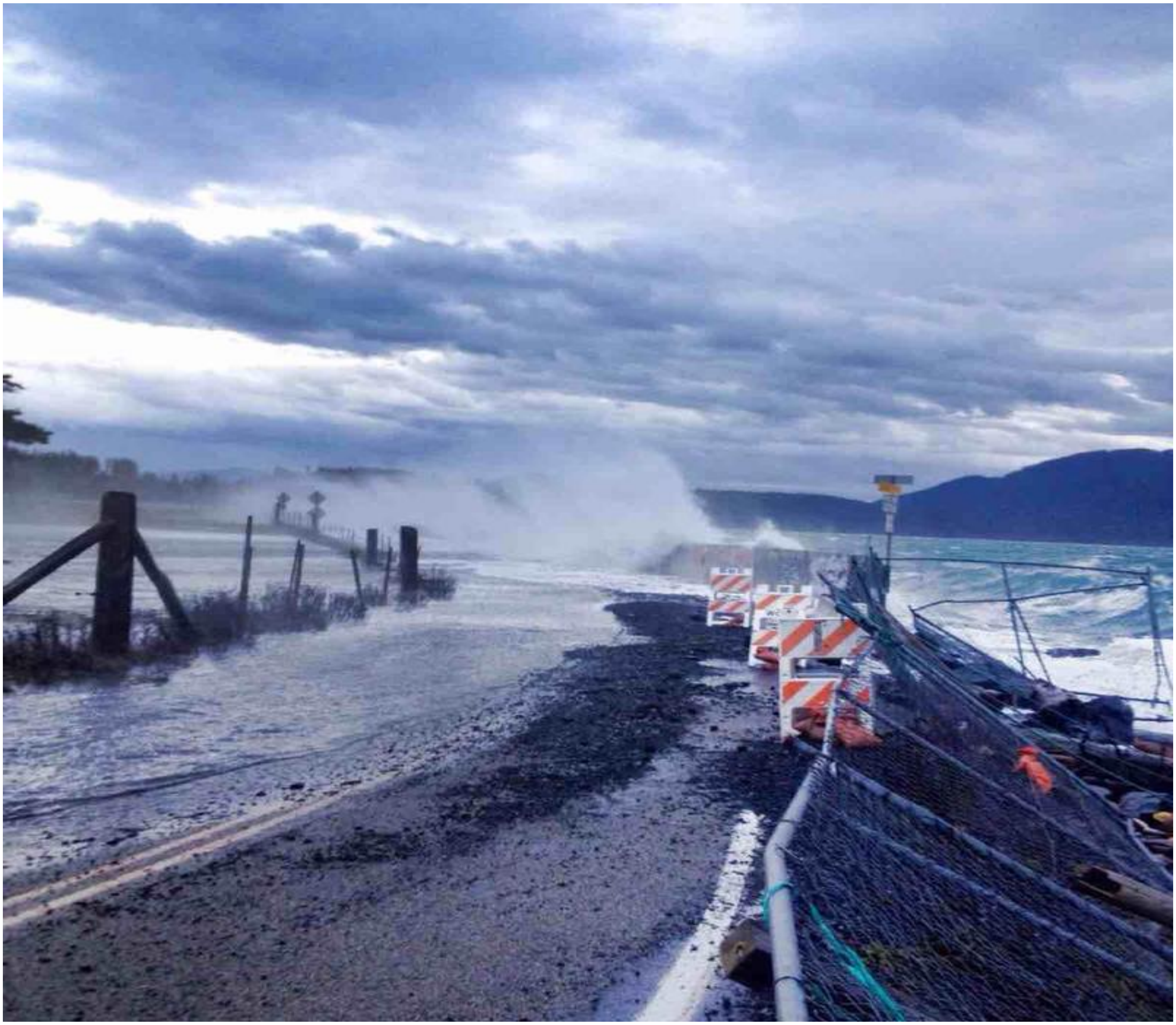

Extreme Coastal Water Level in Washington State

Guidelines to Support Sea Level Rise Planning

The Washington Coastal Resilience Project (WCRP) is a three-year effort to rapidly increase the state's capacity to prepare for coastal hazards, such as flooding and erosion, that are related to sea level rise. The project will improve risk projections, provide better guidance for land use planners and strengthen capital investment programs for coastal restoration and infrastructure. Partners include:

Washington Sea Grant
Washington Department of Ecology
Island County
King County
NOAA Office for Coastal Management
Pacific Northwest National Laboratory
Padilla Bay National Estuary Research Reserve
The City of Tacoma
The Nature Conservancy
U.S. Geological Survey
University of Oregon
University of Washington Climate Impacts Group
University of Washington Department of Earth and Space Sciences
Washington Department of Fish and Wildlife
Western Washington University

The Washington Coastal Resilience Project

Funding Provided by NOAA Regional Coastal Resilience Grants Program (grant #NA16NOS4730015).

Cover image: Lummi Island during a storm, 2015. Photo by Pete Granger.

Prepared for the Washington Coastal Resilience Project

October 2019 | University of Washington

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Joana van Nieuwkoop (Deltares) and Sean Crosby (Western Washington University) assisted in developing modeling grids and workflows for the wave modelling described in Appendix D of this report.

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Suggested Citation

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Purpose of this Report

This document provides guidelines for assessing exposure to current or future coastal flooding during extreme coastal water level events—whether these are due to tides, surge, wave run-up, or, more likely, a combination of the three. These guidelines provide information about the current and future magnitude of extreme coastal water levels across Washington State and the underlying processes that influence them. *This information is intended to be combined with sea level projections to assess future exposure to flooding along Washington's coastline*.

Although the results of our analyses can be combined with any available sea level projections, this report is intended as a companion to the localized sea level rise projections (Miller et al. 2018) developed as part of the Washington Coastal Resilience Project. The Washington Coastal Resilience Project is a three-year effort to rapidly increase the state's capacity to prepare for sea level rise. The project aims to improve risk projections, provide better guidelines for land use planners and strengthen capital investment programs for coastal restoration and infrastructure. Partners in the Washington Coastal Resilience Project included Washington Sea Grant, Washington Department of Ecology, Island County, King County, NOAA Office for Coastal Management, Pacific Northwest National Laboratory, Padilla Bay National Estuary Research Reserve, The City of Tacoma, The Nature Conservancy, U.S. Geological Survey, Pacific Northwest National Laboratory, University of Oregon, University of Washington Climate Impacts Group, University of Washington Department of Earth and Space Sciences, Washington Department of Fish and Wildlife and Western Washington University.

The 2018 sea level projections are described in an accompanying technical report, along with a review of the science related to sea level rise (Miller et al. 2018). The report and all associated supporting information are available on the Washington Coastal Hazards Resilience Network website (http://www.wacoastalnetwork.com/).

Table of Contents

INTRODUCTION

This report is intended to provide guidelines for assessing the magnitude and frequency of extreme coastal water level events in Washington State. We define extreme coastal water level events as those in which the height of the sea surface is unusually high (Figure 1). Sea level rise will push the reach of those extreme coastal water level events higher in elevation, and also increase their frequency. Selecting extreme coastal water level event scenarios is an important step in sea level rise visualization, planning and project design; this report is designed to facilitate that choice.

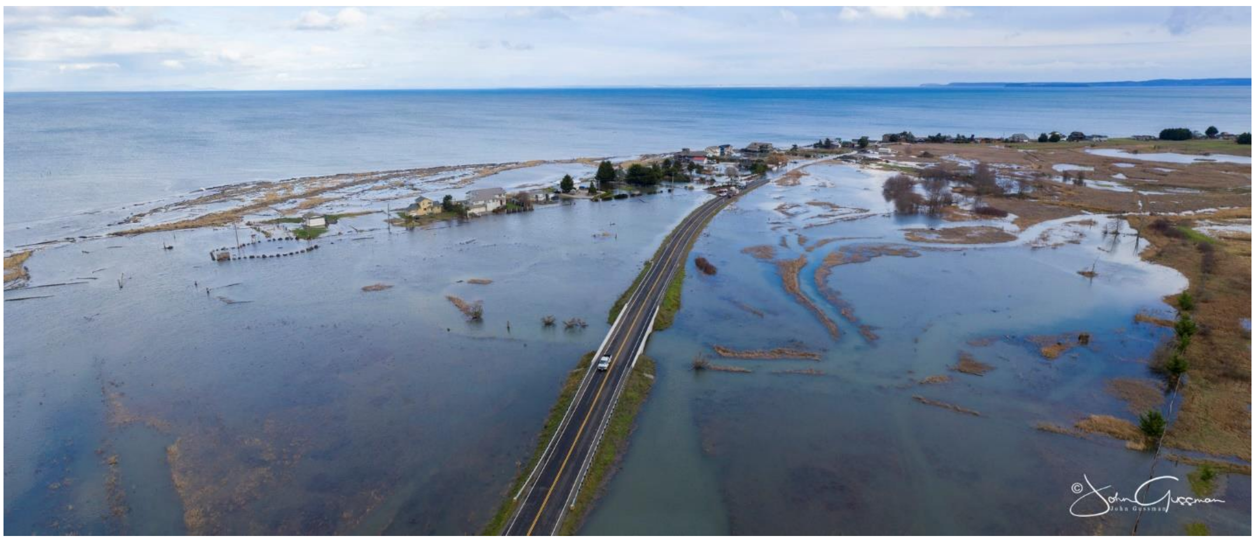


Figure 1. Aerial view of coastal flooding on the Dungeness River delta, near Sequim, Washington, during an extreme coastal water level event on December 20, 2018. Used by permission of John Gussman/Doubleclick Productions.

Many processes, operating over a range of temporal and spatial scales, affect the height of the sea surface in coastal Washington State. Tides, wave run-up and storms lead to variations in coastal water level on time-scales of minutes, hours and days (Figure 2). Variations in weather patterns and climate oscillations (e.g., El Niño Southern Oscillation, Pacific Decadal Oscillation) can drive changes in coastal water level that last months to years (for more on these processes, see Appendix A). All of these processes vary around a multi-decadal rising trend in sea level that has been observed globally and in coastal Washington State over the past century (Miller et al. 2018).

For the purposes of this report, we distinguish between extreme still water level (SWL) and extreme total water level (TWL). SWL is defined as the coastal water level due to all processes except wave run-up on the shoreline, whereas TWL is the maximum elevation that water reaches on the shoreline due to all processes including wave run-up. This distinction is necessary only because of the types of water level observations that are available in Washington State (see Box 1 for more detail).

Figure 2. Three photos of the Statue of Liberty Plaza in Seattle, WA near Alki Beach Park, illustrating the processes at play during two different extreme water level events. Panel A shows the water level during a normal, or average, high tide; panels B and C show two extreme coastal water level events with roughly the same extent of flooding. In each photo, the still water level (SWL) refers to the water level measured at the nearby tide gauge in Seattle (NOAA Station 9447130) at the time the photo was taken, in feet relative to Mean Higher High Water (1983–2001 epoch). The event in panel C had a much lower SWL than the event panel B, but a very similar flooding elevation and extent, illustrating the role that wave run-up can play in coastal flooding. Photos A and C courtesy of Melissa Poe; photo B from West Seattle Blog.

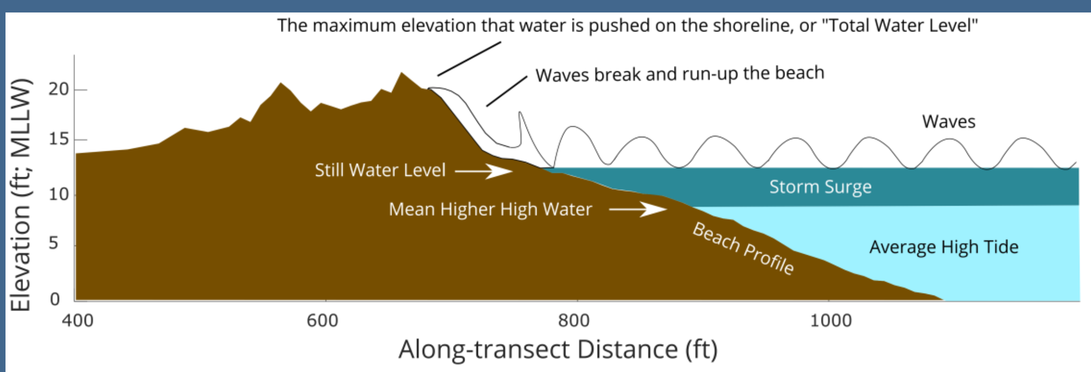
Extreme coastal water level events tend to occur in Washington when various processes coincide; for example, when storm surge (defined here as an increase in coastal water level in response to low pressure and wind; see Appendix A) co-occurs with a high tide. Several times a year, storm surge associated with a passing low atmospheric pressure can elevate the sea surface 1–4 feet above the predicted astronomical tide (i.e., Figure 2B).

Box 1: Still Water Level vs. Total Water Level

For this report, we have adopted terminology from FEMA for describing different types of coastal water level (see Section D.4.2 of NHC, 2005). Specifically:

- **Still Water Level (SWL)** refers to coastal water elevation due to everything except wave run-up: Tides, storm surge, seasonal and annual water level cycles, as well as the long-term average sea level trend. This is the water level measured by tide gauges, which are specifically designed to remove any water level components related to waves.
- **Total water level (TWL)** refers to the maximum coastal water elevation on the shoreline, including waves and wave run-up. Where waves are present, the TWL will be higher than the SWL measured at a nearby tide gauge

This distinction is useful only because of the observational data that we have available; SWL observations are readily available from Washington's network of tide gauges, whereas TWL is rarely measured directly and is challenging to model accurately.



A schematic view of coastal water level during a hypothetical storm event, drawn on a 2017 shoreline profile from Washington's Pacific coast. During this hypothetical event, total water level is near the crest of the berm due to the combination of tides, storm surge and wave run-up. Flooding is imminent if still water level rises any higher or wave run-up increases. Still water level, or what the tide gauge nearest the site would measure, is quite a bit lower than total water level in this hypothetical event, illustrating the importance of understanding wave run-up and its contribution to total water level when assessing coastal flood risk.

