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Assessing Coastal Vulnerability to Storm Surge and Wave Impacts with Projected Sea Level Rise within the Salish Sea

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Assessing Coastal Vulnerability to Storm Surge and Wave Impacts with Projected Sea Level Rise within the Salish Sea

By

Nathan R. VanArendonk

Accepted in Partial Completion of the Requirements for the Degree Master of Science

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Nathan R. VanArendonk

08/13/2019
Assessing Coastal Vulnerability to Storm Surge and Wave Impacts with Projected Sea Level Rise within the Salish Sea

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Nathan R. VanArendonk
August 2019
Abstract

Sea level rise (SLR) in the Salish Sea, a large inland waterway shared between Canada and the United States, is expected to be 0.3 to 1.8 m by the year 2100. Uncertainty in greenhouse gas emissions, global ice sheet loss, and other controls such as vertical land movement all contribute to this range. Valuable property, infrastructure, and critical habitats for shellfish and threatened salmon populations are at risk to coastal changes associated with SLR. Additionally, development in Washington State is expected to accelerate through the end of the 21st century adding extra pressure on protecting ecosystems and people from natural hazards along the coast. Global climate models (GCMs) predict increases in temperature and changes in precipitation, yet little is known about the impacts of climate change on the local wave climate. Understanding the dynamic interactions that SLR and climate change will have on the wave climate and coastal systems within the Salish Sea is vital for protecting these resources and planning for the future.

In support of the Washington Coastal Resilience Project and the United States Geological Survey Coastal Change Impacts Project, I modeled historic and potential future waves in the Salish Sea to evaluate the extent that wave energy reaching the shore may change with 0.3, 0.6, and 0.91 m of SLR. I also assessed potential changes in future wind conditions that drive wave generation projected by the publicly available MACA (Multivariate Adaptive Constructed Analogs) downscaled NOAA GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory Earth Systems Model) GCM. Lastly, I modeled wave runup to assess potential flood and wave impacts along the shore to the year 2100 as part of a case study in support of the City of Tacoma’s climate adaptation planning for parks, sensitive habitats and significant commercial development along Ruston Way.
This project generated the first regional wave model and historical hindcast within the Salish Sea to define the recurrence frequency of a range of extreme events and resolve their variability alongshore at spatial scales relevant for planning. Existing models of future climate indicate little change in extreme wind speeds, but potential changes in wind direction that could affect waves. Model results indicate that annual extreme deep water waves (-10 m NAVD88 depth) may increase up to 30 cm under 0.91 m of SLR with the greatest change occurring in shallow embayments and large river deltas where higher water levels will reduce depth limitation and influence fetch. Wave runup modeling along the demonstration site of Ruston Way in Tacoma, showed that extreme coastal water levels reaching and exceeding the Federal Emergency Management Agency 100-yr Base Flood Elevation (BFE) will significantly increase under 0.85 m of SLR, the 50% probabilistic estimate by 2100 for the city of Tacoma. While the dominant exposure of shorelines to flooding is along south-facing coasts, wave runup modeling elucidated that extreme water levels causing flooding are sensitive to waves and wind stress, especially important along north facing shorelines. Equally important is the finding that intermediate disturbances driving flooding will significantly increase in frequency with sea level rise; today’s 10-yr recurrence storm event under 0.85 m of SLR was projected to exceed FEMA’s 100-yr BFE across more than 50% of locations modeled along Ruston Way, suggesting that FEMA’s BFE may be biased low for projected future sea level change. In the Salish Sea, SLR is expected to drive an increase in coastal flooding extent and frequency where waves amplify the impacts of higher static water levels and further elevate the water surface.
Acknowledgements

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1.0 Introduction

Average rates of global sea level rise (SLR) for the period 1961–2003 were found to be 1.8 +/- 0.5 mm/yr (Mote et al., 2008; NRC, 2012) from a combination of historic tide gauge records and satellite altimeter observations. Globally, the thermal expansion of water, melting of the Earth's cryosphere, and long term variations in the spreading rates of mid-ocean ridges are the primary controls on rates of sea level rise. Regional and finer scale processes such as ocean circulation, interannual climate variations, and vertical land movement (VLM) further impact the relative elevation of the sea surface to the coastline (Milne et al., 2009; Mote et al., 2008; NRC, 2012; Stammer et al., 2013). In Washington State, tide gauge records indicate varying and often differing trends in SLR dependent on location. On the open ocean coast, recorded SLR shows negative trends (-1.77 mm/yr at Neah Bay tide gauge) compared to inside the Salish Sea where the Seattle tide gauge recorded 2.01 mm/yr of SLR from 1900 - 2008 (NRC, 2012). These noted differences in the rate of SLR are primarily attributed to differences in VLM across Washington State.

Both the isostatic rebound (dynamic response in Earth’s crust to the loss of ice mass from the most recent glaciation) and the crustal deformation from the subduction of the Juan de Fuca plate beneath the North American Plate, produce local variations in VLM. As tide gauges measure the sea-surface height referenced to a position on land, VLM amplifies or reduces the recorded SLR signal, generating the differing trends observed in Washington State (Mote et al., 2008). In the Salish Sea (Figure 1) 0.3 m to 1.82 m of SLR is anticipated by the end of the 21st century (Mote et al., 2008; NRC, 2012; Miller et al., 2018), the timing of which will be primarily controlled by anthropogenic inputs of greenhouse gasses to the atmosphere. Assessing the total risk to SLR across the Salish Sea requires knowledge of the spatial variability in processes that
affect total water level and highlights the need for improved predictions of the wave climate and its influence on total water level (Mote et al., 2008; Church et al., 2013; Kopp et al., 2014; IPCC, 2014; NRC, 2012).

Sea level rise in the Salish Sea poses a serious threat to coastal lands, sensitive ecosystems for salmon and shellfish, industry, and infrastructure important to human well-being (NRC, 2012; Mote et al., 2014). SLR in Washington State is expected to increase the frequency of extreme total water level (TWL) events exceeding contemporary flood elevations (Church et al., 2013; Tebaldi et al., 2012). Already, extreme weather events are damaging coastal lands and infrastructure such as the December 10th through December 24th storms of 2018, prompting federal aid and a disaster declaration by FEMA for Jefferson, Island, Snohomish, and Whatcom counties (FEMA, 2019). By the year 2040, Washington State is projected to spend 24 billion dollars in mitigation costs from moderate amounts of SLR (LeRoy and Wiles, 2019) and this number is projected to increase through the end of the century. Additionally, ~ 4,020 kilometers of shoreline in Puget Sound are expected to have a geomorphic response to future higher water levels that in turn will impact the hydrodynamics (waves and currents) and compound the complexity of forecasting future coastal adjustment (NRC, 2012). Ultimately, the Salish Sea will experience a landward migration of coastlines, where they are unconstrained, generating costly problems such as an increase in coastal erosion, wetland loss, flooding, and saltwater intrusion to coastal aquifers (Mote et al., 2014; NRC 2012; Ranasinghe et al., 2012). To fully assess future risk along the coast, the dynamic component of waves must be included and quantitative estimates of the extent and frequency of future disturbance events along the coast are needed.

Wave observations provide historic context and real time information that help define the local or regional wave climate. While offshore wave observations for the continental United
States are plentiful, inside the Salish Sea, long term and reliable wave data are sparse. United States controlled waters host a single wave buoy (NDBC Hein Bank Buoy #46088 while Environment Canada maintains two in the Strait of Georgia (buoys are shown in Figure 2). With only three wave buoys in the Salish Sea, all residing in the largest basins (Strait of Juan de Fuca & Strait of Georgia; Figure 1), there is a limited understanding of the wave climate in the narrower fjordal basins that make up Puget Sound. Without observational data, models provide first-order estimates of wave conditions needed to predict impacts in the coastal zone (Herdman et al., 2018; Hope et al., 2013).

Engineering groups, academic researchers, and government agencies in Puget Sound use numerical models to provide initial estimates on extreme water levels (e.g., Finlayson, 2006; FEMA, 2016). Model results aid in improving and planning for the safety and sustainability of coastal communities, and provide important guidance to local projects in ecosystem protection and restoration strategies (e.g., Puget Sound Partnership, Action Agenda). Few studies have attempted to model waves and wave run-up in Puget Sound (NHC, 2005; FEMA, 2016; Finlayson, 2006) and their scope was limited to the scale of individual counties or site specific projects. Often, these assessments varied in approach, making comparisons of vulnerability to storms and waves across the state difficult. Employing large, high-resolution models requires significant computing resources needed to simulate waves on spatial scales relevant to coastal planners (FEMA, 2016). While previous studies provided the context necessary for designating coastal flood zones and assessing impacts on a site-specific basis, they lacked future context; Puget Sound has yet to have a systematic evaluation of the temporal and spatial variability in the historic wave climate with projected changes into the future.
I performed this level of assessment as part of the NOAA (National Oceanic and Atmospheric Administration) Regional Resiliency Grant titled Washington Coastal Resilience Project (WCRP) and to support implementation of the USGS regional Puget Sound Coastal Storm Modeling System (PS-CoSMoS). The WCRP aims to increase the knowledge surrounding coastal vulnerability throughout Puget Sound and evaluate opportunities to enhance policy needed to achieve regional resilience under projected changes in the coastal climate. My work addressed two main goals of the WCRP grant: 1) improve the understanding of coastal hazards stemming from storm surge and waves, 2) enhance resiliency in coastal communities through pilot studies. The modeling developed for this effort also helped advance the regional wave model and demonstrated the high resolution dynamic wave runup modeling of the USGS PS-CoSMoS program.

