Assessing the Impacts of Coastal Flooding on Treaty of Olympia Infrastructure

A Report to the Quinault Indian Nation, Hoh Tribe, and Quileute Tribe
Prepared by the Oregon Climate Change Research Institute

May 2019

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Cover photo: Coastal Flooding in Ocean Shores, WA due to extreme water levels at the Mouth of Grays Harbor, December 1, 2017; credit – Nick Bird, City of Ocean Shores

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Introduction

Extreme coastal total water levels (TWLs) that result in flooding are the result of the complex interactions between multiple oceanographic, hydrological, geological, and meteorological forcings that act over a wide range of scales (i.e., astronomical tide, wave set-up, wind set-up, large-scale storm surge, precipitation, fluvial discharges, monthly mean sea level, vertical land motions, etc.). Coastal flooding that occurs during extreme TWLs can significantly impact communities and infrastructure resulting in substantial economic losses, even threatening human lives. Climate change may cause an increase in extreme coastal water level events driven by rising sea levels and changing patterns of storminess. An improved understanding of the physical processes during extreme coastal water level events will ultimately lead to an improved ability to predict the present day and future hazards faced by coastal communities. This information, in turn, provides the foundation for building more resilient coastal communities.

The primary objectives of this project were to 1) assess the relative contributions of the various processes that drive extreme coastal TWLs; 2) quantify the impact of a range of climate change scenarios on each of the drivers and on the resulting combined TWLs; and 3) assess the impact of present-day and forecasted future coastal flooding events on infrastructure in several communities within the Treaty of Olympia area.

This report is organized as follows: Sections 1, 2, and 3 highlight the primary results of each project objective listed above. Section 3 ends with a specific discussion of climate change impacts and some possible recommendations for adaptation. The details of the original modeling approaches specifically developed for this study have been published in the peer-reviewed literature and are given in Appendices A and B. Finally, the overarching results of a completed outer coast vulnerability assessment (Chapter 5 of Dalton et al., 2016) are reproduced in Appendix C.

Objective 1: Assess the Relative Contributions of the Various Processes that Drive Extreme Coastal Total Water Levels

Coastal flooding in the Pacific Northwest is often controlled by compound events, in which individual processes, which may or may not be extreme, combine to create extreme events (Zscheischler et al., 2018). For example, storms often generate large waves, heavy precipitation driving increased streamflow, and high storm surges, making the relative contribution of the actual drivers of extreme water levels difficult to interpret. Until recently, the compound nature of coastal flooding was not sufficiently recognized and there remains a paucity of scientific approaches for accurately characterizing risk under a compound flooding regime. Therefore, this project focused on developing new approaches for modeling and evaluating the relative contributions of the various processes that combine to generate high water levels in coastal rivers and estuaries. Due to the difference in environmental settings across the region, two new approaches have been developed, the methodologies of which have been published in the peer-reviewed literature as Parker et al. (2019) and Serafin et al. (2019) (Appendix A and Appendix B, respectively).

1.1 Emulating Extreme Water Levels in Grays Harbor

The first new approach involved developing a technique for modeling spatially variable water levels in the Grays Harbor, Washington area, per personal communication with Carolyn Kelly who encouraged a focus on this area due to the Quinault Marina and RV park, the Quinault Beach Resort and Casino, and other tribal assets in the area. To do this, a coupled hydrodynamic and spectral wave model, "Advanced Circulation Model-Simulating Waves Nearshore" (ADCIRC-SWAN), which has the ability to isolate the influence of processes such as wind set-up, pressure (through the inverse barometer effect), and wave set-up, was used (modeling grid shown in Figure 1). ADCIRC-SWAN has been extensively validated in coastal areas across the world as well as specifically in the Pacific Northwest. It is one of the leading tools for modeling flooding and coastal circulation and thus was an ideal approach to use for this project.

During model development, ADCIRC-SWAN results were first validated by confirming that the model accurately calculated observed water levels within the bay during past storm events (see Parker et al. 2019; Appendix A). In order to evaluate the contribution of processes to many different types of storm events, thousands of iterations of storm conditions would have to be simulated, which would be time consuming due to the computational expense of the model. Thus, this approach developed a 'surrogate' model (or emulator—see Parker et al., 2019 [Appendix A] for more details) in which any possible combination of forcing conditions (e.g., medium waves but high winds and stream flow) can be examined much more rapidly to determine whether or not they may cause flooding. To this end, once the ADCIRC-SWAN model was validated, ~500 ADCIRC-SWAN simulations representing a range of forcing conditions (taking months of computer server time) were generated to replace model runs with a spatially variable statistical representation of water levels in the bay from specified forcing conditions.

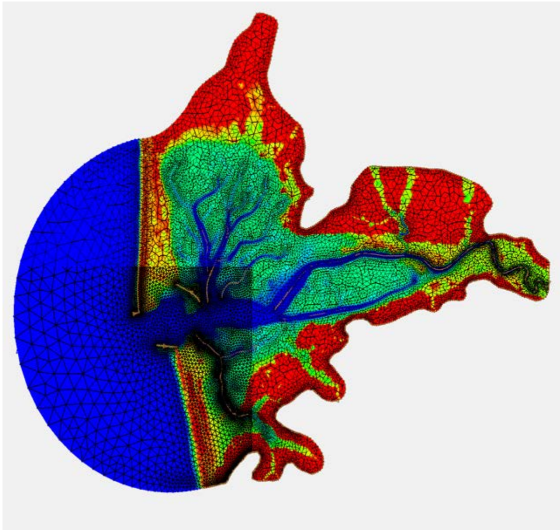

Figure 1 ADCIRC-SWAN model grid for the Grays Harbor, WA area.

This modeling approach provides a unique ability to examine the spatial variability of forcing conditions that contribute to extreme water levels in Grays Harbor. Figure 2 displays East-West and North-South transects of the average relative contribution of each forcing component during annual maxima events for the length of the record (1980s to approximately the present day). The diverse mix of processes that contribute to extreme water levels (WL) at each location, confirm that extreme WLs in Grays Harbor are compound in nature. The mean contribution of each forcing dimension to the extreme WL is significant, suggesting that including all forcing processes is necessary for the proper estimation of the magnitude of extreme WLs. The only exception is streamflow from the Chehalis River, which is found to be nominally important except near the streamflow boundary. This result is likely specific to the Grays Harbor estuary, which has a large estuary volume in comparison to the streamflow input and would be different for a more hydrologically dominated estuary system, which is further explored in Section 1.2.

The relative contribution of each variable to extreme WLs spatially varies across the estuary, leading to both an East-West and North-South gradient in the magnitude and drivers of extreme WLs. For example, waves significantly contribute to annual maximum WLs but only at stations in the northern and eastern reaches of the bay. This is likely due to little to no wave breaking induced setup occurring at the bay's entrance channel. The influence of wind on extreme WLs increases to the north due to the mean wind direction emanating from the south during storm events. The contribution of streamflow to extreme WLs decreases towards the west, moving farther away from the estuary's streamflow inlet. Finally, the influence of pressure anomalies on extreme WLs is found to be uniform. This result is likely from the spatial simplification of sea level pressure fields during the numerical procedures.

Not shown in Figure 2 is the contribution of tidal forcing to extreme WLs. This is primarily for scale reasons as the tidal component is an order of magnitude larger than any other forcing (average of 140 cm). Similar to previous results, tides also vary across the estuary (Figure 2). The contribution of tides to extreme WLs decreases by about 30 cm moving from the center of the estuary toward the North or East.