Periodically, high wind events in Puget Sound can generate waves that push water up the shoreline and lead to additional flooding or shoreline erosion (i.e., Figure 2C). On Washington's Pacific Coast and in parts of the Strait of Juan de Fuca, locally generated waves can co-occur with swell generated in distant parts of the Pacific Ocean, leading to infrequent but damaging large waves. The combination of these processes can lead to coastal flooding or other coastal impacts.

The impacts of sea level rise in Washington State will likely be experienced initially as changes in the magnitude or frequency of extreme coastal water level events: New areas will be flooded during the most extreme events, and coastal areas already exposed to flooding will be impacted more frequently (Vitousek et al. 2017). Therefore, planning for sea level rise impacts requires understanding and accounting for changes in the magnitude and frequency of extreme coastal water level events. This assessment relies on a variety of published resources, along with our own analyses to provide insight about the magnitude and frequency of extreme coastal water level events, as well as expected changes as sea level rises. We also attempt to clarify the limitations and uncertainties of the information that we synthesize and highlight when or where additional study may be useful.

ESTIMATING FUTURE EXTREME WATER LEVEL

Components of Extreme Water Level

Sea level rise will lead to increased flooding during future extreme water level events, sending water higher up the shoreline and further inland. We can conceptually understand extreme coastal water level events as being composed of the sum of various water level processes - tides, storm surge and wave run-up, for example - super-imposed on a changing mean sea level. We can therefore express possible extreme water levels during future events as a simple sum:

$$\begin{aligned}&\mathit{Future\ Extreme\ Water\ Level}\\&= \mathit{Relative\ SLR} + \mathit{Astonomical\ Tide\ Height} + \mathit{Storm\ Surge} + \mathit{Wave\ Run\text{-}up}\end{aligned}$$

Where relative SLR is a change in the average sea level at a particular location (Miller et al. 2018), astronomical tide height refers to the predicted water level driven by gravitational forces, storm surge is defined as an increase in coastal water level in response to low pressure and wind, and wave run-up is the additional elevation up the shoreline that water is pushed by waves. Additional insight about each of these components is provided in Appendix A.

In this analysis, we assume that sea level rise is the most important driver of changing patterns of extreme coastal water level in Washington State. Put another way, existing research is inconclusive about *if* and *how* climate change will change the magnitude of storm surges affecting Washington State's coastline or if climate change will lead to significant changes in the magnitude of wave run-up (see Appendix A for a more detailed discussion). Regardless, future extreme water levels will reach higher up the shoreline because of the projected rise in sea level.

To understand and develop extreme coastal water level event scenarios, each of the components (tides, storm surge, wave run-up) could be quantified and summed. However, doing so is complicated because we have to account for the likelihood that different combinations of tides, storm surge and wave run-up coincide. It is extremely rare, for example that a high tide occurs at the same time as a very large surge event, and even rarer that both occur at the same time as an exceptionally large wave event. As a result, these guidelines, where possible, summarizes extreme coastal water levels in a "return frequency" framework (see Box 2). Such a framework uses historical data or modelling to estimate the likelihood of various components coinciding to result in a particular extreme coastal water level.

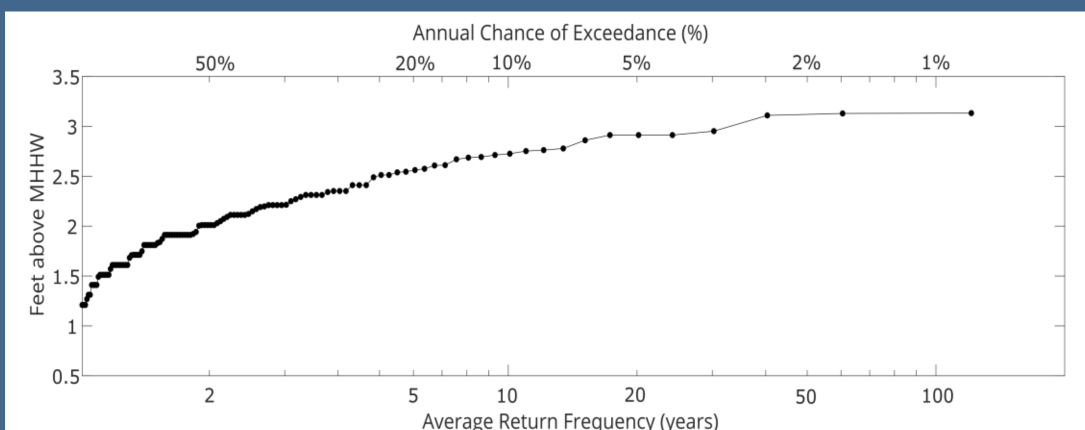
Extreme Still Water Level

Still water level (SWL) is measured directly by tide gauges and incorporates the influence of astronomical tides, storm surges and other processes. SWL does not include the influence of wave run-up directly on the shoreline (see Box 1). We conducted an analysis of tide gauge data available for Washington State and calculated extreme still water level return frequencies for the Puget Sound/Strait of Juan de Fuca, and for the Pacific Coast of Washington (see Appendix B for analysis details). The results are shown in Table 1, along with how the magnitude of extreme still water levels are expected to change as sea level rises.

Box 2: Making Sense of Return Frequencies

Extreme coastal water levels can be described in terms of their return frequency, which is defined based on the probability that an event of a particular magnitude will be exceeded in any given year. For example, a "2-year event" is defined as the coastal water level associated with an event that we would expect, on average, at least once every two years (i.e., that has a 50% chance of exceedance in any given year). Similarly, the 100-year event is defined as the event that has a 1% chance of being exceeded in any given year.

Knowing the return frequency of extreme coastal water levels at a particular location can provide useful insight for planning and design. For example, critical infrastructure that isn't flood tolerant should be placed well above any possible coastal extreme water level. Conversely, a more flood-tolerant shoreline use, parts of a coastal park for example, might be placed to avoid only the most frequent extreme coastal level.



An extreme still water level return frequency curve for Seattle, based on data from NOAA Station 9447130. Each black dot in the plot represents the highest annual water level measured by the tide gauge for each year since the tide gauge began operating in 1898. These are sorted by magnitude in feet, relative to Mean Higher High Water (1983–2001 epoch). Average return frequencies, in years, are shown along the bottom axis, whereas the same information, expressed as an annual likelihood of exceedance, is shown along the top of the box.

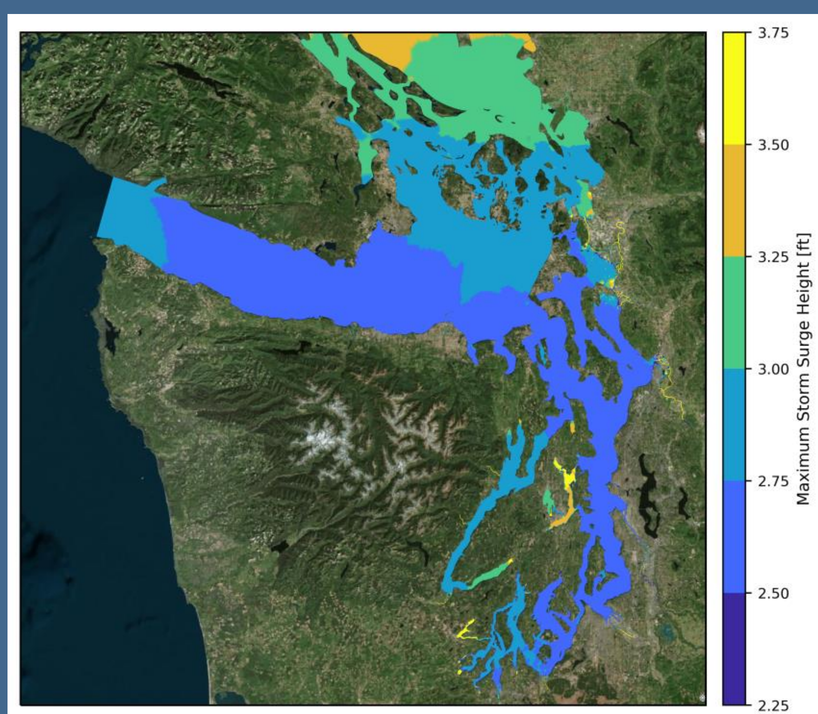
The extreme SWL magnitudes shown in Table 1 are derived from tide gauges, and the distribution of tide gauges may not capture spatial variability in extreme water level across the complex geography of Puget Sound. To investigate this possibility, we also modelled storm surges in Puget Sound for a selection of historical storm events. Model results suggest that certain embayments in Puget Sound—southern Hood Canal, parts of Bellingham Bay and Samish Bay, and in particular Sinclair and Dyes Inlets, Liberty Bay and Hammersly Inlet—may be exposed to higher magnitude extreme SWL than the rest of Puget Sound (see Box 3). Further analysis and modeling would be needed to more accurately estimate storm surge magnitudes in these embayments.

Table 1. Extreme still water level (SWL) magnitudes for Washington's inland sea and the Outer Coast, based on tide gauge data. Current and future SWL magnitudes, in feet relative to current Mean Higher High Water (MHHW), at a variety of return frequencies and sea levels. The changes in magnitude of SWL events are provided for a set of sea levels (left-hand column). See Miller et al. (2018) to assess the timeframe or likelihood of various future sea levels. The 0-foot sea level row refers to contemporary sea level.

		Puget Sound/Strait of Juan de Fuca Extreme Still Water Level Magnitude					*Coast Extreme Still Water Level Magnitude*				
Return Frequency:		***2-yr***	***5-yr***	***20-yr***	***50-yr***	***100-yr***	***2-yr***	***5-yr***	***20-yr***	***50-yr***	***100-yr***
Sea Level Change (feet)	***0***	2.2	2.6	2.9	3.1	3.2	2.9	3.3	3.7	3.9	4.0
	0.5	2.7	3.1	3.4	3.6	3.7	3.4	3.8	4.2	4.4	4.5
	1.0	3.2	3.6	3.9	4.1	4.2	3.9	4.3	4.7	4.9	5.0
	1.5	3.7	4.1	4.4	4.6	4.7	4.4	4.8	5.2	5.4	5.5
	2.0	4.2	4.6	4.9	5.1	5.2	4.9	5.3	5.7	5.9	6.0
	2.5	4.7	5.1	5.4	5.6	5.7	5.4	5.8	6.2	6.4	6.5
	3.0	5.2	5.6	5.9	6.1	6.2	5.9	6.3	6.7	6.9	7.0
	4.0	6.2	6.6	6.9	7.1	7.2	6.9	7.3	7.7	7.9	8.0
	5.0	7.2	7.6	7.9	8.1	8.2	7.9	8.3	8.7	8.9	9.0
	6.0	8.2	8.6	8.9	9.1	9.2	8.9	9.3	9.7	9.9	10.0
	7.0	9.2	9.6	9.9	10.1	10.2	9.9	10.3	10.7	10.9	11.0
	8.0	10.2	10.6	10.9	11.1	11.2	10.9	11.3	11.7	11.9	12.0
	9.0	11.2	11.6	11.9	12.1	12.2	11.9	12.3	12.7	12.9	13.0
	10.0	12.2	12.6	12.9	13.1	13.2	12.9	13.3	13.7	13.9	14.0

Box 3: Modelling Storm Surge in Puget Sound

To investigate storm surge variability in Puget Sound, we modelled the storm surge component of coastal water level for the most extreme coastal storm events between 1980 and 2016 (Yang et al., 2019c). The modelling suggests that most of Puget Sound experiences similar storm surges during extreme events, with an average maximum value between 2.5 and 3.0 ft. There are areas, though, where the model suggests that the 3.0 foot storm surge magnitude may be marginally exceeded (i.e., by a few inches), such as in southern Hood Canal, Bellingham Bay and Samish Bay. There appear to be considerably (up to 1 foot) larger storm surges than are suggested by the tide gauges in some inlet and bay systems, such as Sinclair and Dyes Inlets and Liberty Bay, as well as Hammersly Inlet in south Puget Sound. While in general the results of this modelling study provide some confidence that the regionally averaged extreme still water level return frequencies presented in Table 1 are applicable across *most* of Puget Sound, they may not be accurate in flood risk assessments and sea level rise exposure assessments for communities in the locations listed above.



Map of the modelled maximum storm surge magnitude across 34 extreme events for every model grid point in Puget Sound and the Strait of Juan de Fuca, discretized into 0.25-foot bins.

Extreme Total Water Level on the Wave-exposed Pacific Coast

We also provide modelled estimates across a range of return frequencies for extreme total water level (TWL), though only for two locations on the wave-exposed Pacific Coast of Washington (Table 2). TWL during extreme events is difficult to model, can vary dramatically along the shoreline and is rarely measured directly. In particular, the slope, roughness characteristics, and orientation of the shoreline can substantially alter the magnitude of wave run-up (see Appendix A for more information). This means that

Table 2. Modelled total water level (TWL) estimates for two locations on Washington's wave-exposed Pacific Coast. Current and future extreme TWL, in feet relative to current Mean Higher High Water (MHHW), at a variety of return frequencies and sea level rise scenarios. Projected changes in the magnitude of TWL events are provided for a set of sea level scenarios (left-hand column). See Miller et al. (2018) to assess the timeframe or likelihood of various sea level scenarios. The 0-foot sea level scenario refers to current sea level.

