CITY OF BAINBRIDGE ISLAND SEA-LEVEL RISE VULNERABILITY AND RISK ASSESSMENT

Final Report

Prepared for
City of Bainbridge Island

June 2024

ESA

CITY OF BAINBRIDGE ISLAND SEA-LEVEL RISE VULNERABILITY AND RISK ASSESSMENT

Final Report

Prepared for
City of Bainbridge Island

June 2024

This project was completed by the City of Bainbridge Island using grant funding from the Washington Department of Ecology's 2022- 2024 Shoreline Master Program Competitive – Coastal Zone Management Grant (Grant Agreement No. SEASMPCZM-2224-BainIs-00004) with Federal funds under Washington State Coastal Zone Management Award NA20NOS4190065 from the NOAA Office for Coastal Management, U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of NOAA or the U.S. Department of Commerce.

2801 Alaskan Way
Suite 200
Seattle, WA 98121
206.789.9658
esassoc.com

ESA

D202300123

TABLE OF CONTENTS

List of Figures

List of Tables

Appendix

EXECUTIVE SUMMARY

Coastal communities like Bainbridge Island have faced longstanding exposure to various coastal hazards such as flooding, waves, and erosion. As global climate changes and sea-levels rise, many of these hazards will become more frequent and more intense. Identifying, preparing for, and adapting to the threats posed by sea-level rise will be one of the defining challenges of the century.

Future sea-level rise is expected to create a permanent rise in ocean water levels that will shift the water's edge upward and landward during all tidal levels. Higher sea-levels will also increase erosion of beaches and bluffs and increase wave attack at the toe of coastal bluffs. The combination of higher ocean water levels and erosion will mean that coastal storms will reach farther inland.

This study identifies coastal areas of the city that may be most vulnerable to sea-level rise flooding. The analysis relies on wave and water level modeling for a range of sea-level rise projections to develop hazard zones that show the potential future extent of flooding on Bainbridge Island. These hazard zones can be viewed in the Sea-Level Rise in Bainbridge Island StoryMap online. It is important to note that the city-wide flooding hazard zones modeled in this study are not intended to provide site-specific analysis, but rather to provide a rough approximation of potential future risk to assets so that the City may plan and prioritize adaptation actions. The detailed methods used to select the sea-level rise scenarios and events and conduct the modeling are described in Sections 3 and 4. Conservative scenario and modeling methods were selected in collaboration with the City of Bainbridge Island in order to minimize the risk of not planning for enough sea-level rise.

Future Hazards with Sea-Level Rise and Climate Change

For most of the study area, the modeling results show that the 100-year flooding today (i.e., the FEMA flood mapping) is likely to occur annually to roughly every 10 years with 2 feet of sea-level rise. In other words, extreme flood events will continue to become more frequent through the end of the century.

The most vulnerable City assets include:

- Winslow Wastewater Treatment Plant.
- Wastewater lift stations (Sunday Cove #5, Lovell #6, and Wing Point #7).
- Manitou Beach Dr., Euclid Ave., Point Monroe Dr., Point White Dr., Yeomalt Point Dr., Hawley Way, Eagle Harbor Dr., Crystal Spring Dr., Rolling Bay Walk and other infrastructure supporting coastal development along Crystal Springs Drive NE, Hedley Spit/Point Monroe, Manitou Beach, Hawley Cove, and Lynwood Center, as well as beach access points along these roads.

Additionally, while beaches and wetlands are largely tolerant of fluctuating water levels, those that have been heavily degraded or modified may be less likely to cope with increased water depths. Some habitats may be able to shift inland or upland as sea-level rises, particularly in areas where their migration is not blocked by shoreline armoring, coastal development (e.g., bulkheads, roads), or bluffs (Krueger et al. 2011; Mauger et al. 2015). However, this is unlikely in areas with coastal roads and shoreline armoring, which restrict the ability of habitats to shift inland.

Recommended Next Steps

Based on the findings of this study, the following next steps are recommended:

1. Consider other vulnerabilities. This could include:
    a. Conduct a detailed coastal change and erosion analysis and long-term monitoring program: A detailed erosion analysis could be conducted to understand how the shoreline may change in the future. The analysis could include a delineation of the toe and top of bluffs and wetted beach from aerial imagery, evaluating historic shoreline positions to study past erosion, and conducting beach geomorphology analyses to understand how the beach would change with sea-level rise. The results of this analysis could also be used to adjust the flood extent in the hazard zone based on the predicted future geomorphology.
    b. Conduct wetland habitat (e.g., eelgrass, intertidal, and riparian) evolution/migration modeling: While some habitat data were available for this study, the exposure analysis was focused on risk due to inundation which is a natural and necessary process for intertidal and subtidal habitats. Habitat evolution modeling[1,2] (e.g., how wetland habitats are expected to move upslope with increasing sea-levels based on inundation frequency and salinity exposure) can be used to better understand how coastal habitats will be impacted with sea-level rise (ESA 2015, ESA 2018). This type of modeling could help identify areas to preserve for future restoration and areas most at risk of being submerged under future climate conditions.
2. Develop an Adaptation Plan: Through a public outreach process and in coordination with project partners, the City of Bainbridge Island could develop preferred adaptation scenarios for different areas of the city as part of an Adaptation Plan. A preferred scenario would likely be a combination of adaptation strategies that would be implemented based on monitored triggers (e.g., a certain amount of sea-level rise, flooding more frequently than every year, a certain amount of bluff-top erosion). The plan could include a cost-benefit analysis to understand the tradeoffs of implementing expensive adaptation measures versus the damage that could be caused by flooding and erosion. The plan should also include identification of monitoring priorities (e.g., high water marks during flood events, water level data from gage network, sea-level trends, the best available science) and adaptation triggers. Lastly, the plan could include potential policy language that could be incorporated into the plans listed in #3 below. Since planning documents are updated on specific timelines, developing policy language as part of an Adaptation Plan would provide the City of Bainbridge Island with updated text specific to reducing vulnerability. More and more resiliency funding is becoming available through federal and state grants. The City of Bainbridge Island should continue to work with project partners to develop proof-of-concept adaptation strategies.

---

1 https://www.delmar.ca.us/DocumentCenter/View/4314/Final-Summary_Wetland-Habitat-Migration-Assessment_8162018

2 See Appendix K (page 172) http://www.lospenasquitos.org/wp-content/uploads/2020/09/ESA-FINAL-Los-Penasquitos-Lagoon-Enhancement-Plan-APPENDICES.pdf

3. Implement adaptation strategies through local planning documents. Adaptation could include investments and upgrades to critical utilities and infrastructure, wetland restoration and protection, enhancing flood defenses where appropriate, protecting or adapting parks and public access trails, and community education.
    a. Update the Shoreline Master Program (City of Bainbridge Island 2021), zoning, land division, and critical areas codes including updates to regulations to reflect the results of this study, incorporate adaptation planning, and minimize risk to public and private assets.
    b. Update the Hazard Mitigation Plan: Incorporate policy recommendations to meet new standards under FEMA's Local Mitigation Planning Policy.[3]
    c. Results are currently being incorporated into the Comprehensive Plan Update.
    d. Incorporate results and recommendations into coastal floodplain planning processes and plans.

[3] https://www.fema.gov/sites/default/files/documents/fema_local-mitigation-planning-policy-guide_042022.pdf

1 INTRODUCTION

Coastal communities like Bainbridge Island have long been exposed to coastal hazards such as flooding, waves, and erosion, among others. As the global climate continues to warm and sea levels rise, many of these hazards will become more frequent and more intense. Identifying, preparing for, and adapting to the threats posed by sea-level rise will be one of the defining challenges of the century.

The City of Bainbridge Island contains numerous miles of low-lying shoreline and steep bluffs and is acutely vulnerable to coastal flooding driven by changing climatic conditions. This flooding places the island's residents, infrastructure, natural systems, and cultural heritage at risk. In order to adapt to Bainbridge Island's changing shorelines, it is important for the community to plan now to ensure a sustainable and resilient future. This study focuses on areas identified by the City of Bainbridge Island that may be most vulnerable to sea-level rise.

This vulnerability assessment is organized as follows:

- Section 1: Introduction.
- Section 2: Existing and Historic Conditions, including a summary of existing coastal flooding processes and previous studies.
- Section 3: Climate Change Projections, including regional climate change projections and the identification of the model scenarios for Bainbridge Island.
- Section 4: Hazard Analysis, including description of the different types of hazards considered in this study and development of hazard exposure maps.
- Section 5: Vulnerability Assessment, including an analysis of the exposure, sensitivity, and adaptive capacity of assets in the City of Bainbridge Island's sites.
- Section 6: Recommended Next Steps.

2 EXISTING AND HISTORIC CONDITIONS

Local and regional datasets were collected and reviewed to support the development of wave and flood modeling along Bainbridge Island shorelines.

2.1 Water Levels and Flooding

2.1.1 Tidal Datums and Sea-level Trends

Bainbridge Island experiences mixed semidiurnal tides, or two daily high tides and two daily low tides of differing elevations. These daily tides also vary with the spring-neap tidal cycles, which occur approximately twice a month, as well as king tides, which are exaggerated tides that occur several times per year. King tides cause exceptionally high and low tides, are already causing flooding throughout the Island, and may exacerbate flooding when they occur simultaneously with low pressure storm systems. **Table 2-1** presents the tidal datums for the NOAA Seattle tide gauge (Station #9447130) and the Bremerton tide gauge (Station #9445958), which provides information for water levels along the west shoreline in Sinclair Inlet. Bremerton's tide gauge does not include a conversion to the North American Vertical Datum of 1988 (NAVD88), so NOAA's online vertical datum transformation tool (VDATUM)[4] was used to develop a ft MLLW to ft NAVD88 conversion of -2.84 ft.

TABLE 2-1. TIDAL DATUMS FOR BAINBRIDGE ISLAND

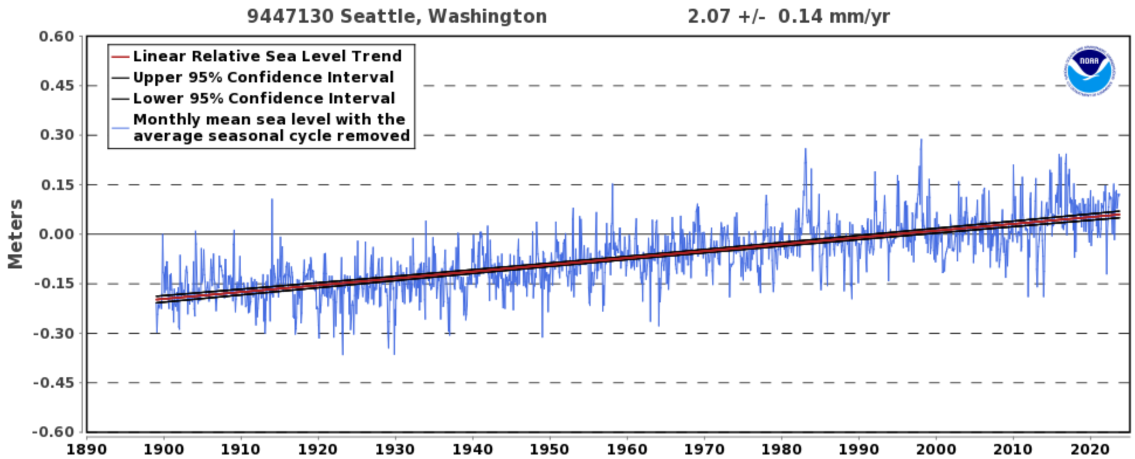
		Seattle (#9447130)		Bremerton (#9445958)	
Tidal datum	**Abbreviation**	**ft MLLW**	**ft NAVD88**	**ft MLLW**	**ft NAVD88**
Highest Observed Tide		15.12	12.78	15.55	12.71
Highest Astronomical Tide	HAT	13.30	10.96	14.09	11.25
Mean Higher-High Water	MHHW	11.36	9.02	11.72	8.88
Mean High Water	MHW	10.49	8.15	10.82	7.98
Mean Tide Level	MTL	6.66	4.32	6.84	4.0
Mean Sea-level	MSL	6.64	4.30	6.82	3.98
Mean Low Water	MLW	2.83	0.49	2.86	0.02
North American Vertical Datum of 1988	NAVD88	2.34	0.00	2.84	0.00
Mean Lower Low Water (MLLW)	MLLW	0.00	-2.34	0.00	-2.84
Lowest Astronomical Tide	LAT	-4.31	-6.65	-4.61	-7.45
Lowest Observed Tide	LOT	-5.04	-7.38	-4.09	-6.93

NOTES: The tidal datums listed above are from the most recent tidal epoch: 1983-2001. Datums were converted from the tide gauge standard to NAVD88 using NOAA's online Vertical Datum Transformation Tool.

SOURCE: NOAA Tides and Currents

[4] https://vdatum.noaa.gov/

The Seattle tide gauge has been recording water level data since 1898. The relative sea-level trend recorded over this period is 2.07 mm/yr (0.08 in/yr) or 0.68 feet in 100 years. (**Figure 2-1**). Future sea-level rise is expected to accelerate (Miller et al. 2018).



SOURCE: NOAA 2023

Bainbridge Island Sea-Level Rise Vulnerability Assessment

Figure 2-1
Monthly Mean Sea-levels over time at Seattle

2.1.2 Coastal Extreme Event Flooding

The Federal Emergency Management Agency (FEMA) produces Flood Insurance Rate Maps (FIRMs) and Flood Insurance Studies (FIS) for areas at risk of flooding. The FIS for Bainbridge Island, Washington and Incorporated Areas was developed with an effective date of February 3, 2017.