Using phase-averaged region-scale numerical wave models and local hydrodynamic numerical models, I simulated wind-wave generation, wave run-up, and subsequent flooding in the Salish Sea. To reduce computational costs, I built a look-up-table (LUT) of wave parameters across the Salish Sea to relate wind speed, wind direction, and water level, to wave parameters (e.g., significant wave height, peak period, wave direction). The LUT was sampled with a publicly available University of Washington Weather Research and Forecasting climate reanalysis based on a National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis project to develop a 60-yr (1950–2010) hindcast of wave parameters spatially. Future climate projections from the NOAA GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory Earth Systems Model) GCM (Global Climate Model) for RCP (Representative Concentration Pathway) 8.5 were analyzed for changes in wind climatology through the year 2100. Minor wind changes (speed increases of < 1 m/s and directional changes
< 10 degrees) are predicted over coastal Washington State but are expected to be better resolved as climate models are advanced. Assuming the wind climate of the Salish Sea remains similar to historic conditions, I assessed changes to the deep water wave climate of the Salish Sea associated with SLR by resampling the LUT and building 60-yr wave hindcasts for SLR scenarios of 0.3, 0.6, and 0.91 m. In addition to the regional analysis, I modeled wave breaking, dissipation and runup that causes flooding in a case study along Ruston Way in Tacoma, WA (Figure 2) using parameterized run-up estimates and hydrodynamic numerical models forced by regional wave model output. Model results and derivative products from this project address the goals of my Masters Thesis defined by the WCRP.

2.0 Setting

2.1 Puget Sound Coastal Landscape

The dynamic advance and retreat of glacial ice during the last glacial maximum of the Pleistocene (~15,000 year ago) carved the deep troughs which make up modern day Puget Sound and the northern straits (Booth, 1994; Finlayson, 2006; Johannessen and MacLennan, 2007). Glacial erosion and deposition provided much of the source material for modern beaches in Puget Sound. Within the steep walls of the U-shaped troughs, wave-cut platforms provided the narrow space for modern beaches to form, backed by steep coastal bluffs, rich in glacial outwash, glacial till, and glaciomarine sediment. These dynamic bluffs, often termed ‘feeder bluffs’ provide necessary sediment to the local beaches, perpetuating the livelihood of mixed sediment beaches, a common shore type in Puget Sound, consisting of coarse sands and gravels (Finalyson, 2006; Johannessen and MacLennan, 2007). Elsewhere, rocky shorelines, large river
deltas, and spit and lagoons systems, make up the complex shorelines of Puget Sound (Johannessen and MacLennan, 2007). For the purpose of this study, the term Puget Sound refers to all of the inland waters of Washington State restricted by the international boundary with Canada and extending to the western end of the Strait of Juan de Fuca (Figure 2).

2.2 Drivers of Coastal Flooding

In the Salish Sea, flooding on the coast is a direct result of high water levels and waves. As the Salish Sea is separated from the Pacific Ocean, outside of the Strait of Juan de Fuca, all wave energy in the region is directly linked to local winds. The macrotidal nature (tidal range of 3-4 meters) of the Salish Sea is the main influence on static water levels with winds and waves influencing the dynamic side of coastal flooding (Figure 3). Weather systems carrying low pressure centers are commonly the catalyst for extreme wind and waves. The most severe being Extra Tropical Cyclones that make landfall on coastal Washington State and Southwest British Columbia (Mass and Dotson, 2010; Read, 2015). These strong mid-latitude cyclones produce low-pressure centers in the range of 955 to 980 millibars and generate extreme wind conditions in the Salish Sea. As the front of the storm moves from the ocean to land, wind speeds increase due to a change in orientation of the isobars surrounding the low-pressure center. The highest wind speeds are observed south of the low-pressure center in a region called the bent-back trough, where wind directions shift with the isobars to be more southerly (Mass and Dotson, 2010).

As the atmospheric pressure fluctuates with these storms, there is a direct response by the water in the Salish Sea depending on the nature of the change. Lower ambient pressure allows
for expansion of the water body resulting in increased sea surface heights—often called storm surge, and is a major component of the non-tidal residual in a tidal record. For this region, storm surge of 30-50 centimeters is common with the major storms, raising the static sea level and facilitating a greater likelihood of flooding. Coincident with changes in pressure are high wind events where the dominant wind directions generally follow the orientation of the major basins (South to North; Phillips, 1968; Overland and Walter, 1963; Finlayson, 2006). During strong wind storms (such as Extra Tropical Cyclones), shorelines facing south are more exposed to the combination of high water (dependent on tide and storm surge) and large waves as they are facing the dominant direction of energy. Infrequently, high magnitude winds from the north are accompanied by higher atmospheric pressure. Throughout such an event, shorelines oriented towards the north are susceptible to wave impacts accompanied by low to negative storm surge. A graphical representation of the various dynamic and static components that influence the total water level elevation on the coast can be found in Figure 3.

3.0 Methods

I modeled wind-waves and wave runup in the Salish Sea using the numerical wave model SWAN (Simulating WAves Near Shore), parameterized TAW (Technical Advisory on Flood Defense), and the hydrodynamic model XBeach. Model results characterized the regional wave climatology and I assessed changes to the deep-water wave climate under future climate scenarios to provide estimates on flood magnitude, frequency of events, and exposure to waves for specific stretches of coastline. I completed these objectives following the methods detailed below (a flow chart of the methods can be found in Figure 4):
1. Bias corrected publicly available WRF (Weather Research and Forecasting) meteorological hindcasts using an empirical correction to account for higher frictional coefficients for land points.

2. Developed complete time series of water levels from 1950-2010 at each of the NOAA tide gauges using the NTR (Non-Tidal Residual) from the Seattle station to fill in data gaps at each station.

3. Built spatial masks to segment the Salish Sea into sections of coast that are represented by the various WRF grid points and NOAA tide gauge stations.

4. Modeled wind waves in the Salish Sea for all potential scenarios of wind speed, wind direction, and water level, including SLR estimates of 0.3, 0.6, and 0.91 m.

5. Extracted the -10 m NAVD88 (North American Vertical Datum of 1988) depth contour every 50 meters along the coast and developed a LUT (Look-Up-Table) of wave parameters at each location using wave model output.

6. Using the spatial masks from step 3, I extracted the correct WRF weather point and NOAA tide gauge to provide concurrent time series of wind speeds, directions, and water levels to interpolate through each LUT and generate hindcasts of wave parameters.

7. Developed hindcasts of wave parameters for SLR scenarios of 0.3, 0.6, and 0.91 m by adding these values to each water level time series prior to sampling the LUT. Wave hindcasts for each SLR scenario were compared to the hindcast time series to assess changes in wave parameters with higher sea levels.

8. Modeled wave runup with parameterized and hydrodynamic models for Ruston Way, Tacoma, WA using model output from the regional SWAN model as boundary conditions. Parametrized runup models generated time series of TWL necessary for
characterizing recurrence intervals of extreme water levels and identifying storm events to model with hydrodynamics.

9. Modeled the 10-yr storm for Ruston Way with full hydrodynamics under contemporary water levels and SLR scenarios of 0.4 and 0.85 m to predict changes in flood inundation and exceedance of the FEMA (Federal Emergency Management Agency) 100-yr BFE (Base Flood Elevation).

3.1 Phase-Averaged Wave Model

The Simulating WAves Nearshore (SWAN) model is a third-generation phase-averaged wave model validated for use in coastal settings and developed in the Netherlands at the Delft University of Technology. It accounts for refraction, whitecapping, shoaling, bottom dissipation, wave-wave interactions, and wind-wave generation by solving the spectral action balance equation (Booij et al., 1999; Ris et al., 1999, SWAN Team, 2019a) for the energy density spectrum, $E(\sigma, \theta)$, which describes the phase-averaged wave energy over frequency ($\sigma$) and direction in degrees ($\theta$). Typically, the action density spectrum, $N(\sigma, \theta) = E(\sigma, \theta)/\sigma$, is solved for rather than the energy density because the action density is conserved in the presence of ambient currents (Whitman, 1974). Here however, currents are not considered as this detail was outside the scope of this project. The spectral action balance equation describes wave generation, propagation, and dissipation (SWAN Team, 2019a; Booij et al., 1999),

$$\frac{\partial N}{\partial t} + \frac{\partial cxN}{\partial x} + \frac{\partial cyN}{\partial y} + \frac{\partial c\sigma N}{\partial \sigma} + \frac{\partial c\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}$$  \hspace{1cm} (1)$$

where the first term represents local changes, the second and third term propagation, and the fourth and fifth terms changes in frequency and direction by current interaction and changes in
The right-hand side characterizes sources and sinks of energy inducing generation and dissipation and additionally, non-linear wave-wave interactions.

3.2 SWAN Model Grid & Bathymetry

Two SWAN grids were developed (light blue and dark blue regions in Figure 1) by colleagues at Deltares in the Netherlands (van Nieuwkoop, 2018) covering the Salish Sea and nested along their boundary. Model output from the marine and Strait of Georgia domain (MO) was saved on the southeastern boundary near Admiralty Inlet (medium blue area in Figure 1; Figure 2) and provided the forcing for the Puget Sound and Hood Canal model (M1). A nested system allowed for seamlessly modeling large spatial scales by breaking up the region into smaller domains which included spatially varying resolution. Variable grid resolution utilizes coarser resolution in deep water with the higher resolution being reserved for shallower coastal environments and bed forms that have a greater influence on waves and currents (SWAN Team, 2019a). Here, a coarser curvilinear grid, M0, with a maximum resolution of 160 meters (1000 m coarsest), spanned the Strait of Juan de Fuca and the Strait of Georgia as well as the San Juan Islands and northern Puget Sound. Near Admiralty Inlet at the eastern end of the Strait of Juan de Fuca (Figure 2), a nested higher resolution grid, M1, (60 m-150 m resolution) covered all of Puget Sound, the Hood Canal and the smaller embayments east of Whidbey Island (e.g., Port Susan Bay and Skagit Bay; Figure 1; Figure 2).