		Toke Point/South Coast Extreme Total Water Level Magnitude					*Makah Bay/North Coast Extreme Total Water Level Magnitude*				
Return Frequency:		***2-yr***	***5-yr***	***20-yr***	***50-yr***	***100-yr***	***2-yr***	***5-yr***	***20-yr***	***50-yr***	***100-yr***
Sea Level Scenario (feet)	***0***	10.9	11.5	12.9	13.6	14.2	9.8	11.6	12.0	12.8	13.2
	0.5	11.4	12	13.4	14.1	14.7	10.3	12.1	12.5	13.3	13.7
	1.0	11.9	12.5	13.9	14.6	15.2	10.8	12.6	13	13.8	14.2
	1.5	12.4	13	14.4	15.1	15.7	11.3	13.1	13.5	14.3	14.7
	2.0	12.9	13.5	14.9	15.6	16.2	11.8	13.6	14.0	14.8	15.2
	2.5	13.4	14	15.4	16.1	16.7	12.3	14.1	14.5	15.3	15.7
	3.0	13.9	14.5	15.9	16.6	17.2	12.8	14.6	15.0	15.8	16.2
	4.0	14.9	15.5	16.9	17.6	18.2	13.8	15.6	16.0	16.8	17.2
	5.0	15.9	16.5	17.9	18.6	19.2	14.8	16.6	17.0	17.8	18.2
	6.0	16.9	17.5	18.9	19.6	20.2	15.8	17.6	18.0	18.8	19.2
	7.0	17.9	18.5	19.9	20.6	21.2	16.8	18.6	19.0	19.8	20.2
	8.0	18.9	19.5	20.9	21.6	22.2	17.8	19.6	20.0	20.8	21.2
	9.0	19.9	20.5	21.9	22.6	23.2	18.8	20.6	21.0	21.8	22.2
	10.0	20.9	21.5	22.9	23.6	24.2	19.8	21.6	22.0	22.8	23.2

estimates of wave run-up for one location, and the resulting TWL, may not be representative of other locations due to differences in shoreline characteristics and local variations in wave orientation and wave height.

The extreme TWL magnitudes in Table 2 were calculated using a modification of the Serafin et al. (2017) TWL model (see Appendix C for additional details), and were only generated for two wave-exposed locations on the Washington Coast. Additionally, the TWL magnitudes in Table 2 are unvalidated; they have not been compared to observations because no such data exist. Despite these limitations, the estimated TWL magnitudes and return frequencies provide useful insight into the possible reach and frequency of extreme TWL on the wave-exposed Pacific Coast of Washington State, especially in the absence of other modelling or information.

Extreme Total Water Level on the Shorelines of Puget Sound and the Strait of Juan de Fuca

Total water level (TWL) estimates for extreme events across a range of return frequencies are not yet available for locations in Puget Sound and the Strait of Juan de Fuca, but are the focus of current research by the US Geological Survey[1]. There are a variety of challenges associated with modelling TWL, especially in a coastal area as topographically complex as Puget Sound. As a first approximation, we modelled historic wave heights throughout Puget Sound, then combined modelled wave height with some simplified assumptions about Puget Sound's shoreline to roughly estimate a 2-year extreme TWL (see Appendix D for model details, results and uncertainties).

There are limitations to our relatively simplistic modelling approach, and it is not intended to provide accurate estimates of TWL. Instead, our modelling is simply intended to answer an important question: Where in Washington's inland sea does wave run-up make a substantial contribution to extreme TWL patterns? Wave run-up can play a role in extreme events in Puget Sound almost anywhere (i.e., Figure 2C). However, throughout most of Puget Sound, waves are small enough, and rare enough, that they are unlikely to dramatically change the expected pattern of extreme water level at a particular return frequency. For example, we assessed the 100-year TWL for a location near Tacoma, Washington, and estimated it to be 3.6 feet relative to the local mean higher high water

[1] See https://www.usgs.gov/centers/pcmsc/science/ps-cosmos-puget-sound-coastal-storm-modeling-system

(MHHW) tidal datum (Van Arendonk, 2019), whereas the 100-year still water level (SWL) for Puget Sound is only a few inches lower at 3.2 feet relative to MHHW (Table 1). This difference is small—suggesting that for many planning and decision-making applications in this location using the SWL return frequency information in Table 1 would be adequate to characterize the coastal flood exposure. This is just one example, and other locations may see a more pronounced influence of wave run-up, necessitating additional customized analysis or modelling to quantify future coastal flood risks.

To evaluate the relative importance of wave run-up throughout the inland sea of Washington State, we differenced our estimates of extreme SWL from Table 1 against our modelled TWL estimates (Figure 3). Our estimates of the uncertainties in our relatively simple TWL approach (see Appendix D) suggest that in areas where the difference shown in Figure 3 is less than 2.5 feet, then the SWL extremes provided in Table 1 can generally be used to approximate coastal flood exposure for many applications.

In areas where the difference shown in Figure 3 is larger than 2.5 feet, or anywhere where a user may want more insight about the potential current or future magnitude of extreme total water level events, a few options exist. First, sea level rise projections can be combined with a single event scenario, such as the *"Base Flood Elevation*" estimated by FEMA. For communities with updated regulatory flood maps (see https://www.fema.gov/coastal-flood-risk-study-process) the Base Flood Elevation for coastal areas provides a modelled estimate of the 100-year extreme TWL. Alternatively, users could evaluate water levels recorded during a single storm, such as a storm of record (i.e., an extreme event observed by a community), and use those as a storm scenario paired with sea level projections. If none of these options exist, or if additional information is required, then additional, customized, modeling and analysis may be needed to determine the height and extent of extreme TWL for a particular location.

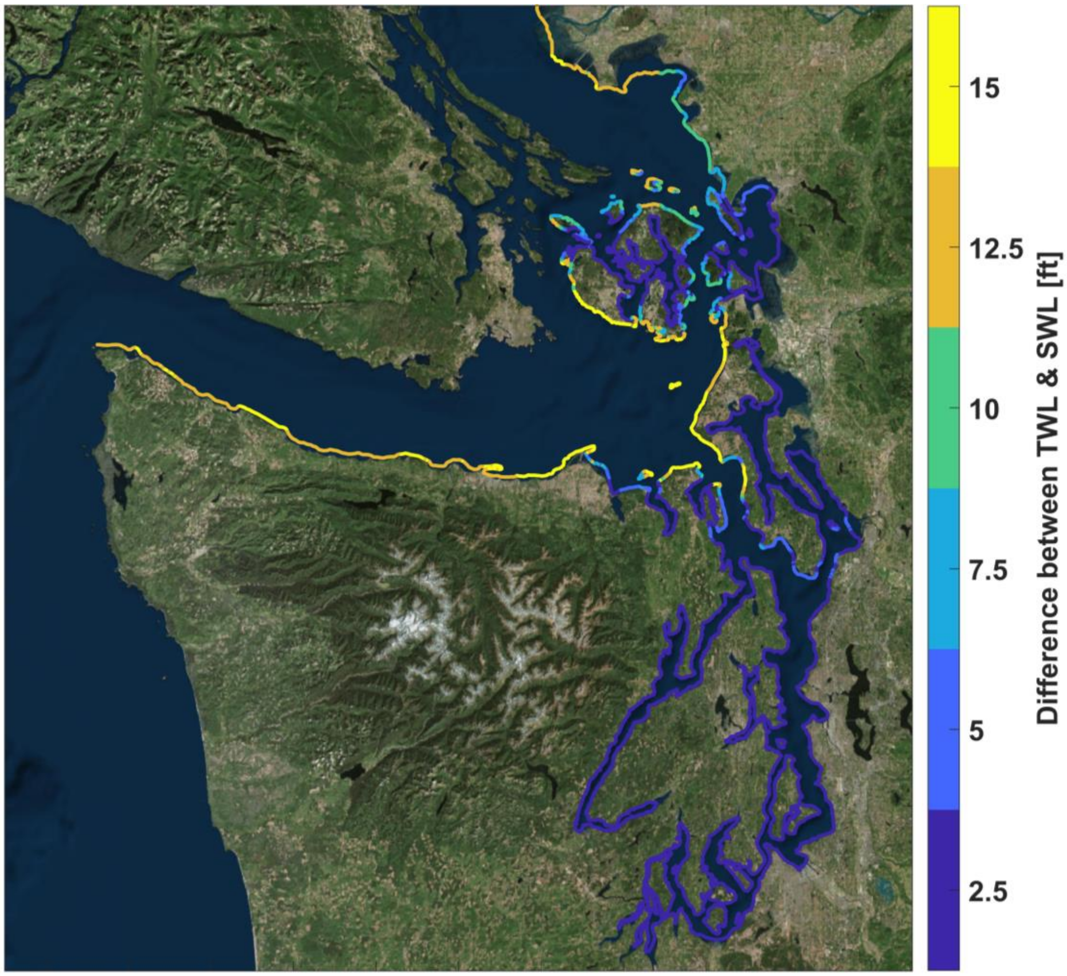


Figure 3. The difference of total water level, modelled as part of the Washington Coastal Resilience Project (see Appendix D) and still water level, in feet, for the 2-year extreme storm in Puget Sound and the Strait of Juan de Fuca (Table 1). Wave run-up magnitudes are calculated using a set of idealized assumptions about the shoreline, and the average annual maximum wave heights at each location in the model domain. For more on the results and limitations of this analysis, see Appendix D.

Summary and Decision Tree

Sea level rise will increase the frequency or magnitude of extreme coastal water level events along Washington's coast. Coastal planners, or others interested in assessing the exposure of Washington's coast to flooding, need to select accurate and decision-relevant extreme coastal water level scenarios to combine with sea level projections. This report is intended to provide insight about the magnitude or frequency of current extreme coastal water level events, in order to facilitate the selection of scenarios that can be combined with sea level projections. Mapping this information can reveal the reach of future possible extreme coastal water level events and reveal existing exposure to this future risk (i.e., current infrastructure that may be placed in a future hazard zone), or land areas that may be unsuitable for particular uses due to their future flood risk.

It is not always easy to estimate the reach of extreme events at any particular location along Washington's complex coast. While we generally have excellent historical records of still water level (SWL) during extreme events (from Washington's network of tide gauges), those records are imperfect for evaluating flood exposure since they do not measure total water level (TWL). Furthermore, tide gauges are not perfectly distributed and may not capture spatial variability in the magnitude of extreme events along the coast. We have very limited observations of TWL, or the reach of water on the shoreline during storms. Modelling TWL is also uncertain, and can be expensive. FEMA's coastal flood studies model the TWL expected to recur on average every 100-years at present sea level, but as of the publication of this report not all of Washington's coastal areas have access to the results of these studies. Additionally, the results of these studies cannot easily be used to estimate the expected TWL at other return frequencies. Regional TWL modelling for coastal storms, like that proposed by the US Geological Survey[1], could help to improve confidence in the expected magnitude and frequency of flooding and other coastal impacts along Washington's diverse coastline.

In the meantime, however, we summarize available information for Washington's coast, and provide a variety of recommendations to support the selection of extreme coastal water level scenarios for Washington's Pacific Coast and the inland sea (Puget Sound and the Strait of Juan de Fuca). Wading through this information and deciding on the best set of numbers for a particular location can be difficult. In order to facilitate these decisions we provide a decision tree (Figure 4) intended to help users identify the best available information for their particular application and location

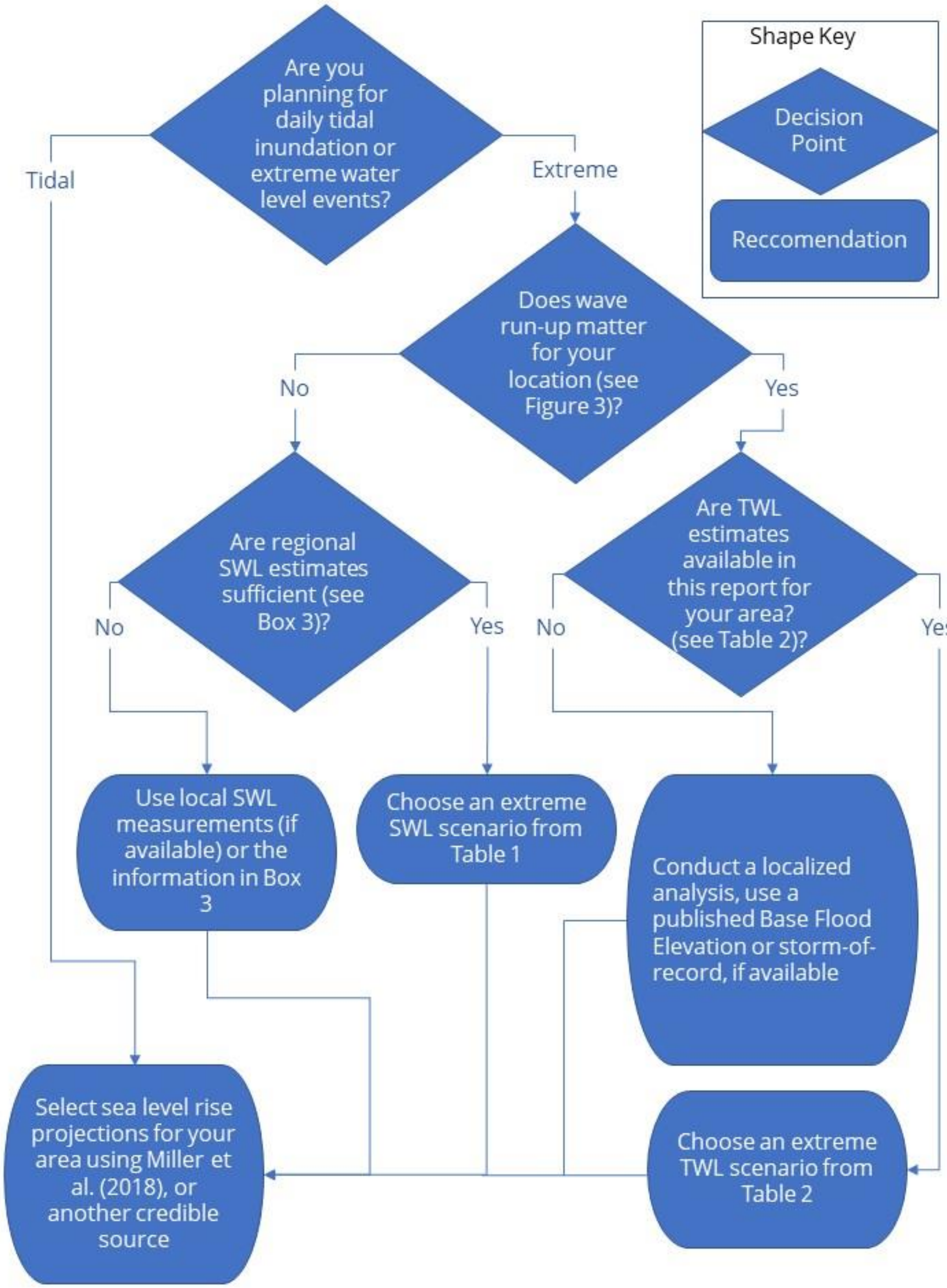


Figure 4. Decision tree with recommendations for selecting data to develop extreme event scenarios and assess future extreme water levels,

APPENDIX A: A PRIMER ON COASTAL WATER LEVEL PATTERNS AND PROCESSES

Numerous processes cause water levels to vary over temporal scales of seconds to decades and spatial scales of feet to hundreds of miles. For example, astronomical forces drive tides that lead to variations in water level on the coast on time-scales of just hours. There are also seasonal and annual water level variations related to regional ocean circulation and other processes. All of these water level variations occur super-imposed upon an observable sea level trend. On the shoreline, wind waves and ocean swells propagating from the Pacific Ocean also play a role in coastal flooding. Wave run-up describes the additional elevation gained by crashing waves as they move inland up the shoreline.

