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

Thesis Proposal for the Masters of Science Degree
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June, 2017

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1. **Problem Statement**
   The Salish Sea provides habitat to valued shellfish populations, endangered salmon species, and large municipalities such as Tacoma, Seattle and Vancouver, BC. It is anticipated that by the years 2070 to 2099, sea levels will rise in the Salish Sea one to four feet (NAS, 2012). Yet, a lack of knowledge exists surrounding the combined influence and impacts of expected changes in storm surge, waves, and related nearshore processes from climate change and sea level rise (SLR), especially in protected embayments and estuaries. In order to ensure regional sustainability, an increased understanding of how the coastline and waterways of Puget Sound will respond to these changes is necessary. As a first step towards accomplishing this, my research project will perform an assessment on the extent that coastal storms and wave impacts within Puget Sound will change with SLR. I propose to implement hydrodynamic modeling to assess spatial and temporal changes in wave amplitude and energy and evaluate the potential impacts to shoreline environments across Puget Sound. In order to gauge variations in future wave energy, I will use the hydrodynamic modeling software Delft 3D/XBeach to examine wave generation and propagation throughout the Salish Sea (Figure 1). I will also characterize historical variability of weather data, extreme events, and the spatial variability in wave energy along shorelines today with the ultimate goal of assessing how storm and wave impacts will vary under different SLR scenarios in the future. Outcomes from my research will inform decision makers in mitigating undesired effects of a changing coastal environment.

2. **Introduction**
   Within the Salish Sea, anticipated SLR of one to four feet by 2100 poses a serious threat to coastal lands, ecosystems for salmon and shellfish, nationally important agriculture, and industry and infrastructure crucial to human well-being (NAS, 2012). Assessments around the open-ocean coasts of the US suggest that nearshore wave energy will increase exponentially as sea levels rise. This will result in today’s 100-year coastal storm becoming a 10-yr event with one foot of sea level rise and a 1-yr event with two feet of sea level rise (Tebaldi et al, 2012). As ocean levels steadily increase, coastlines are expected to migrate landward in response to higher wave energy interacting with the shoreline. This amplified wave energy will create costly problems such as an increase in coastal erosion, wetland loss, flooding, and saltwater intrusion into freshwater aquifers (Ranasinghe et al., 2012). The influence of changing fluvial processes and sediment dynamics are less certain but are likely to compound the complexity of forecasting future coastal adjustment.

   The Puget Sound portion of the Salish Sea has more than 8,000 square kilometers of marine waters and 4,020 kilometers of shoreline that are susceptible to wave generated impacts (NAS, 2012). Therefore, the need to accurately model and assess changes in wave energy is critical to improving and planning for the safety and sustainability of coastal communities. In addition, significant investments in ecosystem restoration are being made to recover salmon, shellfish and diverse valued ecosystem components (Puget Sound Partnership, Action Agenda - http://www.psp.wa.gov/action_agenda_center.php). Evaluating their resilience and potential benefits to reducing impacts associated with coastal flooding hazards are important to prioritizing efforts, enhancing success, and are being mandated as part of the EPA National Estuary Program funding for recovery.
In Puget Sound, a few studies (FEMA; FEMA, 2004; FEMA, 2015; Finlayson, 2006) addressing wave energy and flood risks have attempted to model and understand impacts for various counties and sites of interest. While these studies provide the context necessary for designating coastal flood zones and assessing impacts on a site specific basis, they lack a temporal component; Puget Sound has yet to have a systematic evaluation of the temporal and spatial variability in wave energy today and how it will change in the future. I am proposing to perform this level of assessment as part of the NOAA Regional Resiliency Grant titled Washington Coastal Resilience Project. The Washington Coastal Resilience Project 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 coastal climate. My work will address two main goals of this grant: 1) improve the understanding of coastal hazards stemming from storm surge and waves, 2) enhance resiliency in coastal communities through pilot studies.