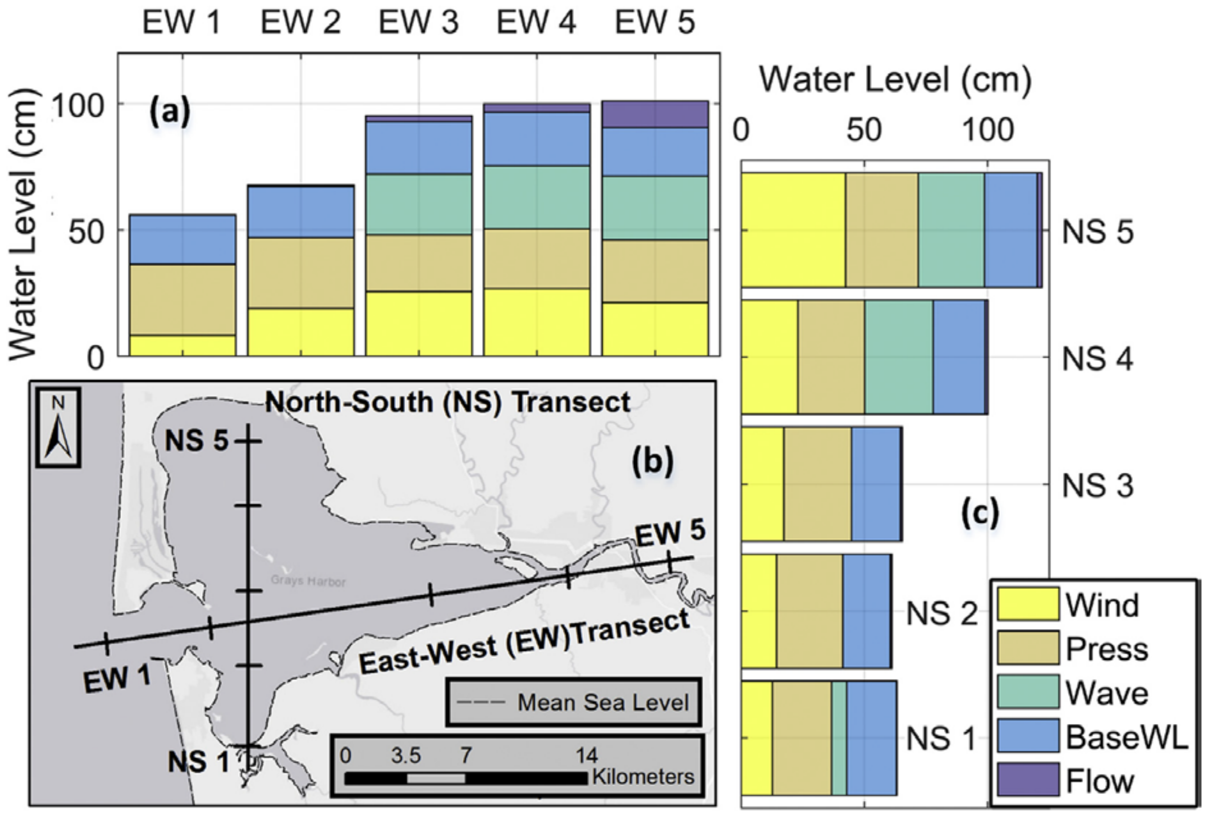

Figure 2 Average water level (WL) contribution from forcing components during extreme events (maximum annual WLs). Two transects are plotted with subplot (b) showing plotted transects, (East-West, EW) and (North-South, NS), with station locations marked as ticks. Tick locations are approximate (within 1 km) to scattered station locations. Subplot (a) is the East-West transect and subplot (c) is the North-South transect.

While this analysis shows important results for Grays Harbor as a whole, three specific locations were chosen for additional analysis due to their specific relevance to the Quinault Indian Nation. Figure 3 shows the locations of the 111 emulators that were constructed from the ADCIRC-SWAN simulations. The three locations chosen for additional analysis are plotted as a green star (Westport tide gage), pink star (near the Quinault Marina and RV park), and a cyan star (immediately offshore of the Quinault Beach Resort and Casino).

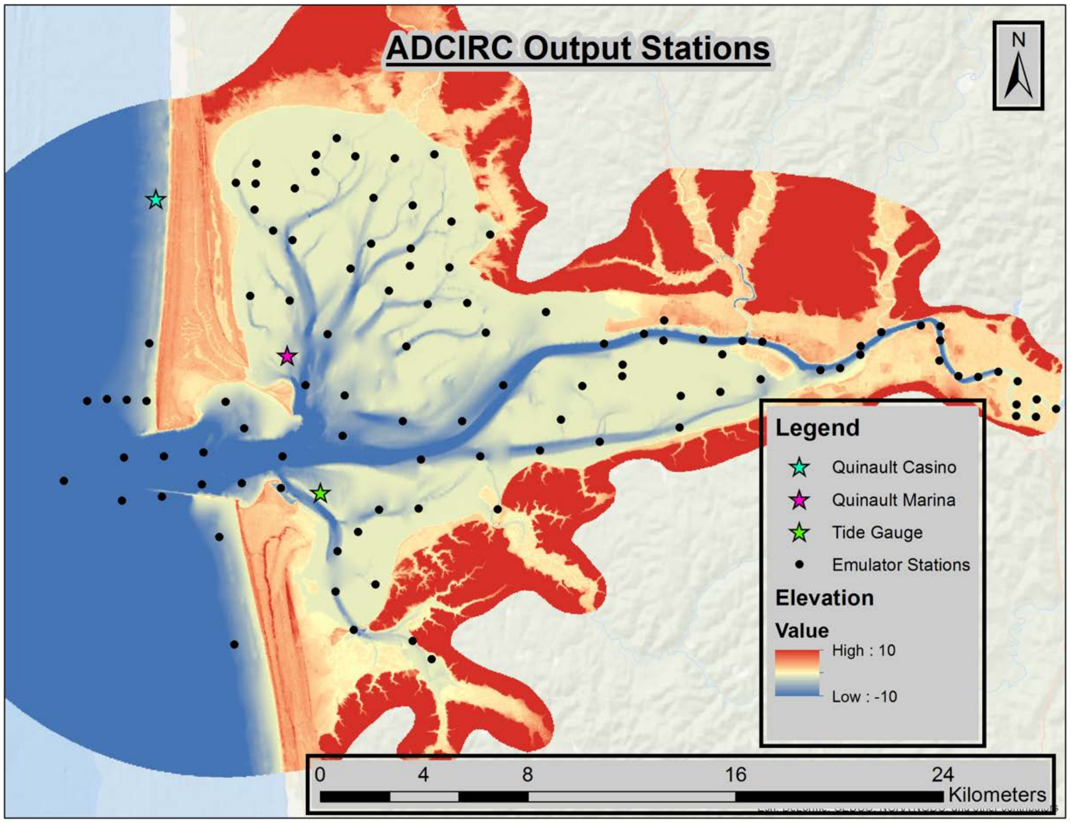

Figure 3 Location of emulators developed from the Grays Harbor ADCIRC model.

Due to differences in open coast and sheltered coast settings, it is expected that locations within and outside of the estuary would have a different composition of forcing variables contributing to coastal flooding. Figure 4 shows pie charts of contributions to extreme events at the Casino location (located along the open coast) and the Marina (within the estuary). Forcing is defined in these plots as “Tide” (deterministic and astronomically controlled), “Stream” (streamflow from the Chehalis River), “Base WL” (variations to local sea level as controlled by seasonality, monthly mean sea level anomalies, etc.), “Wave”, “Wind”, “Press” (pressure), and “LeftOvers” (nonlinear interactions between processes). These plots only show the percentage contribution from each forcing variable, not the magnitude of those contributions

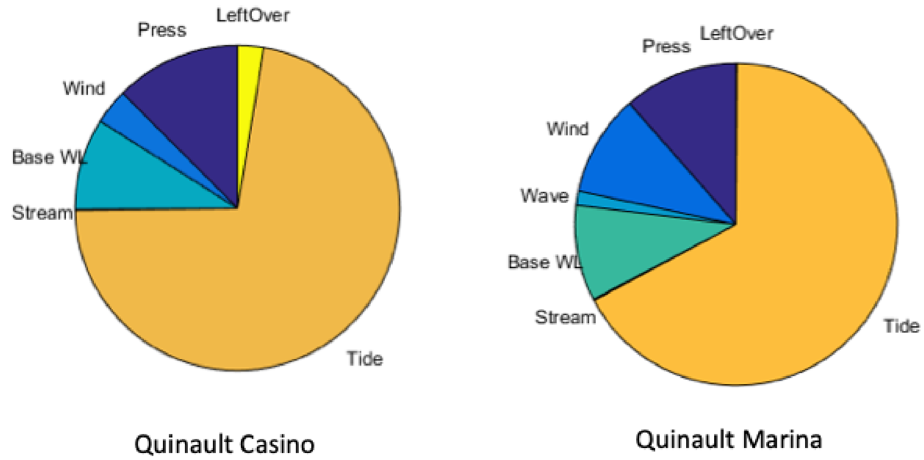

Figure 4 Contributions to extreme water levels at the Quinault Casino (left) and Marina (right)

From Figure 4 we can see that drivers of extreme WLs vary between these two locations. In this analysis, waves are an important component of extreme WLs at the Marina location while not at the Casino location. This is due to the fact that the Casino location is just offshore of the open coast beach and not under the influence of wave runup. This result is sensitive to the specific location of the station offshore, and a location closer to shore would likely show the effect of wave setup. For this reason, a total water level approach is more applicable for understanding hazard risk at this location (see section 2.2). Overall, storm surge forcing is more important at the Marina location while tides are a larger proportional contributor at the Casino. Additionally, we see that streamflow is found to be a negligible contributor in both locations.

The variability of the contribution of each process to extreme WLs for all events is shown in Figure 5 for the Marina location. Here, boxplots allow for a visual representation of how data in a sample (in this case, 30 years of extreme events), varies. The central line within the box represents the median while the bottom and top of the box represents the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme points not considered outliers.