Four bathymetry datasets were used to construct the bottom boundary conditions for the wave model simulations with gridding software (RGFGIRD) and priority given as follows:

1. Puget Lowland Topobathy (Finlayson, 2005)
2. Port Townsend ½ arc-second DEM (NOAA, 2011)
3. British Columbia 3 arc-second DEM (NOAA, 2013)
4. GEBCO 30 arc-second (GEBCO, 2014)

The Puget Lowland (Finlayson, 2005) dataset covered south central Puget Sound and only the eastern portion of the Strait of Juan de Fuca up to latitude 48.45°N. The Port Townsend (NOAA, 2011) dataset covered the Strait of Juan de Fuca and the area up to latitude 48.79°N with the British Columbia (NOAA, 2013) dataset covering the remaining waters of the Salish Sea. GEBCO (GEBCO, 2014) filled in any data gaps outside of the coastal zone on Vancouver Island and mainland British Columbia (van Nieuwkoop, 2018).

3.3 Look-Up-Table Development

A look-up-table (LUT), in the simplest sense, is a tool which catalogues data for a set of input parameters. Different combinations of input parameters can then sample the LUT and the appropriate output data is returned. Previous wave studies have invoked LUT’s to simplify the wave modeling process; Erikson et al. (2018) developed a LUT to evaluate potential changes in the future deep water wave climate along the southern California Bight. When modeling waves, a LUT can significantly reduce the computational costs of modeling larger domains over long time frames and simplify modeling SLR scenarios. Following a similar methodology to Erikson et al. (2018), every combination of plausible wind speed, wind direction, and water level were modeled in SWAN individually and in this case, water levels associated with SLR of 0.3, 0.6, and 0.91 m were included. Wave model output from each unique set of wind speed, wind
direction, and water level was georeferenced to a grid cell and catalogued into a LUT to relate meteorological conditions and water levels to waves in the Salish Sea.

I explored the sensitivity of waves to each parameter at four locations between Tacoma and Seattle by analyzing a series of model runs with varying wind speeds, wind directions, and water levels in the Puget Sound model (M1). Model results (Figure 5) combined with ranges of historical wind speeds and water levels informed my decision for the resolution of each parameter of the LUT. Here, each LUT was constructed by first modeling waves in SWAN with water levels every 1.0 meter from -2.0 m to 5.0 and 5.5 m NAVD88 to capture the SLR scenarios of interest. Wind speeds from 5 m/s to 30 m/s in 5 m/s bins were included with wind directions from 0.0 degrees to 350 degrees with 10-degree directional bins.

3.4 SWAN Physical Parameters

SWAN wave models can be run in a stationary and non-stationary mode. A major assumption when invoking stationary SWAN is that waves are able to grow and propagate instantaneously across the domain, and responses in the wave field to changes in the forcings (e.g., wind speed and direction) are also instantaneous. When dealing with smaller domains, such as the fjordal basins of southern Puget Sound, these assumptions can be valid where fetch-limited wave growth dominates and wave propagation across the domain is faster than changes in the wind or tidal forcing. However, for modeling large areas exceeding 100 square kilometers such as the Strait of Georgia, (SWAN Team, 2019b) non-stationary SWAN is recommended (see Rogers et al., 2006 for more information).
SWAN employs third generation dissipation physics following Cavaleri and Malanotte-Rizzoli (1981) and the equations of Komen et al. (1984) for modeling wind-wave generation. Dissipation due to whitecapping was modeled according to Komen et al. (1984) and nonlinear quadruplet wave interactions were approximated using the discrete interaction approximation developed by Hasselman et al. (1985). Depth-induced breaking was included by using the bore model of Battjes and Janssen (1978) because spectral modeling in shallow water when waves begin to shoal and break is difficult and not well constrained. Influences of bottom friction on energy dissipation were also included, using a coefficient of friction (0.038) derived from the Joint North Sea Wave Project experiments of Hasselmann et al. (1973). Triad wave-wave interactions, important in shallow settings for transferring energy from lower frequencies to higher frequencies, were invoked using the default SWAN settings and the lumped triad approximation. Lastly, the drag coefficient from Wu (1982) related winds prescribed in each model run to the 10-meter elevation and each model was run in the absence of currents (van Nieuwkoop, 2018).

3.5 Wave Hindcast Development

I constructed a LUT of wave parameters (e.g., wave height) referenced to the input parameters of wind speed, wind direction, and water level every 50 m along the -10 m NAVD88 depth contour. Long-term deep water wave hindcasts were built at each point from time series of wind speed, wind direction, and water level that pulled wave parameters from each LUT.
3.6 Wind Forcing Parameter of LUT

The Weather Research and Forecasting historic reanalysis (WRF; Skamarock et al., 2008) weather product covering the Pacific Northwest, subsampled for the state of Washington, provided the meteorological forcings to build each wave hindcast. The WRF mesoscale model had a 6-hourly and 12-kilometer resolution for the period of 1948-2010 and was dynamically downscaled from NCEP/NCAR’s Reanalysis-1 product (Kalnay et al., 1996). A climate model providing a reanalysis, incorporates weather observations during each time step, tuning the model with the best estimates of real-time atmospheric conditions across the entire domain (NCEP, 2018; Dee et al. 2016). Within the WRF weather model, each grid point was classified as either being a land point or a water point. Water points in climate models have a lower associated coefficient of friction, creating higher magnitude wind speeds compared to land points. When building each wave hindcast, only WRF model points classified as over-water were used as a meteorological forcing to query the LUT. Owing to model coarseness, some WRF grid points for the narrow basins of Puget Sound and Hood Canal were classified as land points even though they resided over water. A quantile bias correction was explored to adjust these over-water land speeds to better represent over-water speeds.

3.7 Quantile Bias Correction Using Observed Meteorological Data

A test case of bias correction using observational data from the Seattle WPOW1 weather station (WPOW1 in Figure 6) was completed on the closest WRF water point (Blake Island; Figure 6) to assess impacts on significant wave height and peak period. The quantile-corrected dataset was provided by Sean Crosby, a research affiliate of Western Washington University and
the United States Geological Survey. Wave hindcasts built using the observational bias corrected winds to sample the LUT increased the maximum significant wave heights and peak period (Table 1) compared to uncorrected WRF data. Without wave observations it is unclear if bias correcting improved the wave models skill, however, it is assumed that improved boundary forcing, i.e., wind, will yield more accurate wave predictions.

Where observations are available, a quantile bias correction of WRF model grid points is ideal, however, few research quality weather stations exist in the Puget Sound. A majority of the observations have data coverage less than 30 years (generally needed to establish a climatology) with numerous data gaps and coarse resolution (e.g., 15-deg direction and 1 m/s binning). Lacking long term and quality historical meteorological data proximal to water, applying an observation derived quantile bias correction was not realistic region-wide. I instead created a WRF derived land to water correction factor to be applied at locations where WRF overwater land points exist.

3.8 Model driven bias correction with WRF land-water points

Time series of wind speed for the two WRF water points in southern Puget Sound near McNeil and Blake Island were compared to their eight surrounding WRF land points (Figure 6; Figure 8). The quantiles of the eight land points were averaged and a model land-to-water speed varying correction factor was developed at each location (McNeil and Blake Island) which provided a 1.3% increase in wind speeds (Figure 8). At locations of over-water land points in Puget Sound, the model speeds were adjusted with the bias correction while the wind directions
remained the same. Resulting wind speeds were more representative of over water conditions and should produce more realistic wave predictions.

3.9 NOAA Synthetic Water Levels

In addition to wind forcing, either observed or synthetic water levels were required to query the LUT. Washington State has a total of seven tide gauges in the Salish Sea, operated and maintained by NOAA (Figure 1). At each tide gauge, NOAA reports a predicted astronomical tide and the observed tide level. The observed tide is the actual elevation of the water surface at that time referenced to a vertical datum while the astronomical tide is the predicted water level derived from tidal harmonics which characterize the gravitational influences from celestial bodies like the moon and sun on water levels. The observed tide often differs from the predicted tide and can include influences from winds and waves, but most gauges are sheltered from these effects. Observed values, however, do measure water level changes owing to atmospheric pressure changes and large scale ocean adjustments called non-tidal residual (NTR; e.g., coastal upwelling, density structure changes). These NTRs are observed to be +/- 1.0 m in the Puget Sound and are an important component of total water level and high water hazards.

The seven NOAA tide gauges in Puget Sound have varying temporal coverage and one gauge (the Seattle tide gauge) overlaps with the entirety of the WRF timeframe (1950-2010). When observed water levels were not available, synthetic still water level (SWL) time series were created by first filtering the observed water level signal from Seattle with a 48-hour low-pass filter to extract the NTR. The predicted astronomical component for each station was then added to the NTR from Seattle to create a synthetic SWL time series which filled in any data
gaps in the water level observations and produced continuous water level time series coinciding with the WRF data. When these NOAA water level time series were used to query a LUT and build wave hindcasts, the resulting wave parameters included influences of NTR, specifically storm surge.

### 3.10 Segmentation of Puget Sound, Hindcast Creation, and Validation

Time series of wind speed and wind direction from the WRF weather product were interpolated on to the same hourly water level time series and queried the LUT to create hindcasts of wave parameters. Spatial masks were created with Google Earth to segment the Salish Sea and guided which forcing point was to be used when sampling the LUT at each 50 m point along the -10 m NAVD88 contour. Figure 9 shows the WRF model points used and the segments of coastline and fetch they represent. Special care was taken when building each spatial mask to limit WRF coverage of shorelines to those which would most realistically experience winds characterized by a WRF point. For example, Figure 10 shows a comparison of the wind speeds and directions for the two closest WRF points to the north shore of Orcas Island (orange area in Figure 10). The two points are separated by the island itself and the southern point, isolated in a bay and separated from the north shore, has lower magnitude wind speeds and a lower occurrence of northerly wind. Along the north shore, the wind and resulting wave conditions would be better represented by the WRF water points to the north as they are more characteristic of the winds coming down the Strait of Georgia. Invoking a mask system which followed the orographic confines of an area, ensured the appropriate meteorological and water level time series were chosen for all locations in the Salish Sea.
At each 50-meter point along the -10 meter NAVD88 depth contour, the appropriate WRF point and NOAA tide gauge interpolated through the LUT and populated a time series of hourly wave parameters. The final product being concurrent time series of winds, water levels, and waves across the entire region. Limited by wave observations, the skill of the LUT was compared to the three wave buoys Hein Bank, Sentry Shoal, and Halibut Bank (Figure 2). At each wave buoy location, wave hindcasts were built using the closest and most representative WRF model point and NOAA tide gauge from the nearest SWAN model grid point. The LUT only provided bulk parameters such as wave height rather than spectral data so comparisons were carried out on bulk parameters only.