To accomplish these goals and develop tools needed by policy makers (Brown et al., 2016), I propose to use the open source modeling software Delft 3D to simulate wave generation and impacts for the range of extreme conditions observed historically in conjunction with future SLR projections across Puget Sound. Model simulations will include forcing by tides, sea-level rise, storm surge (inverse barometer effect) and storm winds to predict the temporal and spatial variability of total water levels, wave heights and wave energy approaching the shore. Across the region, I plan to conduct a few case studies to examine likely impacts at spatial scales important to addressing planning and adaptation. These results will be used to identify areas across Puget Sound that will be susceptible to flooding and wave impacts for various storm regimes (e.g., 1 year, 10 year, etc), characterize the extent, magnitude and frequency that flooding will change relative to current conditions, and inform decision makers where protection and restoration efforts may be more resilient. Throughout the following sections, I will provide important information regarding climate change, climate predictions for the Pacific Northwest, previous work, and the modeling tools I propose to accomplish my research goal.

3. Background

3.1 Projections of Pacific Northwest Climate Change

Earth’s Climate System

As atmospheric concentrations of greenhouse gases (CO₂, CH₄, water vapor, etc.) increase, the amount of outgoing radiation from the Earth is affected. These long wave absorbers limit radiation traveling in to space which increases the temperature of the Earth (greenhouse effect; Vardavas et al., 2011). General Circulation Models (GCMs) provide a way for assessing this transfer of energy between the Earth and the Sun such that they simulate, with some uncertainty, the processes (Sun, atmosphere, hydrosphere, biosphere, and cryosphere) that govern the Earth’s radiative energy budget (Kiehl & Trenberth, 1997 & Vardavas et al., 2011).

While improvements to climate models will increase accuracy, current models show the effects that forcings, such as greenhouse gases, have on the radiative energy budget of the Earth. Current models, specifically the NASA Goddard Institute for Space Studies (GISS) model used by Hansen (2005), show that the Earth is experiencing a radiative imbalance where it is absorbing more energy than is being emitted to space. Ocean temperature data spanning from
1955 – 1998 shows an average increase of 10 W year/m² for the oceans heat content indicating that oceans are acting as a sink for the excess energy (Hansen, 2005). As the oceans absorb more energy and temperatures increase, sea levels will rise due to the thermal expansion of water and inputs of freshwater from melting ice sheets (Petersen et al., 2015).

Globally, the oceans influence weather patterns through the circulation and distribution of heat. As global temperatures increase, weather systems have the potential to change which influence observed wind and precipitation patterns (Kug et al., 2006). Over the United States, wind speeds on average have shown a negative trend (Pryor et al., 2009). While in the Pacific Northwest, namely the Strait of Georgia (the largest basin in the Northern Salish Sea), analysis of buoy data has indicated that wind speeds are increasing between 0.019 and 0.093 m s⁻¹ per year (Gower, 2002). While these increasing trends are derived from data spanning roughly seven years, it hints at the regional variability of winds in the Salish Sea. In fact, Seymour (2011) found that, “The regional wave climates of the entire West Coast respond as a system to particular combinations of atmospheric pressure in the Gulf of Alaska and position in the ENSO cycle.” As freshwater inputs and thermal expansion to the Salish Sea drive SLR, and changing weather patterns influence variability in winds, the wave climate of Puget Sound will be affected.

Finlayson (2006) has found that large storm events play the biggest role in shaping Puget Sound beaches. The many diverse topographic features limit wind/wave energy such that beaches within the region have predominately been characterized as a low energy environment. However, regional storms have the ability to generate anomalous high energy conditions, capable of mobilizing coarser sediment and larger clasts which change the morphology of the beach face (Finlayson, 2006). Stronger and variable wind forcings (Gower, 2002) coupled with higher sea levels allows waves to increase in magnitude and reach distances closer to shore before shoaling and breaking. This imparts a more frequent and larger shear force on the beach face and has the ability to change the low energy environment.

Climate of Pacific Northwest

Washington State is home to many unique climate zones spanning from coastal rain forests to glaciated mountains within the Cascade Range. Variation in precipitation exists between physiographic providences and undergoes seasonal variation. Outside of this, yearly cycles driven by processes such as the El Niño-Southern Oscillation (ENSO), controlled by the Pacific Decadal Oscillation (PDO) greatly effect precipitation and weather. The diverse geologic features of Washington combined with yearly climate variability, influence weather systems both temporally and spatially such that they define the climate of the state (Salathé et al., 2010).