Astronomical Tides

Coastal Washington State is subject to mixed semi-diurnal tides, in which there are two high tides and two low tides per lunar day (24 hours and 50 minutes), with strong diurnal inequality (i.e., the two high tides and two low tides may reach different elevations). These astronomical tides that occur on time-scales of hours to days are the largest driver of water level variability on the Pacific Northwest coastline.

Washington State's coast is exposed to large tidal ranges. One measure of tidal range is the Great Diurnal Range (GT), defined as the difference between Mean Lower Low Water (MLLW), the average height of the lowest of the two low tides in each day, and Mean Higher High Water (MHHW), the average height of the highest of the two high tides in each day. In Washington State, GT varies between ~7 to 8 feet on Washington's coast to ~9 or 10 feet in southern Puget Sound (Figure A.1; Skewgar and Pearson 2011).

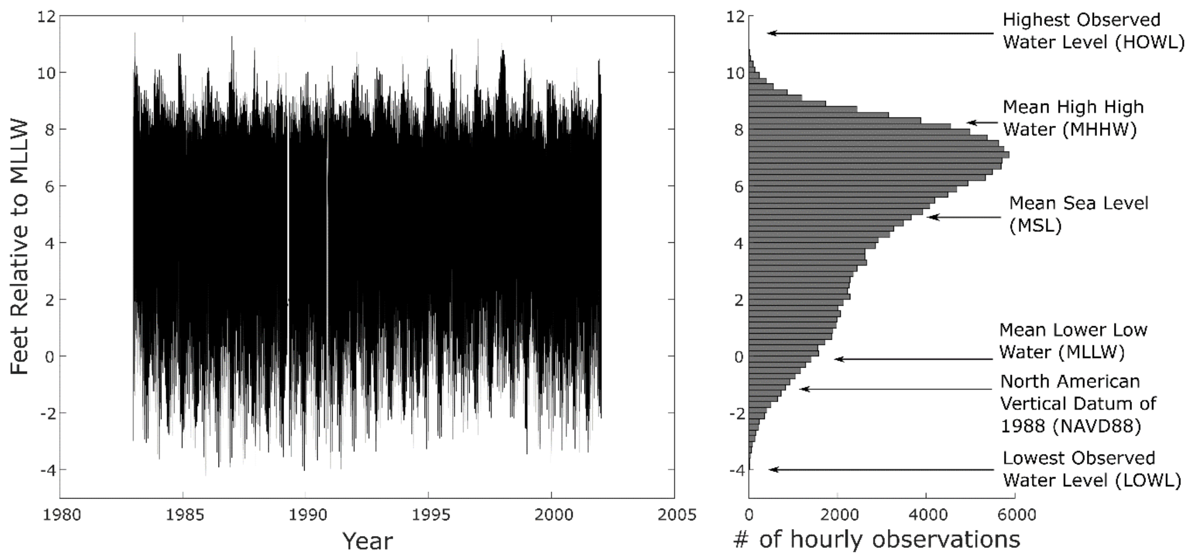


Figure A.1. An example water level time-series (left panel) of hourly observations from Port Townsend, Washington, along with a histogram of the same data (right panel) with a variety of tidal water level datums labelled. Data accessed at https://tidesandcurrents.noaa.gov/

Astronomical tides also vary cyclically on longer time-scales. For example, tides in Washington State experience a bi-weekly cycle, modulated by the orbits of the sun and the moon, which leads to tidal ranges (higher highs and lower lows) that are greater than average during what is known as the spring tide and smaller than average during the neap tide. Tidal cycles also vary annually, with larger tidal ranges occurring in winter and summer in Washington State. The long (18.6-year) lunar nodal cycle is also an important pattern that influences tidal ranges and is discussed in more detail below.

These longer cycles are particularly important in terms of understanding extreme coastal water levels; coastal flooding is more likely to occur when astronomical tides are highest. Higher-than-usual high tides can be expected, for example, during spring tidal cycles or during the peak of the 18.6-year lunar nodal cycle (Sanchez, 2018).

Are astronomical tides sensitive to climate change?

Generally, astronomical tides are viewed as a uniform process that is independent of sea level rise (NRC, 2012); in other words, we assume that the same tidal pattern and range that we have today will continue into the future, independent of how sea level changes. This may not always be the case, however, since the propagation of tides are influenced by the depth of the water. Sea level rise, by changing the depth of water, may influence the patterns of tides in coastal areas (Idier et al., 2017).

Pickering et al. (2017) modelled the effects of a change in sea level of 6.6 feet (2.0 m) on tides using a global tidal model. The authors found that sea level rise (SLR) caused changes in tidal range across the majority of coastal areas around the world. Although some of the differences simulated by the model were large—tidal range increased by over 2 feet in some parts of the globe—changes for Washington State were estimated to be less than a few inches. In addition, not all areas showed an increase in the height of high tide, and the results differed substantially based on assumptions made about the shape of the coastline. Although more modeling could clarify the implications for Washington State, this study suggests that the effect of sea level rise on tides can be treated as negligible for the region.

Storm Surge

Storm surge is a general term for the increase in coastal water level in response to low pressure and wind during storms. We define storm surge as any positive difference between the measured and predicted water level at a particular location (Figure A.2).

In coastal Washington, large storm surges are associated with passing low pressure systems, and therefore tend to last for hours or, at most, days. In Washington State, storm surge is unlikely to exceed 4 ft. on the outer coast and 3 ft. in Puget Sound—and is more commonly in the range of 1–2 ft (Figure A.2). When a high astronomical tide co-occurs with a large storm surge, they can drive anomalously high water levels that could lead to coastal flooding.

Are storm surges sensitive to climate change?

Historical analyses are mixed in regards to identifying historic trends in storminess in the northeast Pacific Ocean; Graham and Diaz (2001), for example identified trends in storm activity that could lead to changes in patterns of storm surges, but couldn't attribute those patterns conclusively to climate change. Perhaps consistent with this analysis, the longest tide gauge record on the west coast (San Francisco) shows a possible increase in the largest storm surges in the record since 2050 (Bromirski et al., 2003), but an analogous analysis of the tide gauge record in Neah Bay, Washington did not replicate this result (Miller, 2013). Other analyses do not show any identifiable historical trends in storm frequency or wind intensity for the Pacific Northwest in particular (Rhein et al. 2013, Bylhouwer et al., 2013), and a longer-term (1950–2001) evaluation of storm patterns in the North Pacific found a possible decrease in pressure, but this change appeared to largely result from the 1976–

1977 PDO shift, and there was no associated change in the frequency or position of storms (Favre and Gershunov, 2006). Forward-looking climate projections are also ambiguous about potential changes in the future (Collins et al. 2013; Christensen et al. 2013).

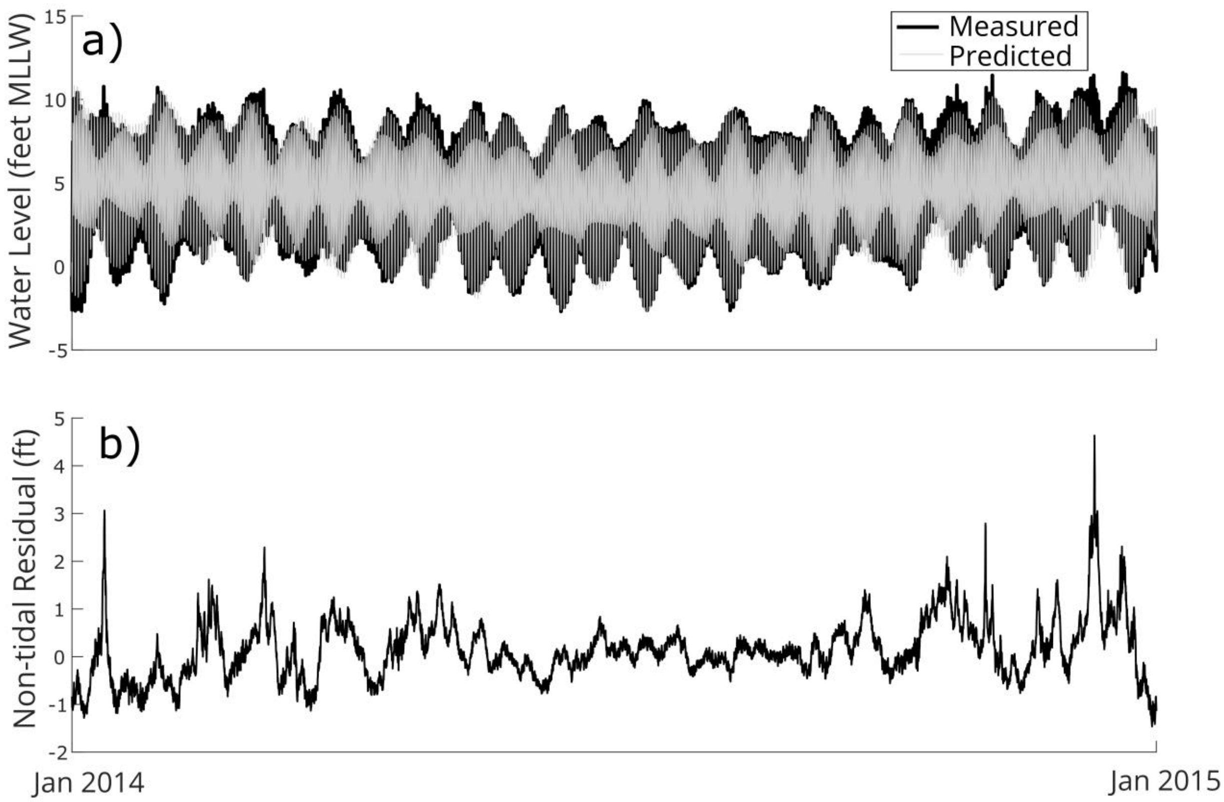


Figure A.2. a) The measured and predicted still water level over a one-year period in La Push, Washington. b) The difference between the two is known as the non-tidal residual but is also commonly referred to as storm surge when greater than zero. Data accessed at https://tidesandcurrents.noaa.gov/

Patterns of seasonal variability in coastal water level

There is a seasonal variability in average coastal water level in Washington State (Figure A.3). In general, across Washington's coastal areas, average monthly water level in winter months is 0.5 to 1.0 feet higher than during the summer, primarily due to large-scale patterns of wind and ocean circulation. This elevated winter water level is cyclical and does not contribute to underlying changes in long-term average sea level, but does have an important consequence: Flooding nearly always occurs in the winter in coastal Washington (Sweet et al. 2014).

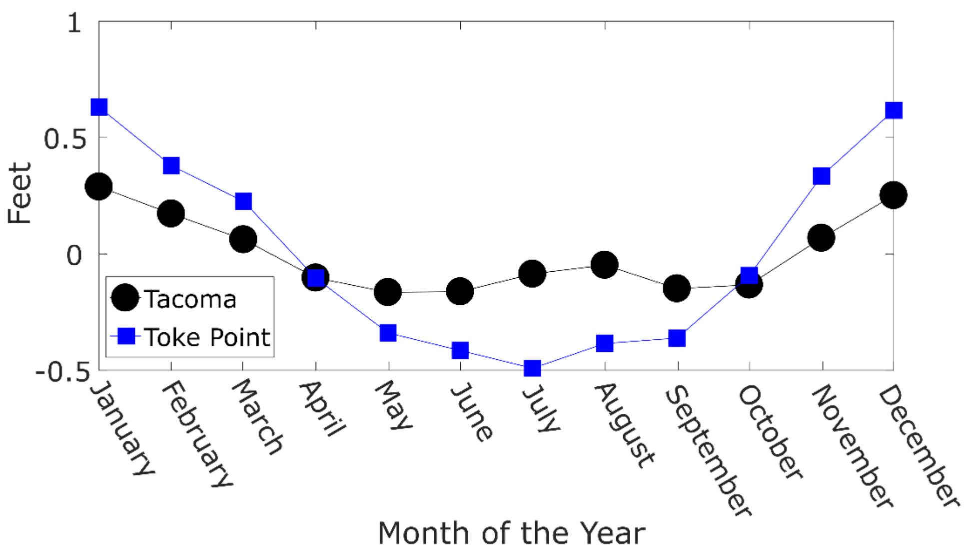


Figure A.3. Monthly average sea level relative to the long-term average water level at Tacoma and Toke Point, based on 10 years of tide gauge data collected between 1999 and 2008. Data accessed at https://tidesandcurrents.noaa.gov/

Patterns of annual variability in coastal water level

Annually averaged sea level also varies in Washington's coastal waters by as much as ~0.5 feet (Figure A.4), with the largest variations generally occurring due to climate variability associated with the El Niño Southern Oscillation (ENSO; Figure A.4) or Pacific Decadal Oscillation (PDO). These variations are important in that they can increase or decrease the likelihood of extreme coastal water level events in any given year. By way of illustration, the highest observed water level (HOWL) at many of Washington's tide gauges date to the winter of 1982–1983, which corresponds to the strongest El Niño on record in Washington State and the highest annual average water level (Figure A.4).

