Sea Level Rise and Coastal Flood Risk Assessment: Island County, Washington

Ian Miller, PhD
Washington Sea Grant

Sascha Petersen, Matt Fougerat
Adaptation International

Dawn Pucci, Lori Clark, Brian Wood
Island County

adaptation international

Sea Grant Washington

Island County Public Health

Contents

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WASHINGTON STATE
RECREATION AND CONSERVATION OFFICE
Salmon Recovery
Funding Board

Investing in the Future

Residents of Island County are accustomed to change. They know that living in a coastal community on Puget Sound means that no two days will be exactly the same; some days will be calm and sunny and other days they will have to prepare for and respond to storms. This variability is just part of living on a dynamic and vibrant coast.

Having the best available information about current and future coastal flood risk can help home owners, coastal managers, and restoration partners better understand, and plan for, that risk. This is particularly important when planning for new infrastructure, siting critical facilities, and providing the appropriate space for key natural resources and species throughout the county. It makes fiscal sense to account for coastal hazards when constructing buildings, roads, water treatment plants, and other infrastructure that are designed to last for decades. It is also fiscally responsible to use the best available information when making large financial investments in salmon and watershed restoration projects. In order to protect those investments and ensure that they continue to function appropriately for their designed lifetime, it is important to consider both current and future risks.

The intent of this study is to provide the best available local information about current and future coastal flood risk in Island County and inform investment choices and planning decisions.

Overview

This assessment provides detailed relative sea level and coastal flood risk projections in a probabilistic framework to support community planning and restoration in Island County.

Rising sea levels are already affecting communities in coastal Washington State (Sweet and others, 2014), and it is nearly certain that impacts due to sea level rise will grow in the future (Petersen and others, 2015; NRC, 2012). Rising sea levels will inundate new areas of the coastline and increase the frequency and magnitude of coastal floods. To help identify those areas that will likely be affected in the future, extreme annual flood risk projections were developed for Island County. This assessment provides the following advancements over previous regional sea level assessments, notably the National Research Council's "*Sea-level rise for the coasts of California, Oregon and Washington: Past, Present and Future*" (NRC, 2012), and "*Sea level rise in the coastal waters of Washington State*", published in 2008 by the University of Washington's Climate Impacts Group and the Washington Department of Ecology (Mote and others, 2008). Specifically, the assessment for Island County includes the following:

- Presents a set of sea level rise projections in a probabilistic framework (instead of a range) based on the work of Kopp and others (2014). This approach provides more nuanced information about the uncertainty in sea level rise projections that can be useful for decision-making and planning.
- Incorporates the annual probability of extreme coastal water level events that occur typically in the winter when a high tide corresponds with a large storm surge. These processes interact with sea level rise to change the frequency or magnitude of extreme events.

- Accounts, to the degree possible based on the data available, for sub-regional variations in vertical land movement that can influence how an individual community experiences changes in local relative sea level.

The Island County assessment does not:

- Assume that patterns of storminess will change as climate changes. If changes in storminess patterns were to occur, then the magnitude or frequency of storm surges or wind-generated waves could change.
- Account for changes in vertical land movement that could be associated with a tectonic event such as a Cascadia subduction zone earthquake.
- Account for the components of water level associated with waves. Waves can "push" water higher in elevation along a shoreline. A lack of data on waves in Puget Sound prohibited its inclusion. As such, this assessment only projects "still water level", or the level of the sea as it is measured by tide gauges excluding waves.
- Project patterns of sea level variability. Annually-averaged sea level, for example, is not the same every year, it varies by up to 6-12 inches (i.e. see Figure 2) typically associated with annual differences in weather, or atmospheric/oceanic process like the El Nino-Southern Oscillation.
- Project shoreline change. The maps generated for this assessment assume a static shoreline, whereas shorelines and beaches will almost certainly evolve in response to sea level change.

All maps and elevations are provided in feet relative to the current mean higher high water tidal datum (1983-2001 epoch).

Summary of Methods

For this assessment, the Island County specific probabilistic sea level rise projections were based on: 1) the average climatically-controlled sea level projections for Seattle, Port Townsend, Friday Harbor, and Cherry Point through 2150 (from Kopp and others, 2014); 2) an estimate of the regional sea level trend associated with glacial isostatic adjustment (GIA; from Kopp and others, 2015); and 3) local vertical land movement. Coastal flood risk was calculated using historic extreme water level data from tide gauges. The sections below provide a brief summary of the approach. A full description of methodologies and data sources is provided in the "Technical Notes" section.

Climatically-controlled Regional Sea Level Projections

Kopp and others (2014) provide probabilistic projections of the climatically-controlled components of absolute sea level change for three representative concentration pathways (climate change scenarios - RCPs; 2.6, 4.5, and 8.5). These projections are based primarily on process-based modelling of the climate system[1], but due to uncertainties surrounding the contributions to future sea level from land-based ice masses in Greenland and Antarctica, are modified using an expert input process (Bamber and Aspinall, 2013). These global projections are modified to account for regional variations in sea level due to processes like "sea-level fingerprinting", in which the changing mass of land-based ice results in gravitationally-driven variations in regional sea level around the globe (Mitrovica and others, 2011).

[1] The Coupled Model Intercomparison Project, see http://cmip-pcmdi.llnl.gov/cmip5/

Glacial Isostatic Adjustment

The geologically recent retreat of the glaciers from the region is still affecting the landscape. Those change will affect the local relative rates of vertical land movement as well as the gravity based attraction of the water surrounding Island County.

Vertical Land Movement

Rates of vertical land movement for Island County were estimated using data from three continuous GPS (CGPS) stations in Island County (Category 1 stations in Figure 1). To assess regional variability in vertical land movement, data from additional stations adjacent to Island County (Category 2 & 3 stations in Figure 1) were considered, but not incorporated into the assessment. Vertical land movement rates were also estimated for four tide gauges in Washington (Seattle, Port Townsend, Friday Harbor, and Cherry Point) using data provided by NOAA[2] coupled with a vertical land movement estimate from a CGPS station (SC02) in Friday Harbor, Washington (following Santamaria-Gomez and others, 2013).

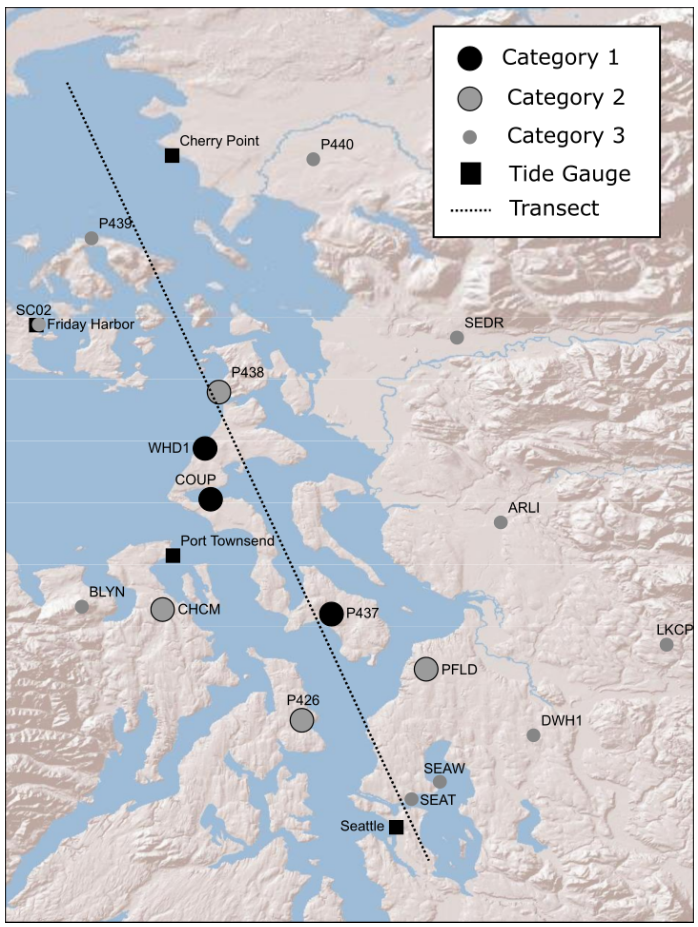


Figure 1. Map of Continuous GPS (CGPS) sites and tide stations used to assess rates of vertical land movement in Island County. *CGPS sites were categorized based on their proximity to Island County; either in Island County (Category 1), adjacent to Island County (Category 2), or distant (Category 3). Only Category 1 sites (black circles) and tide gauges (black squares) were used to quantify vertical land movement for this assessment. The dashed line is a transect along which VLM rates are plotted in Figure 3.*

[2] Available via https://tidesandcurrents.noaa.gov

Coastal Flooding

The annual extreme coastal flood hazard for Island County was estimated using historic extreme water level data from tide gauges in Seattle, Port Townsend, Friday Harbor, and Cherry Point. At this point, there is little basis for assuming that storminess patterns, and therefore coastal flooding patterns, are sensitive to climate change in Puget Sound (Mauger and others, 2015). Thus, we assumed that historical storm patterns represented in the tide gauge data could be used for future projections. For each gauge, the highest annual water level on record was fit with a generalized extreme value (GEV) distribution after the time-series was de-trended (to account for differences in vertical land movement). The resulting distribution was then coupled with relative sea level projections to derive extreme annual still water level projections through 2150.

Summary of Findings

Climatically-controlled Regional Sea Level Projections

Regional climatically-controlled sea level projections for Puget Sound for RCP8.5[3] (a high-emissions scenario) suggest a near certainty (>99.9%) that absolute sea level will rise in the region, with most sea level change occurring after 2050 (Figure 2 and Table 1). However, measurable near-term sea level rise is possible, with a 5% chance of sea level change more than 0.5 feet by 2030. By 2100 there is a strong likelihood (50% probability) of sea level rise greater than 2 feet, and extreme projections far exceed that (e.g. a 1% chance of sea level rise of about 5 feet by 2100, and a 0.1% change of sea level rise of ~8 feet by 2100). Table 3 and Table 4 provide a summary of the sea level and coastal flood risk projections for RCP 4.5 and RCP 2.6, respectively.

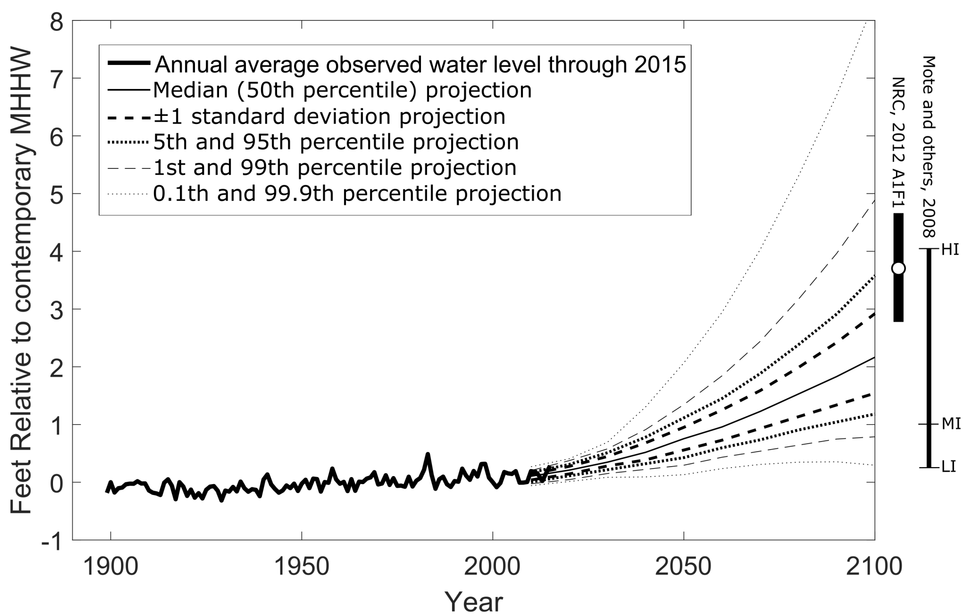


Figure 2. Absolute sea level projections for northern Puget Sound for RCP 8.5 through 2100, coupled with an estimate of the historic absolute sea level (annually-averaged) in northern Puget Sound. *For comparison, projections from two other sources are shown to the right: 1) the National Research Council's (NRC, 2012) 2100 projections for coastal Washington for the A1F1 emissions scenario (mean=circle and standard deviation=thick black line), which is most comparable to the RCP8.5 emissions scenario used here (see Mauger and others, 2015, Section 1 for an excellent discussion and comparison of emissions scenarios); and 2) Mote and others (2008) 2100 sea "high impact" (HI), "medium impact" (MI) and "low impact" (LI) sea level projections for coastal Washington.*

[3] In the Summary of Findings section all reported results will be relative to RCP8.5. Tables of relative sea level projections for RCP2.6 and RCP4.5 are included below. There is no quantitative basis upon which to estimate a likelihood of occurrence of the different RCPs.