Global climate models, as previously discussed above, simulate the climate over large areas. These models tend to lack the spatial acuity needed to capture many of the mesoscale processes (orographic impacts on precipitation for example) which govern the climate of a region. Specific to Washington State, these mesoscale processes heavily influence local and regional climates, placing a need for more accurate models (Salathé et al., 2010). Because of this, regional climate models are employed to provide finer spatial resolution over specified areas. Higher resolution allows regional models to, “simulate the interactions between large-scale weather patterns and local terrain features not resolved by global models.” (Salathe et al., 2010). One commonly used regional climate model is the Weather Research and Forecasting model developed by the National Center for Atmospheric Research. A comparison of regional
and global climate models along with an analysis of historic and current meteorological data shows a marked change in the climate of the Pacific Northwest (Salathe et al., 2010).

Temperatures in Washington State have shown an increase from 1895 to 2011 with an average value of 0.7 °C across the region. Predicted levels are expected to increase 1.9 °C to 5.4 °C for 2070 to 2099 relative to values from 1970 to 1999 dependent on greenhouse gas emissions (Mote et al., 2014). Under high emission scenarios, temperatures in 2050 will show an increase of 1.7 °C to 4.8 °C compared to 1950 – 1999 (Snover et al., 2013). These increasing temperatures have the ability to change freeze levels and natural snowmelt patterns which affects streamflow and sediment supply to rivers. Precipitation levels and sea level will also be affected, generating floods of greater magnitudes with a higher recurrence interval; as sea levels increase, flood waters will be unable to drain into the ocean (Mote et al., 2014 & Peterson et al., 2015).

**Sea Level Rise**

Global sea level is increasing due to the thermal expansion of the oceans and the melting of polar ice caps and mountain glaciers. Across the globe, the effect of SLR will be observed differently depending on regional factors like wind, atmospheric pressure, distribution of water, and tectonic activity. In the Pacific Northwest, many factors play a role in observed SLR and can cause significant variation over short distances. Specifically, atmospheric circulation, tectonic uplift and isostatic rebound from recent glaciation play a big role in the observed variation of SLR (Peterson et al., 2015).

Understanding how SLR will compound hazards and facilitate deviations in the frequency and magnitude of extreme events is crucial (Jevrejeva et al., 2014). One major hazard for coastal communities is flooding, where anomalous high water levels penetrate the backshore and lack the capacity to drain flood and ponded waters, especially across unconfined coastal aquifers. While coastal environments are adept at dealing with daily fluctuations in sea level driven by tides, the co-occurrence of storms with high tides can produce devastating effects (Zervas, 2005).

Major storms characteristically produce high wind speeds and low atmospheric pressure which has the ability to raise sea levels beyond tidal levels (storm surge; McInnes et al., 2002). Storm surge is the product of falling atmospheric pressure and wind stresses on the water which cause a rise in sea level. For every millibar decrease in atmospheric pressure, there is approximately a 1cm increase in sea level; this is commonly known as the inverse barometer effect. Wind stresses have the ability, given enough fetch, to generate waves, currents and set-up of the water surface. As currents approach the coast or encounter a barrier, water and waves will begin to stack up and further elevate sea levels (wave set-up; McInnes et al., 2002). When these process occur together, they can create intense flooding events (e.g., 100-year flood) amplifying the damages to coastal environments (Zervas, 2005).

**3.2 Wind-Generated Waves**

As wind passes over a body of water, frictional forces between the air and the water result in a shear stress on the fluid and a transfer of energy. The combined interaction of wind and pressure variations with a body of water facilitates the formation of waves. Phillips (1957, 1960) developed a resonance model which describes how turbulent eddies in wind fields induce pressure variations on the surface of the water. These differences in pressure result in the formation of surface undulations which grow throughout time. While the resonance model
explains the initial formation of waves, Miles (1957) developed a shear flow model to simulate the continued growth of waves. As wind passes over waves, “a complex air flow pattern develops over the wave,” (Sorensen, 1997) which creates secondary air circulation in the direction of the moving wave. This circulation ultimately results in air flow in the vertical direction which allows the wave to increase in size—size also increases with fetch and wind velocity (Sorensen, 1997).