Within each community, FEMA defines base flood elevations, which are benchmarks for how high water is likely to get during a 100-year coastal flood event. Areas below the base flood elevation are at higher risk for flooding. The 100-year event refers to a storm with a 1 in 100 (or 1%) chance of occurring in any given year, and a ~67% chance of being exceeded once in 100 years. For Bainbridge Island, the base flood elevation ranges from 13 to 17 feet relative to NAVD88.

FEMA maps two flood Special Flood Hazard Areas around Bainbridge Island's coast, zones AE and VE. Both zones indicate the potential for an area to flood, but the VE zone represents coastal areas that face additional risks from storm surge and high wave action during storms. The FEMA FIRM data can be viewed in the Sea-Level Rise in Bainbridge Island StoryMap.

2.2 Previous Studies

<u>Sea-level Rise on Bainbridge Island</u>

In 2019, the Bainbridge Island Climate Change Advisory Committee prepared a report that assessed the sea-level rise impacts on the City of Bainbridge Island. The report provided strategies to adapt and increase the City's resilience to sea-level rise. This study identified several assets such as sewer service, the ferry terminal, the Wyckoff Superfund site, Fay Bainbridge Park, the Winslow Wastewater Treatment Plant, and waterfront residences as exposed coastal areas that already experience or will soon experience inundation from sea-level rise.

Climate Action Plan: A Plan for Mitigating and Adapting to Climate Change on Bainbridge Island

The Climate Action Plan (Climate Change Advisory Committee 2020) focuses on addressing climate change through mitigation and adaptation strategies. The plan acknowledges the urgent need for collective action against the impacts of climate change, which include rising sea-levels, changes in rainfall patterns, increased temperatures, and extreme weather events. The sea-level rise impacts are described as loss of land (including homes, roads, and habitat). Key infrastructure like the Washington State Ferries terminal, the Wyckoff Superfund site, and Fay Bainbridge Park are also at risk. Private property owners, especially in areas like Point Monroe, Manitou Beach, and Schel Chelb Estuary, will face significant challenges with increasing instances of severe flooding and, in some cases, permanent inundation.

The plan outlines a comprehensive roadmap involving the City of Bainbridge Island and the community. It includes strategies for reducing emissions through actions in energy use, transportation, building practices, and community engagement. The plan also emphasizes adapting to climate change impacts and enhancing community resilience, alongside encouraging individual and collective actions to confront climate change effectively.

2015 Risk Report: For Kitsap County including the Cities of Bremerton, Bainbridge, Port Orchard, Poulsbo, the Port Gamble S'Klallam Indian Reservation, the Suquamish Tribe, and Unincorporated Kitsap County

In the 2015 Risk report (2015), FEMA provide information about the number of buildings in the Special Flood Hazard Area (SFHA) and the buildings located within the VE zone (areas with a high potential for flood damage due to storm-induced waves) that are subjected to 3 feet or more of wave inundation and are considered high hazard. Within Kitsap County, the City of Bainbridge Island has the largest number of buildings in the Special Flood Hazard Assessments (SFHA) (1-percent-annual-chance flood zone).

3 CLIMATE CHANGE PROJECTIONS

3.1 Regional Sea-Level Rise Projections

In 2018, as part of the Washington Coastal Resilience Project (WCRP), partners prepared an assessment of projected sea-level rise for Washington State (Miller et al. 2018) as an update to the National Research Council's (NRC) previous assessment (NRC 2012). The study included projections for sea-level rise and vertical land movement at various locations along the Pacific coast and the Puget Sound shoreline. The University of Washington's Climate Impacts Group (UW CIG) developed a website[5] that includes interactive sea-level rise data visualizations (e.g., **Figure 3-1**). The website presents different sea-level rise values based on two global greenhouse gas emissions scenarios:

High Emissions Scenario (Representative Concentration Pathway [RCP] 8.5) – This scenario assumes a future where there are no significant local or global efforts to limit or reduce greenhouse gas emissions. This scenario assumes "high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long-term to high energy demand and greenhouse gas emissions."[6]

Low Emissions Scenario (RCP 4.5) – This scenario assumes more aggressive emissions reduction actions in which greenhouse gas emissions stabilize by mid-century and begin to decrease later in the century.

The 2018 assessment also provides a range of probabilities that were specifically included to guide decision-makers. The probabilities range from "extreme low" (0.1%) to "high" (>83%) and correspond to the likelihood that a given amount of sea-level rise will be exceeded by a certain date. For example, the "extreme low" probabilistic projections correspond to a 0.1% chance of exceedance (i.e., 99.9% of models predict a lower amount of sea-level rise) and a conservatively high estimate of sea-level rise.

While the Miller et al. (2018) study provides projections through 2150, it is important to note that sea-level rise is expected to continue for centuries, because the earth's climate, cryosphere,[7], and ocean systems will require time to respond to the emissions that have already been released to the atmosphere.

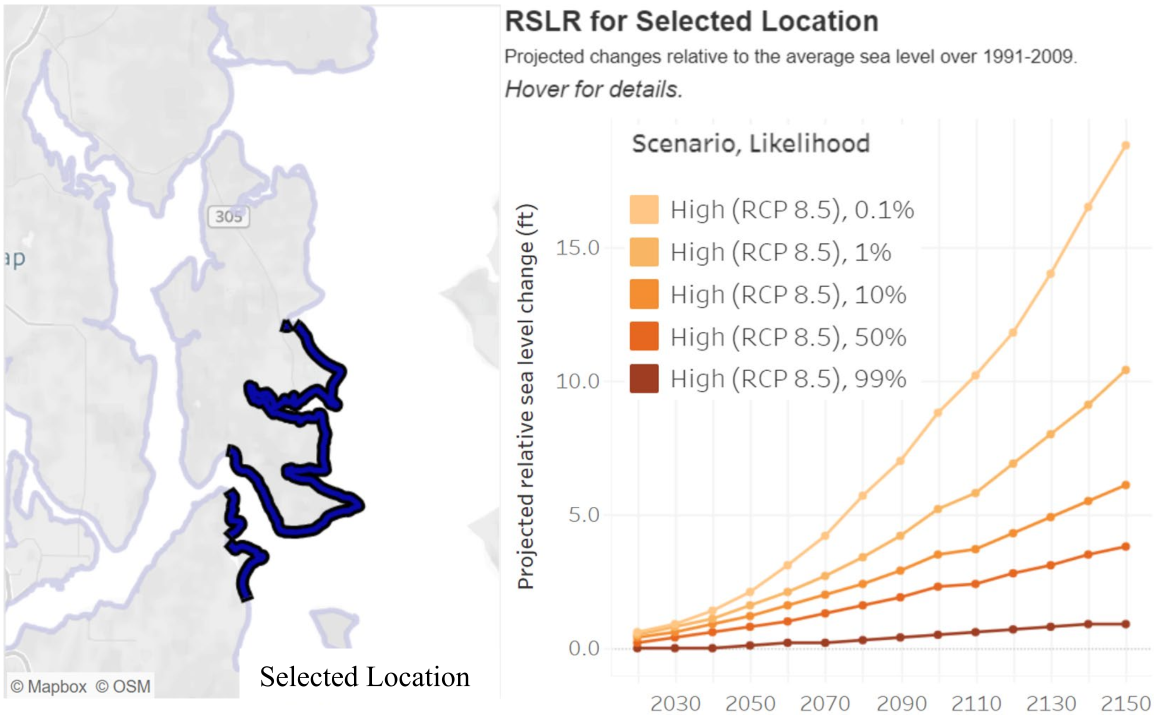
The report "Global and Regional Sea-level Rise Scenarios for the United States" from NOAA (2022) provides updated projections of sea-level rise along U.S. coastlines, integrating data from the Intergovernmental Panel on Climate Change IPCC's Sixth Assessment Report. It emphasizes near-term (2020–2050) and long-term (2050–2150) scenarios, addressing uncertainties in

5 UW CIG. https://cig.uw.edu/projects/projected-sea-level-rise-for-washington-state-a-2018-assessment/

6 Riahi, K., Rao, S., Krey, V. et al., 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Climatic Change 109, 33. https://doi.org/10.1007/s10584-011-0149-y

7 The cryosphere is the portion of the Earth's surface where water is in solid form, like glaciers and ice caps.

emissions and physical processes. Key messages include increased confidence in projected sea-level rise by 2050, significant future impacts on coastal flooding, and the importance of monitoring sea-level rise and its driving processes for adaptive management.



SOURCE: UW CIG, 2018

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 3-1
Example of Relative Sea-Level Rise Projections for the High Emissions Scenario

3.2 Coastal Storm Changes

The effect climate change will have on extreme winds and waves is not as well defined as the effects on sea-levels and precipitation intensity (Mauger et al. 2015). Hence, future conditions exposure mapping and associated vulnerability assessments and adaptation planning typically presume coastal storm surge and wave conditions will be similar to existing values. Existing storm surge is added directly to future water levels with sea-level rise, while run-up associated with storm wind-wave conditions is determined with additional hydrodynamic calculations.

3.3 Bainbridge Island Scenarios

For the purposes of this study, the City of Bainbridge Island considered the high emissions scenario (RCP 8.5) to conservatively evaluate the vulnerability of assets under a high sea-level rise scenario. This scenario is conservative because it assumes emissions are not reduced in the future and will continue increasing. It is unlikely that emissions will exceed this scenario (Mauger et al. 2015). Current studies are showing emissions are tracking somewhere between RCP 4.5 and RCP 8.5 (McClure et al. 2022, Pedersen et al. 2020). The range of sea-level rise projections for the entirety of Bainbridge Island is summarized in **Table 3-1** below.

TABLE 3-1. RANGE OF SEA-LEVEL RISE PROJECTIONS FOR BAINBRIDGE ISLAND, WASHINGTON

	Miller et al. Sea-Level Rise Projections (ft)[1]		
Anticipated Timeline[1]	**10% Probability of Occurrence by this Date**	**1% Probability of Occurrence by this Date**	**0.1% Probability of Occurrence by this Date**
Now	0.0	0.0	0.0
2050	1.1 - 1.2	1.5 - 1.6	2.1 – 2.2
2080	2.3 - 2.4	3.3 - 3.4	5.4 - 5.7
2100	3.3 - 3.5	5.0 - 5.2	8.5 - 8.8
2140	5.2 - 5.5	8.9 - 9.2	16.0 - 16.6

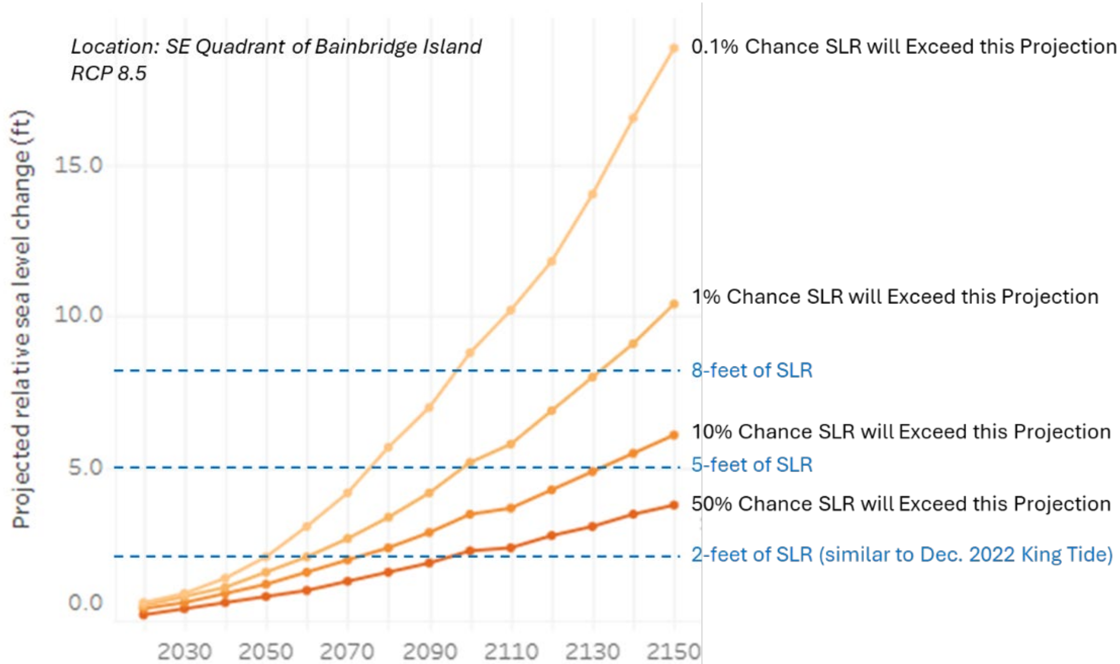
1. The range of projections is noted for the RCP 8.5, high emissions scenarios Source: UW CIG 2018

In order to determine the relevant timeframe of future flood risk due to sea-level rise, a risk tolerance profile must be selected that is relevant to the asset of concern. **Figure 3-2** charts various risk tolerance profiles. For example:

- Very little risk of flooding will likely be tolerated at any point in the future for critical infrastructure (e.g., sewer plants/pumps, hospitals, fire/police stations, etc.), so a very low risk tolerance profile (i.e., 1% or even 0.1% chance that sea-level rise will exceed the projection) would be selected to assess these assets.
- More risk of roadway flooding would likely be tolerated, but not to the significant detriment of emergency service response, so a low risk tolerance profile (i.e., 10% chance that sea-level rise will exceed the projection) would be appropriate for evaluating roads.
- More risk of flooding would likely be tolerated for a parking lot so a moderate risk profile (i.e., 50% chance that sea-level rise will exceed the projection) would be appropriate for evaluating the vulnerability of a parking lot.