Vertical Land Movement

The results of the vertical land movement (VLM) analysis suggest a north-to-south gradient in vertical land movement across northern and central Puget Sound (Figure 3). However, within Island County itself there is only a slight indication of vertical land movement (i.e. Category 1 CGPS sites in Figure 3). CGPS stations immediately north (P438; Figure 1) and south (PFLD, P426) of Island County do suggest subsidence, and the vertical land movement rate derived from the tide gauge in Port Townsend also suggests a small subsidence rate. Given the available information, a single vertical land movement estimate with its uncertainty (-0.4 ± 0.7 mm/yr), derived by averaging the rates from the three CPGS stations in Island County, was applied to the development of relative sea level projections.

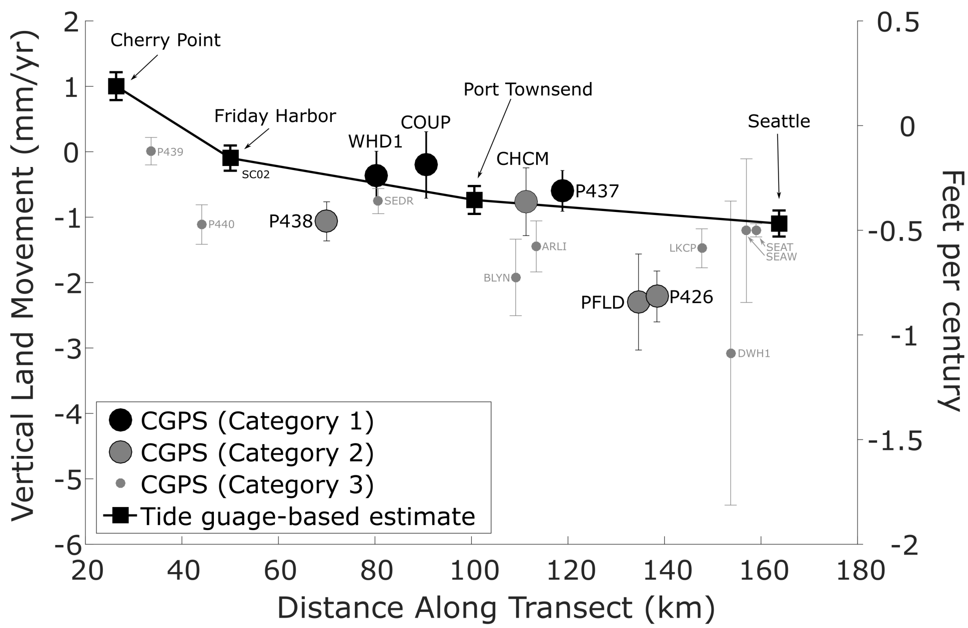


Figure 3. Vertical land movement rates utilized in this project plotted along an approximately North-to-South trending transect (see Figure 1) bisecting Island County. *Error bars are 95% confidence intervals around each vertical land movement rate estimate. Only the Category 1 CGPS stations located within Island County and the Tide Gauge data (shown in black) were used to calculate the VLM rate for this project.*

The vertical land movement rate estimate for each tide gauge also permitted the extraction of an observed absolute sea level rate from the historic relative sea level record at each tide gauge. This analysis suggests that the northern Puget Sound region has experienced absolute sea level change at a rate of 0.8±0.2 mm/yr (0.3 feet/century) since 1900 (Figure 2). This absolute sea level rise rate is lower than previous rates estimated by Mazotti and others (2008; 1.8±0.2 mm/yr). Future work is required to increase confidence in this historic absolute sea level rate estimate, though there is agreement that the region has experienced absolute sea level rise during the 20th century.

Relative Sea Level Projections

Relative sea level projections were derived by coupling the climatically-controlled sea level projections (Figure 2) with an estimate for the sea level trend associated with glacio-isostatic adjustment and the vertical land movement estimate for Island County (-0.4 ± 0.7 mm/yr). For this assessment, the GIA-driven component of sea level change is assumed to be -0.21 mm/yr (sea level fall), based on Kopp and others, (2015) and NRC (2012 – Appendix B). Given the small contributions associated with these last two factors, the relative sea level projections for a given representative concentration pathway are only slightly modified relative to the climatically-controlled sea level projections (Figure 2). Projection tables extend to 2150, though, and it is notable that sea level is almost certain to continue to rise (>99.9% chance) after 2150 (Table 1), with a 1% chance that sea level will exceed 10 feet relative to the current Mean Higher High Water (MHHW) tidal datum (1983-2001) epoch by 2150 for RCP8.5.

Table 1. Relative sea level projections for Island County, Washington for RCP8.5 *relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP 8.5)									
YEAR	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
2010	-0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3
2020	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4
2030	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7
2040	0.1	0.2	0.3	0.5	0.6	0.6	0.8	0.9	1.1	1.3
2050	0.1	0.3	0.5	0.6	0.8	0.9	1.1	1.4	1.7	2.1
2060	0.3	0.4	0.6	0.8	1.0	1.2	1.5	1.9	2.5	3.0
2070	0.3	0.6	0.8	1.1	1.3	1.5	1.9	2.5	3.4	4.1
2080	0.4	0.7	0.9	1.3	1.6	1.9	2.4	3.2	4.5	5.3
2090	0.4	0.7	1.1	1.5	1.9	2.2	3.0	4.0	5.8	6.8
2100	0.3	0.8	1.2	1.8	2.2	2.7	3.6	4.9	7.1	8.4
2110	0.8	1.1	1.4	1.9	2.4	2.9	3.9	5.6	8.4	9.8
2120	0.9	1.2	1.6	2.2	2.7	3.3	4.6	6.7	10.1	11.8
2130	0.9	1.3	1.7	2.4	3.0	3.7	5.3	7.8	11.8	13.8
2140	0.9	1.4	1.9	2.7	3.3	4.2	6.0	8.9	13.6	16.1
2150	0.9	1.4	2.0	2.9	3.7	4.6	6.8	10.1	15.7	18.5

Extreme Still Water Level Projections

To characterize the changing risks associated with annual extreme coastal flooding or high-water events, we coupled sea level projections with still water level (coastal water elevations due to tides and storm surge, but excluding waves) observations from tide gauges. We did not have access to any coastal water level observations from within Island County, so water level data from four tide gauges adjacent to Island County (Cherry Point, Friday Harbor, Port Townsend, and Seattle) were used to characterize patterns of extreme annual still water level for Island County. Note that run-up and set-up associated with waves is not considered here because of a lack of data, though it is an important factor in terms of evaluating the full hazard profile associated with extreme events.

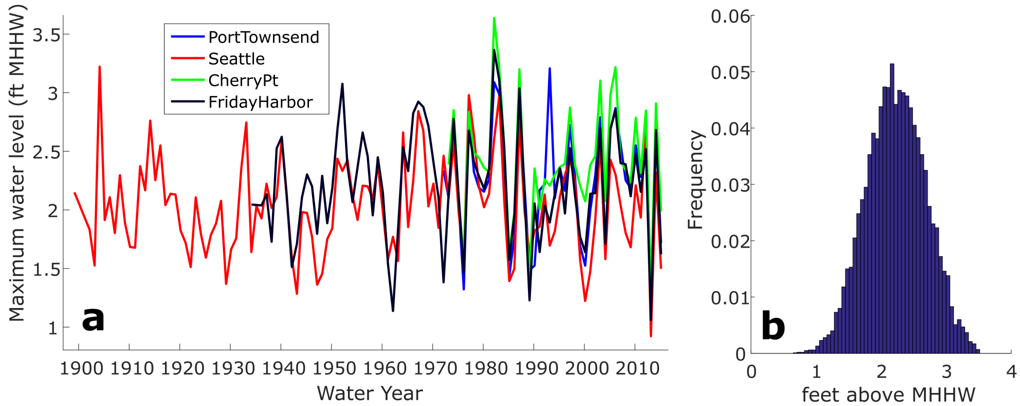


Figure 4. a) The highest water level measured each calendar year at each of four tide stations, *relative to that stations MHHW datum (1983-2001 tidal epoch), and de-trended to account for relative sea level change. Each colored line represents the associated tide gauge (blue = Port Townsend, red = Seattle, green = Cherry Point, black = Friday Harbor*. ***b) Modelled distribution of N=10,000 realizations of annual high water level*** *for a generalized extreme value distribution derived from the data in a). This model was used to incorporate the probability of annual extreme high water event coinciding with sea level change into the future.*

For each tide gauge, the single highest water level for each year of record was extracted (Figure 4a), and used to calculate a Generalized Extreme Value distribution as an estimate for the annual probability of extreme high still water events[4]. An evaluation of the distributions estimated from each of the four tide gauges suggested no basis for distinguishing regions of Island County that may be subject to different coastal flooding patterns. As a result, the four different models were averaged in order to create a single distribution (Figure 4b), which provided an estimate of the likelihood in any given year of the extreme coastal still water level.

This approach suggests a contemporary 5% annual probability (i.e. equivalent to a 1-in-20 year return frequency) of at least one occurrence where still water level will reach or exceed 3.0 feet relative to the current MHHW tidal datum, a 1% annual probability (equivalent to a 1-in-100 year return frequency) that still water level will reach 3.2 feet, or a 0.2% annual probability (equivalent to a 1-in-500 year return frequency) that still water level will reach 3.4 feet relative to the MHHW tidal datum ("Current" Row – Table 2).

For this assessment, it was assumed that the distribution of annual high water events will remain unchanged as climate changes (see discussion in Mauger and others, 2015, Section 4), and the extreme annual water level model was integrated[5] with the probabilistic relative sea level projections to derive a set of annual extreme still water level projections (Table 2). These projections give the probability, at any given decade that water level will reach a certain elevation relative to the current Mean Higher High Water tidal datum (1983-2001 epoch) at least once in a year, due to the combination of sea level rise, tides and storm surge. Table 5 and Table 6 provide a summary of the sea level and coastal flood risk projections for RCP 4.5 and RCP 2.6, respectively.