Wind speeds in the Pacific Northwest display spatial variation in both average and extreme values depending on their location relative to the coast, season, and yearly cycle (ENSO for example). Coastal wind speeds are found to be much higher than those further inland due to roughness over land from biologic, orographic and anthropogenic features (Griffin et al., 2010). Over the past 60 years, there has been a noticeable increase in both the magnitude and frequency of storms in the North Pacific (Bromirski et al., 2003). Open ocean buoy data show an increase in significant wave heights of around 0.015 m/year since the 1970s (Ruggiero et al., 2010).

Some of this wave and wind energy enters the Strait of Juan de Fuca and influences wave impacts in Puget Sound (Figure 1). Further analysis of buoy data has shown an association between deep-water wave heights and the frequency of extreme storm events where a 2.7-meter increase was noted from 1975 – 2000 along the outer coast of Washington (Allan & Komar, 2006). On a global scale, Young et al. (2011) analyzed 2°x2° grids of satellite records of average monthly wind speed and associated wave heights from 1990 – 2010. This study found that the 90th and 99th percentile values of wind speed displayed a positive correlation with increased wave heights, especially at higher latitudes and during storm events.

Using GCMs, researchers are able to model wind-generated waves under future atmospheric conditions. GCMs extending into the mid – late 21st century under RCP 4.5 and RCP 8.5 scenarios show that wind speeds would increase at both the northern and southern regions along the east Pacific, with average wave periods increasing by 1 – 2 seconds (Erikson et al, 2015). Around 50° N latitude and greater, wave heights under extreme conditions are expected to continue increasing resulting in an amplified threat of flooding and coastal erosion under future conditions (Erikson et al., 2015).

While SLR alone poses a real threat to global coast lines, there has been a noted, stronger correlation of total water levels with climate driven hazards. Utilizing total water level models, Ruggiero (2001) found that increases in both the magnitude and period of deep-water waves is more significant for coastal flooding and erosion than SLR (Ruggiero et al., 2001 & Ruggiero et al., 2010b & Ruggiero, 2013). These studies emphasize the need for a dynamic approach to coastal modeling, incorporating different factors such as storm surge, wave set-up, wave run-up, tides, and sea level rise to accurately constrain total water levels at the shoreline.

3.3 Coastal Modeling

Computer modeling provides a useful tool for simulating the complex and non-linear interactions of physical processes that influence coastal morphology and aid in decision making (Brown et al., 2016). Delft 3D has been widely used to examine interactions of currents, waves and modifications of hydrology and sediment transport for coastal engineering and planning at a range of spatial and temporal scales. Delft 3D is a suite of open-source, numerical hydrodynamic and sediment transport algorithms that solves the physical interactions governing coastal processes and in particular shallow wave transformation physics. It can simulate hydrodynamics on both structured and unstructured grids, incorporate vegetation for coastal geomorphology, and depict areas that will experience variations in wetting and drying. For each
time step in Delft 3D, the physics and interactions between flow, waves, sediment transport, and the bottom are all calculated. This allows users to assess morphologic changes at the shore, and in turn, the dynamic influence of sediment accretion on subsequent flow and wave transformation.

In order to model wind-wave generation, Delft 3D incorporates SWAN (Simulating WAves Nearshore), a third generation wave model used to simulate the formation of surface waves. SWAN is able to handle both structured, unstructured, and nested grids when computing wave generation for coastal settings at various spatial scales. Results from SWAN models can then be coupled with other modules in Delft 3D such as Delft 3D-FLOW to better simulate the impact that waves and currents have on one another (Simulation, 2014).

In 2005, the United States Geological Survey (USGS) in collaboration with the United States Army Corps of Engineers (USACE) used Delft 3D for hydrodynamic modeling of the mouth of the Columbia River in Washington State. The study validated the use of Delft 3D as an accurate tool for realistically modeling coastal processes under a range of coastal settings (Elias et al., 2012). By the late 2000s, the USGS began the development of a coastal-hazard modeling project that grew into the Coastal Storm Modeling System (CoSMoS). The CoSMoS is a numerical modeling tool that uses Delft 3D, specifically the FLOW/WAVE and XBeach programs to predict coastal flooding. Regional models focusing on areas of interest, receive boundary conditions from global data sources (WaveWatch III, National Data Buoy Center, Coastal Data Information Program) which are then downscaled and used to determine total water levels at the shoreline. These total water levels are then projected onto high resolution digital elevation models at numerous cross-sections using the software XBeach for determining the extent to which water levels penetrate the back shore and affect the coastal morphology (Barnard et al., 2012).