The City of Bainbridge Island selected 2 and 5 feet of sea-level rise to represent a short- and long-term scenario. The short-term scenario (2 feet of sea-level rise) has a 10% or less chance of occurring by 2050-2080 and a 50% chance of occurring by 2100. The long-term scenario (5 feet of sea-level rise) has a 10% or less chance of occurring by 2080-2140. For each sea-level rise scenario, the City selected the 1-year, 10-year and 100-year storm event to evaluate more frequent versus more extreme impacts.

For certain assets, including the Winslow Wastewater Treatment Plant located in the vicinity of Hawley Cove, the City of Bainbridge Island selected an additional long-term scenario with sea-level rise of 8 feet evaluated for the 10- and 100-year storm events.



SOURCE: Adapted from UW CIG, 2018

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 3-2
Risk Tolerance Profiles for Bainbridge Island

4 HAZARD ANALYSIS

Future sea-level rise is expected to create a permanent rise in ocean water levels that will shift the water's edge landward and upward, exacerbating flooding. Higher sea-levels will also increase erosion of beaches and bluffs and increase wave attack at the toe of coastal bluffs, resulting in smaller buffers between assets and the water. Additionally, the combination of higher ocean water levels and erosion means that coastal storms will cause greater flooding and damage as waves are able to break closer to shore in deeper water. This study analyzed coastal flooding. Other climate hazards related to sea-level rise such as erosion and salinization were not assessed.

4.1 Terms

The following terms are used in the discussion of the hazard zone development and vulnerability assessment:

Wave runup – the inland vertical extent of waves as they break and run up the shore.

Still water level (SWL) – the elevation of the sea when there are no waves affecting it, including tides, storm surge, and regional effects such as the El Niño-Southern Oscillation.

Total water level (TWL) – the total elevation of the water surface where it meets land, including wave run-up; TWL = SWL + wave runup.

Return period – the average amount of time between events, or the frequency at which a given event may occur (also known as a recurrence interval). For example, the 100-year event refers to a storm with a 1 in 100 (or 1%) chance of occurring annually, and a ~ 67% chance of being exceeded once in 100 years.

Asset – any valuable resource, infrastructure, or entity that could be impacted by rising sea levels.

4.2 Flood Hazard Zone Development

The flood hazard assessment involved a two-step modeling process to determine total water levels during the 1-, 10-, and 100-year events with 2 and 5 feet of sea-level rise. An additional sea-level rise scenario of 8 feet was modeled to evaluate the impact on certain assets, including the Winslow Wastewater Treatment Plant. Once the total water level is determined, it can be mapped along the shoreline to show areas that would be inundated during those scenarios.

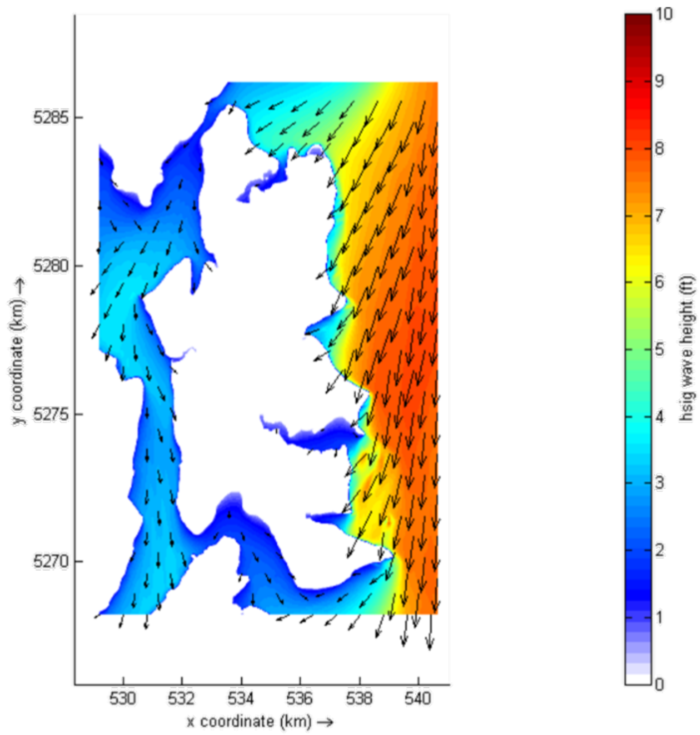
In the first modeling step, the total water level during a storm event is calculated using a representative shoreline slope rather than relying on the intricate site topography and bathymetry. This approach offers a less computationally intensive method to create a time series of total water levels (e.g., water elevations every hour for a 30-year period). This time series can then be used to determine the total water level recurrence interval (e.g., the 100-year event) at each location across the city.

In the second step, one specific event (rather than the whole time series) is identified based on the results of the first step to model specific sites in more detail. This event (e.g., the 1- or 100-year event) is then modeled using detailed site topography and bathymetry and more complex wave processes like wave reflection, diffraction, breaking, and dissipation to provide a more comprehensive and precise assessment of the flood extent.

The following sections offer a concise overview of these modeling steps, while **Appendix A** provides a comprehensive analysis of the modeling efforts.

4.2.1 Step 1: Wave Modeling to Determine Total Water Levels: Regional Scale

The Simulating Waves Nearshore (SWAN) model was used to simulate wave conditions in Puget Sound (**Figure 4-1**). This two-dimensional model forecasts wave behavior in response to various factors such as wind speed, wind direction, water level, shoreline geometry, and bathymetry. The SWAN model takes into account key wave processes, including wave generation, refraction, shoaling, and breaking. The SWAN model was implemented using the Delft3D modeling suite.

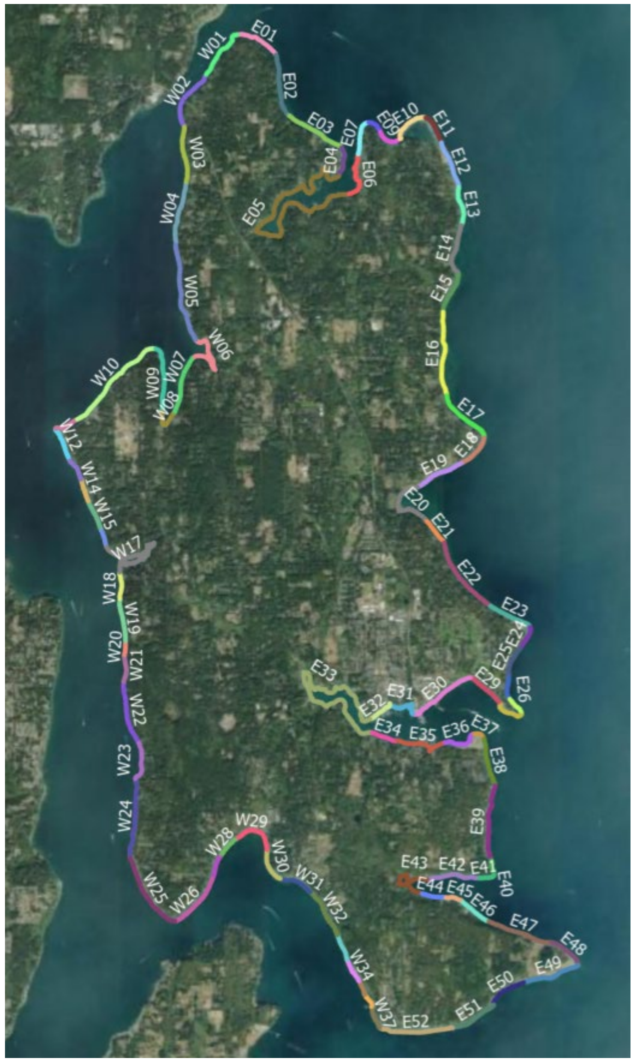


SOURCE: ESA 2023

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 4-1
Wind Waves Example from SWAN Model (40-mph wind, 0 degrees True North)

The SWAN model was used to develop a lookup table that associates wind velocity and direction with the corresponding wave parameters such as wave height, period, and direction for each offshore point. A total of 89 offshore points were used to extract these wave parameters around the entire Bainbridge Island shoreline (**Figure 4-2**). Subsequently, this lookup table enabled the translation of a time series of wind speed and direction into a corresponding time series of wave characteristics. The derived wave height data were then used to calculate the return periods for wave heights at each offshore point.



SOURCE: ESA 2023

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 4-2
Eighty-Nine (89) Shoreline Segments Modeled in Step 1

Using empirical equations, the time series of wave characteristics was used to calculate a time series of wave runup along the shoreline for each site based on a simplified shore slope. The wave runup time series was then added to a time series of still water levels to create a total water level time series. The derived total water levels were then used to calculate the return periods for total water levels at each offshore point.

The Bainbridge Island Total Water Level & Sea Level Rise Calculator downloadable Excel file in the Additional Resources section of the StoryMap provides the TWL results for each of the 89 shoreline segments.

4.2.2 Step 2: Modeling to Determine Flood Extents: Local Scale (Site-Specific)

To provide a more accurate model of coastal flooding, the 1D and 2D version of the XBeach model was used at seven sites selected by the City of Bainbridge (see Section 5.3). XBeach uses wave and water level inputs to propagate offshore waves inland and to estimate the landward extent of coastal flooding. XBeach is too computationally intensive to run for a whole time series and is more appropriate for analysis of specific events. Note that XBeach does not include morphodynamic changes to the shoreline.

Step 1 was used to define what scenarios to run in Step 2. Once the 1-, 10-, and 100-year total water level elevations were identified, specific events that result in this water level could be determined. Since total water level depends on both the still water level and wave runup, a 100-year event could be a combination of extreme waves with an average still water level or an extreme still water level (like during a king tide) and typical waves (or any scenario in between).

It should be noted that an event with a 100-year still water level coinciding with a 100-year wave is not considered, as this event would be more extreme than a 100-year storm event (Garrity et al. 2007).

Upon reviewing the combinations of 1- and 100-year still water levels with 1- and 100-year wave heights, it was concluded that the 1-year wave height paired with 1-, 10-, and 100-year still water level provided the most suitable scenarios for defining practical conditions.

XBeach was then run using the determined wave height and still water level for each site and each scenario (1-, 10-, and 100-year event for 2 and 5 feet of sea-level rise). For Eagle Harbor, an additional 8-ft sea-level rise scenario was developed for the 10- and 100-year events. **Figure 4-3** shows the model extent for the 8-ft sea-level rise scenario. The model results are presented in the hazard maps in the Sea-level Rise in Bainbridge Island StoryMap.

SOURCE: ESA 2023

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 4-3
Model Extent for 8-ft Sea-Level Rise Scenario

5 VULNERABILITY ASSESSMENT

This section uses the future hazard zones described in Section 4 to identify the assets (e.g., roads, utilities, etc.) potentially at risk from sea-level rise impacts. In order to plan actions to address potential sea-level rise flood vulnerability, the risk of not taking action must be understood first. For this reason, the vulnerability assessment considers a "no action" scenario in which the City of Bainbridge Island s does not respond to sea-level rise. This assessment of vulnerability will provide information that can be used to determine the best next steps to improve resilience to the projected impacts.

5.1 Vulnerability Assessment Approach

5.1.1 Exposure to Flooding

To assess exposure to hazards, each potential future hazard zone was overlayed on the assets using geographic information system software (GIS). **Table 5-1** (at the end of Section 5.2) provides an asset risk table summarizing the exposed assets and the type of exposure in both the mid-term (2 feet of sea-level rise) and the long-term (5 feet of sea-level rise).

It is important to note that the city-wide flooding hazard zones modeled in this study are not intended to provide site-specific analysis, but rather to provide a rough approximation of potential future risk to assets so that the City of Bainbridge Island may plan and prioritize adaptation actions.

5.1.2 Sensitivity to Flooding

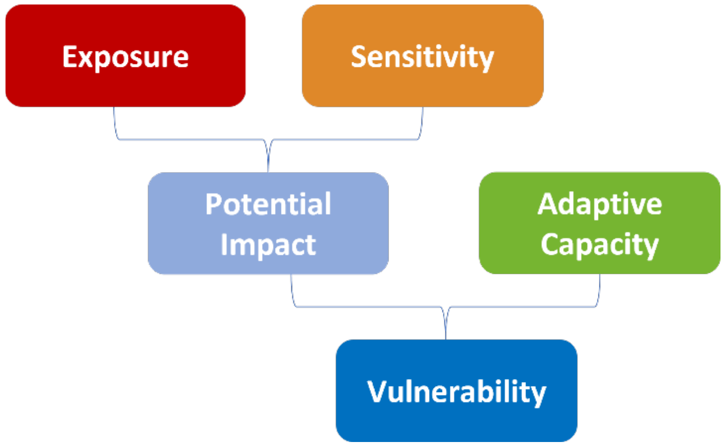
An asset's sensitivity is the asset's level of impairment if flooded or affected by waves. In general, assets that are highly sensitive would lose their primary function if exposed to any degree of flooding whatsoever. If assets can maintain their primary function(s) during inundation, they would have low sensitivity. If assets would lose only part of their function, they would be considered moderately sensitive. A high sensitivity asset would be one where flooding would cause a total loss of its function. For example, if key roads flood, the disruption of vehicular access critical for the provision of emergency services would mean the asset has a high sensitivity.

5.1.3 Adaptive Capacity of Asset

An asset's adaptive capacity is the asset's ability to cope with and recover from impacts. In general, assets that have low adaptive capacity are unable to recover quickly, or at all, if exposed to any degree of flood or erosion. If assets are operational as soon as water recedes, they would have high adaptive capacity. For example, in many cases once waters recede off roads, vehicular access can be restored if little damage was sustained to the roadway itself, which would mean the asset has a high adaptive capacity to flooding. Note, adaptive capacity is inversely correlated with vulnerability (i.e., low adaptive capacity leads to higher vulnerability).

5.1.4 Vulnerability Summary

Overall vulnerability is determined based on a combination of an asset's vulnerability components as shown in **Figure 5-1**.