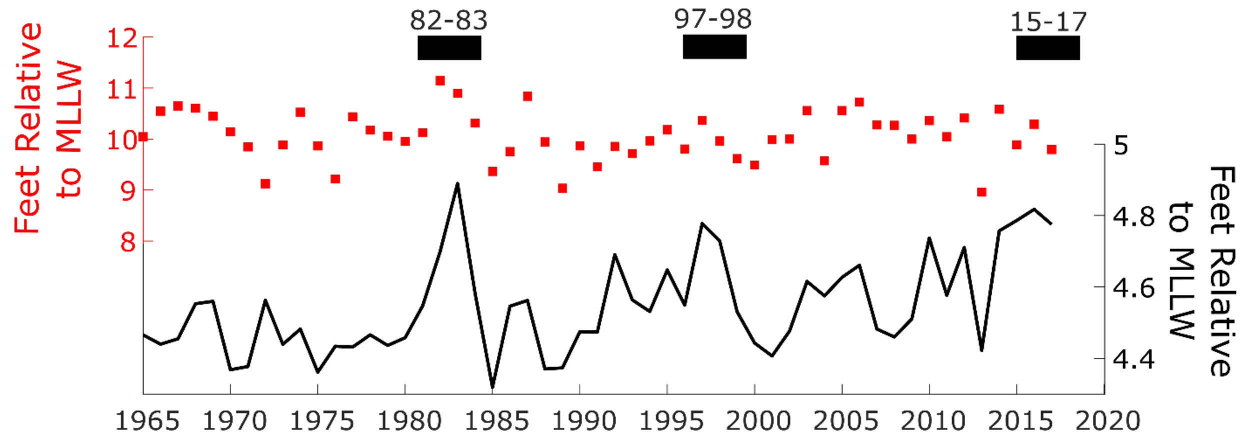


Figure A.4. Annual average water level (black line) and highest observed water level (red dots) measured at the tide gauge in Friday Harbor, Washington, in feet relative to MHHW (1983–2001 epoch). Black bars indicate strong El Niño winter periods over this time period. Data accessed at https://tidesandcurrents.noaa.gov/ and http://esrl.noaa.gov/psd/enso/dashboard.html

Patterns of multi-decadal variability in coastal water level

The lunar nodal cycle is an 18.6-year cycle that affects tidal range (but not average sea level), and is an example of a variety of processes that lead to variability in coastal water level at time-scales of multiple years. The lunar nodal cycle influences the range of tides and has the effect of making high tides marginally higher (by up to an average of ~0.6 feet in Seattle) during the peak of the cycle (Figure A.5). The 19.6 year lunar nodal cycle defines the averaging period, known as an epoch, for NOAA tidal datums, and also the averaging period for the sea level projections in Miller et al. 2018.

Other potential sources of long-term (many years to decadal) coastal water level variability undoubtedly exist. For example, Bromirski et al. (2003) found multi-decadal cycles in patterns of storm surges measured in San Francisco. There are likely other large-scale influences that have yet to be identified.

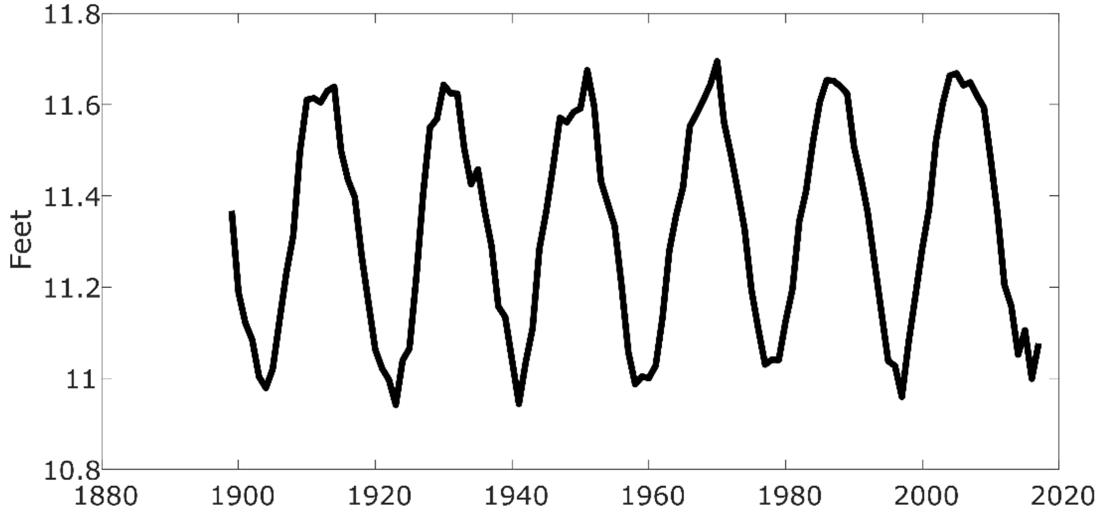


Figure A.5. The monthly average Great Diurnal Range (the difference between mean higher high water and mean lower low water) for the Seattle tide gauge reveals the influence of the lunar nodal cycle. This cycle operates over 18.6-years. The lunar nodal cycle does not influence average sea level, but instead only influences the range of the tides. But, it is important; during the peak of the cycle when high tides are a bit higher, there is a slightly increased chance for extreme water level events. Data accessed at https://tidesandcurrents.noaa.gov/

Sea Level Change

All of these processes occur on top of long-term sea level trends that are observable in Washington's tide gauge records, dating back ~100 years in Washington's coastal waters. These long-term sea level trends can be due to changes in the average sea surface height of the ocean (referred to as "absolute" sea level change in Miller et al. 2018) or changes in the elevation of the land. Long-term changes in absolute sea level (Figure A.6) can be driven by a variety of processes, some of which are related to climate and some of which are not. These include: (1) Glacio-isostatic Adjustment (GIA), (2) ocean thermal expansion, and (3) melting land ice. Long-term changes in sea level relative to the shoreline ("relative sea level") can also be influenced by vertical land movements, which themselves may occur due to a variety of processes, including groundwater extraction and tectonic forces. See Miller et al. (2018) for more detail on long-term sea level change in coastal Washington State.

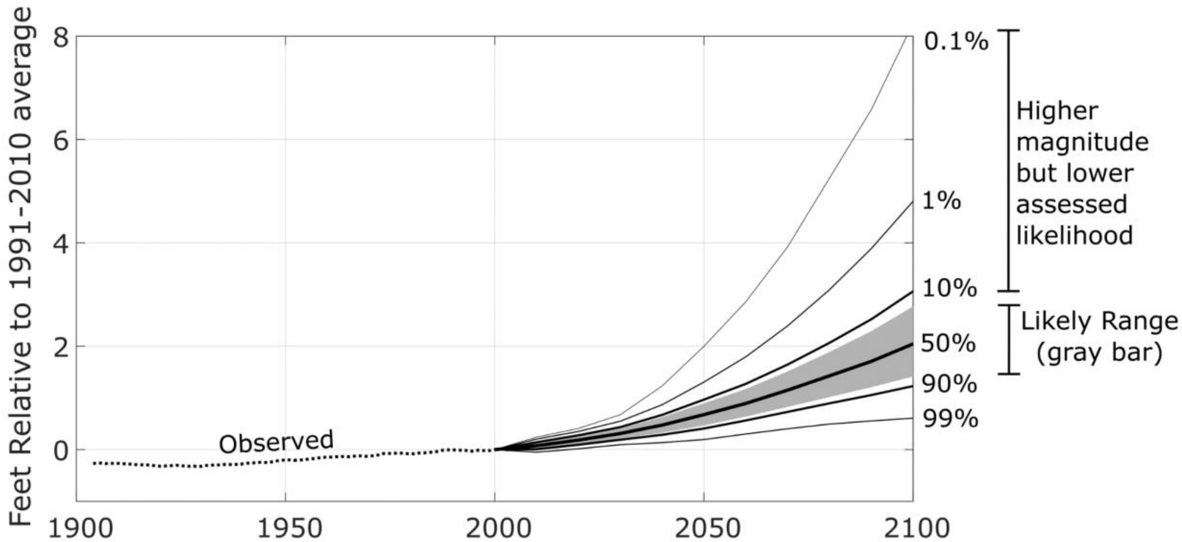


Figure A.6. Observed and projected absolute sea level for Washington State, in feet relative to average sea level between 1991–2010, for a range of assessed probabilities and for a high emissions scenario (RCP 8.5). Long-term average absolute sea level change was calculated by downloading monthly average sea level data for all of Washington's tide gauges, subtracting from those time-series the best estimate vertical land movement rate for the tide gauge, and applying a 20-year moving average across the time-series. Modified from Miller et al. 2018.

Wave Run-up

Ocean surface waves are created by wind blowing across the surface of the water, and the height of surface waves are determined by three factors: (1) The magnitude or speed of the wind, (2) the duration of the wind, and (3) the distance over which the wind interacts with the water's surface (known as "fetch"). On Washington's Pacific Coast, waves can be generated by local wind or they can propagate as swell from distant parts of the Pacific and Southern oceans. Most of Puget Sound, by contrast, is only affected by waves generated by local winds, with much smaller maximum wave heights than are frequent along Washington's Pacific Coast (Yang et al. 2019a). Although waves are smaller in the relatively protected waters of Puget Sound, wave run-up can elevate the water level on the shoreline (i.e. Figure 2C on page 2). Waves also lead to other impacts (e.g., erosion) that are important to consider when assessing possible future shoreline conditions.

When waves break, they are pushed up the shoreline by their own momentum. This is referred to as wave "run-up," and it is included in our definition of total water level (TWL; see Box 2, page 6). In the presence of waves, TWL can be considerably higher than still water level (SWL). Wave run-up is a function of wave height and period and is also influenced by the slope, roughness and orientation of the shoreline relative to the waves. As a result, TWL can vary considerably from one location to the next, and also over time, since shorelines can grow or erode over time. As sea level rises, the base level upon which the various processes, including wave run-up, operate will rise with it. As a result, coastal flooding driven by extreme total water level will reach higher up the shoreline and occur more frequently than in the past.

Waves Characteristics on the Washington Coast and in the Inland Sea

Washington's Pacific Coast is known for its energetic wave climate. Winter storms in the northern Pacific Ocean can produce waves with heights exceeding 30 feet at least once per winter (Oct–Apr; Ruggiero et al., 2010, Yang et al., 2019b). As a consequence extreme total water level events can push water high up the shoreline, perhaps 13 to 14 feet above the current Mean Higher High Water tidal datum on parts of the wave-exposed Pacific Coast (Table 2, page 9).

At the time of this report, published wave measurements characterizing waves in the inland waters of Washington State were restricted to one site in the Strait of Juan de Fuca (Hein Bank, NOAA #46088) and two sites in the Strait of Georgia (see Appendix D, this report), although efforts are underway to add to this database (Crosby and Grossman, 2019).

Fetch is generally limited within the protected waters of Puget Sound, and wave heights are subsequently smaller as compared to waves on the outer coast. However, there are exceptions: Ocean swell often penetrates into the Strait of Juan de Fuca and several areas in the vicinity of the Strait have sufficient fetch that they can experience wave heights ranging between 3–8 feet (Yang et al., 2019a; Appendix D, this report). Anecdotal descriptions of historical storms corroborate that wind waves can play a very important role in driving coastal flooding and erosion in even protected parts of Puget Sound and the Strait of Juan de Fuca (Figure 2, page 2).

Is wave run-up sensitive to climate change?

Recent analyses suggest that there may be trends in wave heights in the northeast Pacific that could influence patterns of TWL and flood exposure on Washington's Pacific coast (Ruggiero et al., 2013). Analysis of "in situ" measurements from the National Data Buoy Center (NDBC; Ruggiero et al. 2010, Seymour, 2011) and satellite altimetry (Young et al. 2011) suggest that over recent decades, there has been an increase in wave heights in the northeast Pacific Ocean. Other analyses have not corroborated that result; Seymour (2011) suggest that some or all of the trend that they identify in wave heights in the northeast Pacific Ocean may be due to climate variability, and Gemmrich et al. (2011) argued that many of the positive trends in wave height identified in the northeast Pacific Ocean are likely due to instrumental biases and data processing methodologies. Similarly, a recent study based on a 32-year high resolution historical wind simulation suggests that wave energy along the U.S. West Coast has a positive correlation to climate variability and a clear response to major El Niño events (Yang et al. 2019b); but while the link to climate variability is clear, it is not clear is if similar changes can be expected as a result of climate change.

Wave climate projections also do not clearly indicate changes that would lead to an increase in wave run-up for Washington's shorelines. Erikson et al. (2015) generated regional wave climate projections using a statistical downscaling method and found no change or small decreases in future wave heights on the wave-exposed coast south of the Strait of Juan de Fuca, but increases north of the Strait on the west coast of Vancouver Island. Erikson et al. (2015), though, did find that wave period is likely to increase across their study area, which could lead to changes in wave run-up and patterns of extreme TWL.

In the wind-dominated wave climate of the inland sea of Washington State, potential changes in wind direction or magnitude may drive important changes in wind-driven waves. However, wind projections for the region do not show any systematic change in wind intensity (Salathé et al. 2015). Some studies suggest that warming will result in a "wavier" (i.e., more variable) storm track in coastal Washington, but this is highly speculative, and it is unclear how this might affect wave heights or wave run-up (Barnes et al. 2013, 2015; Pethoukov et al. 2013; Thomas, 2014). This is consistent with other analyses of climate model projections (e.g., IPCC, 2013), which show a very slight northward shift of about 1° latitude in the average position of the North Pacific storm track; a small shift that would be unlikely to substantially alter wave patterns in the region.