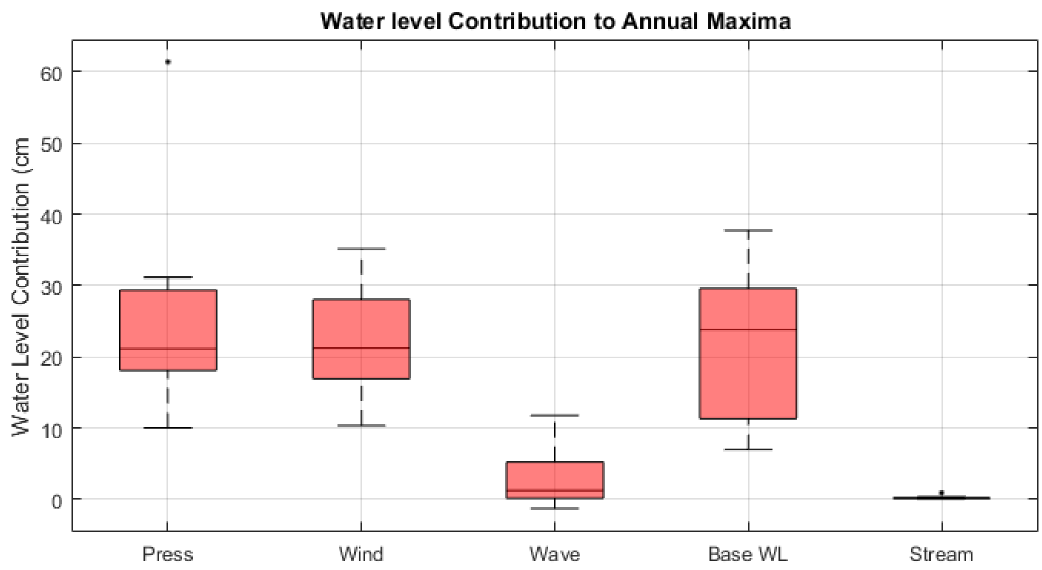

Figure 5 Boxplots showing the variability of contribution to extreme water level (WL) at the Marina location.

Figure 5 reveals that there is significant variability in what contributes to an extreme event at the Marina (shown by the height of the boxes). While one event may be wind-driven, another may be pressure or base WL-driven. This further reinforces the concept that extreme events at the study site are compound in nature. An event-based approach, like that commonly taken in hurricane influenced regions, is not likely applicable in the Pacific Northwest as it is very difficult to know a priori which events will cause coastal flooding. Furthermore, this interconnected nature of flooding means that significant care must be taken looking at climate change, which may simultaneously affect all drivers of coastal flooding as well as the relationships between them.

1.2 Hybrid Modeling of Compound Flooding along the Quillayute River

The proximity of communities like La Push and Taholah to both the ocean and river make them prone to flooding from high tides, coastal storms driving storm surges and large waves, and high streamflow events. While this is a similar situation to that explored in Grays Harbor in terms of compound forcing, these locations have a smaller estuary size (in terms of volume) and larger relative streamflow input. Furthermore, the storm surge signal measured by the tide gauge at La Push tends to coincide with high discharge events (Figure 6). This is likely to be similar at Taholah, but the limited observational data sets at this location makes it difficult to confirm.

It is hypothesized that streamflow is an important contributor to flooding in La Push. To test the hypothesis of strong fluvial control during extreme water level events, an ADCIRC model, similar to that developed in Grays Harbor (section 1.1), was constructed to model the largest streamflow event on record. Results from this modeled storm event show that the simulation including only river streamflow and tides is nearly able to recreate the measured peak storm surge signal measured at the tide gauge. This confirms that streamflow can contribute to high water levels at the study site. This simulation also confirms that the use of ADCIRC for this type of problem is limited since model simulations were found to be very unstable.

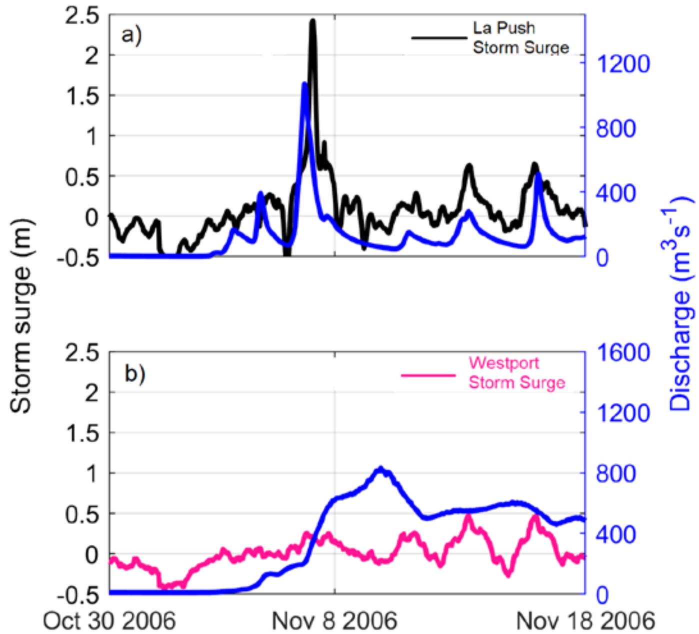

Figure 6 Example storm surge and river discharge relationship at a) La Push, Washington and b) Westport, Washington.

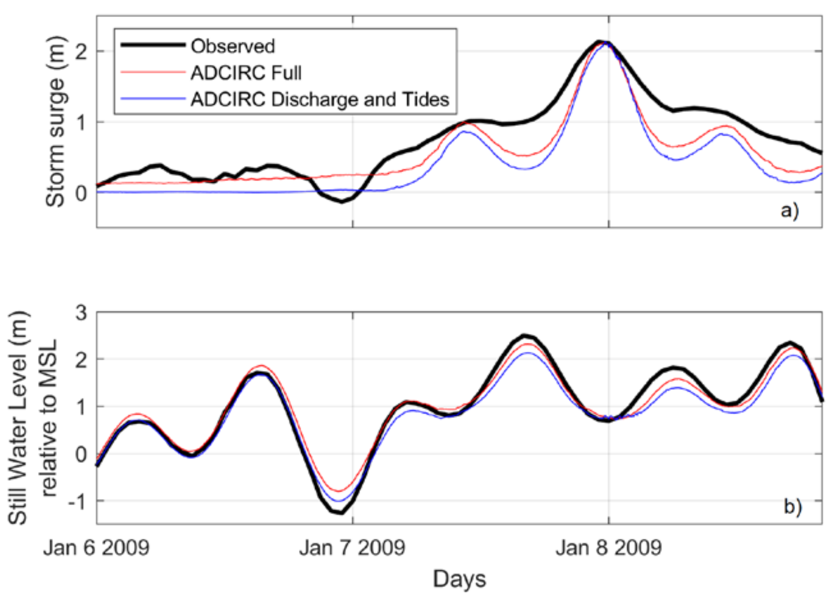

Figure 7 Simulated storm surge (a) and still water level (SWL) (b) at the La Push tide gauge. The full forcing simulation is plotted as a red line, a simulation using only streamflow and tides is plotted a blue line, and the observed storm surge or SWL is plotted as a black line.

While several Treaty of Olympia tribal communities experience these issues, our second modeling approach focused on the Quillayute River and the community of La Push (Figure 8) due to the availability of data for sufficient model calibration and validation. Early in the project we proposed to collect relevant data in the Quinault River to develop the data sets needed to build models at that location, but eventually it was decided that this was not feasible (personal communication with Carolyn Kelly). In general, some of the overall lessons learned from the Quillayute River analysis described below could be applied to other characteristically similar estuary systems, like the Quinault, Queets, and Hoh Rivers.