[4] This approach was selected for consistency with NOAA's approach for modelling extreme water level. See https://tidesandcurrents.noaa.gov/est/Extreme_Water_Levels_Users_Guide.pdf

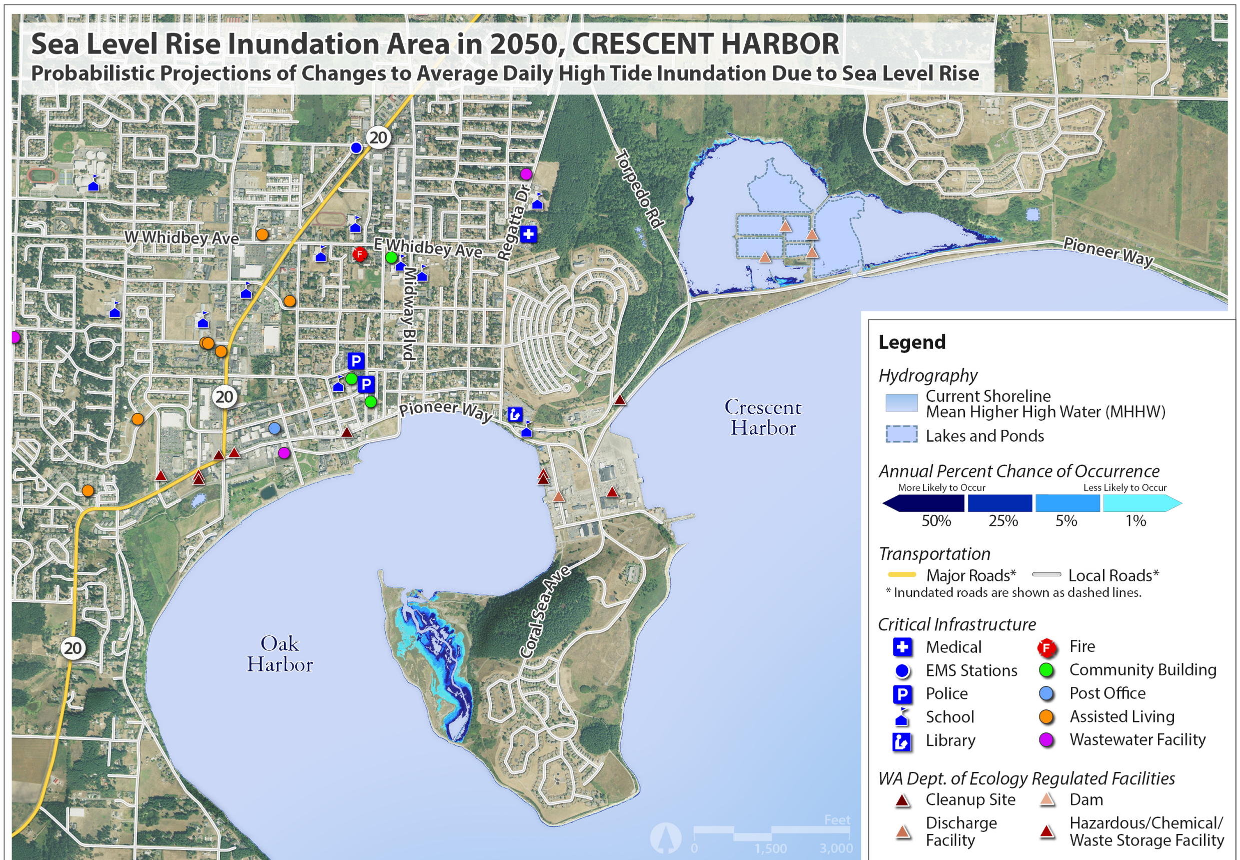
[5] See Technical Notes section for details

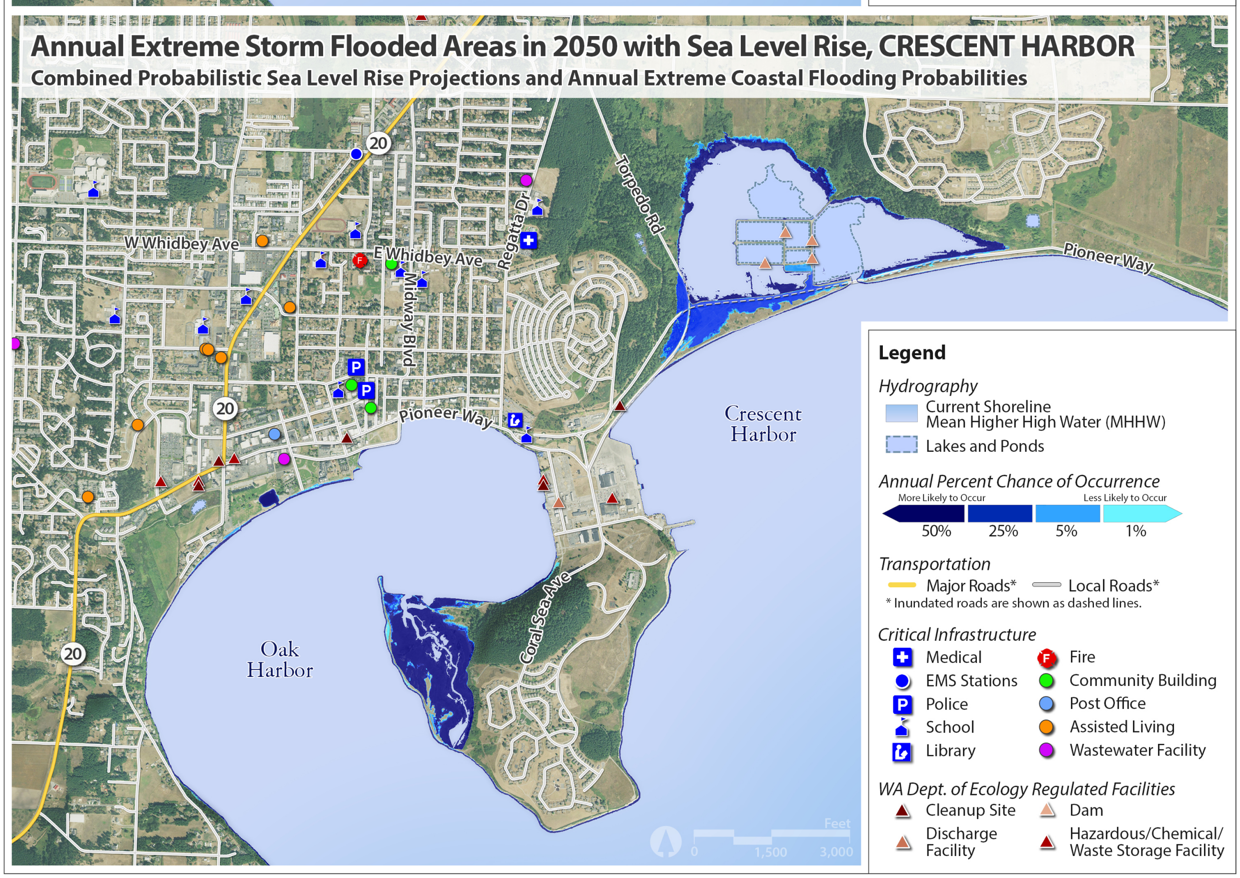
*Table 2. **Annual extreme still water level projections for Island County, Washington for RCP 8.5** relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change, and the modelled distribution of annual extreme water level based on historic records from four tide gauges. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP8.5)									
YEAR	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
Current	0.9	1.2	1.5	1.9	2.2	2.6	3.0	3.2	3.4	3.4
2010	1.0	1.3	1.6	2.0	2.3	2.6	3.1	3.3	3.5	3.5
2020	1.1	1.4	1.7	2.1	2.4	2.8	3.2	3.5	3.6	3.7
2030	1.2	1.5	1.8	2.3	2.6	2.9	3.4	3.6	3.8	3.8
2040	1.3	1.7	2.0	2.4	2.8	3.1	3.6	3.8	4.0	4.1
2050	1.5	1.8	2.2	2.6	3.0	3.3	3.8	4.2	4.5	4.7
2060	1.7	2.0	2.4	2.9	3.2	3.6	4.1	4.5	5.0	5.3
2070	1.8	2.2	2.6	3.1	3.5	3.9	4.5	5.0	5.8	6.4
2080	2.0	2.4	2.8	3.4	3.8	4.2	4.9	5.7	6.9	7.7
2090	2.1	2.5	3.0	3.6	4.1	4.6	5.4	6.4	8.0	9.2
2100	2.2	2.7	3.2	3.9	4.4	5.0	6.0	7.3	9.3	10.9
2110	2.4	2.9	3.3	4.1	4.6	5.2	6.3	7.9	10.6	12.0
2120	2.6	3.1	3.6	4.3	4.9	5.6	7.0	9.0	12.1	14.3
2130	2.7	3.2	3.7	4.6	5.2	6.0	7.6	10.0	14.0	15.9
2140	2.6	3.3	3.9	4.8	5.6	6.4	8.4	11.1	15.8	18.0
2150	2.7	3.3	4.0	5.1	5.9	6.9	9.1	12.4	17.8	20.5

Maps

In order to help illustrate how these projected increases in coastal water levels will affect coastal communities around Island County, the project team created maps for five focus areas: Crescent Harbor, Crockett Lake, Moran Beach, Livingston Bay, and Useless Bay. These maps are based on the probabilistic projections for RCP 8.5 (Table 1 and Table 2) and show scenarios for *Sea Level Rise Inundation Areas* as well as *Annual Extreme Storm Flooded Areas with Sea Level Rise* for the years 2030, 2050, and 2100. Additionally, projections of *Storm Surge Today* were generated for each focus area in order to establish a baseline for comparison. Finally, for each time period, elevation values representing the 50%, 25%, 5%, and 1% annual percent chance of occurrence were taken from the exceedance tables (Table 1 and Table 2) and then mapped using high resolution LiDAR (Light Distance And Ranging) derived digital elevation models (DEMs). The most recent LiDAR based elevation data available for the county was from 2014. The figures below contain pairs of maps for each focus area for 2050s. The upper (or left most) map shows the *Sea Level Rise Inundation* probabilities and the lower (or right most) map shows the *Annual Extreme Storm Flooded Areas with Sea Level Rise*. The full set of maps for each location is available through Island County.


Sea Level Rise Inundation Area in 2050, CRESCENT HARBOR
Probabilistic Projections of Changes to Average Daily High Tide Inundation Due to Sea Level Rise
W Whidbey Ave
E Whidbey Ave
Midway Blvd
Regatta Dr
Torpedo Rd
Pioneer Way
Coral Sea Ave
20
Oak Harbor
Crescent Harbor
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50%
25%
5%
1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Medical
EMS Stations
Police
School
Library
Fire
Community Building
Post Office
Assisted Living
Wastewater Facility
WA Dept. of Ecology Regulated Facilities
Cleanup Site
Discharge Facility
Dam
Hazardous/Chemical/ Waste Storage Facility
Feet
0
1,500
3,000