Changes to wave parameters were assessed by resampling the LUT with water level time series that had been incremented by 0.3, 0.6, and 0.91 m. Due to the high uncertainty surrounding the magnitude and timing of SLR in Washington State (Mote et al., 2008; NRC, 2012; Miller et al., 2018), uniform values were chosen instead of specific projections from the many reports. This way, the general influence of higher sea levels on waves could be addressed under any amount of SLR and related to a time in the future as new estimates of the rates of SLR are furnished.

3.11 Assessment of Future Wind Conditions

Meteorological forcings were assumed unchanged in future SLR scenarios which allowed the same WRF wind forcing to be used for all forecasted wave modeling. I tested this assumption with the best available regional projections: MACA (Multivariate Adaptive Constructed Analogs) downscaled NOAA (National Oceanic and Atmospheric Administration)
GFDL-ESM2M (Geophysical Fluid Dynamics Laboratory Earth Systems Model) global climate model (Dunne et al., 2012; Dunne et al., 2013). The GFDL-ESM2M is part of the CMIP5 (Coupled Model Inter-Comparison Project 5), a consortium of over 20 modeling groups across the globe participating in coordinated experiments to provide the best estimates on future climate conditions through inter-model comparison (Taylor et al., 2012). With CMIP5 comprised of more than 50 different models, the GFDL-ESM2M was chosen based on results from O’Neill et al. (2018) and Erikson et al. (2015). GFDL-ESM2M in these studies was found to have the highest skill when used to model extreme wave conditions along the coast of California (root mean square error of 7-17 cm).

The MACA downscaling GFDL-ESM2M model had daily temporal resolution spanning the period of 1950-2100 and covered only U.S. land and water at a resolution of 4 km. Changes to wind speed and direction between the historic period (1950-2020) and future predictions (2020-2100) under Representative Concentration Pathway (RCP) 8.5 (Figure 11; Figure 13; Figure 14) were analyzed. RCPs represent a set of four greenhouse emission radiative imbalance scenarios where the Earth’s atmosphere traps an additional 2.6 to 8.5 W/m² by the year 2100. The RCP scenarios are used by climate modelers to perform a suite of experiments with GCMs to provide estimates on potential climate scenarios (Vuuren et al., 2011). RCP 8.5 is currently described as the “business as usual” scenario where minimal action in greenhouse gas reduction is taken. Here, emissions of greenhouse gasses will increase through 2100 to the point that atmospheric concentrations of CO₂ will have tripled when compared to pre-industrial levels (Mauger et al., 2015). Analysis of RCP 8.5 over Puget Sound showed minimal change in future wind conditions, indicating that the WRF weather model for historic conditions could be used in forecasting future scenarios.
3.12 High Resolution Wave Runup Modeling

Regional wave model output provided the necessary boundary conditions to demonstrate the potential for modeling wave runup and flooding under different SLR scenarios in a case study along Ruston Way, Tacoma, WA (Figure 2). The case study was part of the WCRP and helped local government in Tacoma (e.g. City of Tacoma, Metro Parks, and Port of Tacoma) better understand impacts from waves and storm surge under SLR and remain resilient to coastal hazards into the future. Following the USGS Coastal Storm Model System (CoSMoS) approach described by Barnard et al. (2009 & 2019), parameterized runup models (Meer, 2002) and the hydrodynamic model XBeach (Roelvink et al., 2009, XBeach, 2015) were coupled to the regional wave model to calculate wave runup and changes in the extent and frequency of coastal flooding along Ruston Way, Tacoma, WA (Figure 2). The CoSMoS workflow takes future projections of climate from GCMs and dynamically downscales the wind and pressures fields to be used as boundary conditions for regional and local scale numerical models in order to predict coastal waves and flooding under different SLR and storm scenarios (Barnard et al., 2009, Barnard et al., 2019). For this test case, I mimicked the CoSMoS modeling train by linking model output from the regional wave model to high resolution localized hydrodynamic models along Ruston Way to simulate wave runup and flooding under different SLR scenarios.

Shoreline orthogonal transects were generated every 100 meters along Ruston Way from a depth of -10 m NAVD88 up to an elevation of 10 m NAVD88. The closest SWAN grid point and LUT to the offshore end of each transect was extracted and provided the boundary wave conditions to model wave runup. First the parameterized TAW (Technical Advisory on Flood
Defense) model (Meer, 2002) produced hourly hindcasts of wave runup and total water elevations along each transect from time series of wave heights, periods, and water levels which identified storms to be modeled with a hydrodynamic model.

### 3.13 Parameterized Wave Runup Modeling

Stockdon et al. (2006) developed a commonly used parameterized model (Stockdon) for estimating wave runup. Stockdon has been tested and calibrated on open coast sandy beaches exposed to long period ocean waves, a different environment than the Salish Sea (Allan et al., 2015; Stockdon et al., 2006). TAW is recommended for situations of wave runup on coastal structures (barriers or steep coastal dunes) due to reduction factors from wave angle of attack, offshore berms, various bed roughness parameters and the ability to handle a wide range of wave conditions (Allan et al., 2015; NHC, 2005). Ruston Way’s shoreline is heavily armored with riprap and other revetments (Figure 12) and only exposed to wind-waves which indicated a better classification with the TAW runup model in place of Stockdon. The TAW equation, equations 2a and 2b in Appendix A, from Meer (2002) were used to estimate the 2% wave runup elevation from time series of wave heights, periods, and water levels. The spectral period ($T_{m-1.0}$) is recommended over the peak period in Equations 2a and 2b and was estimated using Equation 6 in Appendix A.

The wave height at the toe of the engineered structure (riprap along Ruston Way), referred to as the spectral wave height ($H_{mo}$), is required to calculate wave runup. In order to estimate the spectral wave height, Meer (2002) suggests a wave model such as SWAN provide all of the necessary spectral data. Lacking this type of model output with the LUT, Allan (2015)
provided an approach to estimate the spectral wave height (Equation 5 in Appendix A). As a check on the spectral wave height estimate (Equation 5), the regional wave model output was shoaled following Equation 7 which calculated the shallow water wave height at the toe of the structure independent of refraction and assuming all wave energy was conserved. Here, the deep water and shallow water wave group velocities were first calculated and defined the shoaling factor \( K_s \) (Equation 8 in Appendix A) which combined with the deep water wave height to estimate the shallow water wave height. The smaller of the two wave heights (shoaled wave height and spectral wave height) was then used with the spectral period to estimate wave runup with TAW (Equations 2a and 2b).

Regionally, the TAW runup model (Equations 2a and 2b) was applied on an idealized shoreline with a uniform slope (0.2 degrees) and a constant bed roughness of 0.85. As Puget Sound shorelines are highly variable in composition, orientation, and slope, removing the variability in slope and roughness emphasized where waves should have the greatest influence on TWL based on orientation. Results from this regional analysis served as a proxy to identify vulnerable areas to wave driven impacts and further highlights the importance of site specific modeling like CoSMoS to incorporate local topography and bed roughness in flood estimates.

3.14 Runup Modeling and Event Selection – 10-year Storm

I used TAW to generate a hindcast (1950-2010) of wave runup for each transect which I combined with offshore SWL records to generate 60-yr hindcasts of TWL. A coefficient of roughness of 0.8 was used for each calculation which represented coarse gravel and other granular material (Meer, 2002) similar to the typical mixed sediment beaches along Ruston Way.
A wave direction time series from the LUT allowed for reductions in wave heights from oblique wave angles of attack on the order of 10% (see Van der Meer, 2002 for more information on wave reduction factors). Using extreme value theory (Zervas, 2005; An & Pandey, 2006; Guedes Soares & Scotto, 2004) and the $r^{th}$ largest methodology (Vitousek et al., 2017) generalized extreme value probability distribution functions (PDF) were generated for the n-max TWLs each year ($n = 5$, years = 60) at each transect. An extreme value curve was fit to the PDFs of extreme TWLs which provided estimates on the recurrence of extreme TWL elevations and defined storm types. Extreme water levels corresponding to a 10-yr TWL (10% probability of occurrence in any given year) were examined along Ruston Way.

Analysis of entire 60-yr hindcasts of TAW model output revealed a bimodal flood regime for Ruston Way (Figure 27). Here, flooding occurred from two different regimes: (1) high storm surge and low waves and (2) low to negative storm surge and moderate to high waves. From the time series of TWL (SWL + wave runup) at each transect, I identified instances of high water and waves sourced from northerly winds representative of a 10-yr storm event. Given the orientation of Ruston Way, these events (regime 2) will produce larger wave-driven impacts (erosion and high water hazards) for Ruston Way as its shoreline will be protected from strong southerly winds. Having identified impactful storms representative of a 10-yr event, the wave and water level boundary conditions from TAW were extracted and used in hydrodynamic modeling of wave shoaling, breaking, and runup at each transect to estimate flood extent from a dynamic model.
3.15 Hydrodynamic Wave Runup Modeling

The morphodynamic numerical model XBeach modeled the physical processes of wave transformation, wave breaking, and wave runup in intermediate to shallow water depths along Ruston Way. When run in a non-hydrostatic mode, XBeach can resolve the hydrodynamic processes of individual waves on beaches and barriers and wave runup to estimate the total water level, potential overwash of the landscape, and wave processes affecting sediment transport and morphologic change (McCall et al., 2014; Roelvink et al., 2009; XBeach, 2015). One-dimensional XBeach models, following the CoSMoS workflow, were constructed every 100 m along the Ruston Way shoreline for a total of 191 transects using the open earth tools (OET) MATLAB toolbox and scripts developed to help automate the process of model building. Transects covered an offshore distance of two wavelengths with 100 model grid points per wavelength. Collaborators in Tacoma identified two SLR scenarios of interest to be modeled in XBeach: 0.4 m of SLR (the 50% scenario by 2070) and 0.85 m of SLR (the 50% scenarios by 2100), both based on new probabilistic estimates provided by Miller et al. (2018). Wave heights, wave periods and water levels from the regional wave model for a 10-yr storm event (storm regime 2) along Ruston Way were extracted and modeled in XBeach under current and the two future sea level positions.