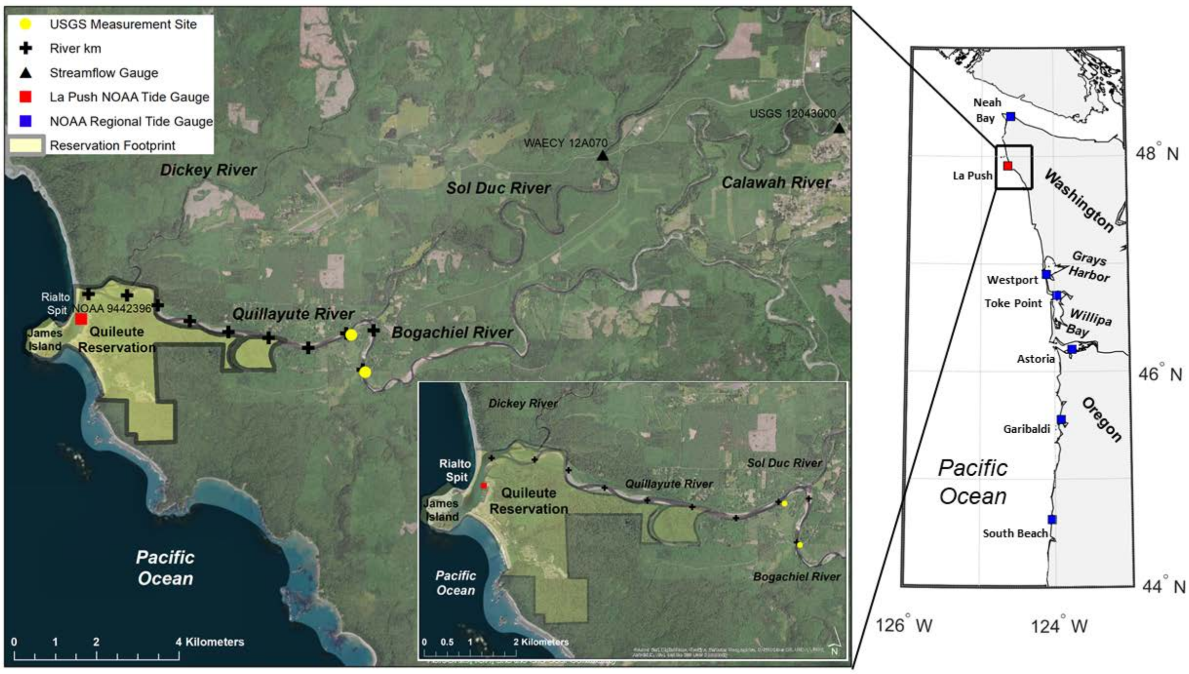

Figure 8 Map of study area (left) for our second modeling approach. The La Push tide gauge is represented as a red square while other regional tide gauges are represented as blue squares (right). The Calawah and Sol Duc river gauges are represented as black triangles and USGS measurement sites from the May 2010 survey are depicted as yellow circles. Approximate river kilometers are denoted as black crosses on the study area map.

To explore the influence of river and ocean forcing on extreme water levels (WLs), our second approach developed a hybrid modeling framework by merging the hydraulic model, Hydrologic Engineering Center's River Analysis System (HEC-RAS, model domain is displayed in Figure 9) for simulating river flow, with probabilistic simulations of co-occurring river and ocean events (Serafin et al. 2019; Appendix B). The HEC-RAS model was initially calibrated to successfully model the water surface elevation along the river during a USGS data collection effort (Czuba et al. 2010). Similar to emulating extreme WLs in Grays Harbor (section 1.1), this technique allows for insights into the extent and the relative importance of each WL component to flooding along a gradient from pure oceanographic forcing to pure riverine forcing.

The probabilistic, full simulation model of Serafin and Ruggiero (2014) was modified to incorporate the dependency between river discharge and the remainder of relevant WL components. This probabilistic model allows for the generation of multiple, synthetic WL records to produce numerous estimates of low-probability events not captured in the observational record. Modeling all of the statistically simulated boundary conditions in a hydraulic model to output along-river water levels would be prohibitively expensive. As an alternative to time consuming simulations, surrogate models are developed to approximate the response of a HEC-RAS simulation at each along-river location. This technique allows for the analysis of along-river water levels driven by a variety of boundary conditions. Long synthetic records allows for the direct empirical extraction of water level return levels rather than an extrapolation from historic observational forcing conditions.

In total, seventy 500-year simulations were run, which allowed for the extraction of the water surface elevation at every along-river location, as well as the ocean and river forcing driving that elevation (see Serafin et al. 2019; Appendix B). Understanding the relative forcing of extreme WLs moving from open ocean boundary conditions to where river processes dominate will help Treaty of Olympia communities better understand the risk of compounding impacts of various environmental forcing, which is important for increasing resilience to future events.

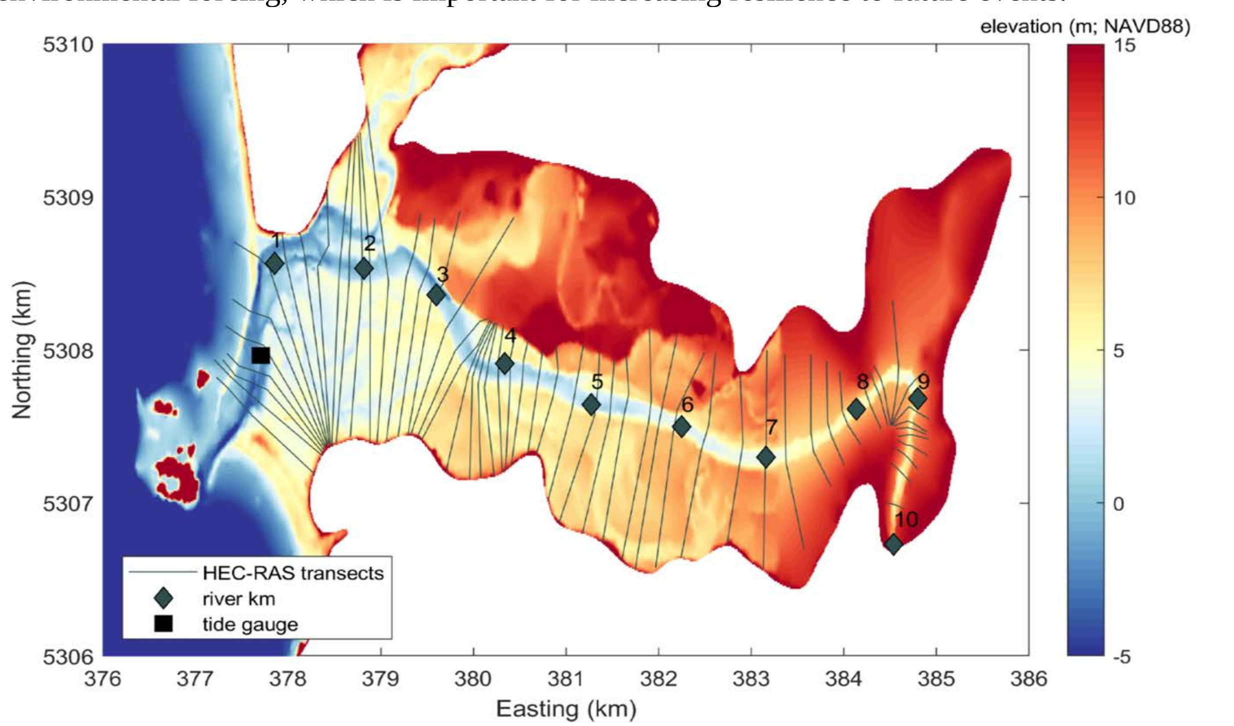

Figure 9 Digital Elevation Model used for the HEC-RAS simulations of the Quillayute River. HEC-RAS cross sections are depicted as grey lines. Approximate river kilometer and the location of the tide gauge are depicted as diamonds and a square, respectively.

The thousands of simulated upstream and downstream boundary conditions show that variability in the ocean boundary conditions impact river water levels, and therefore the potential for flooding and erosion, as far east as river kilometer 5 (Figure 10). Note that this is east of Thunder Field, an area of significant concern due to the potential of river avulsion due to channel migration and streambank erosion.