Annual Extreme Storm Flooded Areas in 2050 with Sea Level Rise, CRESCENT HARBOR
Combined Probabilistic Sea Level Rise Projections and Annual Extreme Coastal Flooding Probabilities
W Whidbey Ave
E Whidbey Ave
Midway Blvd
Regatta Dr
Torpedo Rd
Pioneer Way
Coral Sea Ave
20
Oak Harbor
Crescent Harbor
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Hydrography
Current Shoreline Mean Higher High Water (MHHW)
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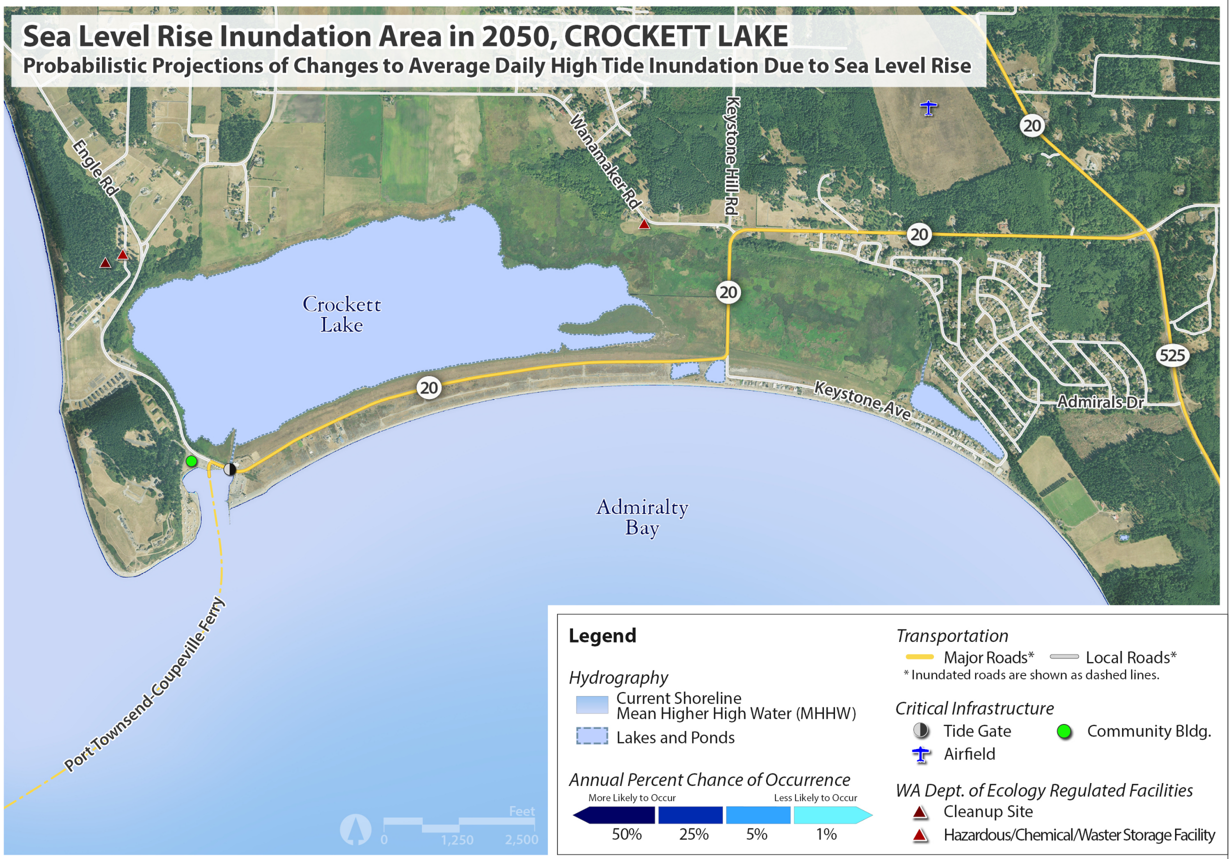
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Medical
EMS Stations
Police
School
Library
Fire
Community Building
Post Office
Assisted Living
Wastewater Facility
WA Dept. of Ecology Regulated Facilities
Cleanup Site
Discharge Facility
Dam
Hazardous/Chemical/ Waste Storage Facility
Feet
0
1,500
3,000

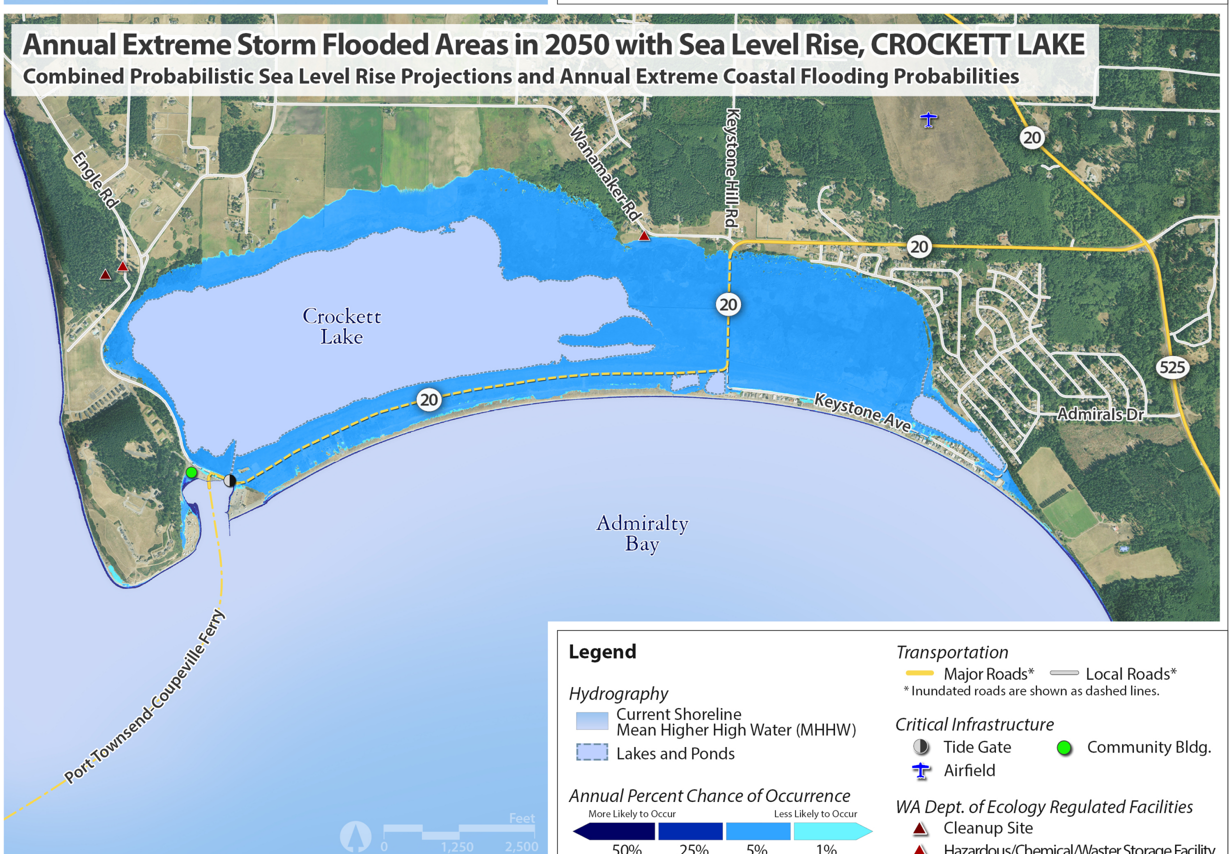
Sea Level Rise Inundation Area in 2050, CROCKETT LAKE

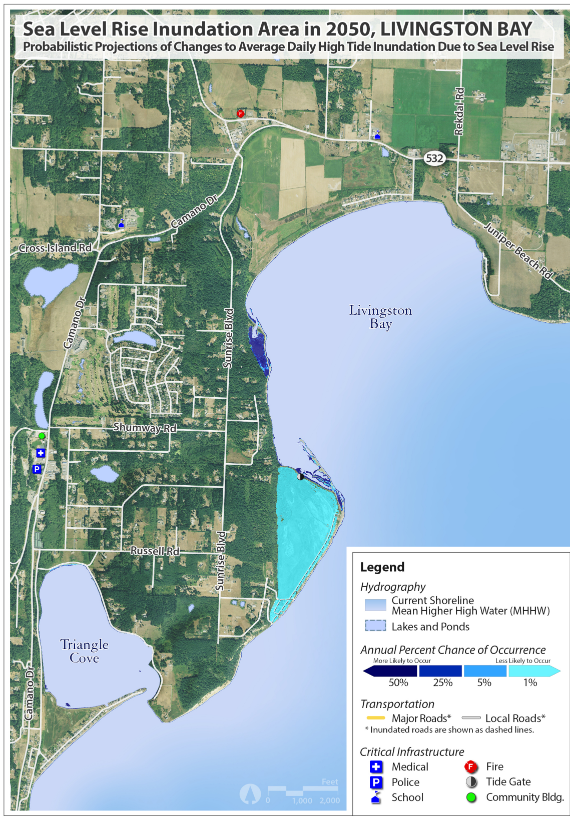
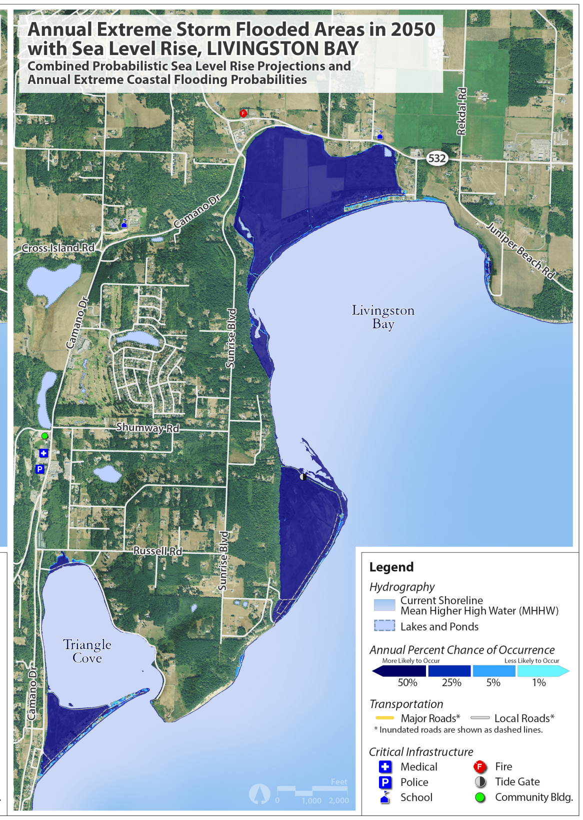
Probabilistic Projections of Changes to Average Daily High Tide Inundation Due to Sea Level Rise



Annual Extreme Storm Flooded Areas in 2050 with Sea Level Rise, CROCKETT LAKE

Combined Probabilistic Sea Level Rise Projections and Annual Extreme Coastal Flooding Probabilities




Sea Level Rise Inundation Area in 2050, LIVINGSTON BAY
Probabilistic Projections of Changes to Average Daily High Tide Inundation Due to Sea Level Rise
Rekdal Rd
532
Camano Dr
Cross Island Rd
Juniper Beach Rd
Livingston Bay
Sunrise Blvd
Shumway Rd
Russell Rd
Triangle Cove
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50%
25%
5%
1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Medical
Fire
Police
Tide Gate
School
Community Bldg.
Feet
0
1,000
2,000