SOURCE: ESA

Bainbridge Island Sea-Level Rise Vulnerability Assessment

Figure 5-1
Components of Vulnerability

5.2 City-wide Exposure Results

Maps of flood exposure are presented in the Sea-Level Rise in Bainbridge Island StoryMap. These maps depict areas vulnerable to inundation under the different sea-level rise scenarios discussed in Section 3.3. **Tables 5-1 and 5-2** provide a summary of the city-wide exposure results. How vulnerable an asset will be to flooding will depend on the asset's exposure, sensitivity, adaptive capacity to flooding. Over time:

- Areas currently at risk of flooding will flood more frequently and experience deeper flood waters.
- The risk of flooding will expand to additional areas that are not currently at risk of flooding.
- Groundwater levels will rise in coastal areas which could affect some underground infrastructure and cause localized ponding.
- Increased flooding could slow emergency service response times to certain neighborhoods and require alternative response equipment/training.

TABLE 5-1. EXPOSURE OF BAINBRIDGE ISLAND ASSETS TO VARIOUS SEA-LEVEL RISE AND STORM SCENARIOS

			Current Conditions		2 ft SLR			5 ft SLR		
Asset	Unit (Count, Feet, or Acres)	Total Analyzed	Existing High Tide	FEMA 100 yr storm	1-yr storm	10-yr storm	100-yr storm	1-yr storm	10-yr storm	100-yr storm
Parcels and Structures										
Undeveloped Parcels (no structure on parcel, according to buildings layer)	Acres	4,123.7	221.3	26.6	238.6	247	249	252	260	263
Buildings	Count	12,520.0	208	308	438	840	1,163	1,497	1,983	2,359
Schools	Count	1	-	-	-	-	-	-	-	-
Libraries	Count	1	-	-	-	-	-	-	-	-
Court, City Hall, Licensing	Count	2	-	-	-	-	-	-	-	-
Post Office	Count	2	-	-	-	-	-	-	-	-
Recycling Facility	Count	1	-	-	-	-	-	-	-	-
Infrastructure										
Water Infrastructure:										
Lateral and Main Lines	Feet	1,080,614.4	311.1	11,022.8	8,970.7	13,304	14,403	15,588	19,820	20,791
Wells	Count	18	-	-	-	-	-	-	-	-
Stormwater Infrastructure:										
Stormwater Open Drainage, Ditch, & Bioswales	Feet	697,778.42	4,443.0	15,276.1	8,722.5	12,317	13,246	14,084	16,786	18,170
Stormwater Control Facility (Detention Ponds, Raingardens)	Count	378	3	2	4	6	6	7	9	9
Stormwater Culverts	Count	423	0	12	7	15	20	24	31	32
Sump Pump	Count	2,434	2	24	15	36	39	45	60	68
Outfall	Count	406	230	75	298	322	329	339	347	349
Sewer/Wastewater Infrastructure:										
Manholes	Count	808	21	4	24	25	26	26	33	34
Forced Main Valve	Count	258	0.0	3.0	1	4	4	4	7	7
System Valve	Count	3,311	0	38	28	37	39	41	48	49
Lift Stations	Count	18	1	2	3	3	3	3	4	4
Treatment Plants	Count	1	-	-	-	-	-	-	-	1
Mains (Gravity and Pressurized)	Feet	185,631.7	2,488.7	2,197.8	3,039.3	4,500	4,752	4,872	5,563	5,755
Grinder Pumps	Count	10	-	-	-	-	-	-	-	-
Easements	Acres	2.8	0.0	0.1	0.1	0.2	0.4	0.5	0.9	1.0
Combined Closed Lines	Feet	461,451.03	2,163.61	7,151.23	6,079.98	10,120	11,268	12,388	15,732	16,859
Cleanouts	Count	225	-	-	-	-	-	-	-	-
Natural Resources										
Wetlands	Acres	1,180.0	20.8	64.2	42.3	48	49	51	54	56
Open Channel Creeks	Feet	386,706.1	9,566.7	16,325.0	15,170.1	18,257	18,903	19,930	22,889	24,419
Emergency Services										
Fire Stations	Count	3	-	-	-	-	-	-	-	-
Fire Hydrants	Count	382	-	4	3	4	4	4	4	4
Hospitals/Clinics	Count	1	-	-	-	-	-	-	-	-
Police Stations	Count	1	-	-	-	-	-	-	-	-
Transportation										
Roads	Feet	1,127,811.0	91.78	14,100.98	9,374.10	15,927.60	17,439.11	19,031.80	23,377.23	24,911.33
Land Use										
Agriculture	Acres	60.1	-	-	-	-	-	-	-	-
Open Space	Acres	63.5	1.3	1.1	2.2	2.3	2.3	2.3	2.3	2.3
Contaminated Site	Count	18	1	-	1	1	1	6	6	6
Recreation										
Park	Acres	37.8	-	10.0	7.5	11	12	14	16	16
Trails	Feet	141,722,243.64	1,059.64	6,104.25	3,816.2	6,358	7,595	9,525	13,268	14,113
Road Ends with Shoreline Access	Count	65	34.00	12.00	46	50	52	55	57	57

NOTES:
* Ground water may influence Treatment Plant before the 5 ft 100 yr scenario

TABLE 5-2. EXPOSURE OF ADDITIONAL EAGLE HARBOR ASSETS AT 8 FEET OF SEA-LEVEL RISE

		8 ft SLR (only modeled for Eagle Harbor, see Figure 4-2)	
Asset	**Unit (Count, Feet, or Acres)**	**10-yr storm**	**100-yr storm**
Parcels and Structures			
Undeveloped Parcels (no structure on parcel, according to buildings layer)	Acres	+2.3	+2.7
Buildings	Count	+83	+128
Infrastructure			
Water Infrastructure:			
Lateral and Main Lines	Feet	+1,083	+1,222
Stormwater Infrastructure:			
Stormwater Open Drainage, Ditch, & Bioswales	Feet	+848	+1,087
Stormwater Control Facility (Detention Ponds, Raingardens)	Count	+1	+1
Stormwater Culverts	Count	-	+1
Sump Pump	Count	+11	+13
Outfall	Count	+3	+3
Sewer/Wastewater Infrastructure:			
Manholes	Count	+6	+9
System Valve	Count	+12	+15
Mains (Gravity and Pressurized)	Feet	+835	+1,216
Easements	Acres	+0.02	+0.03
Combined Closed Lines	Feet	+623	+810
Natural Resources			
Wetlands	Acres	+1.9	+2.3
Open Channel Creeks	Feet	+717	+850
Emergency Services			
Fire Hydrants	Count	+2	+2
Transportation			
Roads	Feet	+677	+792
Recreation			
Park	Acres	+1	+1.1
Trails	Feet	+1,384	+1,628
Road Ends with Shoreline Access	Count	+1	+1

During the 100-year coastal storm with no sea-level rise, 14,100 linear feet (2.7 miles) of road are exposed to flooding. With 2 feet of sea-level rise, the modeling shows 9,374 linear feet (1.8 miles) of road would be exposed annually, meaning a substantial increase in the flooding frequency for many roads. Under this condition, roads like Point White Drive, Eagle Harbor Drive, Hawley Way, Yeomalt Point Drive, Manitou Beach Drive, Point Monroe Drive, and Crystal Springs Drive will be overtopped. With 5 feet of sea-level rise, 24,900 linear feet (4.7

miles) of roads are exposed to flooding during a 100-year coastal storm. **Table 5-3** summarizes the expected road infrastructure impacts over time.

TABLE 5-3. ROAD INFRASTRUCTURE EXPOSURE

Currently	2.7 miles of road are at risk of flooding in the FEMA 100-year flood zone and several roads already experience annual flooding.
By 2070[1]	With 2-feet of sea-level rise: • The roads currently at risk of flooding during a 100-year event will be at risk of flooding during a 10-year storm event, with 1.8 miles of road at risk of flooding annually. • 3.3 miles of road will be at risk of flooding during a 100-year storm event.
By 2130[1]	With 5-feet of sea-level rise: • All of the roads at risk of flooding with the 100-year event today will be at risk of flooding annually. • 4.7 miles of road will be at risk of flooding during a 100-year storm event.

1. Assuming a low (10%) sea-level rise risk tolerance.

The modeling also shows the City's sewer infrastructure is vulnerable to sea-level rise (**Table 5-4**).

TABLE 5-4. SEWER INFRASTRUCTURE EXPOSURE

Currently	2 sewer lift stations and 4 manholes are at risk of flooding in the FEMA 100-year flood zone (1 of these lift stations is already being relocated at significant expense).
By 2060[1]	With 2-feet of sea-level rise: • 3 lift stations and 24 manholes will be at risk of flooding annually during a 1-year storm event. • 3 lift stations and 26 sewer manholes will be at risk of flooding during a 100-year storm event.
By 2100[1]	With 5-feet of sea-level rise: • 4 lift stations and 33 manholes will be at risk of flooding during a 10-year storm event. • The Winslow Wastewater Treatment Plant will be at risk of flooding during a 100-year storm event.

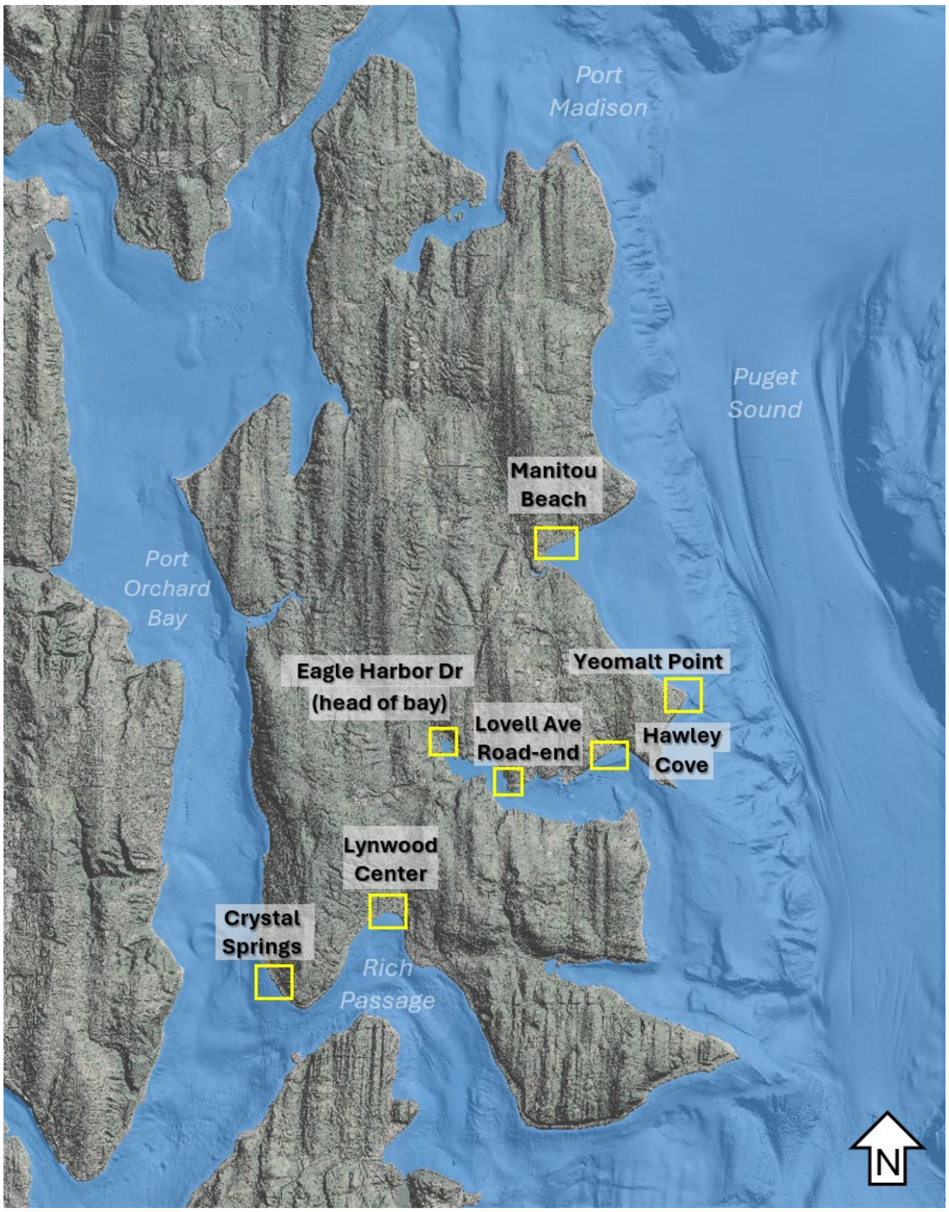
1. Assuming a very low (1%) sea-level rise risk tolerance.

5.3 Site-specific Exposure Results

Seven sites were identified by the City for focused flood modeling. These areas were selected based on the extent of flooding, the number of affected structures, and the critical infrastructure impacted. These sites are presented in **Table 5-2** and shown in **Figure 5-6**. In addition to the City-wide flood results, the Sea-Level Rise in Bainbridge Island StoryMap presents the flood modeling results for each of the following areas. Note that all of Point Monroe is already in the FEMA 100-year flood zone and is very vulnerable to increased flooding due to sea-level rise. Additional modeling was not necessary for Point Monroe.