### 3.4 Case Studies in Puget Sound

In Puget Sound, multiple studies have attempted to constrain SLR and the resulting total water levels at the shoreline. In 2008, one study performed an assessment of SLR estimates for 2050 and 2100 using values generated in the fourth report by the Intergovernmental Panel on Climate Change (Pachauri and Reisinger, 2007). From this report, SLR estimates range from 0.18 – 0.38 m for low emission scenarios and 0.26 – 0.59 m for high emission scenarios (Pachauri and Reisinger, 2007; Mote et al., 2008). When combining the high emission scenario with other factors such as melting polar ice caps, Mote et al., (2008) was able to develop a SLR estimates with a low probability of occurrence for Puget Sound that would have the greatest impact. In this high impact scenario, SLR of 0.55 m is expected by 2050 and 1.28 m by 2100 (Mote et al., 2008).

The most recent assessment of SLR was conducted by the National Research Council (NRC) as part of their 2012 study (NAS, 2012). In this study, the NRC incorporated vertical land motion and gravitational interactions between masses of ice and sea water (called the sea-level fingerprint) in estimates of total water levels. Within Washington State, the NRC estimates SLR to be 0.08 – 0.23 m by 2030, 0.18 - 0.48 m by 2050 and 0.50 – 1.40 m by 2100 with the state wide estimates showing the largest deviation from the global mean (NAS, 2012). Comparing estimates for SLR between various studies (Mote et al., 2008; Tebaldi et al., 2012; NAS, 2012) shows that while there is some overlap in estimates, discrepancy exists surrounding projected SLR estimates. In order to better evaluate TWL at the shoreline, a more dynamic model is needed. These studies represent a static “bathtub” approach that does not capture the full physics
and responses that influence the shoreline (Figure 3). In order to accurately address future conditions, more dynamic models incorporating waves are necessary.

Very little work has been done to assess the variability in wind-generated waves, their potential variability and future impacts in Puget Sound. Most wave studies examine open ocean coasts where large ocean waves are common and impacts are high. Finlayson (2006) assessed the geomorphology of Puget Sound beaches and calculated a single mean significant wave height for the region. Using specific conditions of a 40 km fetch with wind speeds of 25 m/s, Finlayson (2006) determined that a wave of 3.8 m with a period of 7.1 seconds is possible within Puget Sound (Figure 2). These values signify the largest possible wave given sustained wind speeds over open areas of water which is rather uncommon in Puget Sound. Numerous islands and complex networks of coastal waterways disrupt the propagation of winds and subsequent waves such that winds display variability both spatially and temporally (Finlayson, 2006). In order to accurately model wind-wave generation in Puget Sound, a thorough evaluation of the variability in wave energy and wave forcings is needed along with how these parameters may change in the future.

The Federal Emergency Management Agency (FEMA) has performed regional assessments of coastal hazards for flood insurance mapping. While the regional study spans the entire Pacific coast of the US, guidelines exist to adapt FEMA’s methods for specific coastal settings. These methodologies, leading to the creation of Flood Insurance Rate Maps (FIRM), are typically employed on a local and community level to assess impacts on a finer scale (FEMA, 2004). Within the state of Washington, Digital Flood Insurance Rate Maps have been generated for specific counties such as Jefferson, Whatcom, Skagit, and Island County. As part of these studies, FEMA modeled wave generation and flooding for the historical 100-yr coastal storm event using SWAN (Simulating WAves Nearshore) and ADCIRC (a series of computer programs that model fluid flow) for parameterized wind and water level conditions. Total water levels were then imposed on 1-D transects at specific locations designated by the counties to show locations where water will overtop the berm and map regions of potential flooding (FEMA, 2004).