The maximum wave runup elevation with a depth threshold of 5 cm for water over land was extracted at each transect for current sea level positions and the two SLR scenarios to show the extent which water would shift landward under higher seas during a 10-yr storm. Across Ruston Way, XBeach model output for all sea level scenarios was compared to the Federal Emergency Management Agency (FEMA) 100-yr base flood elevation (BFE). FEMA’s BFE is the metric used region-wide for guiding development and designating flood zones along the
coast. Comparisons with the BFE showed exceedance spatially for the two SLR scenarios which highlighted exposed areas and hinted at an increased frequency of flooding in the future.

4.0 Results & Discussion

4.1 Wave height sensitivities

Wave height is a function of the wind speed, wind duration, water depth, and fetch. Modeled wave heights at four deep water locations in the Puget Sound were most sensitive to wind direction and varied up to 1.0 m for a constant wind speed of 20 m/s (Figure 5). Wave heights scaled approximately linearly with wind speed (black line in Figure 5) and varying the water level had negligible impact (changes in wave heights of a few centimeters) for deep water locations. Modeled wave sensitivities indicated that in deep water, especially in fetch limited environments, wind direction and magnitude had the strongest influence on wave heights. These results assisted in determining the resolution for each input parameter (e.g., wind speed, wind direction, and water level) of the LUT and ultimately, how many unique combinations to be modeled in SWAN.

4.2 Historic and Future Wind Conditions in Western Washington

Long term wind records from the Whidbey Island Naval Air Station (NAS) and Seattle WPOW1 (Figure 2) weather stations proximal to the coast showed fluctuations in average wind directions every 3-5 years. Heat maps displaying the probabilities of wind direction (Figure 16) for each station show the dominant wind directions for each station with warmer colors.
indicating a higher probability of occurrence. At the Whidbey NAS, changes of 3-7 degrees every few years (black line in Figure 16) was fairly common in the historic record with the largest shift of ~20 degrees recorded in 1973. Seattle’s WPOW1 station showed similar trends of 3-7 degree shifts with the maximum change of 10 degrees between 1991 and 1993. The Whidbey NAS weather station is positioned at the confluence of three large basins (Strait of Georgia, Strait of Juan de Fuca, and southern Puget Sound; Figure 2) and experiences a larger directional range of winds outside of the dominant north-south regime, likely explaining the higher amounts of variability compared to WPOW1. With decadal shifts in wind direction common in Puget Sound, it is possible that the beaches are already adapted to these cyclical changes. Interannual variability in wind direction likely influences where wave energy is focused on the coast, enhancing changes in erosion and sediment dynamics.

Minimal change in future wind conditions was predicted by the statistically downscaled NOAA GFDL-ESM2M GCM under RCP 8.5 for coastal Washington State. Historic wind speeds (1950-2020) at nine locations throughout the region showed near similar distributions with future conditions (Figure 11). Higher magnitude wind speeds at each location (speeds > 12 m/s) were on average slightly greater (less than 1 m/s), especially in southern Puget Sound, for the period 2020-2100. Spatially, average wind speeds between 1950-2020 and 2020-2100 remained the same or decreased less than 0.2 m/s while extreme wind speeds increased region wide less than 0.5 m/s by 2100. Future decadal averages for maximum wind speeds when compared to average speeds from 1950-2020 predicted areas such as southern Puget Sound to increase by 1 m/s mid-century and decrease more than 0.5 m/s by the end of the 21st century (Figure 15). Any predicted temporal variability could be within the uncertainty of the GCM
requiring comparisons with other future climate projections to determine if this trend is also predicted as changes in extreme wind speeds would prove important for wave impacts.

Average wind directions showed the most change with directional shifts of six degrees or less by 2100 and wind directions associated with higher magnitude wind speeds were predicted to shift a maximum of two degrees into the future across Washington State. Wind rose diagrams (Figure 13) at eight locations similar to Figure 11 characterized identical wind climatologies for both time periods where average differences in wind direction for speeds greater than 10 m/s were less than 1 degree (0.88 degrees). It remains uncertain to what extent subtle change in wind direction will affect extreme water levels, but shifts of just a few degrees is likely to be important to wave energy, coastal erosion and analyses of sediment mobility as observed elsewhere (Norcross et al., 2002). Depending on how variability in wind directions transpire in the future, modeling can help assess potential corresponding wave impacts.

In Puget Sound, the prevailing wind directions (the direction that winds are coming from) are south/southwest during the winter and west/northwest during the summer months with periodic north gales occurring in winter months (Phillips, 1968; Overland and Walter, 1963; Finlayson, 2006). These directions are parallel to the regional orientation of the major fjordal basins which reduce variability in wind direction through topographic funneling during high magnitude events (Overland and Walter, 2918; Schoenberg, 1983). While changes to the climate (e.g., temperature, precipitation) of Washington State are anticipated by 2100, appreciable change to the Puget Sound landscapes that influence wind directions, is not. Generally, variations in wind conditions (directional shifts of 3-5 degrees and speeds changing less than 1 m/s) could be important to certain shoreline orientations but the changes predicted by the MACA downscaled GFDL-ESM2M GCM hint at a future wind and wave climate largely similar to the
current regime in Puget Sound. Similar meteorological conditions by the year 2100 indicated that the historic (1950-2010) WRF wind product (the only available reanalysis product) could be used to model future climate conditions and extreme weather events important for waves from the LUT with some degree of uncertainty. Future forecasts for winds are rarely publically available and often limited to United States waters (such as the GFDL-ESM2M GCM), neglecting areas of fetch meaningful to shorelines in the United States (i.e., nearly all of the Strait of Juan de Fuca and all of the Strait of Georgia are not included in the GFDL-ESM2M model; spatial coverage of GFDL-ESM2M can be seen in Figure 15). As climate models improve and future products come online that cover more of Washington State spatially and temporally, the assumption of homogeneity into the future can be explored in more detail along with the spatial and temporal variability this MACA downscaled model predicted.

4.3 Impact of an Observation Derived Quantile Bias Correction

Modeled wind speeds from the WRF weather model point closest to the Seattle WPOW1 weather station (Blake Island in Figure 6) are underpredicted over the entire wind range with higher magnitude speeds (> 10 m/s) being 8 m/s slower (Figure 7). Distributions of wind speed showed the WRF data has a higher occurrence of lower magnitude wind speeds (4 - 7 m/s), a lower occurrence of winds greater than 8 m/s, and a higher percentage of winds from the south/southwest than the observational dataset (Figure 7). An observation-derived quantile bias correction of model data was used to adjust the WRF predictions at this location and improved the modeled representation of the climatology. Average wave heights calculated with the bias-corrected winds at a deep water location west of Seattle WPOW1 increased less than 5 cm, while
the maximum wave height increased by 50 cm. The average peak period showed no appreciable change while the maximum peak period at this location increased ¾ of a second (Table 1). With no historical wave data available at this location, it is unclear if the bias correction improved model skill; a wind forcing that better reflects the actual conditions, should produce more accurate wave predictions.

Ideally, quantile corrections from wind observations would be applied region wide, however, there is a lack of long term, quality, meteorological stations close to, over, or representative of open water. In fact, WPOW1 is the single station in southern Puget Sound that meets these criteria being free of frictional effects associated with land, vegetation and urbanization. Until additional observations become available model predictions will provide the best spatial estimate of wind conditions but may underestimate winds over water or require corrections for frictional effects of land.

4.4 Empirical correction to adjust for higher friction over land

I adjusted the wind speeds of WRF land points in Hood Canal and southern Puget Sound to more accurately model extreme wave heights associated with flooding and coastal hazards from waves. Owing to spatial coarseness (12-km), many WRF model grid points located over water were in fact classified as “land.” Wind speeds of these grid points were examined and found on average to be 1.3 times less than nearby over-water points (Figure 8). This difference scaled with higher magnitudes such that at winds speeds of 20 m/s, land points were on average 7 m/s slower than over water points. When applied, the empirical correction to wind speeds increased the maximum wave height from the LUT 25 cm and 0.6 seconds for the peak period at
open water settings north of Ruston Way in Tacoma (Figure 2; Figure 8). In Puget Sound, average wind conditions are lower in energy (< 5 m/s; Finlayson, 2006) and were more frequent in the WRF model (Figure 7). The higher frictional coefficient of WRF land points had little effect on modeled wave heights for the average conditions (lower wind speeds) while the need to adjust over-water land points was apparent when modeling higher magnitude wind conditions. Providing an empirical bias correction adjusted the wind speeds of over-water land points to better represent over-water conditions, which should provide a more accurate prediction of wave heights from the LUT.

4.5 LUT Validation at Hein Bank, Sentry Shoal & Halibut Bank

The skill of the LUT was evaluated at the Hein Bank, Halibut Bank, and Sentry Shoal wave buoys (Figure 2). A quantile-quantile comparison (Figure 17) of the modeled and observed wave heights at all three available buoy locations (Figure 2) indicated the LUT, on average, over predicted wave heights greater than 0.5 m by half a meter or more depending on location. The large amounts of scatter in Figure 17 and higher RMSE was due in part to violations of the LUT assumptions and a lack of open ocean swell, specific to Hein Bank. LUT predictions at Halibut Bank showed the highest skill with a root-mean-square-error (RMSE) of 0.4 m and a bias of 0.09 m (Table 2). All three wave buoys are situated in the largest basins of the Salish Sea where stationary and uniform wind conditions are unlikely, lowering the validity of the LUT. A second source of error are wind predictions themselves, which I quantified by using wind observations at the Hein Bank buoy to build a hindcast of wave parameters from the LUT. Using the observed winds at Hein Bank instead of the WRF model data reduced the
RMSE of Hs from 0.42 m to 0.27 m and reduced the bias to less than 5 cm. This suggests that a significant amount of error stems from the WRF modeled winds and errors for LUT predictions are likely more modest than they appear. Subtracting errors in quadrature (assuming no correlation) reduced errors driven by the LUT to 0.38 m. Additionally, there is error within the wave measurements themselves the extent of which remains uncertain.