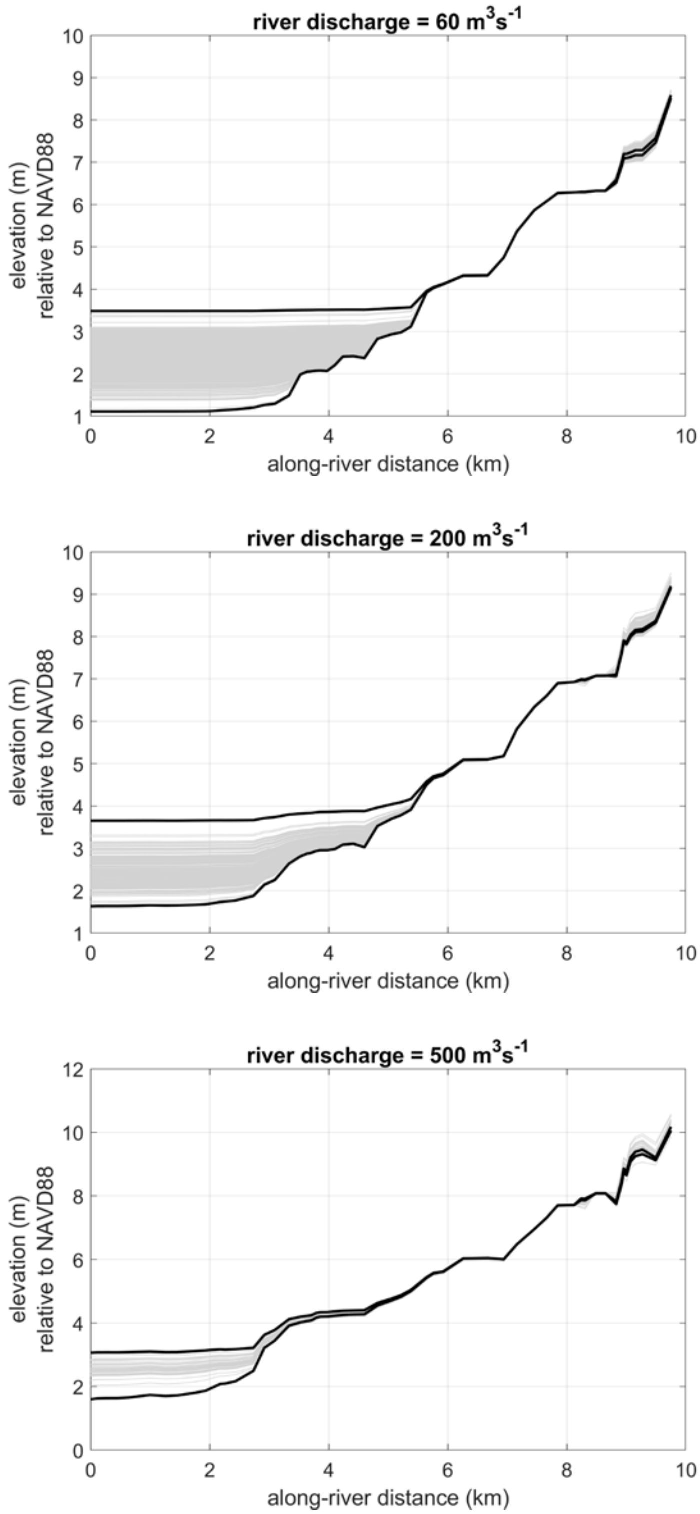

Figure 10 Results from HEC-RAS modeling on the Quillayute River showing water surface elevations for various scenarios. Three discharges are modeled for a wide range of different still water levels showing the varying influence of oceanic processes moving upstream. Each grey line represents one example simulation for the flow in the title +/- 0.5 m^3s^{-1} and the water surface profile extracted. Black lines represent maximum and minimum still water level boundary conditions.

Objective 2: Quantify the Impact of a Range of Climate Change Scenarios on Each of the Various Components and on the Resulting Combined Total Water Levels.

A vital consideration in any attempt to quantify climate change impacts is the associated uncertainty in the resulting estimates. The ability to predict the future climate is limited for a variety of reasons ranging from the difficulty of modeling the full earth system to the inability to know how human impact on the climate will evolve. A typical way to characterize this uncertainty is to consider “scenarios” which follow various plausible trajectories of the future climate. This project approaches Objective 2 using state-of-the-art estimates of future sea level rise as the basis for four climate change impact scenarios. These climate change impact scenarios were applied to both modeling approaches described above to explore the impacts on hazards.

An additional source of uncertainty is from the chaotic nature of the climate system. Consideration of a single climate time series is generally considered inadequate as this time series may or may not be indicative of the overall behavior of the system. For example, a single time series may be uncharacteristically extreme due to the stochastic nature of the climate system. Analysis based solely on this single time series could therefore produce biased results. To reduce this source of error, as well as to better characterize uncertainty in the analysis, this report takes the approach of considering multiple iterations (an ensemble) of climate time series.

2.1 Climate Change Impact Scenarios

Climate change impact scenarios were developed based on sea level rise (SLR) projections for the Washington coastline developed by Miller et al. (2018). At the time of the analysis for Grays Harbor, absolute SLR projections (i.e., sea level relative to a fixed, unmoving point) had been completed, and researchers were still in the process of creating relative SLR projections (i.e., sea level relative to land, which incorporates vertical land movement such as uplift and subsidence) for the Washington coast. The SLR scenarios in the Grays Harbor work use absolute sea level projections for RCP 8.5 from Appendix A of Miller et al. (2018) and incorporate the best estimates of vertical land movement specific to Grays Harbor at the time (1.5 mm/yr on average), as well as uncertainty around those estimates (Figure 11). SLR scenarios for the La Push study site (latitude of 47.9N and a longitude of 124.6W) were developed based on the newly completed relative SLR projections, which include vertical land movement developed by Miller et al. (2018) (Figure 11).

In both approaches, the low impact SLR scenario uses a low-end projection that is 95% likely to be exceeded. The medium impact SLR scenario used a mid-range projection and has a 50% exceedance probability. The high impact SLR scenario uses a high-end projection that is 5% likely to be exceeded. Finally, a “worst case” scenario was explored which has only a 0.1% chance of being exceeded.

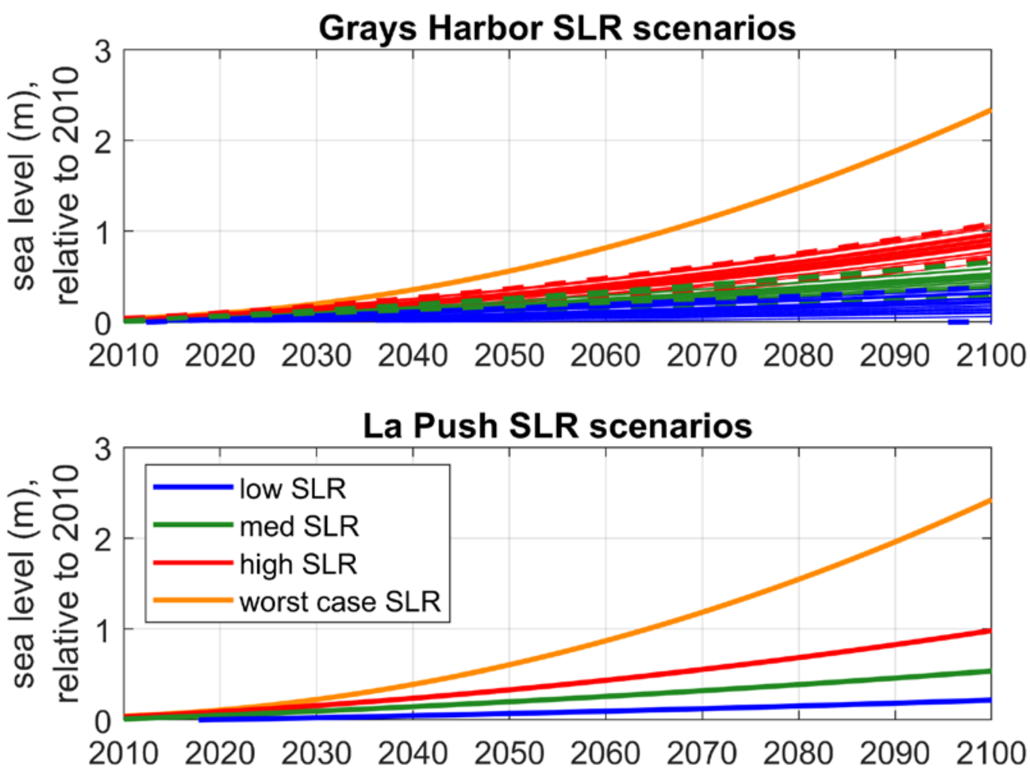

Figure 11 Envelope of four primary sea level rise (SLR) scenarios plotted as colors (blue for low, green for medium, red for high, and orange for worst case), relative to 2010 sea levels. Each SLR iteration in the top panel for scenarios low, medium, and high incorporates a range of vertical land movement, while the bottom panel SLR scenarios were developed from relative SLR scenarios.

While SLR is expected to be the largest driver of long-term increasing coastal flood hazards in the Pacific Northwest (PNW), other controls on flooding are also expected to change. Research has shown that changing wave climate has recently been a major driver of intensifying coastal hazards in the PNW (Ruggiero 2013). This is because for PNW open coastlines, waves are one of the largest contributors to extreme total water levels (TWLs) (Serafin et al. 2017). For this reason, we also explored the possibility of changes to the PNW wave climate. Projected changes in wave height were estimated by shifting wave height distributions (Figure 12) based on future estimates of wave height change in the Northeast Pacific from global climate model projections (Hemer et al. 2013; Wang et al. 2014). Water levels and wave heights are also affected by major El Niño events, which have been associated with severe flooding and erosion in the PNW (Barnard et al. 2017). The frequency of major El Niño events was allowed to double and halve the present-day frequency, which is approximately once every 7–10 years. In our Grays Harbor work, thirty-three probabilistic TWL simulations for each high, medium, and low climate change impact scenario, resulted in 99 different 100-year projections of daily maximum TWL (Figure 13). One TWL simulation was also completed for the “worst case” climate change impact scenario.