When generating these maps, FEMA modeled specific processes independently, such as storm surge and wave run up to establish 1% water levels which ultimately mark zones of flooding (FEMA; FEMA, 2015; FEMA, 2004). This process differs from that of the CoSMoS modeling approach, which incorporates storm surge, wave set-up/run-up, tides and any seasonal effects with each calculation to better constrain total water level and the physics inherent in coastal storms inundating the coast. FIRM modeling provides a rough baseline for water levels from a 100-year coastal storm and its impacts, but does not address how wave energy will likely change with sea level rise and climate change.

4. Proposed Work

To advance assessments of future coastal climate change beyond static models, I propose to develop a physically based model that simulates the processes of storm surge, waves, wave set-up, and run-up. These process models will allow me to perform a regional assessment of the variability in wave energy today and assess the extent that wave energy and coastal storms will change with sea level rise (Figure 3). Through the creation of these models, I am proposing to address three main hypotheses with my research:

1. Significant wave height and annual energy reaching the shore will increase in
magnitude more with projected sea-level rise than forecasted changes in climate.

2. Upper foreshore morphologic and substrate change will be more significantly impacted by projected increases in recurrence frequency of high water events than by increases in projected wave heights.

3. Observed wind direction decadal oscillations of 10 to 15 degrees significantly impact shoreline exposure to incident wave energy.

5. Methods

I will integrate computational modeling and field studies to characterize historical conditions, modern processes, and evaluate potential future change. This research project will be completed following the scope of work outline below:

1. Develop a catalogue of historic meteorological, tidal, and wave data for various stations throughout Puget Sound.

2. Assess the climatology of the region through statistical analysis of historic data.

3. Perform extreme value analysis on historic data in order to estimate the recurrence interval of extreme events and project into the future under various SLR scenarios.

4. Create grids of varying resolution for major basins within the Salish Sea which will be coupled for modeling of the entire region. Perform sensitivity analyses on each grid in order to calibrate and compare to observed data.

5. Deploy weather stations and wave sensors needed for model validation. Other field techniques, such as structure from motion, will be employed to evaluate beach substrate and topography. This will be assessed throughout the fall and winter for any changes after major storm events.

6. Model wind-wave generation and propagation for each grid in the Salish Sea using Delft 3D and SWAN. To cover the entire region, the coupling of models will be used to generate the TWL at the shoreline.

7. Perform site-specific case studies using X-Beach to evaluate morphologic changes to the beach face and the extent of flooding from TWL values derived from Delft 3D. Assessments for SLR scenarios will use TWL values from Delft 3D but increasing them according to different SLR estimates.

5.1 Historic Data – Climatological Assessment

Historic records of continuously measured sea level pressure, water levels, wind speed and direction from stations throughout the Salish Sea will be analyzed using time-series environmental statistical approaches. Analyses will examine distributions, general statistics, extremes, and trends with which to characterize climatologies, classify storm events, and quantify recurrence intervals of extreme events and phenomena of interest. Time-series will also be essential for developing boundary conditions (inputs) for modeling. Data sources include NOAA – NCDC (National Oceanic and Atmospheric Administration – National Climatic Data Center), NOAA – NDBC (National Data Buoy Center), Naval or Air Force base weather data sources, and other observational data sets proximal to shore (e.g., airports, schools, etc. General climatologies will be visualized with wind-rose plots and extreme and recurrence interval analyses will be derived using block maxima and \( r \)th largest approaches (Yang et al., 2014; Zervas, 2005; Tebaldi et al., 2012; An & Pandey, 2006; Guedes Soares & Scotto, 2004; Vitousek
et al., 2017) under extreme value theory. Code necessary for performing analyses will be generated in MATLAB, R and Python to be applicable to future and/or additional analyses as new data sources are identified. Metadata will be generated for each set of data and results will conform to USGS data reporting requirements.

Publically available numerical weather prediction service data will also be used to characterize climate and for use in modeling. These data are spatially and temporally varying gridded weather data from global climate models like the University of Washington Climate Impacts Group’s 12-km Weather Research and Forecasting reanalysis hindcast (1950-2010), Environment Canada’s 2.5-km High Resolution Deterministic Prediction System (available for 2015-present), and NOAA’s Climate Forecasting System 2.0. Individual storm events identified in each of these model outputs will be analyzed to examine the resulting wave regime and to place extreme events into the context of natural variability.