TABLE 5-6. BAINBRIDGE ISLAND STUDY AREAS

Study Areas
Manitou Beach
Yeomalt Point
Hawley Cove
Lovell Ave Road-end
Eagle Harbor Dr (head of the bay)
Lynwood Center
Crystal Springs



SOURCE: ESA 2024

Bainbridge Sea-Level Rise Vulnerability Assessment

Figure 5-2
Site-Specific Study Areas

5.3.1 Site #1: Manitou Beach

With 2 feet of sea-level rise, the modeling shows that the 1-year event would overtop approximately 1,800 linear feet of Manitou Beach Drive and inundate 10 structures and 10 storm drain culverts and outfalls. This condition floods most of the designated wetland area. With 2 feet of sea-level-rise, the 10-year event inundates 13 structures and 12 storm drain culverts, outfalls, and sump pumps. The 100-year event under 2 feet of sea-level rise is very similar to the 1-year event under 5 feet of sea-level rise, and the modeling shows a total of 16 structures and 14 culverts, outfalls, and sump pumps are affected under these conditions. The 100-year event under 5-feet of sea-level rise has a slightly greater extent of flooding, including 21 structures and 2,900 linear feet of Manitou Beach Drive.

5.3.2 Site #2: Yeomalt Point

Under 2 feet of sea-level rise, the modeling shows that the 1-year event overtops approximately 620 linear feet of NE Yeomalt Point Drive and inundates 20 structures, 8 storm drain culverts and outfalls, and 19 sewer and wastewater valves and hydrants. The 10-year event with 2 feet of sea-level-rise modeling results show inundation of 22 structures. The 100-year event under 5 feet of sea-level rise overtops approximately 820 linear feet of Yeomalt Point Drive, though no additional buildings would be flooded under this scenario.

5.3.3 Site #3: Hawley Cove

During the 1-year event with 2 feet sea-level rise, the model shows water levels inundate 325 linear feet of Hawley Way, including 4.5 acres of delineated wetland, 4 buildings, 2 storm drain culverts and outfalls, and 14 sewer valves. Under the 10-year flood and 2 feet sea-level rise, water levels inundate 580 linear feet of Hawley Way, 6 buildings, 4 storm drain culverts and outfalls, and 15 sewer valves or manholes. The 10- and 100-year events under 5 feet of sea-level rise are very similar; they overtop approximately 760 linear feet of Hawley Way and inundate 13 structures and 6 storm drain culverts and outfalls, and 17 sewer and wastewater valves. A portion of the wastewater treatment plant is inundated under these scenarios. Additional scenarios including 10-year and 100-year flood with 8 feet sea-level rise were evaluated for this site. Under these conditions the water treatment plant is flooded, including the southeast building of the site.

5.3.4 Site #4: Lovell Ave Road-End

With 2 feet of sea-level rise, the modeling shows that the 1-year event flood affects one outfall and 10 sewer manholes and the Lower Lovell sewer lift station. The 10- and 100-year events under 5 feet of sea-level rise are very similar. Under these scenarios, portions of three buildings and 3 outfalls are inundated. Also, approximately 65 linear feet at the end of Lovell Ave are overtopped during these scenarios.

5.3.5 Site #5: Eagle Harbor Road (head of the bay)

During the 1-year flood with 2 feet sea-level rise, the modeling shows that water levels inundate two buildings and 6 stormwater outfalls including a significant portion of designated wetland area. Under the 10- and 100-year flood with 2 feet sea-level rise, approximately 100 linear feet of Eagle Harbor Road and 5 buildings are inundated. The 10- and 100-year events under 5 feet of sea-level rise are very similar. Under these scenarios approximately 1,250 linear feet of Eagle Harbor Road are overtopped, and 10 buildings are affected by the flood condition.

5.3.6 Site #6: Lynwood Center

With 2 feet of sea-level rise, the 1-year event overtops approximately 940 linear feet of Point White Drive and inundates 2 structures and 11 storm drain culverts and outfalls. This condition floods approximately 50% of the designated wetland area. The 2 feet of sea-level-rise with the 10-year event overtops 2,300 feet of Point White Drive and affects 6 structures. Under this scenario, 75% of the designated wetland area is flooded. The 10- and 100-year events under 5 feet of sea-level rise are very similar; they overtop approximately 2,900 linear feet of Yeomalt Point Drive and inundate 18 structures, 28 storm drain culverts and outfalls, and 7 sewer valves. This scenarios floods 100% of the designated wetland area.

5.3.7 Site #7: Crystal Springs

Under 2 feet of sea-level rise, the 1-year event overtops approximately 660 linear feet of Crystal Springs Drive, inundates 15 storm drain culverts and outfalls, and one building. The 2 feet of sea-level-rise with the 10-year event inundates approximately 2,070 linear feet of Crystal Springs Drive and two buildings. The 100-year event under 5 feet of sea-level rise overtops approximately 4,500 linear feet of Crystal Springs Drive and floods 10 buildings.

5.4 Sensitivity and Adaptive Capacity

This section discusses the sensitivity and adaptive capacity of the exposed asset categories discussed above.

Parcels and Structures

Flooding of buildings or structures can lead to water damage of the structure as well as impacts to equipment and belongings inside (i.e., medium sensitivity). Additionally, flooding can disrupt safe access to and from buildings. Long-term operational interruption could occur if flooding of mechanical and plumbing systems is present on the ground floor and are subject to damage. Buildings that are exposed to annual flooding will have a lower adaptive capacity than those only exposed to the 10- or 100-year flood events. Undeveloped parcels have low sensitivity and high adaptive capacity but may be at risk of development depending on zoning.

Water Infrastructure

Flooding of critical infrastructure (pumps, utilities) could disrupt operations and potentially damage important equipment (i.e., high sensitivity). However, buried lateral and main lines are not expected to be greatly impacted by inundation (i.e., low sensitivity), although rising ground water levels may eventually place unanticipated buoyancy forces on buried pipelines, potentially leading to leaks and/or pipe failure. Additionally, flooding may temporarily limit access to facilities and pipelines for maintenance and operations (medium adaptive capacity).

Stormwater Infrastructure

Flooding may lead to blockage of or reverse flow into stormwater inlets or outlets (medium sensitivity). Tide gates are particularly susceptible to blockage due to high downstream water levels. Higher coastal water levels can cause insufficient capacity in the stormwater system for rainfall, which also may increase with climate change. Failure of the storm drainage system can cause flooding inland of the coast, and associated property damage, as well as impacts to water quality if stormwater comes into contact with contaminants. Once water recedes, stormwater infrastructure is likely to be operational fairly quickly (i.e., high adaptive capacity).

Wastewater Infrastructure

Flooding of critical infrastructure (lift stations, the treatment plant) could disrupt operations and potentially damage equipment (i.e., high sensitivity). Flooding of manholes will also result in increased rates of inflow and infiltration into the wastewater collection system. These additional flows can have multiple impacts:

- Increased flow rates within the collection system, potentially beyond the capacity of the collection system to convey wastewater. This could result in sanitary sewer overflows and regulatory action against the City.
- Increased flows of wastewater to the treatment plant resulting in higher pumping and treatment costs.
- Increased levels of chlorides and total dissolved solids from brackish/saltwater inflow and infiltration into influent flows could potentially impact the treatment process and quality of final effluent and recycled water.

Pipelines and manholes experiencing infiltration can be lined or wrapped to reduce inflow and infiltration issues. Manhole frames and covers outside of roadways can be raised to elevate frames and covers above maximum water levels. Manhole frames and covers unable to be raised can be sealed to reduce inflow. These adaptations are not anticipated to fully address these identified vulnerabilities but can reduce them substantially.

The Winslow Wastewater Treatment Plant treats wastewater from approximately 1,500 acres including downtown Winslow (Carollo 2015). According to the General Sewer Plan, the treatment plant uses "fine screens, grit removal, plug-flow aeration basins, three secondary clarifiers, UV disinfection and effluent pumping" to treat the wastewater (Carollo 2015). The sensitivity of flooding at the treatment plan site may be great depending on the condition and elevation of facilities and whether they are flood proofed or are sensitive to flooding. Aside from impacts to the operational function of the facilities, access to certain facilities may be impaired during flood events.

Additionally, elevated groundwater levels and emergent groundwater caused by sea-level rise can cause issues at the treatment plant site including poor drainage and ponded water during/after rain events, buoyancy forces on below-grade structures, and inflow and infiltration into collection pipes and other facilities and corrosion in the case of saline groundwater.

Habitats

In general, sea-level rise will reduce the extent of some coastal and nearshore habitats, while expanding others. For example, sandy and rocky beach habitats are vulnerable to conversion to open water (Smith and Liedtke 2022) while estuarine wetlands may expand (Glick et al. 2007). The vegetation composition of some freshwater wetlands will likely shift to more salt-tolerant vegetation as wetlands are inundated (Reeder et al. 2013), and increased water depths will alter light availability and potentially reduce eelgrass growth rates (Shaughnessy et al. 2012). In general, sea-level rise is expected to reduce available nearshore habitat for forage fish (e.g., surf smelt, sand lance, Pacific herring), shellfish (e.g., Dungeness crab), and shorebirds and seabirds (Glick et al. 2007; Krueger et al. 2011). As Surf Smelt are exclusively dependent on upper intertidal areas for spawning, they are likely to experience some of the earliest and most direct consequences of rising sea-levels (Whitman et al. 2014). The "coastal squeeze" phenomenon, where armored shorelines restrict the landward movement of beaches in response to rising sea-levels, is likely to cause significant reduction and potential loss of surf smelt spawning grounds.

While wetlands are largely tolerant of fluctuating water levels, those that have been heavily degraded or modified may be less likely to cope with increased water depths. Some habitats may be able to shift inland or upland as sea-level rises, particularly in areas where their migration is not blocked by shoreline armoring or coastal development (e.g., bulkheads, roads) (Krueger et al. 2011; Mauger et al. 2015). This is unlikely throughout developed areas given the presence of homes, structures, and roads along the coast that restrict the ability of habitats to shift inland.

Emergency Services

Flooding would likely impact emergency response capabilities and response time. Of the emergency-services related assets that this study assessed, only 6 fire hydrants were identified as at risk of exposure based on the modeling results. Fire hydrants have high sensitivity (very important in case of a fire) but likely have high adaptive capacity as well.

Transportation

Flooding may disrupt pathways critical for emergency services (high sensitivity) as well as transportation links to local businesses, residences, and municipal infrastructure (medium sensitivity). Once water recedes, roads may be operational fairly quickly (i.e., high adaptive capacity), although the ferry terminal may have greater impacts (i.e., low adaptive capacity). However, erosion of roads would cause longer disruptions until the road can be repaired and debris may require road cleaning and maintenance.

Recreation

Increased frequency of flooding is likely to lead to water damage and other flood related damage for recreational buildings (i.e., medium sensitivity). Flooding and erosion also cause loss of access to recreational amenities and associated commercial services. Depending on park facilities, parks may be fairly adaptive to flooding and once water recedes, recreation can resume.

An increased frequency of flooding is likely to lead to water damage and other flood related damage for support buildings at marinas. Long-term operational interruptions could occur if flooding or mechanical and plumbing systems are present on the ground floor and are subject to damage. Flooding would disrupt access and potentially damage boats, and docks in marinas as well. Increased flooding can cause erosion or deterioration of boat ramps. Boats can often be relocated before a storm to reduce damage. Depending on the facilities (e.g., docks), marinas may be fairly adaptive to flooding and once water recedes, operations can resume.

Hazardous Materials

Increased flood risk at the Wyckoff Superfund site or certain coastal commercial/industrial facilities may increase the likelihood of an accidental hazardous material release. An accidental release of hazardous materials (high sensitivity) may lead to the:

- Mobilization of hazardous materials in surface water.
- Mobilization of hazardous materials in groundwater.
- Airborne/Aerosol release of hazardous materials.
- Contamination of soil.

Such a release may expose humans and wildlife to toxic, corrosive, or otherwise harmful materials. The consequences of exposure can vary greatly depending on the type of hazardous material, and the mode, duration, and amount of exposure.

Communities

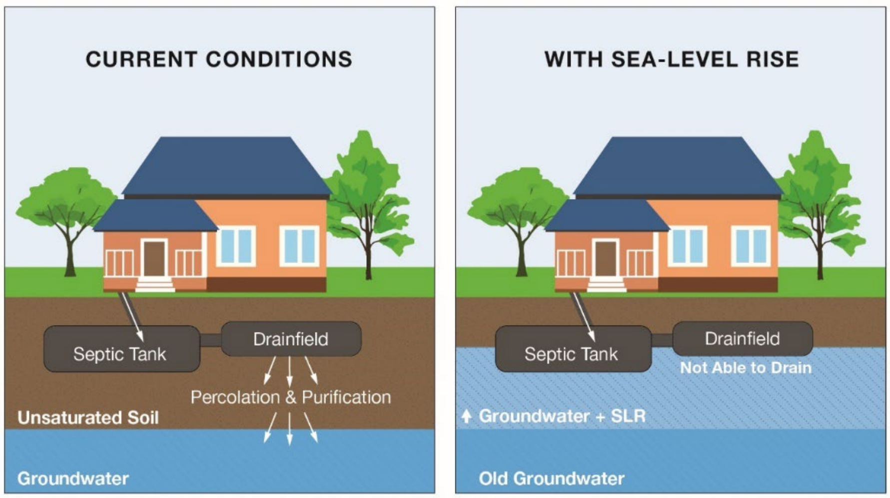
Sea-level rise and increased flooding are likely to affect communities by creating health, safety, and housing challenges. For example, increased coastal flooding may cause temporary or permanent displacement of residents and disruption to critical transportation routes for medical, food, and other services and supplies. Existing social and economic factors such as age, disability, income, housing, and access to information may amplify a community's sensitivity to sea-level rise and flooding and challenge the ability to cope with or recover from these impacts. For example:

- Age: Children and seniors are typically more sensitive to sea-level rise and flooding given existing health conditions, dependence on others for support, and reliance on critical services and infrastructure such as medical support, schools and daycares, and nursing homes or assisted living facilities.
- Disability: Residents with disabilities may have a harder time evacuating or accessing critical services due to disruptions to critical transportation routes.
- Income: Low-income and fixed-income residents are more at risk of displacement given resource constraints. Limited access to expendable income restricts the ability to rebuild and recover.
- Housing Occupancy and Type: Renters are typically more at risk of displacement than homeowners. Manufactured and mobile homes may be more susceptible to flood damage.
- Computer and Internet Use: Limited access to internet services can affect a resident's ability to access emergency alerts and apply to and receive funding from recovery programs.