Annual Extreme Storm Flooded Areas in 2050 with Sea Level Rise, LIVINGSTON BAY
Combined Probabilistic Sea Level Rise Projections and Annual Extreme Coastal Flooding Probabilities
Rekdal Rd
532
Camano Dr
Cross Island Rd
Juniper Beach Rd
Livingston Bay
Sunrise Blvd
Shumway Rd
Russell Rd
Triangle Cove
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
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Annual Percent Chance of Occurrence
More Likely to Occur
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Transportation
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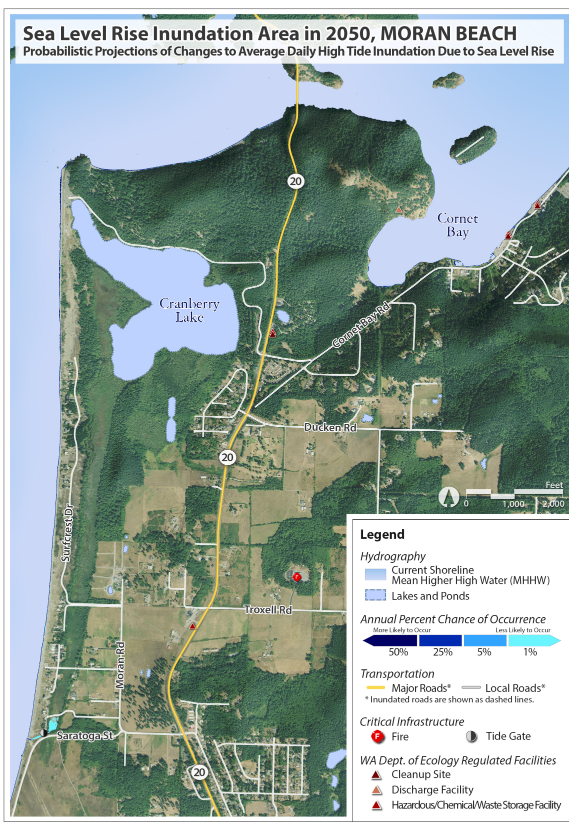
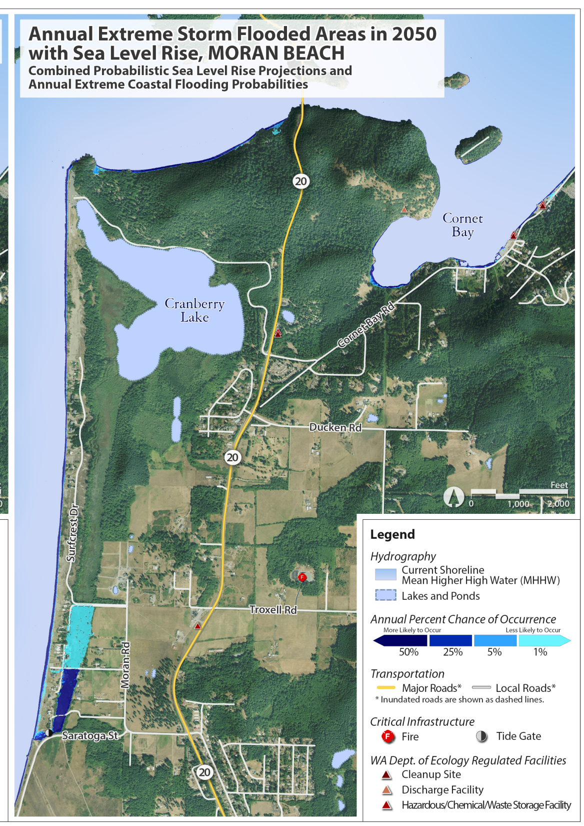
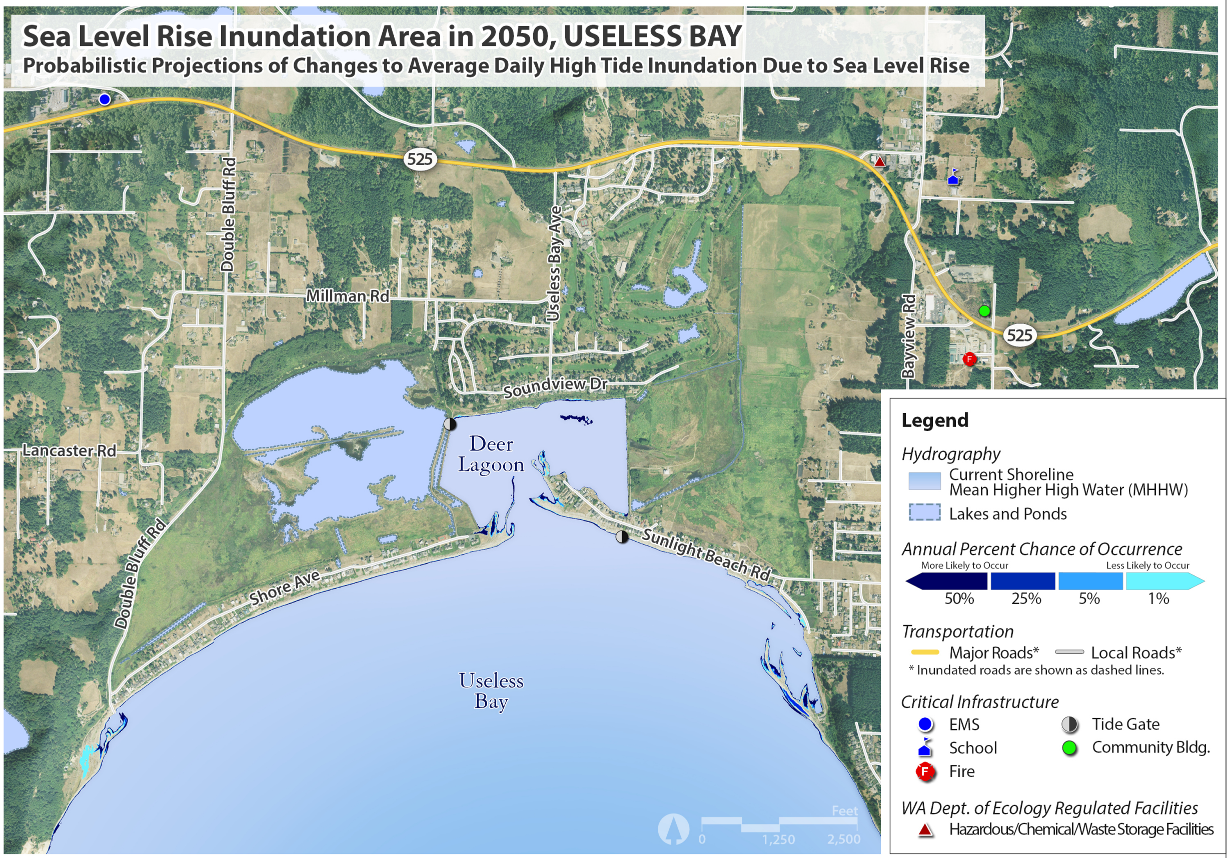
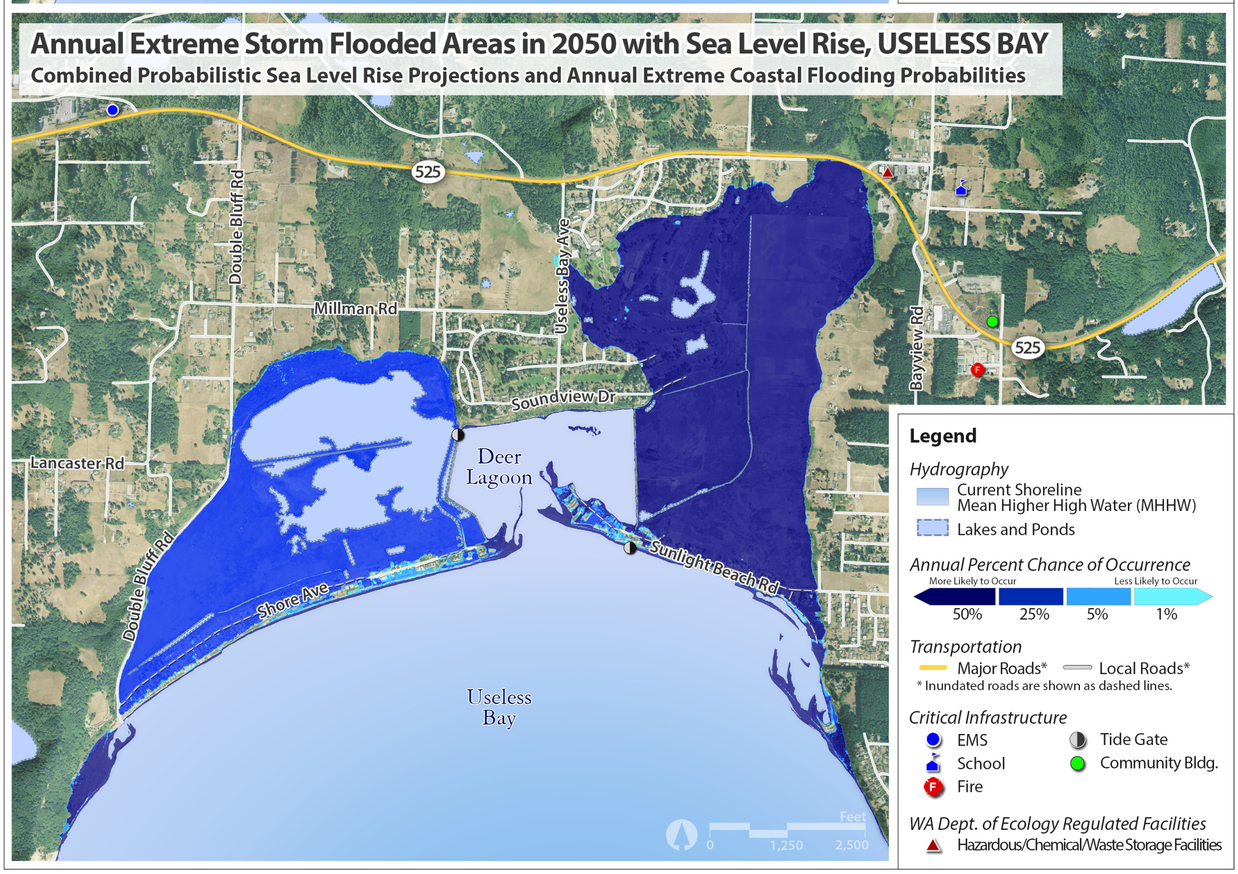
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Medical
Fire
Police
Tide Gate
School
Community Bldg.
Feet
0
1,000
2,000

Sea Level Rise Inundation Area in 2050, MORAN BEACH
Probabilistic Projections of Changes to Average Daily High Tide Inundation Due to Sea Level Rise
20
Cornet Bay
Cranberry Lake
Cornet Bay Rd
Ducken Rd
Surfcrest Dr
Troxell Rd
Moran Rd
Saratoga St
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50%
25%
5%
1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Fire
Tide Gate
WA Dept. of Ecology Regulated Facilities
Cleanup Site
Discharge Facility
Hazardous/Chemical/Waste Storage Facility
Feet
0
1,000
2,000

Annual Extreme Storm Flooded Areas in 2050 with Sea Level Rise, MORAN BEACH
Combined Probabilistic Sea Level Rise Projections and Annual Extreme Coastal Flooding Probabilities
20
Cornet Bay
Cranberry Lake
Cornet Bay Rd
Ducken Rd
Surfcrest Dr
Troxell Rd
Moran Rd
Saratoga St
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50%
25%
5%
1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
Fire
Tide Gate
WA Dept. of Ecology Regulated Facilities
Cleanup Site
Discharge Facility
Hazardous/Chemical/Waste Storage Facility
Feet
0
1,000
2,000


Sea Level Rise Inundation Area in 2050, USELESS BAY
Probabilistic Projections of Changes to Average Daily High Tide Inundation Due to Sea Level Rise
525
Double Bluff Rd
Useless Bay Ave
Millman Rd
Bayview Rd
Soundview Dr
Lancaster Rd
Deer Lagoon
Sunlight Beach Rd
Shore Ave
Useless Bay
Feet
0 1,250 2,500
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50% 25% 5% 1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
EMS
School
Fire
Tide Gate
Community Bldg.
WA Dept. of Ecology Regulated Facilities
Hazardous/Chemical/Waste Storage Facilities


Annual Extreme Storm Flooded Areas in 2050 with Sea Level Rise, USELESS BAY
Combined Probabilistic Sea Level Rise Projections and Annual Extreme Coastal Flooding Probabilities
525
Double Bluff Rd
Useless Bay Ave
Millman Rd
Bayview Rd
Soundview Dr
Lancaster Rd
Deer Lagoon
Sunlight Beach Rd
Shore Ave
Useless Bay
Feet
0 1,250 2,500
Legend
Hydrography
Current Shoreline Mean Higher High Water (MHHW)
Lakes and Ponds
Annual Percent Chance of Occurrence
More Likely to Occur
Less Likely to Occur
50% 25% 5% 1%
Transportation
Major Roads*
Local Roads*
* Inundated roads are shown as dashed lines.
Critical Infrastructure
EMS
School
Fire
Tide Gate
Community Bldg.
WA Dept. of Ecology Regulated Facilities
Hazardous/Chemical/Waste Storage Facilities

Relative Sea Level Projection Tables RCP 4.5 and RCP 2.6

These tables provide a summary of the sea level rise and coastal flood risk projections for two additional climate scenarios (RCP 4.5 and RCP 2.6).