The decrease in RMSE and bias in LUT predicted wave heights with wind observations from the Hein Bank buoy indicate that the WRF 1950-2010 hindcast may contain substantial error at this location. In the smaller and narrower basins of Puget Sound, the LUT is expected to have more skill where more uniformity in the WRF outputs particularly during extremes is observed and helps satisfy the assumption of spatial homogeneity in the LUT. Ultimately, a higher resolution wind product and more wave observations in Puget Sound are needed as the only points of comparison exist in the Strait of Juan de Fuca and Strait of Georgia.

4.6 Wave Exposure in Puget Sound

I characterized the deep water wave climatology for the period 1950-2010 (Figure 18) which displayed directional similarities with meteorological conditions (Figure 13), with prevailing directions of both reflecting the overall basin orientation. In southern Puget Sound the dominant directions of wave energy were north/south with locations closer to and in the SJDF having a third component of wave energy from the west. The average annual maximum wave height across Puget Sound (Figure 19) quantified the potential exposure to waves each year but failed to identify specific locations where waves could be impactful. On a sub-basin scale, the average amount of hours each year where waves were predicted to exceed 0.5 m highlighted
stretches of coast with a greater exposure to wave driven hazards and processes (e.g., erosion, longshore currents; Figures 20-24). Wave runup on a simplified shoreline further identified areas where waves should play a role in influencing TWL and driving flooding and erosion (Figure 28).

In south central Puget Sound (Figure 22), south facing shorelines were predicted to see ~400 more hours each year of wind-waves exceeding 0.5 meters with distinct changes in exposure apparent at inflection points in shoreline orientation. Elsewhere in Puget Sound, this spatial trend was prevalent with shorelines in the SJDF predicted to have a third component of exposure to waves from the west. Directional changes of 10 degrees or less in the average wind conditions predicted by the MACA downscaled GFDL-ESM2M GCM are likely to influence wave exposure at the coast. Shorelines facing south are projected to see a higher frequency of impacts from waves into the future as dominant wind directions remain from the south. However, slight variations in decadal average wind directions may affect shear stress on the bed and wave-induced currents, prompting a geomorphic response and influencing wave transformations in the nearshore. Additional research to assess the potential for morphologic change and the impact of temporal variability in wind direction on waves is advised. For Puget Sound, this assessment (Figures 19-24) provides one of the first regional characterizations of shoreline exposure to waves, serving as a first order approximation highlighting where waves will be impactful in TWL elevations. However, local features like bed roughness and slope must be included to provide a thorough assessment of TWL, requiring tools like CoSMoS and my case study for Ruston Way.
4.7 Impacts of SLR on Offshore Wave Climate

Locations like Skagit Bay (Figure 2) and the remaining ~19 large river delta systems of Puget Sound are likely to experience an increase in wave energy with SLR as higher seas reduce fetch and depth limitations to support wave growth. Model results indicated that SLR will primarily affect fetch in terms of frequency rather than extent. Even so, I examined SLR effects on wave generation and propagation and found no systematic change to deep water waves under SLR scenarios of 0.3, 0.6, and 0.91 m. The average significant deep water wave height changed by 5 cm or less and the average peak period increased 0.1 seconds or less with 0.91 m of SLR. The mean annual maximum wave height displayed the largest increase ranging 30 cm (Figure 25). The general lack of change to the deep water wave climate across the deeper fjordal settings of Puget Sound for 0.3, 0.6, and 0.91 m of SLR is not surprising. Unlike beaches of the east and Gulf coasts of the United States, most Puget Sound shorelines lack low-gradient shelves and are comprised of deep U-shaped troughs. With 0.3 m of SLR on steep and narrow coastal settings, the footprint of the area impacted is smaller than what would be affected on a low-gradient slope. In Puget Sound, most of the area impacted by SLR will be constrained by the already steep slopes and prevalent bluff backed beaches. In these locations, much of the focus in hazard mitigation is on the influence that storms and waves will have on wave runup and TWL with SLR.

Model results in the embayments and waterways of southern Puget Sound and the area surrounding Port Angeles and Discovery Bay in the SJDF (Figure 2) showed the most change in deep water waves with SLR. Elsewhere, changes of 10 cm or less were estimated for all three SLR scenarios. Lacking a principal component of the wave climate (long period swell) in the LUT which will impact these predictions for locations in the SJDF, only the model results for
southern Puget Sound will be discussed in further detail. In southern Puget Sound, maximum deep water wave heights increased on average by 15 – 25 cm for the maximum SLR scenario of 0.91 m (Figure 26). Extreme fluctuations in fetch are common in these macrotidal areas where the tidal range is 3 – 4 m, potentially explaining the change predicted by the LUT. Higher sea levels effectively shift tidal ranges up the shoreline assuming that flow geometries and tidal propagation is unaffected. Shorelines accustomed to intermittent wetting and drying will see an increase in exposure to water and therefore waves. Relatively flat areas like the many large river deltas in Puget Sound should experience the largest change in wave heights with SLR as there will be an increase in both fetch and depth. The extent that depth limitation is modified by SLR remains uncertain and will depend on the efficiency that waves and currents control accommodation space for sedimentation fed by fluvial and/or littoral sources.

Skagit Bay sits at the terminus of the Skagit River on the eastern side of Whidbey Island and is one of the highest suppliers of sediment and freshwater to Puget Sound, providing 40% and 35% respectively (Czuba et al., 2011). The low angle, expansive tidal flat of the Skagit delta significantly reduces fetch in Skagit bay at low tide and with slow and steady SLR, this area is expected to be underwater for a higher percentage of time. The macrotidal nature of Puget Sound may buffer upper shorelines and the back beach from wave energy as only storms during high tide impact flooding and coastal erosion higher up the beach. Mobility of sediment and morphologic change during a storm at low tide is important for addressing ecosystem and habitat restoration, but coastal hazards to humans and infrastructure are minimized during a low tide.

Across Skagit Bay under 0.3 m of SLR, minimal change (5 cm or less) was predicted for the annual maximum wave height in deep water (Figure 26). With 0.91m of SLR, a bay wide increase of 10-20 cm in the annual maximum wave height was estimated with ~20 cm of
increase predicted near the shoreline and on the tide flat (Figure 26). One thing to note is the model resolution in SWAN at Skagit Bay is too coarse along the coast (~100 m resolution) to resolve the local levees (~3 m width) that restrict flooding and waves and likely provided over-estimates wave heights at these locations. A basin specific model with a higher grid resolution (25-50 m), implementing modeling techniques such as thin dams to represent levees and an accurate digital elevation model are needed to model this area and predict change with SLR. Overall, the amount of change in wave height for locations like Skagit Bay will depend on climate controls of sediment flux to these areas and the resulting extent of sedimentation promoting transgression or regression of the shoreline as my predictions operated under the assumption of a static bed morphology.

4.8 Parameterized Runup Modeling & Coastal Hazards

Fine scale parameterized runup models along Ruston Way characterized recurrence intervals for TWL elevations and projected changes in the frequency of the high TWL events for Ruston Way under two SLR scenarios. To accurately model wave runup across the region, site-specific characterizations of bed roughness and beach slope are required to capture the local features influencing runup as sensitivity tests showed wide ranges dependent on slope and roughness (roughness increased runup by as much as 81% and slope as high as 97%). I performed a site specific risk assessment of coastal hazards for Ruston Way and explored how wave runup and TWL will be affected by SLR, storms and waves, to inform adaptation planning for the City of Tacoma. Historical and potential future wave runup, TWL, and flood risk were modeled and two flood regimes governed by wind direction and atmospheric pressure change
were found to be important. Large NTR co-occurring with small waves (10-20 cm) was identified in the TAW runup model as an impactful storm type for Ruston Way while the other regime was characterized by large waves (50 cm or larger) occurring with little or even a negative NTR (high atmospheric pressure that periodically depress the sea surface height; Figure 27). Under the second storm type, flooding was predicted due to the contributions of large waves and effects of northerly winds (wind stress and setup) despite lower still water level associated with higher pressure.

Ruston Way is oriented north/northeast (Figure 30) and will be relatively protected from events representative of the first flood regime. Anecdotal evidence from collaborative partners in Tacoma suggested SWL flooding (regime 1) has occurred historically but is less impactful for coastal erosion. Concerns for this scenario encompass high water hazards restricting access to Ruston Way and salt water fouling of infrastructure. The TAW runup model predicted high TWL less frequently during events with waves exceeding 50 cm and storm surge ranging from -20 cm to 5 cm (regime 2; Figure 27). Yet these storms are a primary concern for groups in Tacoma working to protect investments and infrastructure along Ruston Way as these events are already eroding and impacting Ruston’s shoreline (Figure 32). My results suggested an increase in the frequency of TWL elevations exceeding 4.0 m NAVD88 (the approximate average elevation of the FEMA 100-yr BFE along Ruston Way) for the SLR scenario of 0.4 m and 0.85 m (Figure 29), especially for storm regime 2. Planning for SLR along Ruston Way will benefit from addressing the projected increase in frequency of flooding and wave impacts associated with both flood regimes as well as hydrodynamic models that include local topography in flood predictions.
4.9 XBeach Wave Runup Modeling

To address flood and wave hazards at a high detail and demonstrate the entire CoSMoS modeling train, wave transformation, wave breaking, and wave runup were modeled for a 10-yr storm (regime 2) in XBeach and runup and total water level extent were mapped along Ruston Way, Tacoma, WA. XBeach model output showed impactful changes to the amount of landward inundation from a 10-yr storm event under the two SLR scenarios of 0.4 and 0.85 meters (the 50% scenarios) by 2070 and 2100 provided by Miller et al. (2018). On average, under 0.4 meters of SLR, XBeach predicted 2.6 m more of landward inundation for the 10-yr storm compared to current estimates and the maximum extent of flooding for this scenario was found to be 27 m farther inland. For a SLR scenario of 0.85 meters, the average amount of inundation increased to 5.9 m more than current levels and the maximum inundation increased to 82 m (Figure 30). Across Ruston Way, 23% of the runup model transects predicted wave runup from the 10-yr storm to exceed the 100-yr BFE for contemporary sea levels. With 0.4 meters of SLR, 31% of the modeled locations predicted exceedance and 51% were predicted to surpass the 100-yr BFE with 0.85 meters of SLR for the 10-yr storm (Figure 31). These results indicate that the FEMA 100-yr BFE may be biased low for a number of locations along Ruston Way as XBeach is predicting exceedance of the BFE under current sea levels during a 10-yr storm.