Many wave climate studies are based on relatively coarse wave and wind modeling. It is possible that local changes in wind speed and wave heights may be important especially in Puget Sound, but cannot be resolved at the scale of contemporary climate models. Observations from weather stations in coastal Washington show multi-year to decadal variations in mean wind direction of 5–10 degrees (VanArendonk, 2019) that have been shown to play a role in coastal change in other regions (Norcross et al. 2002). Additional research is needed to determine if waves influencing Washington's coast can be expected to change in the future, due to human-caused climate change, in a way that would change coastal flooding exposure.

APPENDIX B: TIDE GAUGE ANALYSIS AND RESULTS

Return frequencies for extreme still water level (SWL) were calculated for ten tide gauges in Washington State using a block maximum approach (Coles, 2001). We also included the tide gauge in Astoria, Oregon, in this analysis in order to better characterize and analyze extreme SWL patterns on the coast. A generalized extreme value distribution was fit to the highest water level recorded in each calendar year at each tide gauge. The extreme value distribution is described by three parameters; a "shape" parameter that characterizes the skewness of the distribution, a "scale" parameter describes the width of the distribution, and a "location" parameter that characterizes the magnitude of the extreme values. These three parameters were calculated for the annual maximum water level from each tide gauge (Table B.1), along with an estimate of their confidence intervals using the gevfit function in MATLAB.

Based on a visual analysis of the results, we concluded that the coastal waters of Washington State could be divided into two geographies, each where a different extreme SWL pattern predominates. We inferred that the tide gauges in Puget Sound and the Strait of Juan de Fuca share a generalized extreme value distribution, and those on the coast share a second distinct distribution (Table B.1). The data suggest that the Pacific Coast of Washington is subject to higher magnitude extreme SWL events than Puget Sound, relative to the local Mean Higher High Water tidal datum. There is much greater variability for coastal tide stations, though (for the location parameter in particular, see Table B.1), and while this may suggest an additional distinct extreme SWL regime on the coast, we believe that the observed differences are likely due the small sample size resulting from relatively short water level records.

Table B.1. Generalized extreme value (GEV) distribution parameters and their confidence intervals for each of ten tide gauges in Washington State and one in Oregon, partitioned by geography (coast and Puget Sound). A weighted average for each geography is also shown.

	Tide Gauge	Length of Record (yrs)	Shape Parameter	Scale Parameter	Location Parameter
Outer Coast	**Neah Bay**	*80*	*-0.27±0.16*	*0.14±0.03*	*0.87±0.04*
	La Push	*11*	*-0.17±0.81*	*0.12±0.07*	*0.99±0.09*
	Westport	*11*	*-0.51±0.60*	*0.13±0.08*	*0.87±0.09*
	Toke Point	*39*	*-0.20±0.23*	*0.22±0.06*	*1.00±0.08*
	Astoria	*84*	*-0.25±0.18*	*0.12±0.02*	*0.79±0.03*
	Averaged Synthetic GEV Parameters for Washington's Coast		***-0.26***	***0.14***	***0.85***
Puget Sound	**Cherry Point**	*45*	*-0.25±0.16*	*0.15±0.03*	*0.68±0.05*
	Port Angeles	*41*	*-0.25±0.23*	*0.14±0.03*	*0.67±0.05*
	Port Townsend	*46*	*-0.39±0.20*	*0.15±0.03*	*0.64±0.05*
	Friday Harbor	*71*	*-0.29±0.12*	*0.14±0.02*	*0.65±0.03*
	Seattle	*119*	*-0.21±0.10*	*0.12±0.02*	*0.58±0.02*
	Tacoma	*20*	*-0.53±0.33*	*0.15±0.06*	*0.66±0.07*
	Averaged Synthetic GEV Parameters for Puget Sound		***-0.27***	***0.13***	***0.62***

We developed a synthetic average generalized extreme value distribution for the coast and a separate one for Puget Sound by averaging each of the three parameters, using a weighted averaging approach, in which parameters with smaller confidence intervals were assigned more weight in the averaging process. We then calculated synthetic extreme SWL return frequency curves using these average parameters (presented in Table B.2 below, and on Table 1 on page 7). We argue that, based on the available evidence, there is enough similarity within these regions to apply these averaged return frequency curves to the selection of extreme SWL in vulnerability assessments. It is important to note that these are *averaged*; applications of these estimates to certain questions may demand additional accuracy or precision and require customized analyses (see Box 3, page 8).

Based on this finding, we used the results of our analysis to create regionally averaged return frequency information for extreme SWL (Table B.2). Although an approximation, these statistics permit a quick assessment of likely extreme water levels in locations without tide gauges.

Table B.2. Still water level return frequencies for four tide gauges in Washington State in feet relative to the local Mean Higher High Water, (MHHW), compared to our regionally averaged return frequencies. The difference between our regionally averaged return frequencies and those estimated for specific tide gauges with long records are typically less than 4 inches (0.3 foot).

	Return Frequency				
	2-yr	***5-yr***	***20-yr***	***50-yr***	***100-yr***
Seattle	*2.3*	*2.6*	*2.9*	*3.1*	*3.3*
Friday Harbor	*2.2*	*2.8*	*3.0*	*3.3*	*3.3*
Puget Sound Regional Average	***2.2***	***2.6***	***2.9***	***3.1***	***3.2***
Neah Bay	*3.0*	*3.4*	*3.7*	*3.9*	*4.1*
Astoria	*2.6*	*3.1*	*3.7*	*3.7*	*3.9*
Pacific Coast Regional Average	***2.9***	***3.3***	***3.7***	***3.9***	***4***

APPENDIX C: TOTAL WATER LEVEL ESTIMATES FOR WASHINGTON'S WAVE-EXPOSED COAST

Still water level (SWL) is only part of the story when it comes to understanding coastal flood exposure. Wave run-up can also push water up the shoreline and contribute to flooding (see Box 2, page 6). Coastal Washington only has a handful of wave buoys, and only one of those has operated within Washington's inland sea with sufficient time to test wave models (Figure C.1). Direct observations of wave run-up on shorelines are nearly non-existent. As a

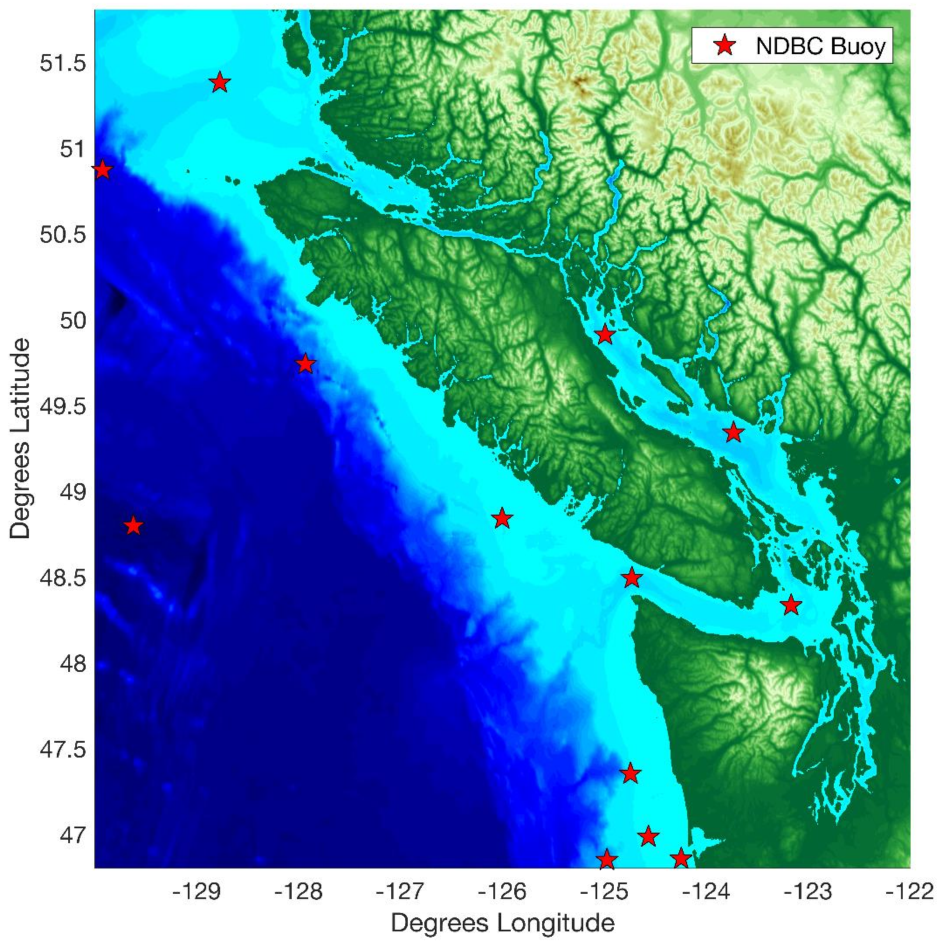


Figure C.1. Locations (red stars) of stations in or around coastal Washington where waves are measured and available on-line via the National Data Buoy Center (NDBC). Blue shades signify depth, with darker shades being deeper.

consequence, total water level (TWL) is typically modelled, and in places where wave data are limited, wave heights themselves must be modelled.

Serafin et al. (2017) derived TWL for the Pacific Coast of Washington State using water level records from tide gauges and a database of deep-water wave simulations (Perez et al., 2017). They modelled TWL for the past 30 years at locations along the west coast of the United States in order to investigate the relative importance of TWL components. They included in their study two representative sandy beach locations on the Washington Coast. These TWL estimates are particularly valuable for assessing flood exposure on the open wave-exposed coast of Washington, where wave run-up is a major contributor to extreme coastal water level magnitudes during extreme events (see Box 1, page 3).

TWL estimates may have large uncertainties when applied at the site level. Most importantly, there can be considerable variability in TWL from location to location, driven by variations in the slope and surface characteristics of the shoreline (Serafin et al., 2017). In order to get some additional insight about the magnitude of extreme TWL for the two available study locations, we modified the Serafin et al. (2017) TWL model to include a more realistic beach slope for Washington, changing the West Coast representative average beach slope of 0.05 that they applied in their study to 0.02 based on data from Ruggiero et al. (2012). The resulting extreme TWL estimates for Washington's wave-exposed Pacific Coast are shown in Table 2 (found on page 9).

How accurate are these extreme total water level estimates for the wave-exposed coast of Washington? There are no validation data to compare them to, but the highest magnitude TWL for the wave-exposed Washington Coast shown in Table 2 are higher than the Base Flood Elevations estimated for FEMA's coastal flood studies. As of publication, only two of Washington's Pacific coastal counties had completed FEMA coastal flood studies[2]. These studies estimate that the 100-year TWL on wave-exposed coastal beaches in Grays Harbor and Pacific Counties ranges between 9 and 11 feet relative to the local Mean Higher High Water (MHHW) tidal datum. In contrast, our adaptation of the Serafin et al. (2017) TWL model suggests extreme TWL between 13.2 and 14.2 feet, again relative to local MHHW (Table 2, page 9). Further study is needed to better understand the difference between the two findings.

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[2] See "Washington State RiskMAP Projects" at https://ecology.wa.gov/Water-Shorelines/Shoreline-coastal-management/Hazards/Floods-floodplain-planning/Risk-MAP/Washington-state-projects

In the absence of improved high resolution modelling of TWL, the information in Table 2 can provide useful insight about the potential reach of current and future storms when combined with higher sea levels on the wave-exposed Pacific Coast of Washington State. An important caveat to these results is that they do not apply to coastal communities in embayments (e.g., inside Grays Harbor or Willapa Bay). These communities are not subject to the high-energy wave climate of the open coast. As a result, the TWL magnitudes described in Table 2 are not suitable for coastal flood exposure assessments in those locations.

APPENDIX D: MODELLED WAVE RUN-UP ESTIMATES FOR PUGET SOUND

Wave run-up can play an important role in coastal flooding—even in the relatively calm waters of Puget Sound (Figure 2c, page 2). In Puget Sound, the intricate network of fjords, islands, embayments and land topography influences wind and waves in complex ways, limiting fetch in some locations and enhancing wind effects in others. Combined with a general lack of wave measurements in Puget Sound (Figure C.1), this means that observationally based estimates of wave exposure are very limited in Puget Sound.

While Puget Sound is generally characterized as a low-wave-energy or semi-protected environment (Finlayson, 2006), extreme storm events that pass over Washington annually bring intense low-pressure systems and associated high winds, even occasionally reaching hurricane strength (>74 mph). These temporarily turn Puget Sound into a high-energy wave environment (Mass & Dotson, 2010).

For this project, we used a modelling approach to provide some insight about the potential magnitude of wave run-up on the shoreline during the most extreme events. Historically, this type of wave and total water level (TWL) modelling is expensive and time consuming, but is becoming more accessible. FEMA, for example, models the TWL for a storm with an average return frequency of 100 years as part of their coastal flood study process (Northwest Hydraulic Consultants, Inc., 2005). However, there can be potentially large uncertainties in modelling approaches for estimating flood magnitudes (Wing et al., 2018). For example, TWL is a function, in part, of the specific topography and sediment type at a shoreline location, which often are not known or incorporated into models. The resolution of wind forcing inputs may also contribute to the uncertainties of modeling waves in Puget Sound, especially under storm conditions (Yang et al., 2019a).

Model Description

The wave model for this project was created using SWAN, (Simulating WAves Nearshore), which is a third-generation wave model developed at Delft University of Technology in the Netherlands. SWAN is a phase-averaged wave model commonly applied in coastal settings. It incorporates the processes of white-capping, shoaling, refraction, wind growth and dissipation, and bottom dissipation in the computation of waves (Booij et al., 1999; Ris et al., 1999). Two nested SWAN model domains were generated for this project following the regional modeling approach of the USGS Coastal Storm Modeling System (Figure D.1; O'Neill et al., 2018; Erikson et al., 2018). These domains consisted of a large curvilinear grid covering the Strait of Juan de Fuca, the San Juan Islands, Northern Puget Sound and the Strait of Georgia and a smaller curvilinear grid covering the remaining area of south Puget Sound and Hood Canal. The SWAN models have spatially varying grid size resolutions ranging from ~200 feet close to shore and up to 1000 feet in deep water, where higher resolution is less important for modeling wave processes.