Additional Assets

Although data was not available for private water wells and septic systems, the majority of residential structures on Bainbridge Island are on septic and well water. Both of these assets associated with residential structures would be sensitive to sea-level rise. Inundation of wells with salt water would make the water undrinkable. Rising surface waters may limit access to facilities and pipelines for maintenance and operations and rising groundwater levels may place unanticipated buoyancy forces on buried pipelines, potentially leading to backflow, leaks, and/or pipe failure. However, pressurized pipes are not expected to be very sensitive to infrequent flooding.

Inundation of septic systems and grinder pumps would cause system failure and may impact water quality. Septic systems would likely need to be replaced. If inundation becomes more frequent, the septic system will not function, and sewage will back up into homes (see **Figure 5-3**). Additionally, systems are usually managed by individual homeowners, so the burden of repair would fall on individuals.



SOURCE: ESA 2023

Bainbridge Island Sea-Level Rise Vulnerability Study

Figure 5-3
Components of Septic Tank Vulnerability to Groundwater with Sea-Level Rise

5.5 Vulnerability Assessment Results

For most of the study area, the modeling results show that the 100-year flooding today (i.e., the FEMA flood mapping) is likely to occur annually to roughly every 10 years with 2 feet of sea-level rise. In other words, flood events will continue to become more frequent through the end of the century.

The most vulnerable City assets include:

- The Winslow Wastewater Treatment Plant
- Wastewater lift stations (Sunday Cove #5, Lovell #6, and Wing Point #7)
- Manitou Beach Dr., Euclid Ave., Point Monroe Dr., Point White Dr., Yeomalt Point Dr., Hawley Way, Eagle Harbor Dr., Crystal Spring Dr., Rolling Bay Walk and other infrastructure supporting coastal development along Crystal Springs Dr., Point Monroe, Manitou Beach, Hawley Cove, and Lynwood Center, as well as beach access points along these roads.

Additionally, while beaches and wetlands are largely tolerant of fluctuating water levels, those that have been heavily degraded or modified may be less likely to cope with increased water depths. Some habitats may be able to shift inland or upland as sea-level rises, particularly in areas where their migration is not blocked by shoreline armoring, coastal development (e.g., bulkheads, roads), or bluffs (Krueger et al. 2011; Mauger et al. 2015). However, this is unlikely in areas with coastal roads and shoreline armoring, which restrict the ability of habitats to shift inland.

6 RECOMMENDED NEXT STEPS

This study presented the results of a city-wide flooding vulnerability assessment that is intended to provide the basis for future site-specific assessments and broader adaptation planning. Based on the findings of this study, the following next steps are recommended:

1. Consider other vulnerabilities. This could include:
   a. Conduct a detailed coastal change and erosion analysis and long-term monitoring program: A detailed erosion analysis could be conducted to understand how the shoreline may change in the future. The analysis could include a delineation of the toe and top of bluffs and wetted beach from aerial imagery, evaluating historic shoreline positions to study past erosion, and conducting beach geomorphology analyses to understand how the beach would change with sea-level rise. The results of this analysis could also be used to adjust the flood extent in the hazard zone based on the predicted future geomorphology.
   b. Conduct wetland habitat (e.g., eelgrass, intertidal, and riparian) evolution/migration modeling: While some habitat data were available for this study, the exposure analysis was focused on risk due to inundation, which is a natural and necessary process for intertidal and subtidal habitats. Habitat evolution modeling[8,9] (e.g., how wetland habitats are expected to move upslope with increasing sea-levels based on inundation frequency and salinity exposure) can be used to better understand how coastal habitats will be impacted with sea-level rise (ESA 2015, ESA 2018). This type of modeling could help identify areas to preserve for future restoration and areas most at risk of being submerged under future climate conditions.
2. Develop an Adaptation Plan: Through a public outreach process and in coordination with project partners, the City of Bainbridge Island could develop preferred adaptation scenarios for different areas of the city as part of an Adaptation Plan. A preferred scenario would likely be a combination of adaptation strategies that would be implemented based on monitored triggers (e.g., a certain amount of sea-level rise, flooding more frequently than every year, a certain amount of bluff-top erosion). The plan could include a cost-benefit analysis to understand the tradeoffs of implementing expensive adaptation measures versus the damage that could be caused by flooding and erosion. The plan should also include identification of monitoring priorities (e.g., high water marks during flood events, water level data from gage network, sea-level trends, the best available science) and adaptation triggers. Lastly, the plan could include potential policy language that could be incorporated into the plans listed in #3 below. Since planning documents are updated on specific timelines, developing policy language as part of an Adaptation Plan would provide the City of Bainbridge Island with updated text specific to reducing vulnerability. More and more resiliency funding is becoming available through federal and state grants. The City of Bainbridge Island should continue to work with project partners to develop proof-of-concept adaptation strategies.
3. Implement adaptation strategies through local planning documents. Adaptation could include investments and upgrades to critical utilities and infrastructure, wetland restoration and

[8] https://www.delmar.ca.us/DocumentCenter/View/4314/Final-Summary_Wetland-Habitat-Migration-Assessment_8162018

[9] See Appendix K (page 172) http://www.lospenasquitos.org/wp-content/uploads/2020/09/ESA-FINAL-Los-Penasquitos-Lagoon-Enhancement-Plan-APPENDICES.pdf

protection, enhancing flood defenses where appropriate, protecting or adapting parks and public access trails, and community education.

a. Update the Shoreline Master Program (City of Bainbridge Island 2021), zoning, land division, and critical areas codes including updates to regulations to reflect the results of this study, incorporate adaptation planning, and minimize risk to public and private assets.

b. Update the Hazard Mitigation Plan: Incorporate policy recommendations to meet new standards under FEMA's Local Mitigation Planning Policy.[10]

c. Results are currently being incorporated into the Comprehensive Plan Update.

d. Incorporate results and recommendations into coastal floodplain planning processes and plans.

10 https://www.fema.gov/sites/default/files/documents/fema_local-mitigation-planning-policy-guide_042022.pdf

7 REFERENCES

Carollo. 2015. City of Bainbridge Island, General Sewer Plan. July 2015. General Sewer Plan - July 2015 | Bainbridge Island, WA - Official Website (bainbridgewa.gov)

City of Bainbridge Island. 2019. Sea Level Rise on Bainbridge Island, A Preliminary Assessment. October 24, 2019.

City of Bainbridge Island. 2020. Climate Action Plan: A Plan for Mitigating and Adapting to Climate Change on Bainbridge Island. Prepared by Cascadia Consulting Group. November 12, 2020. Final-Bainbridge-Island-Climate-Action-Plan-November-12th-2020 (bainbridgewa.gov)

City of Bainbridge Island. 2021. *Shoreline Master Program: As amended through Ord. 2020-17*. Effective March 5, 2021. https://www.bainbridgewa.gov/DocumentCenter/View/14966/Shoreline-Master-Program.

ESA. 2015. Los Peñasquitos Lagoon Enhancement Plan Update, Baseline Conditions Habitat Projection Modeling. Prepared for the Los Peñasquitos Lagoon Foundation. July 2015. http://www.lospenasquitos.org/wp-content/uploads/2020/09/ESA-FINAL-Los-Penasquitos-Lagoon-Enhancement-Plan-APPENDICES.pdf (starting on page 173).

ESA. 2018. Del Mar Local Coastal Program Amendment, San Dieguito Lagoon Wetland Habitat Migration Assessment. Prepared for the City of Del Mar. August 2018. https://www.delmar.ca.us/DocumentCenter/View/3473/ESA-Del-Mar-Lagoon-Wetland-Habitat-Migration-Assessment-Report_31418?bidId=

FEMA. 2005. "Guidelines and Specifications for Flood Hazard Mapping Partners: Wave Setup, Runup, and Overtopping." FEMA

FEMA. Risk Report for Kitsap County including the Cities of Bremerton, Bainbridge, Port Orchard, Poulsbo, the Port Gamble S'Klallam Indian Reservation, the Suquamish Tribe, and Unincorporated Kitsap County. December 30, 2015. Risk Report - Kitsap County - Final.pdf

FEMA 2018. Flood Insurance Study (FIS) for Bainbridge Island, Washington and Incorporated Areas. June 20, 2018.

Krueger, K.L., K.B. Pierce, T. Quinn, and D.E. Penttila. 2011. Anticipated Effects of Sea-level Rise in Puget Sound on Two Beach-Spawning Fishes. Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop. https://wdfw.wa.gov/sites/default/files/publications/01210/wdfw01210.pdf

Mauger, G.S., J.H. Casola, H.A. Morgan, R.L. Strauch, B. Jones, B. Curry, T.M. Busch Isaksen, L. Whitely Binder, M.B. Krosby, A.K. Snover. 2015. State of knowledge report: 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, WA.

McClure, K., A. Breitenother, S. Land. 2022. Guidance for Using Maryland's 2018 Sea-level Rise Projections.

Miller, I.M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., Welch, M., Grossman, E. 2018. Projected Sea-level Rise for Washington State – A 2018 Assessment. A collaboration of Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon, University of Washington, and US Geological Survey. Prepared for the Washington Coastal Resilience Project. updated 07/2019

Miller, I., Faghin, N., and Fishman, S. 2022. Sea-level Rise and Management Options for Washington's shorelines. A collaboration of Washington Sea Grant and the Washington Department of Ecology. Prepared for the Washington Coastal Resilience Project.

National Oceanic and Atmospheric Administration (NOAA). 2023. Datums for 9447130, Seattle, WA. Available: https://tidesandcurrents.noaa.gov/datums.html?id=9447130.

National Oceanic and Atmospheric Administration (NOAA). 2023. Datums for 9445758, Seattle, WA. Available: https://tidesandcurrents.noaa.gov/datums.html?id=9445758.

National Oceanic and Atmospheric Administration (NOAA). 2022. *Global and regional sea-level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along U.S. coastlines* (NOAA Technical Report NOS 01). National Oceanic and Atmospheric Administration, National Ocean Service. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

National Research Council (NRC). 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Committee on Sea-level Rise in California, Oregon, Washington. Board on Earth Sciences Resources Ocean Studies Board Division on Earth Life Studies The National Academies Press. http://nap.edu/13389#

OCM Partners, 2021: CoNED Topobathymetric Model of Puget Sound, Washington, 1887 to 2017, https://www.fisheries.noaa.gov/inport/item/59971.

Pedersen, J.S.T., D. van Fuuren, B. Aparicio. 2020. Variability in historical emissions trends suggests a need for a wide range of global scenarios and regional analyses. Commun Earth Environ 1, 41, 2020. https://www.nature.com/articles/s43247-020-00045-y

Reeder, W.S., P. Ruggiero, S.L. Shafer, A.K. Snover, L.L. Houston, P. Glick, J.A. Newton, S.M. Capalbo. 2013. Chapter 4: Coasts. Complex changes affecting the Northwest's diverse shorelines. Pages 67–109 in Dalton, M.M., P.W. Mote, A.K. Snover, editors. Climate change in the Northwest: Implications for our landscapes, waters, and communities. Island Press, Washington, DC.

Shaughnessy, F.J., W. Gilkerson, J.M. Black, D.H. Ward, and M. Petrie. 2012. Predicted Eelgrass Response to Sea-level Rise and its Availability to Foraging Black Brant in Pacific Coast Estuaries. Ecological Applications 22 (6): 1743-1761. doi: 10.1890/11-1083.1.

Smith, C.D., and T.L. Liedtke. 2022. Potential effects of sea-level rise on nearshore habitat availability for surf smelt (Hypomesus pretiosus) and eelgrass (Zostera marina), Puget

Sound, Washington: U.S. Geological Survey Open-File Report 2022–1054, 17 p., https://doi.org/10.3133/ofr20221054.

TAW (Technical Advisory Committee for Water Retaining Structures). (2018). Wave run-up and overtopping at dikes. Rijkswaterstaat.

University of Washington, Climate Impacts Group. 2018. Interactive Sea Level Rise Data Visualizations. Interactive Sea Level Rise Data Visualizations (uw.edu)

U.S. Army Corps of Engineers. (2006). Coastal Engineering Manual (EM 1110-2-1100). Washington, D.C.: U.S. Army Corps of Engineers.

Weiner, H.M., G.M. Kaminsky, A. Hacking, D. McCandless, K. Bolles, M. Gostic, J. Liljegren, and H. Drummond, 2018. Mapping Bluffs and Beaches of Puget Sound to Quantify Sediment Supply, Estuary and Salmon Restoration Program Learning Project Final Report. Shorelands and Environmental Assistance Program, Washington State Department of Ecology, Olympia, WA. Publication #18-06-008. Available at: https://fortress.wa.gov/ecy/publications/summarypages/1806008.html

Appendix A.
Wave Climate Assessment & Coastal Flood Analysis

This memorandum summarizes Environmental Science Associates (ESA's) Wave Climate Assessment and Coastal Flood Analysis for the City of Bainbridge Island, which was used to develop the Hazard Analysis and Vulnerability Assessment described in the main report. In Step 1 of the modeling process (Section A.1 and A.2), ESA conducted a wave climate assessment at a regional and local level to estimate wave conditions around Bainbridge Island. The estimated wave conditions were then used to conduct a coastal flood analysis and calculate flood elevations at the shore resulting from the combined effect of tides and waves for conditions expected to occur during the 100-year storm scenario (i.e., the storm scenario with a 1% chance of occurring in a given year), the 10-year storm scenario (i.e., the storm scenario with a 10% chance of occurring in a given year) and the 1-year storm scenario (100% annual chance of occurrence). The methods used in this study are consistent with previous studies done in the area (PWA 2004; FEMA 2005; ESA 2016, 2017a, 2017b; and Yang, et al. 2019).