The area that showed the highest amount of exceedance of the 100-yr BFE, specifically for contemporary sea levels, was the northern tip of Ruston Way (Figure 31) at a location called Owen Beach. Here the shoreline is low-sloping and more natural, lacking the extensive shoreline armoring found on Ruston Way (Figure 12). Towards the middle of Ruston Way where the coast is armored with riprap, no XBeach transects predicted wave runup to exceed the
100-yr BFE under all sea level scenarios, indicating a lower risk of vulnerability to waves and high water. Farther south along Ruston Way, the Alder Way intersection was predicted by XBeach to have the highest amount of landward inundation with exceedance of the 100-yr BFE predicted for contemporary sea levels (subset map in Figure 30).

The Alder Way intersection was identified as an area of concern by collaborators in Tacoma, specifically for flood hazards from Puget Creek. Puget Creek is a small creek (Figure 30) which was engineered to be redirected underground, flowing beneath Ruston Way, and daylighting and draining into the Sound just beyond the Alder Way Intersection. Flow restrictions and flooding of Puget Creek are a major concern with SLR and climate change for the city. During a site visit to the Alder Way intersection in March of 2019, wave scouring of the back beach was observed (Figure 32) validating the XBeach model results that contemporary storms are already eroding this location. Although quantitative wave data immediately offshore during specific wave events is lacking, the observed erosion suggests that higher sea levels will allow greater wave energy to impact the upper foreshore more frequently and add to wave scour and erosion, similar to impacts shown in Figure 32.

While previous studies (McCall et al., 2014; Roelvink et al., 2009) have tested and validated XBeach for modeling storm impacts and current work is being done by graduate students at Western Washington University studying runup attenuation on mixed sediment beaches, validation datasets would benefit vulnerability assessments and provide error statistics of XBeach projections for flooding along these Tacoma shorelines. Lacking validation, I performed sensitivity tests for maximum wave runup on an idealized shoreline and varied the
slope from 0.1 to 0.3 and the roughness from 0.55 to 1.0. These tests showed average increases of 81% between the highest and lowest representative roughness values for the parameterized model TAW. Validation of wave runup would help constrain appropriate roughness parameters native to XBeach and test newer digital elevation models currently being built by the USGS Coastal National Elevation Database. Recent efforts by the USGS to map Ruston Way with unmanned aerial vehicle photogrammetry will help quantify roughness for this purpose, improving models that can be instructive for assessing risk. Fortunately, new and cost effective remote sensing techniques are already being used in the Puget Sound to measure wave runup and could be deployed along Ruston Way.

The City of Tacoma, like many coastal communities is expected to experience increasing challenges mitigating and adapting to SLR along Ruston Way. At the forefront of their concerns is the flooding potential along Alder Way. While this project only addressed flooding from the coast, it will be important to incorporate climate projections for changes to rainfall as any difference in the amount of discharge through Puget Creek will play a major role in controlling or exacerbating flooding for this area. Engineering options such as tide gates, pumps, or structures can be used to mitigate this issue, however, the lifespan and cost (environmental and fiscal) of each solution will need to be considered. Fortunately, the City of Tacoma is taking an active role and already formulating plans to address these difficulties. Through community involvement in rethinking the design of the waterfront to participating in the WCRP, they are taking the proper steps to ensure resilience under a changing coastal climate.
4.10 Future Outlook on Wave Studies for Puget Sound

Additional wave observations, over-water wind measurements, and higher-resolution
wind predictions based on dynamic modeling, and model advancements will improve future
wave modeling predictions. Ongoing efforts by the USGS to deploy wave gauges in locations
across a gradient in exposure to winds (fetch) and waves such as Bellingham Bay, Skagit Bay
and Whidbey Island will provide important datasets to validate models including the LUT
approach described here. However, these datasets do not overlap with the timeframe of the LUT
(1950-2010). With advances in GCMs, climate reanalysis products, and computational
resources, the availability of higher resolution wind products for use with the LUT will increase,
leveraging the prospect of finer scale wind fields for more recent periods in history. Until then,
evaluating the skill of the LUT in Puget Sound relies on error statistics from Hein Bank, Halibut
Bank, and Sentry Shoal (Figure 2).

5.0 Conclusion

Change in the Earth's climate system over the past century and into the next is predicted
to increasingly affect coastal processes and accelerate into the future. Climate induced
variability in ocean circulation patterns, polar ice sheet coverage, and changes in the frequency
of extreme weather events will create costly problems and impact resources necessary for
ecological and anthropogenic functions. In Washington State, the effect of sea level rise is
projected to increase flood hazards on the coast and lead to high mitigation costs, impacts to
ecosystems, etc., and this study examined the potential behavior of storms and waves to better
evaluate the total threat from interactions of SLR with winds and waves. These complex and
dynamic interactions are difficult to forecast and regions like the Puget Sound will benefit from models like CoSMoS aimed at predicting hazards from coastal processes with climate change. A more thorough understanding of how changes to storms, waves, and water levels will impact infrastructure, sediment loads, and coastal hazards has been noted as important for resilience planning as the Puget Sound region continues to grow and expand.

My work produced the first regional wave hindcast for the period 1950-2010 which characterized the 60-yr historic wave climatology within the Salish Sea. The regional wave hindcast based on the 1950-2010 WRF climate reanalysis helps define the historic wave climate with metrics including wave heights in the context of return frequency, and the exposure of shorelines to various thresholds of wave heights (e.g., maximum, annual maximum, >0.5m, etc.) providing statistics about the wave regime at a resolution relevant for planners and managers. In Puget Sound, shorelines oriented south had hundreds of more hours each year with waves exceeding 0.5 m, a result of the prevailing southerly winds. Analyses of meteorological conditions through 2100 provided by the MACA statistically downscaled NOAA GFDL-ESM2M GCM for Washington State indicated slight temporal variations in wind speed between 2050 and 2080 but a relatively little difference from historic in the year 2100. Because of this insignificant difference, extremes from the historic wave climate based on the 1950-2010 WRF climate reanalysis were used with future sea level positions to forecast change in flooding and wave impacts. Simulating the historic 60-yr wave regime with future SLR, showed increases in deep water wave heights of 30 cm or less with 0.91 m of SLR. Locations of depth limitation (e.g., large tidal flats) indicated the most change in wave height with SLR will occur where increases in fetch and depth will support wave growth. Accurately quantifying coastal bed
morphology and how these settings will respond to changes in water level and wave energy will therefore be important.

Regional wave model output provided the boundary conditions for high resolution wave runup modeling, which demonstrated that total water level can vary up to 2.5 m due to differences in slope and roughness. Higher resolution coverage of intertidal elevations and morphology will therefore benefit vulnerability assessments of Puget Sound beaches. Finer and regional scale runup modeling revealed the influence of shoreline orientation on coastal hazards where south facing shorelines experienced a higher threat and occurrence from large waves and storm surge while shorelines oriented north were more sensitive to extreme total water level events influenced by waves and wind stresses. Along Ruston Way, fine scale runup modeling projected an increase in extent and frequency of low to moderate storms, like the 10-yr flood, exceeding FEMA's 100-yr BFE with ~51% of the area exceeded with ~0.9 m of SLR. For Puget Sound to increase its ability in evaluating coastal hazards and impacts, validation datasets are needed (wave and wave runup) with a regional characterization and mapping of the intertidal zone to define bed roughness and fill in crucial data gaps limiting runup model skill.
6.0 References


LeRoy, S., and Wiles, R., 2019, High Tide Tax, The Price to Protect Coastal Communities from Rising Seas: The Center for Climate Integrity Resilient Analytics.


7.0 Tables

<table>
<thead>
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Table 1. Look-up-table derived wave height results from native and biased corrected Weather Research and Forecasting model data from 1950-2010 at a location of deep water near Seattle.
Table 2. Error statistics between observed and modeled wave heights at the three wave buoys in the Salish Sea.