Table 3. Relative sea level projections for Island County, Washington for RCP 4.5 *relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP 4.5)									
Year	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
2010	-0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2
2020	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4
2030	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.7
2040	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.2
2050	0.1	0.3	0.4	0.6	0.7	0.8	1.0	1.3	1.6	1.9
2060	0.1	0.3	0.5	0.7	0.9	1.1	1.4	1.7	2.3	2.7
2070	0.1	0.4	0.6	0.9	1.1	1.3	1.7	2.2	3.2	3.6
2080	0.2	0.5	0.7	1.1	1.3	1.6	2.1	2.8	4.1	4.7
2090	0.2	0.5	0.8	1.2	1.5	1.9	2.5	3.5	5.2	6.0
2100	0.1	0.5	0.9	1.4	1.7	2.2	3.0	4.2	6.4	7.4
2110	0.1	0.6	0.9	1.5	1.9	2.4	3.4	5.0	7.7	8.9
2120	0.1	0.6	1.0	1.7	2.1	2.7	3.9	5.8	9.1	10.6
2130	0.1	0.6	1.0	1.8	2.3	3.0	4.4	6.7	10.6	12.4
2140	-0.1	0.5	1.0	1.9	2.6	3.3	4.9	7.7	12.3	14.3
2150	-0.1	0.5	1.1	2.0	2.8	3.6	5.5	8.7	13.9	16.4

Table 4. Relative sea level projections for Island County, Washington for RCP 2.6 *relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP 2.6)									
Year	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
2010	-0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3
2020	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4
2030	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.7
2040	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.2
2050	0.1	0.2	0.4	0.6	0.7	0.8	1.0	1.3	1.7	1.9
2060	0.1	0.3	0.5	0.7	0.9	1.0	1.3	1.7	2.3	2.6
2070	0.2	0.4	0.6	0.8	1.0	1.2	1.6	2.1	3.2	3.6
2080	0.1	0.4	0.6	0.9	1.2	1.4	1.9	2.7	4.1	4.7
2090	0.1	0.4	0.7	1.0	1.3	1.6	2.3	3.3	5.2	5.9
2100	0.0	0.4	0.7	1.2	1.5	1.9	2.8	4.1	6.4	7.3
2110	0.3	0.6	0.8	1.2	1.6	2.0	3.0	4.7	7.5	8.7
2120	0.3	0.6	0.8	1.3	1.7	2.2	3.4	5.5	8.8	10.3
2130	0.4	0.6	0.9	1.4	1.9	2.4	3.9	6.4	10.3	12.1
2140	0.4	0.6	0.9	1.5	2.0	2.7	4.4	7.3	11.9	14.1
2150	0.2	0.6	0.9	1.5	2.2	2.9	4.9	8.3	13.6	16.2

*Table 5. **Annual extreme still water level projections for Island County, Washington for RCP4.5** relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change, and the modelled distribution of annual extreme water level based on historic records from four tide gauges. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP 4.5)									
Year	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
Current	0.9	1.2	1.5	1.9	2.2	2.5	3.0	3.2	3.4	3.4
2010	1.0	1.3	1.6	2.0	2.3	2.6	3.1	3.3	3.5	3.6
2020	1.0	1.4	1.7	2.1	2.4	2.8	3.2	3.5	3.6	3.7
2030	1.2	1.5	1.8	2.3	2.6	2.9	3.4	3.6	3.8	3.9
2040	1.4	1.7	2.0	2.4	2.8	3.1	3.5	3.8	4.0	4.1
2050	1.5	1.8	2.1	2.6	2.9	3.3	3.8	4.1	4.4	4.5
2060	1.6	2.0	2.3	2.8	3.1	3.5	4.0	4.4	4.9	5.2
2070	1.7	2.1	2.4	3.0	3.3	3.7	4.3	4.8	5.5	6.2
2080	1.8	2.2	2.6	3.2	3.6	4.0	4.6	5.3	6.5	7.1
2090	1.8	2.3	2.7	3.3	3.8	4.2	5.0	5.9	7.4	8.4
2100	1.8	2.3	2.8	3.5	4.0	4.5	5.4	6.6	8.5	9.8
2110	1.8	2.4	2.9	3.7	4.2	4.8	5.8	7.3	9.9	11.3
2120	1.9	2.5	3.0	3.8	4.4	5.0	6.3	8.1	11.4	12.9
2130	1.9	2.5	3.1	3.9	4.6	5.3	6.8	9.1	12.7	14.6
2140	1.8	2.4	3.1	4.0	4.8	5.6	7.3	10.0	14.4	16.7
2150	1.8	2.5	3.1	4.2	5.0	5.9	7.8	10.9	16.3	18.5

*Table 6. **Annual extreme still water level projections for Island County, Washington for RCP2.6** relative to the current MHHW tidal datum (1983-2001 epoch), accounting for the climatically-controlled components of sea level change, coupled with vertical land movement, and GIA-driven sea level change, and the modelled distribution of annual extreme water level based on historic records from four tide gauges. Numbers are in feet above the current MHHW level.*

	Probability of Exceedance (RCP 2.6)									
Year	**99.9**	**99**	**95**	**75**	**50**	**25**	**5**	**1**	**0.2**	**0.1**
Current	0.9	1.2	1.5	1.9	2.2	2.6	3.0	3.2	3.4	3.4
2010	1.0	1.3	1.6	2.0	2.3	2.6	3.1	3.4	3.5	3.6
2020	1.1	1.4	1.7	2.1	2.4	2.8	3.2	3.5	3.6	3.7
2030	1.2	1.5	1.8	2.3	2.6	2.9	3.4	3.6	3.8	3.9
2040	1.3	1.7	2.0	2.4	2.7	3.1	3.5	3.8	4.0	4.1
2050	1.4	1.8	2.1	2.6	2.9	3.3	3.7	4.1	4.3	4.5
2060	1.5	1.9	2.2	2.7	3.1	3.4	4.0	4.4	4.8	5.1
2070	1.7	2.0	2.3	2.9	3.2	3.6	4.2	4.7	5.5	6.1
2080	1.7	2.1	2.5	3.0	3.4	3.8	4.5	5.2	6.4	7.1
2090	1.7	2.1	2.5	3.1	3.6	4.0	4.8	5.8	7.3	8.4
2100	1.7	2.2	2.6	3.3	3.8	4.3	5.2	6.5	8.7	9.9
2110	1.9	2.3	2.7	3.4	3.8	4.4	5.4	7.1	9.7	11.1
2120	1.9	2.3	2.8	3.5	4.0	4.6	5.8	7.8	11.0	12.9
2130	2.0	2.4	2.8	3.6	4.1	4.8	6.3	8.7	12.5	14.7
2140	1.9	2.4	2.9	3.7	4.3	5.0	6.7	9.5	14.2	16.6
2150	1.9	2.4	2.9	3.7	4.4	5.2	7.2	10.5	15.8	18.6

Glossary and Description of Terms

Absolute Sea Level (ASL): The long-term (multi-decadal) average level of the ocean relative to an absolute reference frame, and irrespective of the vertical position of the land. In this report, ASL is conceptualized as being modified by climatically-controlled sea level change (see below), as well as small rates of sea level change associated with GIA (see below).

Climatically-controlled sea level: This is a concept drawn from Kopp and others (2014) that is intended to describe those portions of absolute sea level change that are modified by climate change, primarily the contributions to sea level from the melting of land-based ice, and the expansion of sea water as it warms.

Continuous GPS: Also known as Continuously Operating Reference Stations (CORS), these fixed, continuously operating GPS receivers provide Global Navigation Satellite System (GNSS) data in support of three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States.

Generalized Extreme Value (GEV) **Distribution**: A family of continuous probability distributions developed with extreme value theory and frequently used for modelling the return frequency of coastal water levels.

Glacio-isostatic adjustment (GIA): The long-term (many millennia) response of the Earth system to the global redistribution of ice and water associated with deglaciation after the last glacial maximum about 20,000 years ago. GIA has a vertical land movement component, and also a gravitational component, that can modify absolute sea level.

IGS08: A global (absolute) reference system based on Global Navigation Satellite System (GNSS) and designed to be consistent with ITRF2008 positions. The ITRF2008 positions of a particular site may differ from its corresponding IGS08 position but their velocities remain identical[6].

Mean Higher High Water (MHHW**):** Coastal Washington state experiences a mixed semi-diurnal tidal pattern, with two unequal low and high tides per day. Mean higher high water is the average of the highest water level each tidal cycle over the period of interest. An official MHHW tidal datum is established by NOAA for each tide station by averaging over a designated 19.6-year period (an "epoch"). Tidal datums for stations in coastal Washington are currently referenced to the 1983-2001 epoch.

Relative Sea Level (RSL): Relative sea level is defined simply as the *long-term average level of the ocean relative to the land*.

Representative Concentration Pathways (RPCs): RCPs are greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.

Still Water Level (SWL): The level of the ocean associated with tides and storm surge, excluding processes (set-up and run-up) associated with waves.

Vertical Land Movement (VLM): The multi-decadal rate of change of the surface of the land relative to an absolute reference frame.

[6] See https://igscb.jpl.nasa.gov/network/refframe.html

Technical Notes

Relative sea level is composed of the following two components.

- Absolute Sea Level (ASL) is the ocean water level measured in a geocentric reference frame (i.e. relative to the center of the earth, and independent of any movements of the land). Considered over the entire globe and over long time-scales (multiple decades) changes in ASL are driven by climatically-controlled processes like the melting of land-based ice and the expansion of seawater as it warms. Global ASL change is modified regionally by a variety of processes like "sea-level fingerprinting", and glacio-isostatic adjustment.
- Vertical Land Movement (VLM) is the movement of the land in the vertical dimension. In the coastal Pacific Northwest, tectonic deformation generally accounts for most vertical land movement, with GIA accounting for a smaller component (Burgette and others, 2009).

Sea level rise (SLR) projections are typically provided in a geocentric reference frame and have historically been focused on changes to global average sea level. In order to provide relative sea level projections at the community-scale, they must take into account processes that modify regional sea level and be coupled with estimates of vertical land movement.

Sea Level Change Projections

Changes in absolute sea level driven by climate change (known as the "climatically-controlled" components) are driven largely by two processes:

1. Melting of land-based ice, particularly in Greenland and Antarctica.
2. The expansion of sea water as it warms (known as "thermosteric" effects).

To be credible at the regional level, these projections must take into account processes that modify global absolute sea level and give it a unique regional expression. These process include:

1. Global variations in heat and salinity that lead to regional differences in the thermosteric component of sea level change, here called "oceanographic processes" (after Kopp and others, 2015);
2. "Sea-level fingerprinting" due to the uneven distribution of water around the globe as land-based ice melts (NRC, 2012); and
3. Multi-decadal variations in wind (Moon and others 2013) or sea level pressure (Johnstone and Mantua, 2014) may modify regional sea level. These factors are not explicitly incorporated into sea level projections due to uncertainties about their temporal scale and relative long-term importance in driving sea level change.

Kopp and others (2014) constructed projections of climatically-controlled sea level change for three different scenarios (RCP 2.6, 4.5, and 8.5). The components of ASL change related to the melting of land-based ice were derived from the projections of the IPCC AR5, but modified (especially at the tails of the distribution) using expert input (see Kopp and others, 2014). The global sea level contributions from the melting of land-based ice were then modified to account for regional variations due to "sea-level fingerprinting".

Regional variations in absolute sea level attributable to oceanographic processes are projected using global climate model output from the Coupled Model Intercomparison Project 5. Kopp and others (2014) modified the projections within a region by using the model output from the nearest ocean grid cell value, where each grid cell has a resolution of ~ 1 degree. This approach may not take into account sea level variations driven by local currents, winds, or bathymetry, but offers a rigorous approach for projecting regional variations in absolute sea level due to oceanographic processes.

Sea Level Rise Approach

Projection tables, with their "background rate"[7] removed, were downloaded using the LocalizeSL package[8] for Seattle, Port Townsend, Cherry Point, and Friday Harbor. These tables represent many realizations (N=10,000) of projected "climatically-controlled sea level" for each of the four locations, accounting for the uncertainty in the multiple source terms (melting of Antarctica and Greenland, thermosteric components, regional modifications due to sea-level finger-printing, etc.). The individual tables for each location are combined into a master table (N=40,000), from which a set of exceedance percentiles for each decade are extracted (i.e. see Figure 1). Probabilities of exceedance selected for all tables in this project are 99.9, 99, 95, 75, 50, 25, 5, 1, 0.2 (selected specifically to coincide with probabilities of interest in FEMA's RiskMap process) and 0.1%.