In Step 2 of the modeling process (Section A.3), site-specific flood modeling was conducted using detailed site topography and bathymetry and more complex wave processes like wave reflection, diffraction, breaking, and dissipation to provide a more comprehensive and precise assessment of the flood extent in these areas.

A.1 Wave Climate Assessment

A.1.1 Wave Climate

Wave climate describes the typical characteristics of waves (i.e., period, direction, height) for particular locations. This section describes the process used to model the wave climate for all of Bainbridge Island.

The shorelines around the island are expected to experience different wave climates. Broadly, the shorelines were divided based on whether they are on the east or the west of the island. The east shoreline receives wind-waves coming from the Central Puget Sound and are exposed to fetches from the northeast (Possession Sound), east (Elliot Bay), and southeast (Puget Sound East Passage). The west shoreline is exposed to the wind-waves generated locally across Port Orchard Bay and from the northwest (Port Orchard Bay) and southwest (Sinclair Inlet).

A.1.1.1 Wind Waves

Wind waves are the dominant waves for Bainbridge Island. Driven by the direction and strength of wind in the areas of interest, these waves are generated locally and have lower periods and shorter wavelengths compared to the open coast. Wind waves along Bainbridge Island are considered "fetch-limited," meaning that the areas (fetches) of open water available for wind wave generation are small, limiting the size of waves at these locations. The shoreline formation and topography constrain the winds and limit the number of directions waves can come from.

A.1.2 Regional Wave Model

A numerical model was used to estimate waves at the different study areas. This section describes the model configuration, including model grid development and scenario selection. ESA modeled the wave conditions using the industry-standard Simulating Waves Nearshore (SWAN) model.

This two-dimensional model predicts waves likely to occur in response to wind speed, wind direction, water level, and the site's shoreline geometry and bathymetry. The relevant wave processes included in the SWAN model include wave generation, refraction, shoaling, and breaking. The SWAN model was implemented using the Delft3D modeling suite.

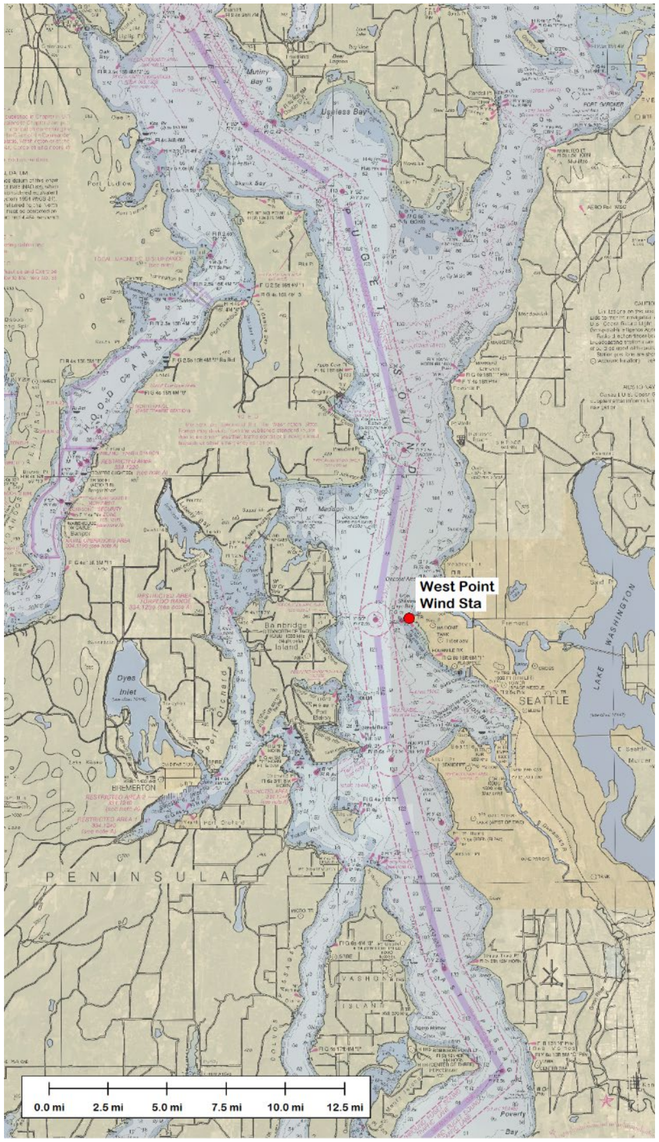
A.1.2.1 Wind

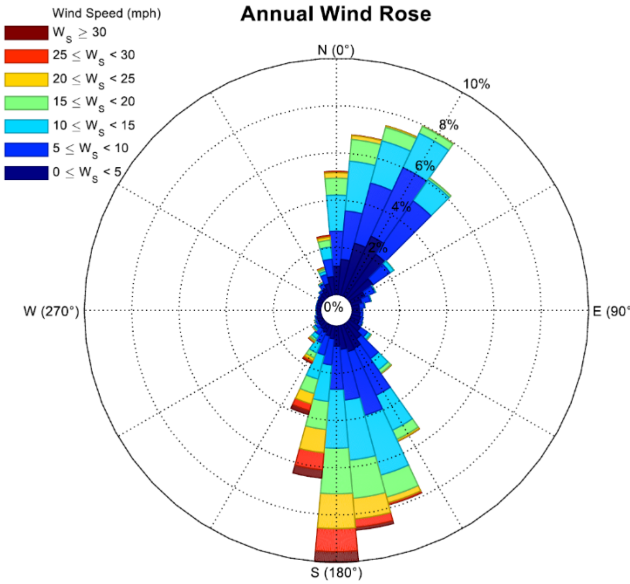
ESA reviewed regional wind data around the island and one station was selected to characterize the wind driving waves due to proximity and length of data record (West Point; NDBC #WPOW1). The station description is listed in **Table A-1**.

TABLE A-1
WIND DATA RECORDS USED IN THIS STUDY

Station Name	ID	Years of Record	Source
West Point	WPOW1	1984-present	NDBC

Wind data from West Point station were analyzed using Matlab to summarize wind direction and statistics. The raw data was evaluated, and questionable values were removed. Wind data was adjusted to a standardized duration of two minutes and to a 10-m height as needed according to Resio and Vincent (1977) and the Coastal Engineering Manual (USACE 2006). Figure A-1 shows the location of the wind station and the wind speed and directional distribution for the adjusted data. The wind rose depicts the dominant wind from the northeast and south directions.





SOURCE: ESA 2023, NOAA Chart 18840

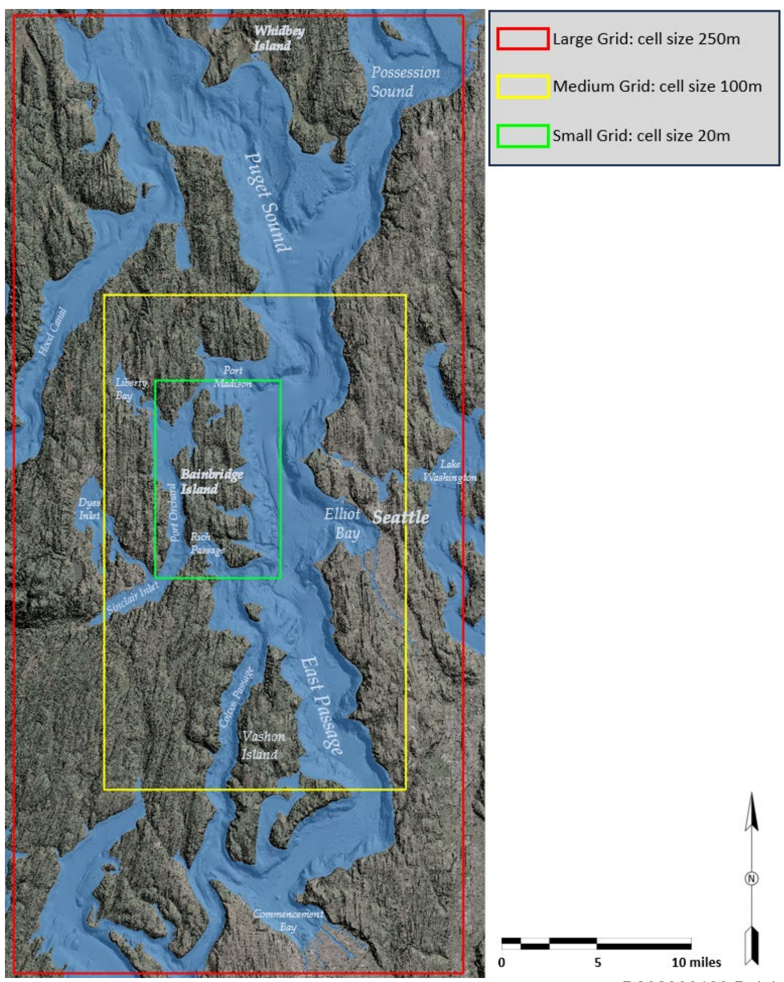
D202300123 Bainbridge Island SLR Study

Figure A-1
Wind Station and Wind Rose (1984-present)

Wind direction is reported in the typical meteorological convention (the direction from which the wind is blowing). Winds from the north show a bimodal distribution from north, north-east, south, and southeast consistent with the topography and geometry of the Central Puget Sound. The wind rose presented in Figure A-1 shows that the most common wind directions are from the north, northeast, south, and southeast. Winds from the south exhibit the highest wind speeds (shown by warm/red colors), with maximums speeds exceeding 30 mph.

A.1.2.2 Model Configuration

The modeling approach employed a variation of the Puget Sound Central SWAN model developed by ESA. The bathymetry for the SWAN model was generated using the NOAA Coastal National Elevation Dataset (CoNED; OCM partners 2023). The SWAN model was implemented using nested, rectilinear grids with different spatial resolution across the Central Puget Sound region as shown in **Figure A-2**. The largest and medium SWAN grids employed in the model, with a cell size of 250 m and 100 m, respectively, were used to simulate wave growth and propagation. The small grid with a cell size of 20 m was used to evaluate the localized effects of bathymetric variation and wave sheltering as pertinent to this study.



SOURCE: ESA 2024

D202300123 Bainbridge Island SLR Study

Figure A-2
Regional SWAN Model

A.1.2.3 Scenarios

The SWAN model was used to investigate a range of wind speeds, wind directions, and water levels that represent likely conditions in the region. The wind speed was systematically varied in 5-mph increments ranging from 2.5 mph to 52.5 mph. Similarly, wind directions from 10 to 360 degrees were modeled in 10-degree increments. This approach accounted for all the possible fetch directions surrounding and within the islands. In total, the SWAN model simulated 360 unique input combinations to provide a high-resolution wind-wave hindcast (historic wind waves based on existing wind measured records) for each location.

A.1.2.4 Model Output – Wind Waves

Wave height, period, and direction resulting from the wind-wave interactions were extracted from the SWAN model at specific points offshore of each of the 89 study areas (**Figure 4-1**). The extracted data were then tabulated in lookup tables that associated wind velocity and direction with the corresponding wave parameters (wave height, period, and direction) at each output location. The tables were then applied to the wind data time series to develop a wave height time series from 1984 to 2024.

A.1.3 Extreme Wave Analysis

An extreme value analysis was conducted for the 89 offshore points located along Bainbridge shoreline (**Figure 4-2**) on the estimated wave height time series, with adjustments made to remove spurious values or periods of missing data. The maximum wave height value for each year was found and subsequently fitted to GEV distribution, which in general represented the best fit. As expected, the modeled wave heights were higher at the more-exposed exterior regions on the east side of the island compared to the west shoreline.

A.2 Coastal Flood Analysis

Coastal flooding is the result of high-water levels combined with larger waves. The implicit assumption is that high winds and high-water levels are partly but not completely dependent. It is then important to determine the joint occurrence of these two “forcing parameters” to understand coastal flood events. However, accurately defining the joint-occurrence statistics (e.g., how often a particular wave height is exceeded for a given water level) is challenging because there is no direct correlation between high water levels and high wave heights. To solve this, a coincident time series of the forcing parameters (still water level (SWL) and wave run-up) is estimated to develop a response time series of total water level (TWL). This time series inherently addresses joint probability as well as non-linear responses (Garrity et al. 2007).

The Bainbridge Island Total Water Level & Sea Level Rise Calculator downloadable Excel file in the Additional Resources section of the StoryMap provides the TWL results for each of the 89 shoreline segments.