<table>
<thead>
<tr>
<th>Buoy Name</th>
<th>Root Mean Square Error [meters]</th>
<th>Bias [meters]</th>
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<tbody>
<tr>
<td>Hein Bank</td>
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<td>0.12</td>
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<tr>
<td>Halibut Bank</td>
<td>0.40</td>
<td>0.09</td>
</tr>
<tr>
<td>Sentry Shoal</td>
<td>0.50</td>
<td>0.18</td>
</tr>
</tbody>
</table>
8.0 Figures

Figure 1. Map of the Salish Sea showing nested wave model coverage (light and dark blue) and National Oceanic and Atmospheric Administration tide gauges.
Figure 2. Complimentary regional map depicting points of interest, the spatial extent of the Puget Sound within the Salish Sea, and names of the basins which comprise Puget Sound.
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Figure 18. Wave rose diagrams showing the deep water wave climatology for the period 1950-2010 in the United States waters of the Salish Sea.
Figure 19. Regional wave model output of the average maximum wind–wave height per year from the 60-yr record along the -10 m NAVD88 depth contour. Areas with the gray spatial mask are likely to experience long period open ocean swell.
Figure 20. Wave model output highlighting the average number of hours per year that significant wave heights were predicted to exceed half a meter for Hood Canal during the period 1950-2010.
Figure 21. Wave model output highlighting the average number of hours per year that significant wave heights were predicted to exceed half a meter for southern Puget Sound during the period 1950-2010.
Figure 22. Wave model output showing the average number of hours per year that significant wave heights were predicted to exceed half a meter for south central Puget Sound during the period 1950-2010.
Figure 23. Wave model output highlighting the average number of hours per year that significant wave heights were predicted to exceed half a meter for northern Puget Sound during the period 1950-2010.
Figure 24. Wave model output highlighting the average number of hours per year that significant wave heights were predicted to exceed half a meter for the Strait of Juan de Fuca during the period 1950-2010.
Figure 25. Predicted change to the average annual maximum deep water wave heights for 0.3, 0.6, and 0.91 meters of sea level rise in the Salish Sea.
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Figure 27. Parameterized runup model output for a transect in the middle of Ruston Way. Each circle represents a time step from the runup model where warmer colors represent higher total water level.
Figure 28. Estimated runup on uniform slopes (0.2) with uniform roughness (0.85) across all of the Salish Sea from the parameterized runup model.
Figure 29. Parameterized runup model output for contemporary sea levels and sea level rise scenarios of 0.4 and 0.85 meters at one transect along Ruston Way, showing a higher occurrence of TWL exceeding 4.0 m NAVD88 by 2100.
Figure 30. Site map of Ruston Way displaying spatial coverage of the high resolution wave runup model transects. Sample output from XBeach at the Alder Way intersection in the lower left subset map shows the maximum wave runup for the 10-yr storm modeled for the two sea level rise scenarios of 0.4 and 0.85 meters compared with the Federal Emergency Management Agency 100-yr base flood elevation (black line).
Figure 31. XBeach model transects colored by predicted wave runup exceeding the Federal Emergency Management Agency 100-yr base flood elevation for contemporary (tan), 0.4 m (orange) and 0.85 m (red) sea level scenarios. Exceedance under contemporary levels implies continued exceedance for the two sea level rise scenarios.
Figure 32. Wave scouring on the top of the armored berm at the Alder Way intersection of Ruston Way, Tacoma, Washington.
9.0 Appendix A

Equations

*Spectral Action Balance Equation*

\[
\frac{\partial N}{\partial t} + \frac{\partial cxN}{\partial x} + \frac{\partial cyN}{\partial y} + \frac{\partial c\sigma N}{\partial \sigma} + \frac{\partial c\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma}
\]  

(1)

where:

\[
\frac{\partial N}{\partial t} = \text{Rate of change of Action Balance [units/time]}
\]

\[
\frac{\partial cxN}{\partial x} = \text{Rate of change for geographic space (x) [units/time]}
\]

\[
\frac{\partial cyN}{\partial x} = \text{Rate of change for geographic space (y) [units/time]}
\]

\[
\frac{\partial c\sigma N}{\partial \sigma} = \text{Rate of change in frequency [units/time]}
\]

\[
\frac{\partial c\theta N}{\partial \theta} = \text{Rate of change in direction [degrees/time]}
\]

\[
\frac{S_{tot}}{\sigma} = \text{Sources and sink of energy affecting wave growth, dissipation, and transformation}
\]

*TAW (Meer, 2002) equation for calculating the 2% wave runup elevation for a breaker parameter less than 1.8:*

\[
R_{2\%} = 1.65 \ast H_{mo} \ast \gamma_{b} \ast \gamma_{f} \ast \gamma_{\beta} \ast \xi_{O}
\]  

(2a)

and a breaker parameter exceeding 1.8

\[
R_{2\%} = H_{mo} \ast \gamma_{f} \ast \gamma_{\beta} \ast (4.0 - 1.5/\sqrt{\xi_{O}})
\]  

(2a)

where:
\[ R_{2\%} = 2 \% \text{ wave runup elevation above the water level offshore [m]} \]

\[ H_{\text{mo}} = \text{Significant wave height at the toe of dike [m]} \]

\[ \gamma_b = \text{Influence factor of offshore berm [dimensionless]} \]

\[ \gamma_f = \text{Influence factor of roughness of slope [dimensionless]} \]

\[ \gamma_\beta = \text{Influence factor of wave angle [dimensionless]} \]

\[ \xi_0 = \text{Breaker Parameter [dimensionless]} \]

Breaker parameter:

\[
\xi_0 = \frac{\tan \alpha}{\sqrt{H/L_0}}
\]  

where:

\( \alpha \) = Beach slope [degrees]

\( H \) = Wave height [m]

\( L_0 \) = Wave length [m]

Wave length:

\[
L_0 = \frac{g}{2\pi} T^2
\]  

where:

\( g \) = Acceleration of gravity [m/s\(^2\)]

\( T \) = Wave Period [seconds]

\textit{Calculation of dynamic water level at the toe of engineered structure (Allan et al., 2015)}:

\[
\text{DWL}_{2\%} = \text{SWL} + 1.1 \times \left( \eta_a + \frac{\eta_b}{2} \right) - D_{\text{low}}
\]  

where:
SWL = offshore tide level

\[ \eta_a = 0.35 \times \tan \beta \sqrt{H_s \times L} \]

\[ \eta_b = 0.06 \times \sqrt{H_s \times L} \]

\[ H_s = \text{Significant wave height [m]} \]

\[ L = \text{Wave length [m]} \]

\[ \beta = \text{Beach slope [degrees]} \]

\[
\text{Relationship between peak period and spectral period described in Meer (2002):}
\]

\[ T_p = 1.1 \times (T_{m-1.0}) \quad (6) \]

\[ T_p = \text{Peak period [seconds]} \]

\[ T_{m-1.0} = \text{Spectral period [seconds]} \]

\[
\text{Shoaling of waves in shallow water following Dean & Dalrymple (2004):}
\]

\[ H_{toe} = H_o \times K_s \quad (7) \]

where:

\[ H_{toe} = \text{Wave height at toe of structure [m]} \]

\[ H_o = \text{Deep water wave height [m]} \]

\[ K_s = \frac{C_{go}}{\sqrt{C_g}} = \text{Shaoling coefficient [dimensionless]} \quad (8) \]

\[ C_{go} = \text{Deep water wave group velocity} \left(\frac{L}{T}\right) \]

\[ C_g = \text{Shallow water wave group velocity} \left(\frac{L}{T}\right) \]
Acronyms

ECDF = Empirical Cumulative Distribution Function
ESM = Earth Systems Model
GCM = Global Climate Model
GFDL = Geophysical Fluid Dynamics Laboratory
NAVD88 = North American Vertical Datum of 1988
NCAR = National Center for Atmospheric Research
NCEP = National Centers for Environmental Prediction
NOAA = National Oceanic and Atmospheric Administration
OET = Open Earth Tools Matlab Toolbox
PDF = Probability Density Function
RMSE = Root Mean Square Error
SWL = Still Water Level
SGA = Strait of Georgia
SJDF = Strait of Juan de Fuca
SLR = Sea Level Rise
SWAN = Simulating Waves Near Shore
TAW = Technical Advisory on Waves
TWL = Total Water Level
USGS = United States Geological Survey
VLM = Vertical Land Movement
WA = Washington State
WCRP = Washington Coastal Resilience Project
WRF = Weather Research and Forecasting
Terminology

**Base Flood Elevation:** The TWL elevation on the coast that has a 1% chance of being exceeded in any given year (100-yr return frequency) commonly used to designate flood zones by the Federal Emergency Management Agency.

**Fetch:** The distance and area of water that wind blows over when generating waves.

**Isostatic Rebound:** Dynamic response in the elevation of the Earth’s crust to the loss of ice mass.

**Iribarren Number:** Dimensionless parameter composed of wave height, wave length, and beach slope used to describe the type of breaking waves (spilling, plunging, or surging) on a beach.

**Non-tidal Residual (NTR):** The component remaining after the removal of astronomical tides from observations of sea surface elevations resulting from influences of winds, waves, water density structure, seasonal climate variability and predominantly, atmospheric pressure variations often called storm surge.

**Peak Period:** The period of a wave (time that it takes to complete one wave cycle – crest to crest) in the recorded energy derived from spectral analysis.

**Puget Sound:** Large coastal estuary comprised of complex networks of interconnected waterways under United States control, spanning south from Bellingham with connection to the Pacific Ocean in the Strait of Juan de Fuca.

**Shoaling:** The change in wave height as surface waves enter shallow water and the wave group velocity is reduced.

**Salish Sea:** Large inland sea shared by the United States and Canada comprised of Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia.

**Storm Surge:** The response by a body of water to changes in atmospheric pressure variations also called the inverse barometer effect where a 1 mb fluctuation in pressure warrants a 1
cm change in sea surface elevation. The magnitude of the response is controlled by the density structure of the water and with Puget Sound being a large estuarine environment, changes exceeding 1 cm are not uncommon.

**Significant Wave Height:** The average wave height of the top 33% from a distribution of wave measurements.

**Thin Dam:** A sub-grid obstacle that can be added to a SWAN wave model which restricts the propagation of waves from one grid point to the next.

**Total Water Level (TWL):** The final elevation of the surface of the water commonly recorded at the shoreline, composed of astronomic tides, non-tidal residual, and influences of waves.

**Wave Bore:** Simplification of a shallow water wave by assuming uniform velocities and hydrostatic pressure throughout the water column. Using a wave bore simplifies modeling the total dissipation of a wave due to depth-induced breaking, a process that is poorly understood.

**Wave Runup:** The uprush of water from a breaking wave on a beach or coastal structure.

**Wave Setup:** Increase in the elevation of the sea surface due to the presence of breaking waves.

**Wind Setup:** Increase in the elevation of the sea surface due to wind stresses on a body of water.

**2% Wave Runup Elevation:** Elevation of the TWL that 2% of the observed wave runup will reach or exceed commonly used to assess flooding risks with waves.