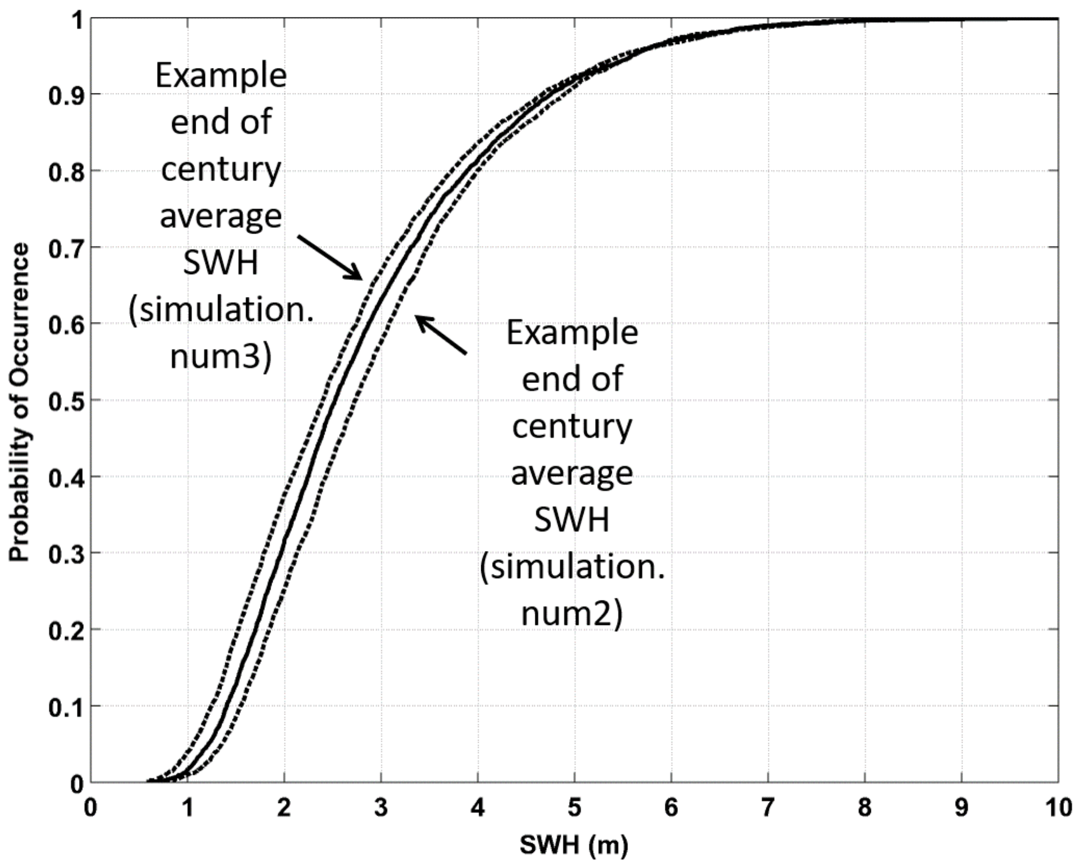

Figure 12 Envelope of wave climate variability in terms of shifting wave height (SWH)

For the Quillayute River site, climate change-controlled modifications to streamflow were also incorporated within the uncertainty. The western Olympic Peninsula is projected to experience increased winter precipitation (Mote et al. 2013), which could subsequently increase the frequency or intensity of high streamflow events along the Quillayute River. However, there are currently no specific estimates of changes to future streamflow specific to the Quillayute watershed. We therefore completed a sensitivity analysis where we allow for the average winter streamflow to increase by 2, 5, 10, and 20%.

A key strength common to both of the new approaches developed by this project is the ability to consider future uncertainty in projections. This allows a more robust estimation of the most likely future hazard as well as an understanding of how drastically the hazard could vary from this most likely outcome. Figure 13 gives an example of how this project has approached uncertainty through the perspective of TWLs. The colors show variability as a function of SLR scenario while the shaded regions show variability as a function of climate iteration. From this plot it can be seen how important consideration of uncertainty is, with future predicted TWLs in the year 2100 differing at the scale of meters and predicted average annual TWLs for each scenario varying by about half a meter.

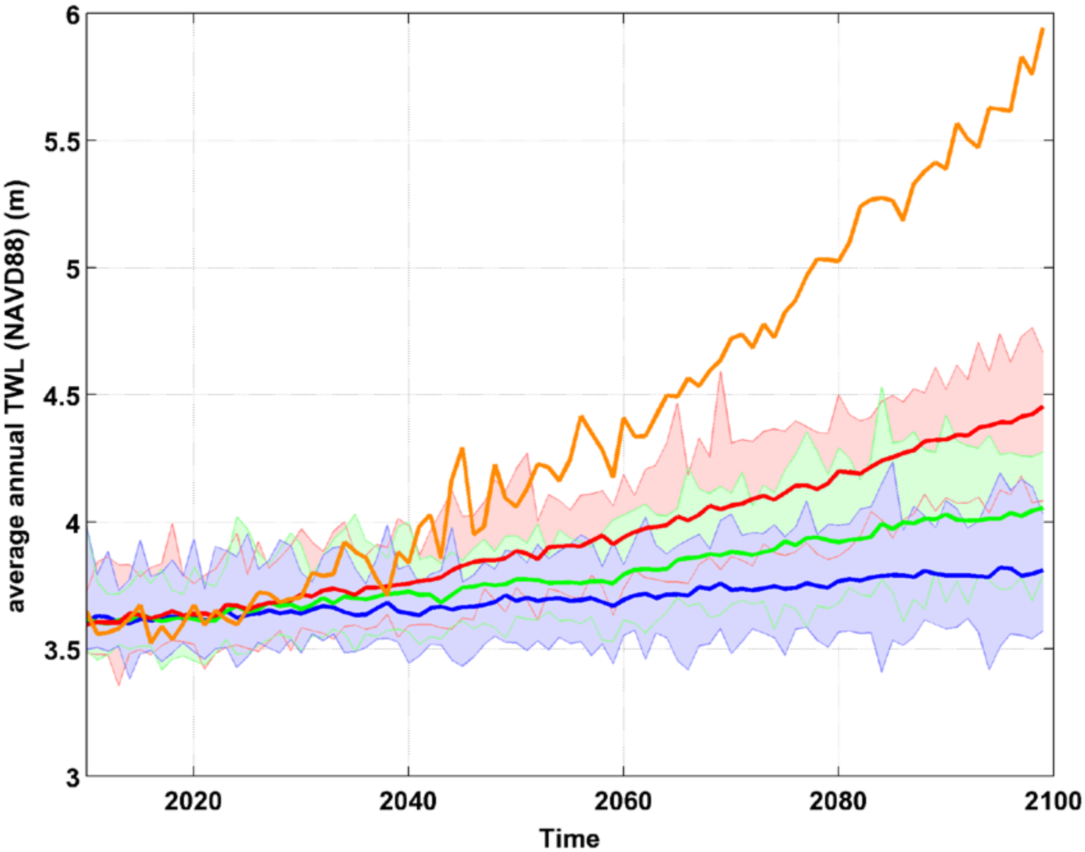

Figure 13 Influence of climate change on average annual total water levels (TWLs). The solid line depicts the average for each climate impact scenario, while the shaded regions depict the variability due to changes in the wave climate, frequency of major El Niño events and vertical land movement.

2.2 Impact of Climate Change on Emulated Grays Harbor Water Levels

Once emulators of the Grays Harbor ADCIRC model were built, time series of forcing variables were passed through to estimate extreme water levels (WLs) at a variety of locations. Here we refer to WLs as the integrated effect of a variety of forcings/processes on the water level of a location. For emulating WLs within Grays Harbor, this does not include surface waves or any type of runup but rather can be thought of as the water level that would be measured if there were a tide gauge at this location. Within bays this is the water level metric that best corresponds to inundation. To explore the influence of climate change on WLs relevant to tribal infrastructure, we focused our efforts on the three emulators specified earlier (see Figure 3): the Westport tide gage, near the Quinault Marina and RV park, and immediately offshore of the Quinault Beach Resort and Casino.

Using the emulators, we explored the time varying WLs at these stations for a range of sea level rise (SLR) scenarios. Figure 14 shows an example synthetic WL time series at the Marina station for the four climate change impact scenarios.

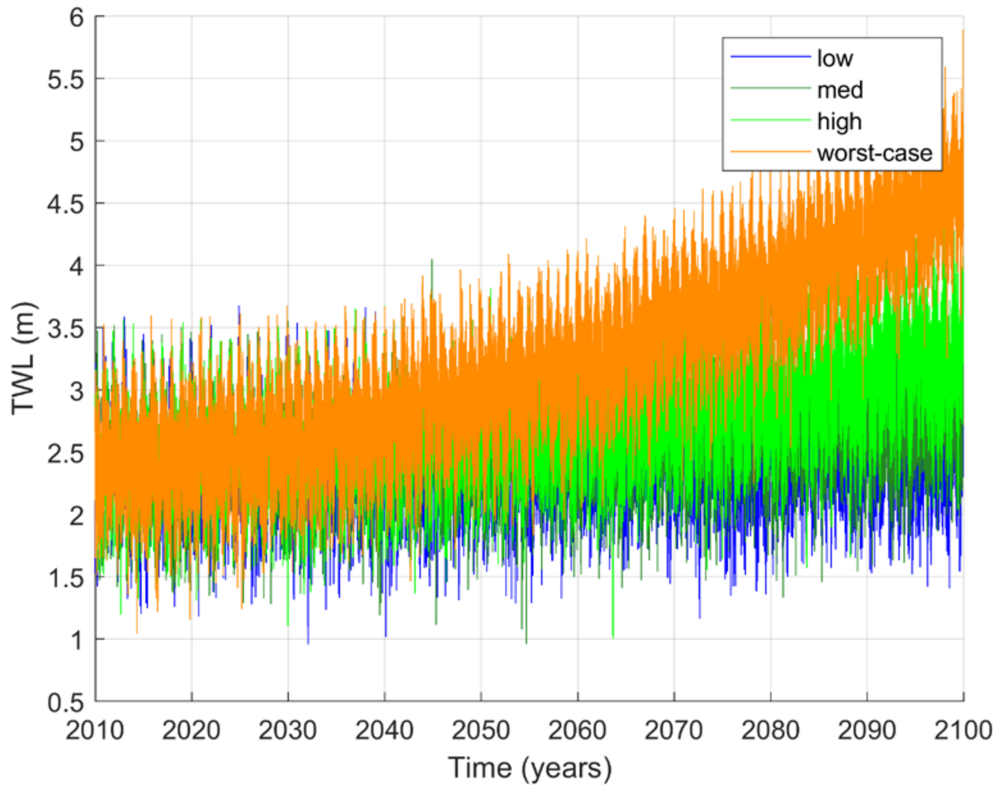

Figure 14 Example time series of total water levels (TWL) at the Marina for a range of sea level rise scenarios.