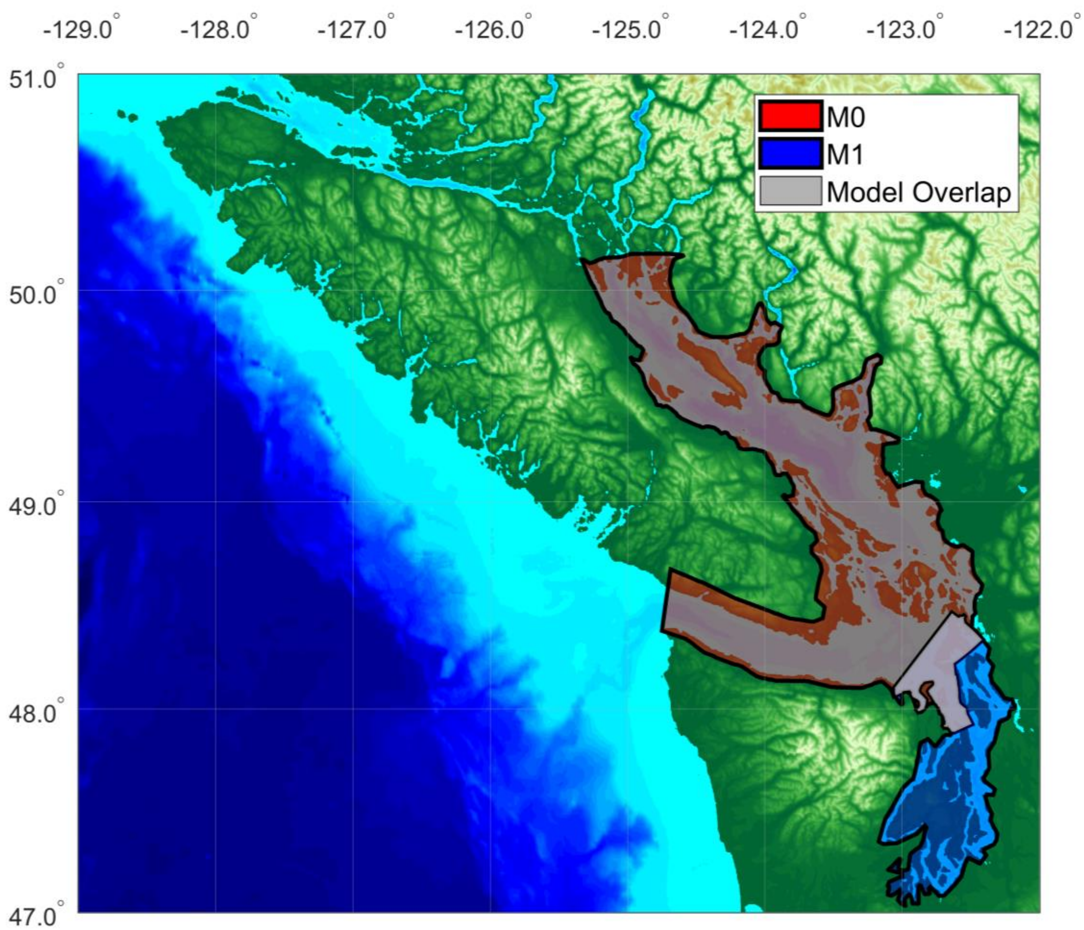

Figure D.1. Spatial extent of two SWAN wave model domains (M0 and M1) used in this study, along with areas of overlap between them.

For this project, waves were modeled using a look-up table (LUT) approach, following a similar framework described by Erikson et al. (2018). The LUT, in this case, was used to relate offshore water levels and over-water wind speed and direction to wave parameters at each model grid point across the Salish Sea. Given the high computational requirements needed to simulate an entire time series of spatially varying meteorological forcing in SWAN, a LUT provides an efficient alternative modeling strategy. This approach, however, focuses only on waves generated by local winds; in the Strait of Juan de Fuca, swell can be important (Yang et al., 2019a). Lacking this component, the LUT may underestimate wave exposure within the Strait of Juan de Fuca. In order to build a LUT, discretized bins of wind speed, wind direction and tide level were first modeled in both SWAN domains. The modeling is completed in an iterative fashion such that all potential scenarios of wind speed and direction are modeled. Once the SWAN model runs are finished, wave parameters are cataloged over the entire Salish Sea and referenced to their associated wind inputs.

Time-series of tide levels and meteorological conditions are used to query the LUT and generate hindcasts of wave parameters across the Salish Sea. Wind fields from a historical simulation produced using the Weather Research and Forecasting mesoscale model (WRF; Skamarock et al., 2008), a 6-hourly 12-kilometer resolution weather product covering the Pacific Northwest, provided the meteorological forcing needed for this project. The WRF simulation was forced with NCEP/NCAR’s Reanalysis-1 product (Kalnay et al., 1996), which optimally incorporates weather observations from a wide array of sources into a single best estimate of global atmospheric conditions at each 6-hour time step (NCEP, 2018; Dee et al., 2016). Historic water level information from the Puget Sound NOAA tide gauges supplied the necessary water level time series. NOAA's tide gauge records provide historic water levels that incorporate the astronomical tide levels as well as any non-tidal residual such as storm surge. These components are all included when developing wave hindcasts with a LUT even though they are not dynamically modeled in SWAN. The end product of each LUT is a concurrent time series of water level, wave height and wave period, which is used as the boundary forcing for the next phase of modeling wave run-up.

In Puget Sound, short period waves are the main driver of run-up on beaches, and beach slope and substrate type vary considerably more than on the open ocean coast. Given the complex nature of Puget Sound beaches, lower energy wave climate and prevalent shoreline armoring, we chose to use the Technical Advisory Committee for Water Retaining Structures (TAW) method (Van der Meer, 2002) for estimating wave run-up in this study. TAW is a Dutch model developed for engineering purposes, which specifically estimates the 2 percent wave run-up on steep dikes and coastal structures, and it is quite sensitive to a prescribed beach slope and bed roughness (a value quantifying the friction of the beach face; Van der Meer, 2002). The 2 percent wave run-up is the elevation of wave run-up that 2 percent of incoming incident waves will reach or exceed. For Irribarren numbers less then 1.8 the following expression was used:

$$Z_{2\%} = 1.65 * H_{mo} * \gamma_b * \gamma_f * \gamma_\beta * \xi_O \quad \text{(E.1)}$$

where:

$Z_{2\%} =$ *The elevation of run-up that* 2 % of incoming waves will reach or exceed [m]

$H_{mo} =$ Significant wave height at the toe of structure [m]

γ_b = Influence of offshore berm [dimensionless]

γ_f = Influence of roughness of slope [dimensionless]

γ_β = Influence of wave angle [dimensionless]

ξ_O = Iribarren Number [dimensionless]

The Iribarren number is defined as:

$$\xi_O = \frac{\tan\alpha}{\sqrt{H/L_0}} \quad \text{(E.2)}$$

where:

$\alpha =$ Slope angle [degrees]

$H =$ Wave height [m]

$L_0 =$ *Deep water* wave length [m]

And the deep water wave length is calculated as:

$$L_0 = \frac{g}{2\pi}T^2 \quad \text{(E.3)}$$

where:

$g =$ Acceleration of gravity $[\mathrm{m/s^2}]$

$T =$ Wave Period [seconds]

In situations where the Irribarren number exceeded 1.8, an alternative expression was used to estimate 2 percent wave run-up:

$$Z_{2\%} = H_{mo} * \gamma_b * \gamma_f * \gamma_\beta * (4.0 - \frac{1.5}{\xi_O}) \quad \text{(E.4)}$$

Reliable and up-to-date elevation data of the nearshore in Puget Sound is often lacking. In addition, there are data quality concerns with existing elevations: Artifacts in slope derived from interpolated gaps in the data, bias associated with the water surface in lidar, etc. It was beyond the scope of this project to contend with these issues. Instead, we used representative values of slope and roughness in the wave run-up expressions above; Finlayson (2006) showed that Puget Sound beach slopes range from 0.01 to 3.2; we used a uniform slope of 0.2 representative of many steeper stretches of beach in urban areas and revetments. We used a coefficient of roughness of 0.8, characteristic of coarse sediment and armor rock (Van der Meer, 2002), which is common to many Puget Sound beaches.

To compute wave run-up, we extracted the annual maximum wave height and associated period from SWAN grid points every 328 feet (100 meters) along the shore, following the 32 foot (10 meter) depth contour, chosen because at this depth waves should remain unaffected by bathymetry. For each of these locations, the wave parameters were used as input to equations E.1 or E.4, E.2, and E.3 to estimate wave run-up. Waves were assumed to be approaching at a perpendicular angle to the shoreline, meaning that the term γ_β could be ignored. The presence of a berm was also neglected, incorporating only the reduction factor γ_f, the influence of bed roughness, when calculating wave run-up. On each profile consisting of a uniform slope of 0.2, the height above an arbitrary initial water level (zero in this case) was estimated based on the offshore annual maximum wave height and period.

An estimate of total water level was arrived at for every grid point and every time step in the model domain, and every model time-step by querying the closest NOAA tide gauge to the grid point for an observed still water level relative to MHHW, and coupling that with the modelled wave run-up estimate. Because of the simplifying assumptions employed in this analysis, both in the estimation of wave run-up, and in the estimate of still water level, we do not expect that our total water level estimates are accurate enough for planning purposes, but uncertainties were not explicitly quantified. Full details of the analysis are available in Van Arendonck (2019).

Results

For every location in the model domain, we summarized the modelled time-series of significant wave height by averaging the maximum wave heights from each year at every location (Figure D.2). Significant wave height is defined as four times the standard deviation of the instantaneous water surface elevation measured by a wave sensor. Not surprisingly, given the complex shoreline and topographic variability in Puget Sound, annual maximum significant wave heights vary considerably. The protected embayments of south, central and northern Puget Sound generally experience the smallest waves, ranging from 1 to 3 feet (Figure D.2). In contrast, the exposed shorelines of the Strait of Juan de Fuca and San Juan, Lopez and Whidbey Islands are impacted by the largest waves, with annual maximum wave heights exceeding 8 feet (Figure D.2). For the western Strait of Juan de Fuca, this

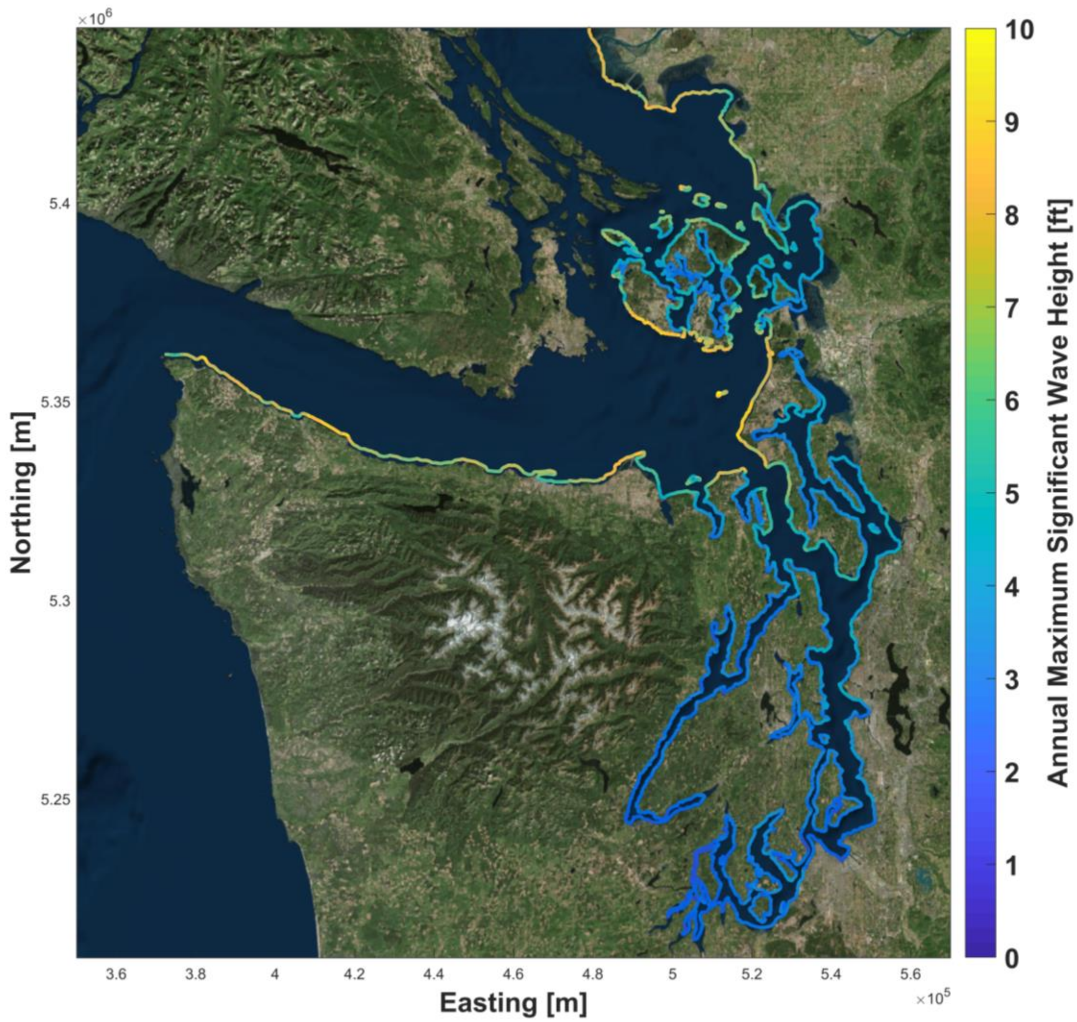

Figure D.2. Modeled annual average maximum significant wave height, in feet, for Puget Sound and the Strait of Juan de Fuca in Washington State.

approach likely underestimates wave heights because it is based only on locally generated waves and does not include open ocean swell.