5.2 Statistical Analysis – Extreme Value Theory

Using methodology laid out by Zervas (2005), An & Pandey (2006), Guedes Soares & Scotto, (2004) and Vitousek et al., (2017), generalized extreme value theory probability distribution functions (pdfs) will be generated to determine the magnitude and frequency of extreme events and storm statistics. For time series showing either seasonality or a trend, it will be important to remove these before determining extreme values. After determining maximum values (daily, monthly, yearly) for specific data types (wind speed, water level, etc.), statistical software packages will be used to fit pdfs to the maximum values (block maxima, rth largest). These pdfs can then be used to generate exceedance probability curves and represent both recurrence intervals and values for specific storm events (100 year storm vs 10 year storm (Zervas, 2005).

5.3 Hydrodynamic Modeling

To refine our understanding of the Puget Sound wave climate, I will use hydrodynamic modeling to assess wave generation and propagation at a regional scale. Emphasis of this project will be to evaluate the spatial variability in deep-water wave characteristics (>5 m depth) approaching shore today and the extent it will change in the future due to sea level rise. This will fulfill the goals of the parent NOAA Washington Coastal Resilience Project (WCRP) which had resources sufficient to examine wave energy approaching the shore but not the complex physics and interactions of wave dissipation and impact along the entire 4,020 km of Puget Sound Shoreline. I will also couple the regional model outputs to high-resolution cross-shore models at select “case study” sites being defined by the WCRP to evaluate potential changes in impacts with sea level rise relative to today.

As part of the FIRM project, FEMA took the approach of classifying the 150 highest water levels generally associated with storms and high tides at the NOAA Seattle tide gage throughout time. USGS and partners have examined the history of non-tidal residuals (e.g., storm surge anomalies) and atmospheric pressure anomalies from Seattle and several other tide/weather gages. Select events from this list as well as the 100-yr, 50-yr, etc., conditions I calculated from extreme value analyses will be used as boundary conditions to simulate the resulting wave fields using Delft3D and SWAN. From this I will assess the full spectra of wave characteristics expected given the historical conditions and recurrence intervals of events in Puget Sound. Results from each model run will be compared with measured wave statistics where available, and with recorded meteorological data to assess model accuracy and aid in calibration. Upon
validation, I will run each simulation again but under future SLR estimates. Model outputs for each congruent scenario will be compared and results alongshore will be extracted to show the percent change and any expected changes at the beach face.

The regional evaluation I complete for my thesis will be used in a Phase II analysis by the USGS Puget Sound CoSMoS project to validate and characterize projected coastal impacts associated with waves including flooding, extent and depth of flood waters, erosion, etc. The regional model I help develop will evaluate wave generation and propagation for the range of dominant wind intensities and directions and joint occurrence of tides and storm surge anomalies experienced today. This will be accomplished using a coupled USGS Delft3D-Flexible Mesh model of the Salish Sea for tidal flow (shown in Figure 4) and a structured wave model built in SWAN. This will provide a characterization of the historical variability and extremes in wave exposure that can then be used with scenarios of higher sea level position to assess how sea level rise will influence wave impacts.

Modeling will allow for the assessment of how extreme events may change through time. Binning historical wind data into select directional groups (3 – 5 degrees) and assessing the distribution of wind speeds within each group, will lead to estimates of the recurrence intervals of specific wind regimes above thresholds of concern and show the extent that wind directions have changed through time (Figure 5). As part of a sensitivity analysis on wind-wave generation in Puget Sound, I will model incrementally increasing wind directions and assess the extent that wind direction affects wave energy. Coupling historic wind variability with model results, I can then assess how wave energy may have changed through time, including incident wave energy, and help to test whether an increase in sea level will bring about any changes in dissipation, refraction or other physics that affect wave impacts at the shore.

After completing the regional wave assessment, I intend to examine two site specific case studies: one exploring the influence of SLR and waves on bluff retreat along the Island County bluff-barrier spit system of Iverson Lagoon; the other aims to assess how to apply the regional model of future extreme coastal conditions to the urban infrastructure of Tacoma. These case studies will incorporate cross-shore 1D models needed to solve for wave dissipation, set up and run up to predict inundation, potential for erosion and any geomorphic change that could impact habitats or local infrastructure. This modeling effort will use the results of the regional wave study to propagate wave energy to the shore along high-resolution digital elevation models and likely utilize XBeach or a similar 1D wave transformation algorithm that USGS has integrated into the CoSMoS framework.