Vertical Land Movement (VLM) Analysis

Vertical land movement was estimated for the project area using the following two data sources.

1) Continuous GPS (CGPS) data from sites in and adjacent to Island County. CGPS data provide a direct estimate of vertical land movement in a geocentric reference frame, but rates are typically derived from relatively short records (the oldest date back to the mid-1990's, most are younger). Additionally, regional variations in vertical land movement are not always easily explained, suggesting that the formal error estimates associated with vertical rates as provided by CGPS do not capture the full uncertainty in these data.
2) Tide gauge data from stations adjacent to Island County, Washington.

A description of the specific methodology used for each source of information follows. There is uncertainty regarding the temporal variability in rates of vertical land movement (NRC, 2012 – Chapter 4); in the seismically-active Pacific Northwest, for example, earthquakes can dramatically alter patterns of vertical land movement. For this project, the rates of vertical land movement derived from CGPS and from tide gauges were assumed to apply to future projections (i.e. potential vertical land movements associated with earthquakes or other tectonic processes were not taken into account).

Continuous GPS

Continuous GPS (CGPS) data was obtained from NASA's Jet Propulsion Laboratory[9] for a set of 17 CGPS sites located in or adjacent to Island County. CGPS sites were then categorized according to whether they were in Island County (Category 1), outside of but within a 20 km buffer around Island County (Category 2), or more than 20km away from Island County (Category 3; see Figure

[7] Kopp and others (2014) estimate a "background rate" of relative sea level change for each tide gauge that attempts to account for GIA (both the VLM and GLS components), vertical land movement due to tectonics and other "non-climatic effects". While a useful tool for global analysis, given the spatial variability of vertical land movement in the Pacific Northwest the approach outlined here relies on direct measurements of vertical land movement to reduce uncertainty.

[8] Available at http://zenodo.org/record/27485#.VtiNYpwrKUk

[9] http://sideshow.jpl.nasa.gov/post/series.html

1). The estimated geodetic vertical rate and uncertainty (the 95% confidence interval a linear regression slope) was obtained for each station[10]. Vertical rates are calculated from daily high-accuracy position estimates for each station after a process to remove outliers and to remove "breaks" in the data[11]. Vertical rates are then derived by a process of linear regression to the station's daily position estimates referenced to an absolute reference frame (IGS08).

Tide Gauge-based VLM Rate Estimates

Following Santamaria-Gomez and others (2013), the long-term relative sea level trend at a particular tide gauge may be written as:

$$RSL = ASL + VLM + E \qquad (1)$$

Where RSL is the relative sea level trend at a tide gauge, ASL is the absolute sea level change rate, VLM is the vertical velocity of the tide gauge in a geocentric reference frame, and E is a term that encompasses all of the unaccounted for error due in particular to short-term sea level variability or water level measurement error. Typically, the error term *E* is quite large for an individual tide gauge in the Pacific Northwest due to long-term water level variability; seasonal, annual, or over longer-time scale variation in sea level due to factors like El Nino-Southern Oscillation, typical storm season variability, or longer term climate oscillations (like the Pacific Decadal Oscillation). This substantial variability can obscure the vertical land movement and absolute sea level trends affecting the long-term water level at a tide gauge.

One approach for addressing the large source of error "E" is to difference the monthly water level records from nearby tide gauges, effectively removing the shared components of sea level between the stations (which would include both the short-term sea level variability, as well as most or all of the long-term absolute sea level change), such that Equation 1 can be written as:

$$\Delta RSL = \Delta ASL + RVLM + e \qquad (2)$$

Where ΔRSL now represents the difference in relative sea level change between two nearby tide gauges, ΔASL is any difference in the long-term rate of absolute sea level change between stations, RVLM is the difference in vertical land movement between the two stations (called *Relative Vertical Land Movement*), and e is the error represented by the residual sea level variability (which we interpret as being primarily measurement error in the monthly average sea level at a tide gauge). For nearby tide gauges, and especially those within semi-enclosed seas, a valid assumption can be made that the difference in ASL between tide gauges (the term ΔASL) is zero (Santamaria-Gomez and others, 2013). As such, Equation 2 can be re-written as:

$$RVLM = \Delta RSL + e \qquad (3)$$

Using equation 3, the rates of relative vertical land movement between nearby tide gauges within a semi-enclosed sea (i.e. Puget Sound) can be estimated simply by differencing their relative sea level records.

[10] see http://sideshow.jpl.nasa.gov/post/tables/table2.html
[11] See http://sideshow.jpl.nasa.gov/post/tables/GPS_Time_Series.pdf

This process leaves one remaining challenge: How can relative vertical land movement estimates be tied to an absolute reference frame for direct comparison to other absolute rate estimates? Vertical land movement can vary significantly over short distances (NRC, 2012 – Appendix A) – therefore one approach is to identify a tide gauge within a network used for RVLM estimates that is co-located with a CGPS station. In Washington State, the only co-located tide gauge/CGPS system is at Friday Harbor, where NOAA station 9449880 is located <400 meters from CGPS station SC02[12], which was installed on bedrock in November 2001.

Tide Gauge-based VLM Rate Estimates Approach

RVLM was estimated using tide gauge data from 4 locations adjacent to Island County (Figure 1; Cherry Point, Seattle, Friday Harbor, and Port Townsend). For each location, all monthly average sea level data were downloaded from the start of the available record through October 2015 direct from each station's home page at NOAA's Tides and Currents site[13]. Friday Harbor, due to its long record and co-location with a CGPS station, was designated as the "reference" station, and the monthly average water level data for each station were differenced against Friday Harbor's record.

A linear trend was fit to the difference, providing an estimate of the relative vertical land movement between coastal tide stations surrounding Island County. Reported uncertainties are the 95% confidence interval of the trend. Finally, each vertical rate was corrected to a geocentric reference frame using the estimated vertical land movement at CGPS Station SCO2 in Friday Harbor. All vertical land movements are relative to IGS08, an up-to-date geocentric reference frame. Additionally, since IGS08 rates can be referenced to an ellipsoidal or orthometric elevation[14], they are directly comparable to relative sea level rate estimates derived from tide gauges, which themselves are referenced to orthometric elevations.

Table 7. Relative and absolute vertical land movement estimates (mm/yr) for each of four tide stations adjacent to Island County, Washington. *Relative vertical land movement at each station was estimated using the framework in Santa-Maria Gomez (2013). Absolute rates are referenced to the International Terrestrial Reference System (ITRF) 2008. The absolute rate estimate for Friday Harbor is provided by NASA JPL.*[15]

Station	Relative VLM	Absolute VLM Estimate
Friday Harbor	Reference	-0.17±0.16
Cherry Point	1.10±0.09	0.93±0.21
Port Townsend	-0.64±0.09	-0.81±0.21
Seattle	-1.05±0.05	-1.22±0.20

The average VLM rate of the three CGPS sites within Island County (-0.39±0.70 mm/yr) is statistically not different from zero, but the well-resolved coastal rate derived for the tide gauge in Port Townsend tide station (Table 7), which overlaps with the rate from CGPS sources on Island County, suggests the possibility that a low rate of subsidence may be a factor in Island County. Therefore, a uniform estimate of -0.39±0.70 mm/yr was applied as an estimated vertical land movement rate for all of Island County. The rate was incorporated into relative sea level projections, but with its uncertainty (i.e. for each relative sea level calculation an estimated vertical

[12] http://www.unavco.org/instrumentation/networks/status/pbo/overview/SC02
[13] https://tidesandcurrents.noaa.gov
[14] http://vdatum.noaa.gov/docs/datums.html
[15] http://sideshow.jpl.nasa.gov/post/links/SC02.html accessed on 8 February 2016

land movement rate was drawn randomly from a normal distribution with the stated mean and standard error).

Vertical land movement estimates have been made by a number of investigators in order to support historic or future sea level estimates. There is considerable variability in those estimates (Table 8), some of which is attributable to the different methods applied to the problem, improvements in reference frames used in the analysis of CGPS data, or the length of CGPS time-series available. Table 8 presents the vertical rate estimates derived from the project from the differencing of tide-gauge data, the estimates of Santamaria-Gomez and others (2013), which are derived partially from satellite altimetry data, the analysis of Mazotti and others (2008) derived from CGPS time-series, and the vertical rate estimates utilized in the National Academies of Science report derived from CGPS data. The disagreement between the rates used in this assessment and that of Mazotti and others (2008) for Cherry Point is not surprising given issues identified in Mazotti and others with their rate estimate for that site. There is no obvious explanation, though, for the relatively large difference, between the rate estimate for Friday Harbor estimated for this project, and by both Mazotti and others (2008) and NRC (2012).

Table 8. A comparison of vertical rate estimates derived as part of this project to three other regional studies that incorporated estimates of vertical land movement. *"NE" stands for "No Estimate".*

Station	This Project	Santamaria-Gomez, 2013	Mazotti and others, 2008	NRC, 2012
Friday Harbor	-0.17±0.16[b]	NE	0.7±0.9	0.90±0.7
Cherry Point	0.93±0.21	1.33±0.43	-0.7±0.9	NE
Port Townsend	-0.81±0.21	-0.47±0.76	-0.1±1.8	NE
Seattle	-1.22±0.20	-0.62±0.70	-0.9±0.7	-1.10±0.94

Building Relative Sea Level Projections

Relative sea level projections are derived by coupling the climatically-controlled sea level projections with estimates of Vertical Land Movement and Glacio-isostatic Adjustment.

1. Vertical Land Movement. In this instance, because the project estimate for vertical land movement is so small and varies little over the project area, a single rate of -0.39±0.70 mm/yr was incorporated. The large uncertainty will be accounted for by generating a set of VLM rates randomly from a modelled normal distribution, where the rate is represented by the mean and standard error given above.
2. Glacio-isostatic Adjustment (GIA). GIA has an influence on vertical land movement, typically associated in the Puget Sound region with uplift as the land responds to the removal of glaciers at the end of the Pleistocene. There is also a sea level response, as the ocean responds to changes in gravity induced by modifications and adjustments to the mantle and crust. The component of GIA associated with the movement of the land is measured directly in the vertical land movement analysis above. By contrast, the change in sea level is not. For this assessment we use a regionally uniform rate estimate of -0.2 mm/yr (sea level fall) derived from Kopp and others (2015), but note that there is model-dependent variability in estimates of this component of relative sea level change (NAS, 2012 – Appendix B).

Applying both factors a set of RSL tables for Island County are generated for RCP2.6, RCP4.5, and RCP8.5 (e.g. see Table 1).

Incorporating Storm Surge to Develop Still Water Level (SWL) Projections

For each of the four tide gauge water level records available from NOAA, the following process was used to develop a probabilistic estimate of coastal flood risk elevations.

1. The highest still water level relative to the local Mean Higher High Water (MHHW) tidal datum (1981-2000 epoch) at each station was extracted for each calendar year of record.
2. The annual high water time-series was de-trended to account for changes in relative sea level that were present at some of the tide stations. The resulting time-series of the highest annual water level is shown in Figure 4.
3. A generalized extreme value (GEV) distribution was then fit to the de-trended data for each station using the gevfit function in Matlab, which produced three fit parameters, along with their 95% confidence intervals (Table 9).
4. The GEV fit parameters, along with their confidence intervals, were used to look for differences between the annual extreme water level patterns at each station that might be used to justify partitioning the study area, and assigning different areas of Island County different levels of flood risk. However, taking the uncertainties into account, there was little basis upon which to draw distinctions between the four stations analyzed. As a result, and absent any additional detailed information, the approach applied here was to average the parameters from each station to develop a synthetic GEV that could be applied across Island County (Figure 4b).
5. The synthetic GEV parameters were used to generate a random set of annual worst case flood events (N=10,000) that were then added to the set of sea level rise realizations for each decade derived using the LocalizeSL package. A set of probabilities were then extracted from the resulting table, representing the combined uncertainty, given the uncertainties associated with sea level rise projections AND annual maximum still water level, that still water level will reach a given elevation over the contemporary MHHW elevation at a given point in time (Table 2).