Of note, Figure 14 shows only one of the more than 30 climate iterations analyzed for each climate change impact scenario (other than Worst-Case which only was considered with one iteration). Figure 14 displays the seasonal and interannual variability in WLs at the Marina location, as well as how these may change moving forward with possible changes to the climate. However, the impact of these results on flooding hazards can be better understood by viewing TWLs from a threshold exceedance perspective.

Figure 15 illustrates the number of days per year that WLs at this location exceed an elevation of 3.2 m (NAVD88), which is approximately the elevation associated with minor nuisance flooding at this location. Figure 15 (bottom) includes the worst-case climate change impact scenario and reveals that by the end of the 21st century nuisance flooding may start occurring every day under this scenario. Figure 16 displays the same plot but for the location of the Westport tide gauge, a proxy for flooding in and around the Westport Marina.

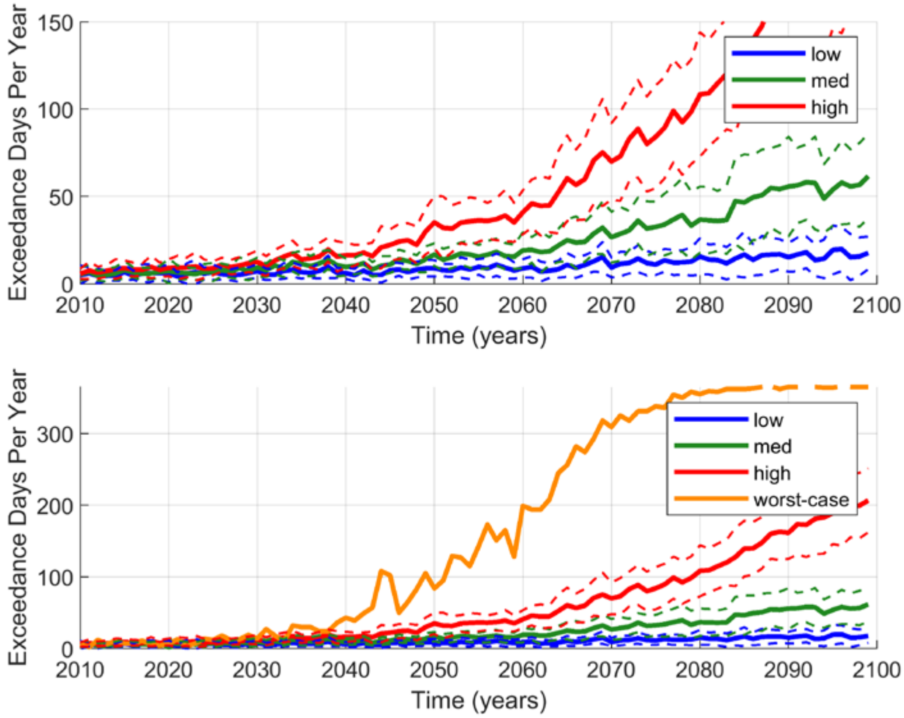

Figure 15 Exceedance days per year when total water levels at the Quinault Marina and RV Park exceed an elevation of 3.2 m NAVD88.

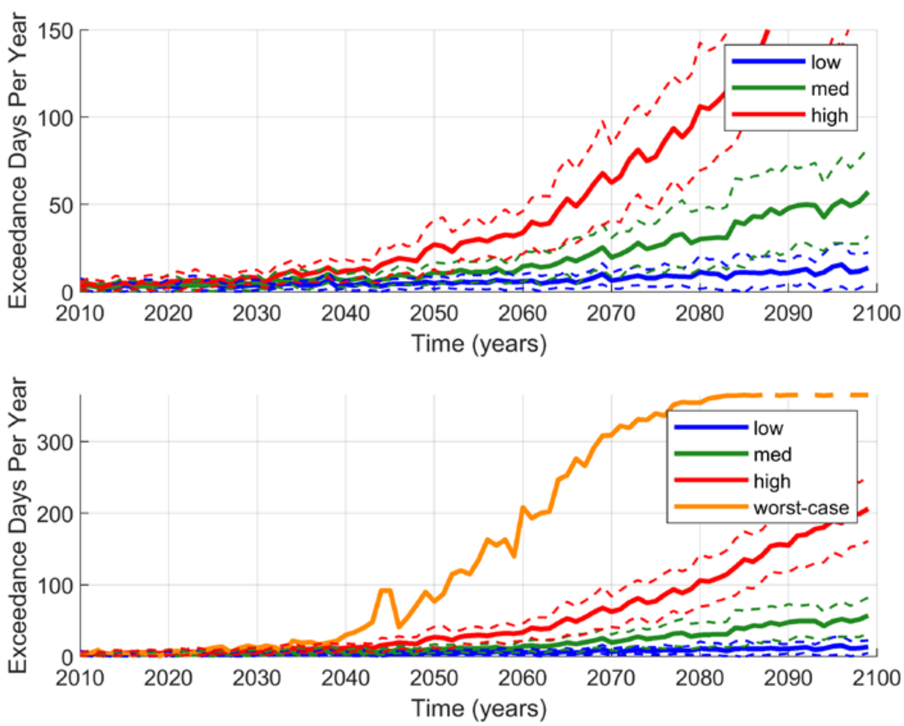

Figure 16 Exceedance days per year when total water levels at the Westport Marina (tide gauge) exceed an elevation of 3.2 m NAVD88.

The final example of total water level (TWL) exceedance elevations in and around Grays Harbor is along the outer coast fronting the Quinault Beach Resort and Casino. Similarly to locations within the bay, extreme coastal TWLs along the outer coast are the result of interactions between multiple oceanographic, hydrological, geological, and meteorological forcings that act over a wide range of scales (e.g., astronomical tide, wave set-up, large-scale storm surge, monthly mean sea level, vertical land motions, etc.). However, the additional presence of large breaking waves means that, at any given time, the elevation of the TWL, relative to a fixed datum, is comprised of two components such that

$$TWL = SWL + R \qquad \textit{Eq. 1}$$

where the *SWL* is the still water level, or the measured water level from tide gauges, and R is a wave induced component, termed the wave runup (Figure 17). The wave runup calculation is often dependent on the wave height, wavelength, and the local beach morphology (e.g., Ruggiero et al. 2001), making it a highly site-specific computation. Because we are interested primarily in extreme events, R is parameterized using R2%, defined as the 2% exceedance percentile of runup maxima.