6. Expected Results

The goal of this project is to assess the variability of wave energy today and the impact that sea level rise will have on wave energy in the future throughout the Salish Sea. Regional maps of the variability in significant wave height and energy approaching the shoreline under various SLR scenarios and different extreme storm events (Figure 6) will help inform coastal managers and policy makers of spatial considerations of future risk. These maps will depict annual forecasted maximum wave heights along the shore, percent changes relative to today and the extent of flooding/morphological changes to the beach face for site specific studies. Such maps have been identified as important and valuable tools for coastal managers and policy makers to better plan for the changing wave climate. Results in the form of tables and maps by basin and
priority sites (major urban or industrial centers) will also summarize climatologies, changes in extreme event recurrence intervals, and modeled changes in expected wave energy.

From the climatological assessment of multiple weather, tide, and wave gauges I plan on developing tables that quantify different metrics of current extreme events and the observed recurrence intervals for such events. As part of this data table, I will show any deviations in dominant wind directions through time at different temporal resolutions (e.g., decadal vs. entire time series). A key output will be the joint probability of extreme weather events occurring during high tides.

Similar to the climatology results, I will produce data tables of wave heights, energy, and total water levels for various locations under different SLR scenarios. This will demonstrate the absolute and relative change in future coastal climate from historical and current values. To better represent wave energy, I will generate plots of directional wave spectra for entrances to many of the basins in Puget Sound (e.g., multiple locations during different storm events under varying SLR). Understanding wave spectra at basin entrances will aid in assessing any variability in the wave climate under various SLR scenarios.

**Project Significance**

Storm surge and SLR display a positive relationship; as sea levels increase, storm surge will continually increase. Even though agreement regarding exact SLR estimates for Puget Sound does not exist, coastlines throughout the region will experience changes in storm surge and flood frequency due to any increment of SLR (Tebaldi et al., 2012). In order to maintain current infrastructure and important ecosystems along the coast, policy makers and coastal managers need tools in order to make informed decisions about the potentially devastating impacts of SLR (Passeri et al., 2015). Developing coastal models and regional maps that accurately depict changes in wave energy at the shoreline through time will be an important first step towards sustainability.

As part of the NOAA WCRP, the results of this project will help meet the needs of the regional project objectives and the diverse set of partners and co-managers of resources, restoration and planning across the State of Washington. The model and results will also be the basis for constructing additional models including the USGS PS-CoSMoS and other assessments at the regional and local scale. Understanding the extent that coastal impacts associated with storms, waves and sea level rise will change relative to today, will help increase the knowledge and support of Puget Sound communities and ultimately enhance resiliency.
## 7. Timeline

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8. References


Ruggiero, Peter. “Is the Intensifying Wave Climate of the U.S. Pacific Northwest Increasing


9. Figures

Figure 1: Map of the Salish Sea, showing the area of study for this research project
Figure 2: Wave climate maps of Puget Sound showing mean significant wave height (left) and period (right) of statistically summarized wind storms from 1996 – 2000. Taken from Finlayson (2006)
Figure 3: Photographs of Alki Beach in West Seattle, showing the difference between calm seas during high tide in contrast with wind generated waves interacting with the shoreline during high tide. Provides a visual representation of a static vs. dynamic approach to coastal modeling.
Figure 4: Image of the Delft 3D – FM (Flexible Mesh) model domain for the entire Salish Sea.
Figure 5: Wind rose diagrams for Paine Field and Whidbey Island Naval Air Station located in Washington. Data spans from the early 1940’s to present. Both stations are proximal to the coast and are separated by roughly 35 miles. Over this short distance, variability in wind direction is easily noticed where Whidbey has dominant W and SE winds while Paine Field has dominant N/NW and S/SE winds.
Figure 6: Sample map showing the desired output from the regional study. In this example Whidbey Island, WA is shown with a hypothetical east blowing wind. This sample map shows how locations directly exposed to the westerlies will see the highest wave energy compared to areas protected by land to the west.