Table 9. Generalized Extreme Value distribution parameters derived from the distribution of annual maximum water level measurements at each of four tide stations adjacent to Island County, Washington. *The average parameter used to incorporate an estimate of the flood hazard into sea level rise projections for this project is also given.*

Location	# of Years	Shape Parameter	Scale Parameter	Location Parameter
Port Townsend	44	-0.371±0.214	0.152±0.037	0.640±0.050
Seattle	117	-0.205±0.105	0.119±0.016	0.572±0.024
Cherry Point	43	-0.252±0.165	0.147±0.033	0.682±0.048
Friday Harbor	81	-0.302±0.112	0.143±0.023	0.627±0.034
Used for this project		-0.2852	0.14025	0.63025

Historic sea level change for Island County

Historic absolute sea level change is difficult to measure directly. Tide gauges directly measure relative sea level, whereas, global absolute sea level has been measured directly using satellite altimetry only since the early 1990's, and its usefulness for evaluating regional absolute sea level at small spatial scales for sites near the coast is not clear.

The development of vertical land movement estimates for each tide gauge in this project allows the absolute sea level change estimate for each station to be extracted. For each tide gauge:

1) The seasonal variability in water level was calculated for the 1999-2008 period, and then removed from the entire record to derive a monthly sea level anomaly for each station.
2) The vertical land movement estimate was then removed from each monthly sea level anomaly for each station.

The absolute sea level anomaly from each station was then averaged by month to produce an estimate of the absolute sea level anomaly for the region. Over the entire record (1899-2015) there is a linear trend of 0.8±0.1 mm/yr (equivalent to approximately 4 inches; Figure 5), with the reported uncertainty being an estimate of the 95% confidence intervals around the trend.

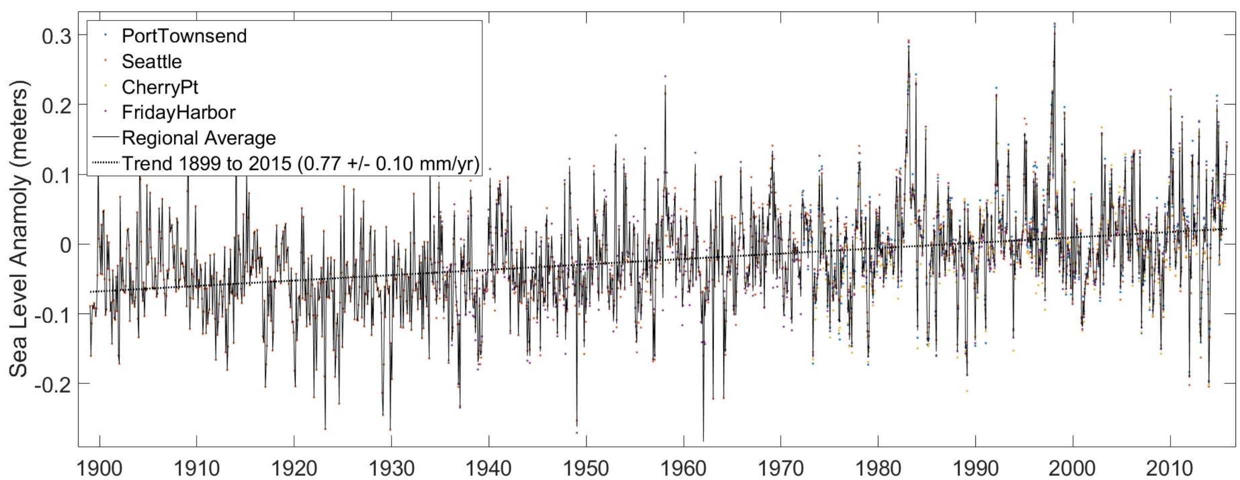


***Figure 5. Monthly absolute sea level estimate for the north Puget Sound region**, based on relative sea level data from tide gauges in Seattle, Port Townsend, Friday Harbor and Cherry Point, coupled with vertical land movement estimates for each tide gauge*

References

Bamber, J. L., and W. P. Aspinall (2013), An expert judgement assessment of future sea level rise from the ice sheets, Nature Climate Change, 3, 424–427

Burgette and others, 2009. Intersesimic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. Journal of Geophysical Research (114): B01408

Johnstone and Mantua, 2014. Atmospheric controls on northeast Pacific temperature variability and change, 1900-2012. Proceedings of the National Academy of Sciences (111): 14360-14365

Kopp and others, 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future (2): 383-406

Kopp and others, 2015. Geographic variability of sea-level change. Current Climate Change Reports (1): 192-204

Mauger and others, 2015. State of Knowledge: Climate change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. Available at https://cig.uw.edu/resources/special-reports/ps-sok/

Mazzotti and others, 2008. Relative and absolute sea level rise in western Canada and northwestern United State from a combined tide gauge-GPS analysis. Journal of Geophysical Research (113): C11019

Mitrovica, J. X., N. Gomez, E. Morrow, C. Hay, K. Latychev, and M. E. Tamisiea (2011), On the robustness of predictions of sea level fingerprints, Geophysical Journal International 187(2), 729–742

Moon and others, 2012. Multidecadal regional sea level shifts in the Pacific over 1958-2008. Journal of Geophysical Research Oceans (118): 7024-7035

Mote, P. and others, 2008. Sea level rise in the coastal waters of Washington State. Available at http://www.cses.washington.edu/db/pdf/moteetalslr579.pdf

National Research Council, 2012. Sea-level rise for the coasts of California, Oregon and Washington: Past, Present and Future. Available at http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington

Petersen, S., J. Bell, I. Miller, C. Jayne, K. Dean and M. Fougerat. 2015. Climate change preparedness plan for the North Olympic Peninsula. Available at www.noprcd.org

Santamaria-Gomez and others, 2013. Long-term vertical land motion from double-differenced tide gauge and satellite altimetry data. Journal of Geodesy (88): 207-222

Sweet, W., J. Park, J. Marra, Zervas, C., and S. Gill. 2014. Sea level rise and nuisance flood frequency changes around the United States. NOAA Technical Report NOS CO-OPS 073.

GIS Data Sources, Process, and Methods

This section summarizes the GIS data sources, processes, and methods used to map probabilistic sea level rise (SLR) and coastal flood projections for areas of Island County, Washington. All GIS data and maps developed as part of this project has been provided to the Island County Department of Natural Resources for future reference and use.

Data Sources

The GIS data used in this project were acquired from a number of federal, state, and local sources. Only published and verified data sources were selected. An abbreviated list of the most essential GIS data layers, as well as their sources, are provided in Table 10.

Table 10. List of Key GIS Data Layers and Sources for those layers.

GIS Layers	***Source***
Aerial Orthoimagery	United States Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) 2013 (1 meter resolution), http://www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai
Hydrography	USGS National Hydrography Dataset (NHD), http://nhd.usgs.gov/; Island County GIS, https://www.islandcounty.net/maps/data/
Lakes and Ponds	Island County GIS, https://www.islandcounty.net/maps/data/
Transportation	Island County GIS, https://www.islandcounty.net/maps/data/
Critical Infrastructure	Island County; WA Department of Ecology
WA Department of Ecology Regulated Facilities	WA Department of Ecology
Lidar Digital Elevation Model (DEM)	Puget Sound LIDAR Consortium (PSLC) 2014, http://pugetsoundlidar.ess.washington.edu/

Data Processing and Mapping

Once obtained, procedures to assure quality and comparability were applied to all GIS data. This included an assessment of overall alignment of spatial data and existence and accuracy of metadata by Adaptation International staff, as well as the use of a standard horizontal (NAD 1983 HARN, US Feet) and vertical datum (NAVD 88, US Feet). For this project, all data were projected using NAD 1983 HARN State Plane Washington North FIPS 4601 in US feet. For any data not in this projection upon receipt, a transformation was applied. Map layout and design was created using ESRI ArcMap 10.3.1 software.

Sea Level Rise Scenarios

The project team developed locally specific relative sea level rise projections, adjusted for vertical land movement, for each of the five focus areas (Crescent Harbor, Crockett Lake, Moran Beach, Livingston Bay, and Useless Bay) using probabilistic methods derived from Kopp et al. (2014) for RCP8.5 and described above. Based on these projections, scenarios for *Sea Level Rise Inundation Area* (SLR), as well as *Annual Extreme Storm Flooded Areas with Sea Level Rise* (AES) were defined for each focus area for the years 2030, 2050, and 2100. Additionally, projections of *Storm Surge Today* were generated for each focus area in order to establish a baseline for comparison. Finally, for each scenario, elevation values representing the 50%, 25%, 5%, and 1% probable annual percent chance of occurrence were specified and then mapped using LiDAR derived digital elevation models (DEMs) which have been hydrologically corrected using the ArcMap "Fill" tool in the "Spatial Analyst" toolbox. Please note that processing the DEMs in this way ensures that areas are shown to be inundated only after natural or man-made barriers, such as levees, are overtopped. To show the present location of existing waterbodies, the "Lakes and Ponds" data layer, accessed from Island County GIS (https://www.islandcounty.net/maps/data/), was superimposed on the SLR projections.

LiDAR (LIght Distance And Ranging, also known as Airborne Laser Swath Mapping or ALSM) is a technology that employs an airborne scanning laser rangefinder to produce high-resolution topographic surveys of unparalleled detail. LiDAR data for Island County were acquired by Island County Public Works in 2014 and made available as DEMs through the Puget Sound LiDAR Consortium. In addition to the LiDAR derived elevation data, aerial orthoimagery (used as the base images for the sea level rise scenarios) were obtained through the United States Department of Agriculture's (USDA) National Agriculture Imagery Program (NAIP) via the USDA's Geospatial Data Gateway[16]. The analysis used the most recently available imagery with 1-meter resolution, which was recorded in 2014. The metadata for the aerial imagery is available.

Finally, key resources, landmarks, and infrastructure within the five focus areas were mapped using a combination of obtained GIS data, data from the Washington State Department of Ecology, information provided by the consultant team, and through review of the orthoimagery. The precise locations of community resources were confirmed by project staff.

Complete List of Maps

A total of 35 maps were developed for this project and are provided as part of this report. A complete list of maps is provided in below. Seven sea level rise projection maps were created for each of the five focus areas (Crescent Harbor, Crockett Lake, Moran Beach, Livingston Bay, and Useless Bay). There are some important notes for all of the maps:

- The mapped "Current Shoreline" is the Mean Higher High Water (MHHW) based on the current tidal datum (the 1983-2001 epoch) as provided by the National Oceanic and Atmospheric Administration (NOAA).
- Maps use only elevation data to map areas of inundation and do not model hydrology, subsurface flow pathways, or shoreline engineering.
- Maps do not reflect shoreline change or erosion.
- Annual extreme flooding probabilities derived from historical data collected at nearby NOAA tide stations and do not take into account possible climate-related changes to storminess patterns.
- Maps do not reflect the additional flood risk associated with waves in elevating water level during storms.

[16] https://gdg.sc.egov.usda.gov/

Table 11: Complete list of all GIS Maps created for the project. SLR = Sea Level Rise and AES = Annual Extreme Storm Flooded Areas with Sea Level Rise.

Crescent Harbor	**Crockett Lake**	**Moran Beach**	**Livingston Bay**	**Useless Bay**
Storm Surge Today	Storm Surge Today	Storm Surge Today	Storm Surge Today	Storm Surge Today
SLR 2030	SLR 2030	SLR 2030	SLR 2030	SLR 2030
AES 2030	AES 2030	AES 2030	AES 2030	AES 2030
SLR 2050	SLR 2050	SLR 2050	SLR 2050	SLR 2050
AES 2050	AES 2050	AES 2050	AES 2050	AES 2050
SLR 2100	SLR 2100	SLR 2100	SLR 2100	SLR 2100
AES 2100	AES 2100	AES 2100	AES 2100	AES 2100