluff erosion in a particular area are poorly understood, which leads to substantial uncertainties in reliably projecting future rates of bluff erosion. In coastal Washington State even basic information on historic rates of coastal bluff erosion are difficult to come by.

Historical bluff erosion rates along the Strait of Juan de Fuca have been estimated by Parks¹ and Kaminsky and others² for the Elwha and Dungeness Bluffs along the central Strait of Juan de Fuca, Keuler³ on the Quimper Peninsula, and the Jamestown S'Klallam Tribe (in press) for the Dungeness Bluffs and Miller Peninsula. Average short-term erosion rates for the Elwha bluffs between 2001 and 2012 were estimated to be ~0.9 feet/year, while longer-term average rates (between 1939-2001) were ~1.4 ft/yr. On the Dungeness bluffs, shorter-term (between 2001 and 2012) and longer-term (between 1939-2001) erosion rates were ~1.2 – 1.3 feet/year⁴. For both sets of bluffs, the maximum erosion rates on particular sections (not averaged over the entire length of the bluffs) exceeded 5 feet/year between 2001 and 2012, and individual instantaneous failure events are known to erode >20 feet of bluff. On the Quimper Peninsula (inclusive of bluffs on Protection Island) Keuler estimated average long-term (> 20 years) bluff erosion rates of between 0.2 and 1.0 feet/year⁵.

A variety of approaches have been applied to the problem of projecting bluff erosion rates under changing climate conditions. Revell and others⁶ simply hypothesize a correlation between the amount of time that the ocean is in contact with the toe of the bluff, and the historic erosion rate, and calculate how the erosion rate would be expected to change as sea level changes. On average, across the state of California, they estimate that an average statewide coastal bluff erosion rate of ~0.9 feet/year would increase to rates of ~1.4 feet given sea level rise of 3-4 feet. Another approach hypothesizes that the response of bluffs is dependent on the rate of sea level rise (not simply the amount that sea level changes). The application of a model based on this premise would estimate that erosion rates of coastal bluffs along the central Strait of Juan de Fuca could increase by as much as 0.2 feet/year⁷ given the sea level rise scenarios of Mote and others (Figure 3).

It should be noted that, given the complex interplay of factors influencing bluff erosion, both of the approaches described above likely have large uncertainties. In regards to the approach of Kaminsky and others⁸ for projecting future bluff erosion on the Strait of Juan de Fuca, the sea level rise projections used in their bluff erosion model are lower, with lower rates of sea level rise, than those in this report at most probability levels. Therefore, it is possible that future rates of bluff erosion could be higher than those projected by Kaminsky and others⁹ for the central Strait of Juan de Fuca.

As a general management recommendation for bluff-top construction, Parks¹⁰ suggests multiplying the long-term mean erosion rate over the time horizon of interest, and adding to that an “event-scale” buffer to account for the possibility of instantaneous bluff failures. For this

preliminary assessment we apply this approach but include estimated maximum future rates of bluff erosion (+0.2 feet/year)¹¹. Total set-backs for construction on the bluffs of the central Strait of Juan de Fuca of >145 feet for planning horizons exceeding 100 years are required to avoid risks associated with bluff erosion (Table 1).

Table 1. Bluff-top building setbacks for planning horizons of 50-125 years based on management recommendations in Parks (2015), utilizing historic (Parks 2015) and projected (Kaminsky and others 2014) bluff erosion rates for the central Strait of Juan de Fuca.

Historic Erosion Rates (ft/yr)	Future Erosion Rate (ft/yr)	Planning Horizon (yrs)	Event-scale failure (ft)	Total set back (ft)
1.2 – 1.4	1.4-1.6	50	25	95-105
1.2 – 1.4	1.4-1.6	75	25	130-145
1.2 – 1.4	1.4-1.6	100	25	165-185
1.2 – 1.4	1.4-1.6	125	25	200-225

E. Locating the Mean Higher High Water contour

For this assessment, we use the Mean Higher High Water (MHHW) tidal datum (1983-2001 epoch) in each community for locating the contemporary shoreline. For reference, the position of MHHW relative to both NAVD88 (a datum often used as the vertical datum for LiDAR-derived Digital Elevation Models (DEMs)) and MLLW (the datum most frequently used in navigational charts) is given in Table 2 below.

Table 2. The relationship between the contemporary (1983-2001 epoch) MHHW and MLLW tidal datums, and the North American Vertical Datum of 1988 (NAVD88) in feet for each coastal community on the Strait of Juan de Fuca (in feet). Values are from the NOAA Tides and Currents website, except those with an asterisk, which indicates values derived from the software VDatum¹².

	<i>MHHW relative to NAVD88</i>	<i>MHHW relative to MLLW</i>
<i>Port Townsend</i>	8.09*	8.52
<i>Port Angeles</i>	6.64	7.06
<i>Clallam Bay – Sekiu</i>	6.87*	7.47*
<i>Neah Bay</i>	7.12	7.96

¹ Parks, D. 2015. Bluff recession in the Elwha and Dungeness littoral cells, Washington, USA. Environmental and Engineering Geoscience, 21(2): 129-146.

² Kaminsky, G., Baron, H., Hacking, A., McCandless, D. and Parks, D. 2014. Mapping and monitoring bluff erosion with boat-based LIDAR and the development of a sediment budget and erosion model for the Elwha and Dungeness littoral cells, Clallam County, Washington. Project report, Washington DFW contract 12-1119.

³ KEULER, R. F., 1988, Map Showing Coastal Erosion, Sediment Supply, and Longshore Transport in the Port Townsend 30-by- 60-Minute Quadrangle, Puget Sound Region, Washington. U.S. Geologic Survey Miscellaneous Investigation Map I- 1198-E, scale 1:100,000.



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- ⁴ Parks, D. 2015. Bluff recession in the Elwha and Dungeness littoral cells, Washington, USA. Environmental and Engineering Geoscience, 21(2): 129-146.
- ⁵ Keuler, 1988
- ⁶ Revell, D.L., Battalio, R., Spear, B., Ruggiero, P. and Vandever, J. 2011. A methodology for predicting future coastal hazards due to sea-level rise on the California Coast. Climatic Change, 109 (Supplement 1): 251-276
- ⁷ Kaminsky, 2014
- ⁸ Kaminsky, 2014
- ⁹ Kaminsky, 2014
- ¹⁰ Parks, 2015
- ¹¹ Kaminsky, 2014
- ¹² NOAA. "Vertical Datum Transformation: Integrating America's Elevation Data." Available: <http://vdatum.noaa.gov/>