To provide some insight about the possible scale of annual maximum wave run-up in Puget Sound during the most extreme wave events, the modelled wave heights shown in Figure D.2 were used to calculate the 2 percent wave run-up using an average Puget Sound beach slope (see Methods section, above). Results are shown in Figure D.3. The 2 percent wave run-up magnitudes show the additional elevation that water can be driven up the shoreline by wave-breaking during an average year's most extreme event. The wave run-up

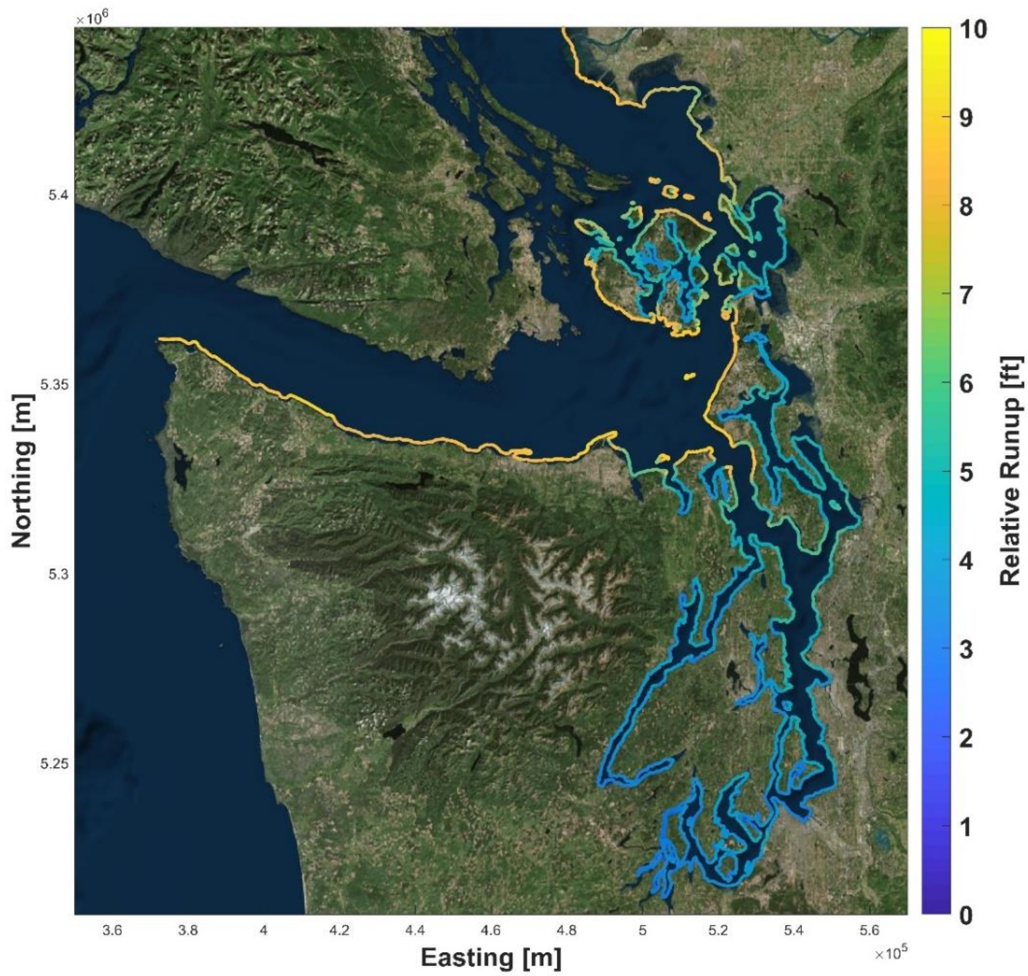

Figure D.3. Modelled wave run-up magnitudes, in feet, for the average annual extreme storm in Puget Sound and the Strait of Juan de Fuca. These wave run-up magnitudes are calculated using an idealized shoreline and the average annual maximum wave heights at each location in the model domain.

estimates are always larger than the significant wave height estimates in Figure D.2. The largest wave run-up is in the Strait of Juan de Fuca, the west slope of Whidbey Island, and the southwest-facing shorelines of the San Juan Islands (Figure D.3). The smallest wave run-up occurs in the protected embayments within Puget Sound, where wave heights are small (Figure D.3)

Our project estimates of total water level in Puget Sound are uncertain, but were used to evaluate locations in the inland sea of Washington State where wave run-up contributes significantly to existing and future patterns of coastal flood exposure. An approximate TWL was be estimated by coupling wave run-up estimates with observed water level data from the closest NOAA tide gauge in the model domain. We then calculated an annual average maximum TWL, roughly approximating a recurrence interval of two years (see Box 2, page 6). Results are shown in Figure 3 (page 12 of the main body of the report).

REFERENCES

Barnes, E.A. & Screen, J.A. (2015). The impact of Arctic warming on the mid-latitude jet-stream: Can it? Has it? Will it? Wiley Interdisciplinary Reviews: Climate Change, 6(3): 277-286.

Barnes, E.A. & Polvani, L. (2013). Response of the mid-latitude jets, and of their variability, to increased greenhouse gases in the CMIP5 models. Journal of Climate, 26(18): 7117-7135.

Booij, N., Ris, R. C., & Holthuijsen, L. H. (1999). A third-generation wave model for coastal: Model description and validation. Journal of Geophysical Research: Oceans 104 (C4): 7649–66.

Bromirski, P. D., Flick, R. E., & Cayan, D. R. (2003). Storminess variability along the California coast: 1858–2000. Journal of Climate, 16(6): 982–993.

Bylhouwer, B., Lanson, D. & Kohfeld, K. (2013). Changes in the onset and intensity of wind-driven upwelling and downwelling along the North American Pacific Coast. Journal of Geophysical Research, 118(5): 1-16.

Christensen, J.H., Krishna, K. K., Aldrian, E., An, S.,Cavalcanti, I.F., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, I., Lau, N.C., Renwick, J., Stephenson, D.B., Xie, S.P. & Zhou, T. (2013) Climate phenomena and their relevance for future regional climate change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M. Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Collins, M., Knutti,R., Arblaster, J., Dufresne, J.L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J. & Wehner, M. (2013). Long-term climate change: Projections, commitments and irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Coles, S. (2001). An introduction to statistical modeling of extreme values. Springer Series in Statistics. London: Springer.

Crosby, S.C. & Grossman, E.E. (2019). Wave observations from nearshore bottom-mounted pressure sensors in Skagit and Bellingham Bays, Washington, USA from Dec. 2017 to Feb. 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9JZ5F00

Erikson, L., Hegermiller, C., Barnard, P., Ruggiero, P., van Ormondt, M. (2015). Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. Ocean Modelling 96: 171-185

Erikson, L., Barnard, P., O'Neill, A., Wood, N., Jones, J., Finzi Hart, J., Vitousek, S., Limber, P., Hayden, M., Fitzgibbon, M., Lovering, J. & Foxgrover, A. (2018). Projected 21st century coastal flooding in the southern California bight. Part 2: Tools for assessing climate change-driven coastal hazards and socio-economic impacts. Journal of Marine Science and Engineering, 6(3)

Favre, A., Gershunov, A. (2006). Extra-tropical cyclonic/anticyclonic activity in North-Eastern Pacific and air temperature extremes in Western North America. Climate Dynamics, 26: 617-629.

Finlayson, D. P. (2006). The Geomorphology of Puget Sound Beaches. University of Washington. Ph.D Dissertation, pps. 236.

Gemmrich, J., Thomas, B., Bouchard, R., 2011. Observational changes and trends in northeast Pacific wave records. Geophysical Research Letters 38.

Graham, N.E., Diaz, H.F. (2001). Evidence for intensification of North Pacific winter cyclones since 1948. Bulletin of the American Meteorological Society 82: 1869-1893.

Idier, D., Paris, F., Le Cozannet, G., Boulahya, F., & Dumas, F. (2017). Sea-level rise impacts on the tide of the European Shelf. Continental Shelf Research, 137: 56-71.

Intergovernmental Panel on Climate Change (IPCC) (2012). Glossary of terms. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M. & Midgley, P.M. (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 555-564.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., & Zhu, Y. (1996). The NCEP/NCAR 40-year reanalysis project. Bulletin of the American meteorological Society, 77(3), 437-472.

Miller, I.M. 2013. Increasing frequency and severity of storms. In: Miller, I.M., Shishido, C., Antrim, L, and Bowlby, C.E. Climate Change and the Olympic Coast National Marine Sanctuary: Interpreting Potential Futures. Marine Sanctuaries Conservation Series ONMS-13-01. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 238 pp.

Norcross, Z. M., Fletcher, C. H., Merrifield, M. (2002). Annual and interannual changes on a reef-fringed pocket beach: Kailua bay, Hawaii. Marine Geology, 190(3-4): 553-80

Northwest Hydraulic Consultants, Inc. (NHC) (2005). Final draft guidelines for coastal flood hazard analysis and mapping for the Pacific Coast of the United States; report prepared for FEMA: West Sacramento, Calif., Northwest Hydraulic Consultants, Inc., pps. 344

O'Neill, A.C., Erikson, L.H., Barnard, P.L., Limber, P.W., Vitousek, S., Warrick, J.A., Foxgrover, A.C. & Lovering, J. (2018). Projected 21st Century coastal flooding in the Southern California bight. Part 1: Development of the third generation CoSMoS model. Journal of Marine Science Engineering, 6.

Perez, J., Menendez, M. & Losada, I.J. (2017). GOW2: A global wave hindcast for coastal applications. Coastal Engineering, 124: 1-11

Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L.D. & Wang, F. (2013). Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex V. & Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ris, R. C., Holthuijsen, L. H., & Booij, N. (1999). A third-generation wave model for coastal regions: Verification. Journal of Geophysical Research: Oceans 104(C4): 7667-81

Ruggiero, P., Kaminsky, G.M., Komar, P.D. & McDougal, W.G. (1997). Extreme waves and coastal erosion in the Pacific Northwest. Ocean Wave Measurement and Analysis, Proceedings of the 3rd International Symposium, Waves ’97, pp. 947-961.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J. & Beach, R.A. (2001). Wave run-up, extreme water levels and the erosion of properties backing beaches. Journal of Coastal Research, 17, 407-419.

Ruggiero, P., Komar, P.D. & Allan, J.C. (2010). Increasing wave heights and extreme value projections: The wave climate of the U.S. Pacific Northwest. Coastal Engineering, 57: 539-552.

Ruggiero, P., Kratzmann, M.G., Himmelstoss, E.A., Reid, D., Allan, J. & Kaminsky, G. (2012). National assessment of shoreline change—Historical shoreline change along the Pacific Northwest Coast: U.S. Geological Survey Open-File Report 2012–1007, pps. 62

Ruggiero, P. (2013). Is the intensifying wave climate of the U.S. Pacific Northwest increasing flooding and erosion risk faster than sea-level rise? Journal of Waterway, Port, Coastal, Ocean Engineering., 88-97.

Salathé, E.S., Mauger, G. (2015). Final project report: Regional modeling for windstorms and lightning. Report prepared for Seattle City Light by the Climate Impacts Group, University of Washington, Seattle.

Sanchez, A.H. (2018). Nuisance flooding in Honolulu, HI: A case study of summer 2017. B.S. Thesis, University of Hawaii, Honolulu, HI.

Serafin, K.A., Ruggiero, P. & Stockdon, H.F. (2017). The relative contribution of waves, tides, and nontidal residuals to extreme total water levels on U.S. West Coast sandy beaches. Geophysical Research Letters, 44(4), pp.1839-1847.

Seymour, R.J. (2011). Evidence for changes to the Northeast Pacific wave climate. Journal of Coastal Research, 27(1): 194-201.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G. & Powers, J.G. (2008). A description of the advanced research WRF version 3, NCAR Technical Note. National Center for Atmospheric Research, Boulder, CO, USA.

Sweet, W.V., Park, J., Marra, J., Zervas, C. & Gill, S. (2014). Sea level rise and nuisance flood frequency changes around the United States. NOAA Tech. Rep. NOS CO-OPS 073.

Tebaldi, C., Strauss, B. & Zervas, C.E. (2012). Modeling sea level rise impacts on storm surges along U.S. coasts. Environmental Research Letters, 7.

Thomas, K. (Ed.) (2014). Linkages between Arctic warming and mid-latitude weather patterns: Summary of a workshop. National Academies Press.

Van Arendonk, N. (2019). Assessing coastal vulnerability to storm surge and wave impacts with projected sea level rise within Salish Sea (Unpublished master's thesis). Western Washington University, Bellingham, WA, USA.

Wing, O.E.J., Bates, P.D., Smith, A.M., Sampson, C.C., Johnson, K.A., Fargione, J. & Morefield, P. (2018). Estimates of present and future flood risk in the conterminous United States, Environmental Research Letters, 13.

Yang, Z., Garcia, G., Wu, W.C., Wang, T., Leung, R., Castrucci, L. & Mauger, G. (2019a). Modeling analysis of the swell and wind-sea climate in the Salish Sea. Estuarine, Coastal and Shelf Science, https://doi.org/10.1016/j.ecss.2019.04.043.

Yang, Z., Garcia, G., Wu, W.C. & Wang, T. (2019b). Wave resource characterization for the U.S. West Coast, Part II: Characteristics and variability of the nearshore resource. Renewable Energy (in review).

Yang, Z., Wang, T., Castrucci, L., & Miller, I.M. (2019c). Modeling assessment of storm suge in the Salish Sea. Coastal and Shelf Science (in review)

Young, I.R., Zieger, S. & Babanin, A.V. (2011). Global trends in wind speed and wave height. Science, 332: 451-455.