A.2.1 Developing a Total Water Level Time Series

The A TWL time series can be estimated by combining the still water levels near the offshore point and the coincident wave runup. The relationship is expressed as follows:

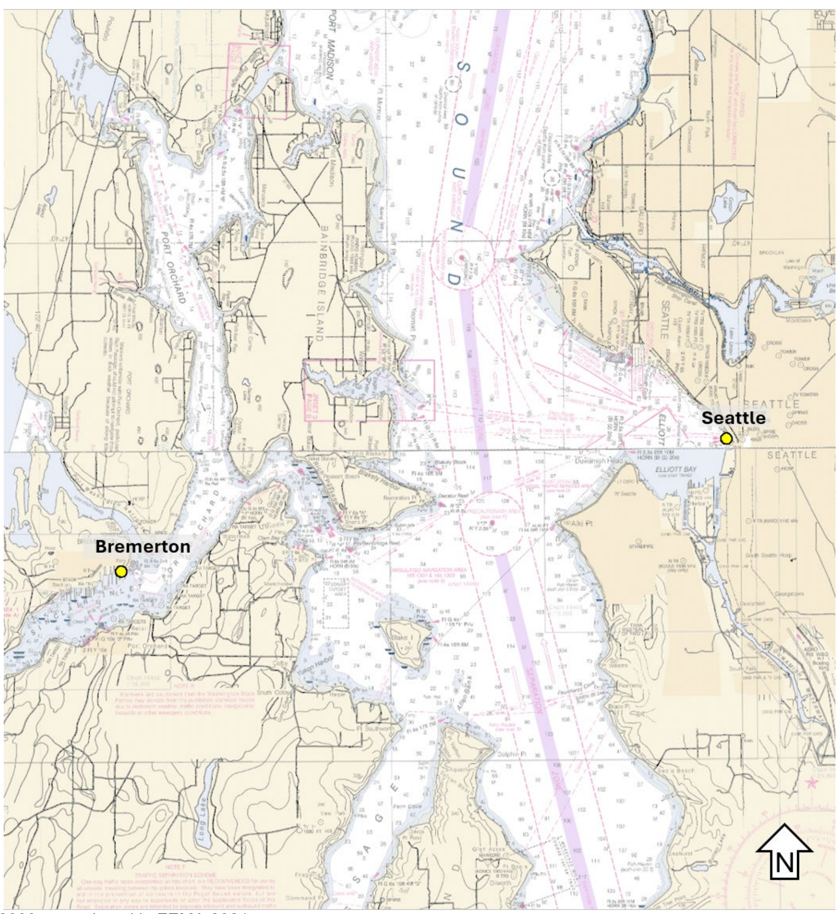
$$TWL(t) = SWL(t) + Runup(t)$$

Where t is time.

A.2.1.1 Still Water Levels

Still water levels for this project were obtained from Seattle (#9447130) and Bremerton (#9445758) NOAA tide gauges (**Figure A-3**). Tidal datums and sea-level trends associated with both stations are discussed in detail in Section 2.1.1 of the main report.

NOAA does not present datums for the Bremerton gauge in NAVD88 on NOAA's website, so conversions from MLLW to NAVD88 were determined using VDATUM, NOAA's online datum transformation tool. At Bremerton, VDATUM estimates NAVD88 = MLLW – 2.84 ft.



SOURCE: FEMA 2003, reproduced in FEMA 2021

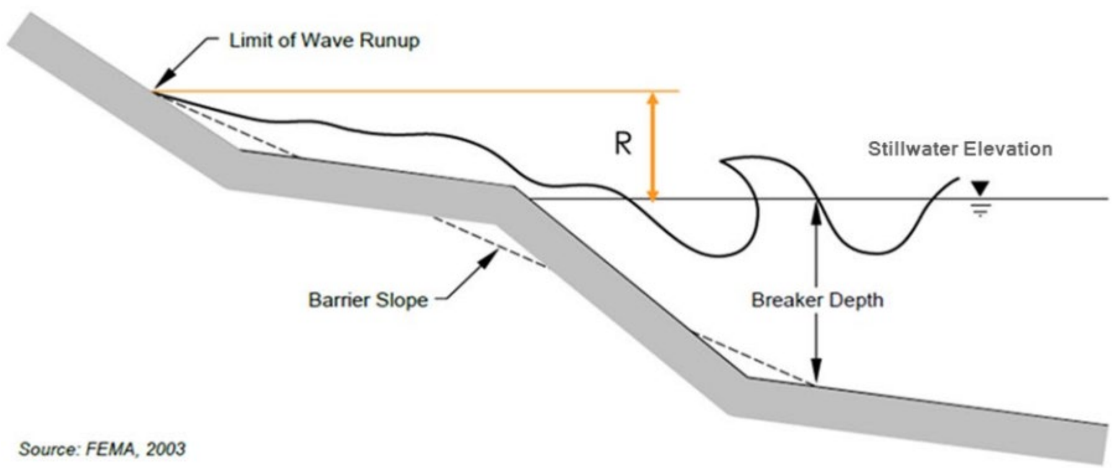
D202300123 Bainbridge Island SLR Study

Figure A-3
Tide stations

A.2.1.2 Wave Runup

Figure A-4 shows that wave runup refers to the inland vertical extent of waves as they break and run up the shore, and that runup is a parameter dependent on the site-specific slope. This study uses the 2% exceedance probability wave runup, which is the amount used for FEMA flood mapping.

A wave runup time series was developed using the wave hindcast parameter time series described in Section A.1.2.4 and a simplified backshore slope based on the beach characteristics of each shoreline segment. For medium slopes (slopes >8:1 and <15:1) the Direct Integration Method (DI based on the FEMA guidelines (FEMA 2005)) was used. For steep slopes (slope <8:1), the TAW[11] method (TAW 2018) was implemented, and for gentle slopes (slope >15:1) the Stockdon Equation was used. TWLs estimated using simplified slopes are typically higher than TWLs calculated using actual profiles because the simplified slope is projected vertically above the actual shoreline profile elevations to simulate the potential runup and TWL at the shoreline.



SOURCE: FEMA 2003, reproduced in FEMA 2021

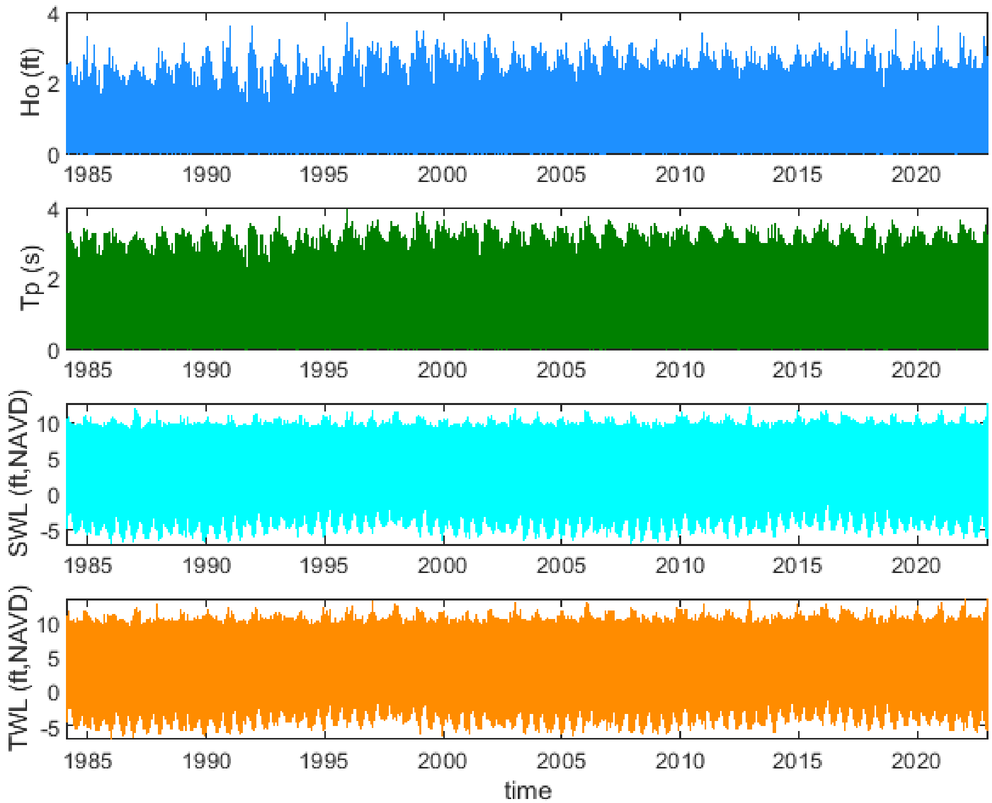
D202300123 Bainbridge Island SLR Study

Figure A-4
Wave Runup Schematic

A.2.1.3 Total Water Level Time Series

A TWL time series was developed for each of the 89 shoreline segments by adding the SWL and wave runup at each time step. **Figure A-5** shows the wave height, runup, and still water level time series and the subsequent TWL time series at one example location.

[11] Technical Advisory Committee for Water Retaining Structures (in Dutch, "Technische Adviescommissie voor de Waterkeringen")



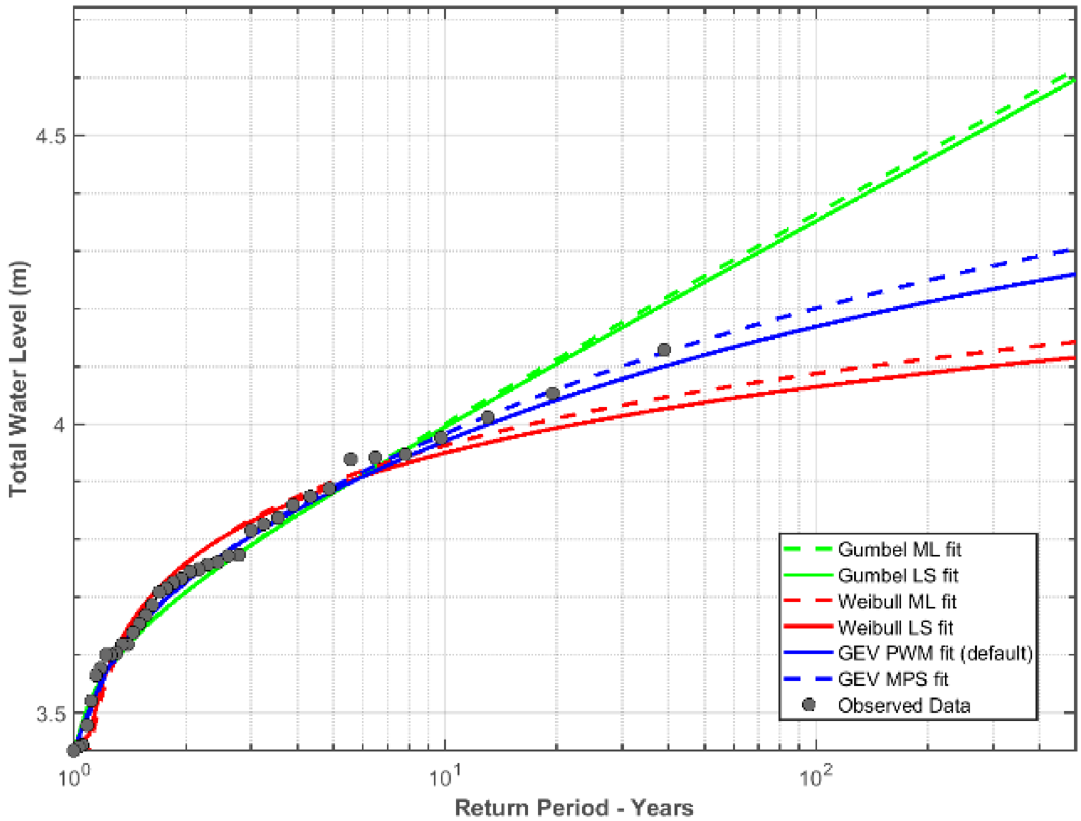
SOURCE: ESA

D202300123 Bainbridge Island SLR Study

Figure A-5
Total Water Level Time Series at Point Monroe

A.2.4 Extreme Total Water Level Analysis

An extreme value analysis was performed on the modeled TWL time series for each shoreline segment. The maximum water level for each year was found and fitted to a GEV distribution, as shown graphically in **Figure A-6**. Model performance was evaluated visually for each shoreline segment.



SOURCE: ESA 2023

D202300123 Bainbridge Island SLR Study

Figure A-6
Extreme Value Analysis at Example Site Near Point Monroe

A.2.5 Sea-Level Rise

As described in Section 3.1 of the main report, this study uses the regional sea-level rise projections prepared as part of the Washington Coastal Resilience Project. Sea-level rise was added directly to the TWL estimates to calculate future TWL scenarios.

A.3 Site-Specific Flood Events and Process-Based Analysis

To accurately capture relevant processes in the swash zone,[12] dynamic setup, and complex bathymetry at seven sites selected by the City of Bainbridge (see Section 5.3), waves were modeled using the XBeach storm response model on non-hydrostatic mode (Roelvink et al. 2009), which allows for a quantitative estimate of complex processes such as the peak wave runup, overtopping flow, and velocity. XBeach uses wave and water level inputs to propagate offshore waves inland and to estimate the landward extent of coastal flooding. XBeach is too

12 The swash zone refers to the area characterized by turbulent water where waves run up the beach face or a structure.

computationally intensive to run for a whole time series and is more appropriate for analysis of specific events. Note that XBeach does not include morphodynamic changes to the shoreline.

XBeach 2D was utilized for complex shoreline areas like Eagle Harbor, and XBeach 1D was developed for less complex shorelines.

Step 1 was used to define what scenarios to run in Step 2. Once the 1-, 10-, and 100-year total water level elevations were identified, specific events that result in this water level could be determined. Since total water level depends on both the still water level and wave runup, a 100-year event could be a combination of extreme waves with an average still water level or an extreme still water level (like during a king tide) and typical waves (or any scenario in between). Statistically, a 100-year scenario is expected to be exceeded about once in 100 years. Therefore, it is not likely that the 100-year event has occurred in the wind records this study is using, so the water levels and waves that force the 100-year TWL are not known.

Upon reviewing the combinations of 1- and 100-year still water levels with 1- and 100-year wave heights, it was concluded that the 1-year wave height paired with 1-, 10-, and 100-year still water level provided the most suitable scenarios for defining practical conditions.

XBeach was then run using the determined wave height and still water level for each site and each scenario (1-, 10-, and 100-year event for 2 and 5 feet of sea-level rise). For Eagle Harbor, an additional 8-ft sea-level rise scenario was developed for the 10- and 100-year events. **Figure 4-3** shows the model extent for the 8-ft sea-level rise scenario.

The modeling results are presented in the Sea-level Rise in Bainbridge Island StoryMap.