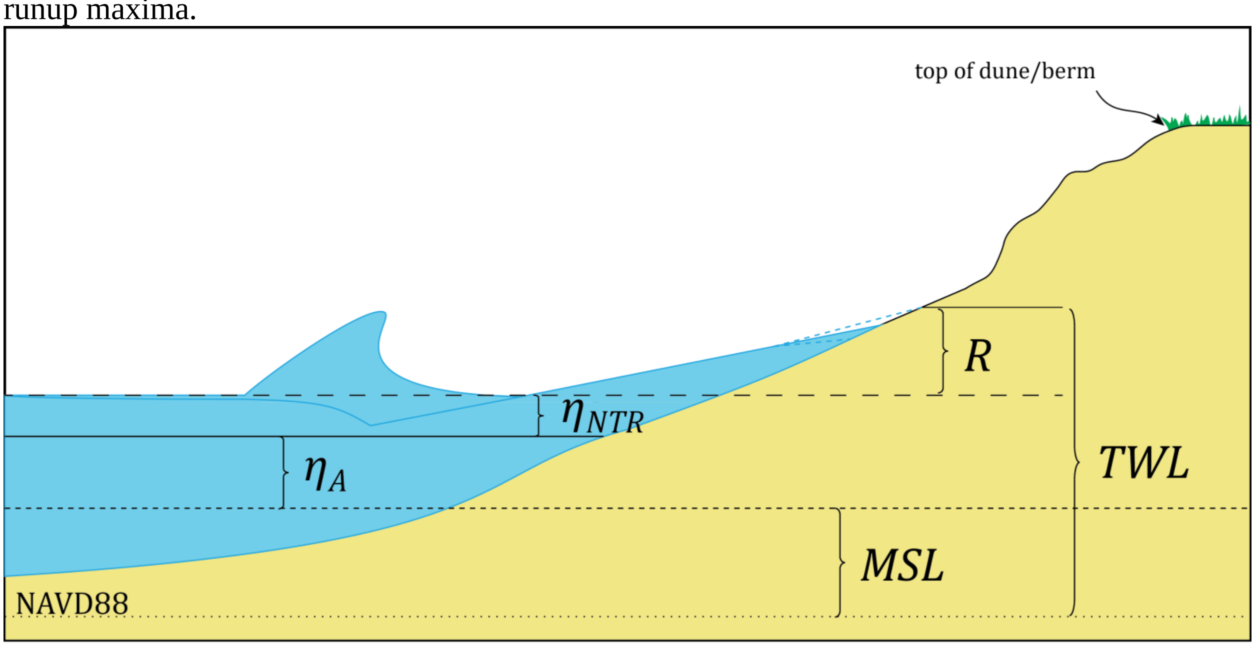

Figure 17 Definition sketch of total water levels (TWL). Dune/bluff erosion or infrastructure damage occurs when the TWL, relative to a datum such as the land based NAVD88 datum, exceeds the elevation of the dune/structure toe, and overtopping/flooding occurs when the TWL exceeds the elevation of the dune or structure crest (figure from Serafin and Ruggiero, 2014).

TWLs can then be compared to backshore morphology to estimate the percentage of time certain contours are inundated as well as the risk of coastal flooding and erosion. Figure 18 shows topographic beach profiles collected just in front of the Casino (http://nvs.nanoos.org/BeachMapping). From these data we extracted quantitative information such as the beach slope, the average elevation of the dune toe, and the average elevation of the dune crest relative to NAVD88. Figure 19 shows one example time series of forcing conditions, including TWLs calculated using equation 1, fronting the Casino. Similar to our analyses for stations within Grays Harbor, Figures 20 and 21 show days of exceedance in which TWLs are projected to be above the dune toe (a proxy for coastal erosion, Figure 20) and above the dune crest (a proxy for inland flooding, Figure 21).

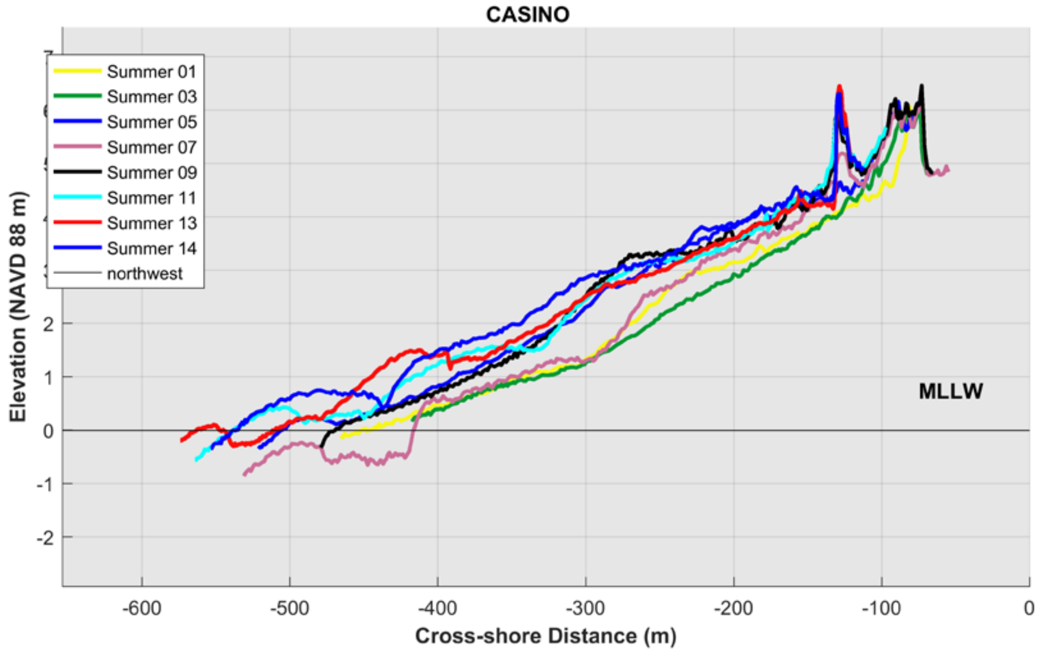

Figure 18 Beach profile fronting the Quinault Beach Resort and Casino

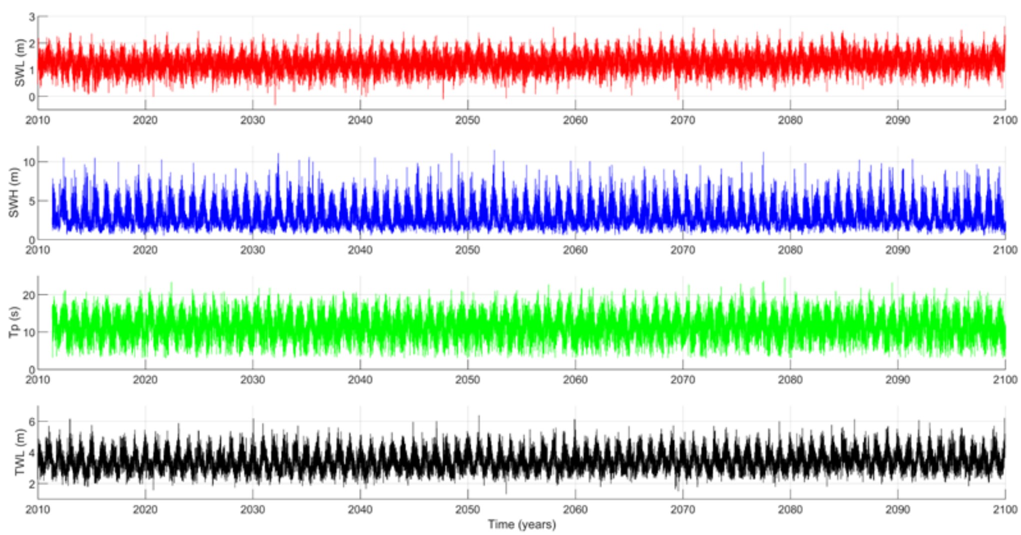

Figure 19 Forcing conditions for computing total water levels fronting the Quinault Beach Resort and Casino.

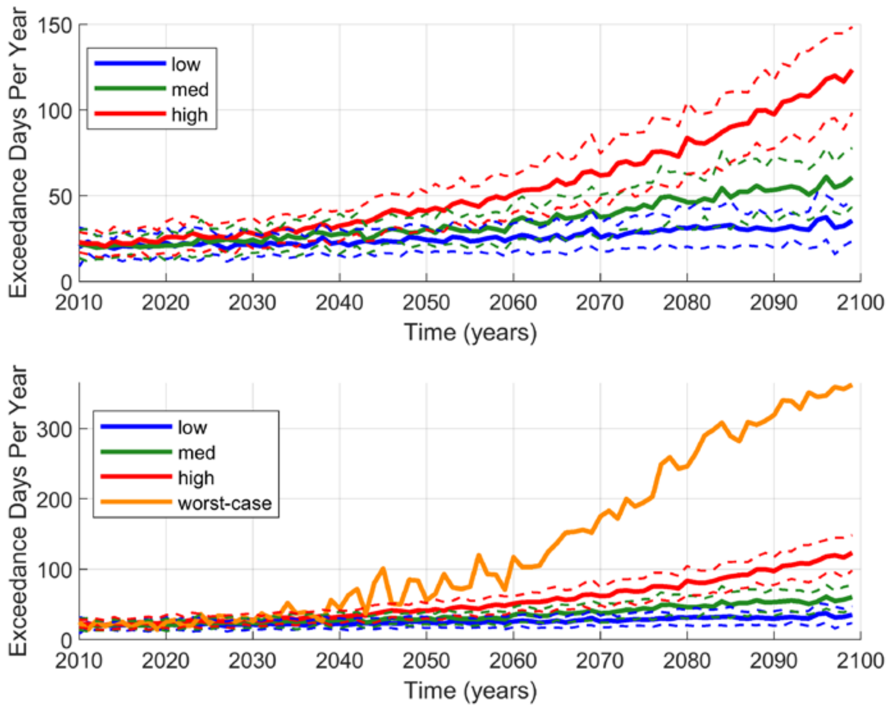

Figure 20 Exceedance days per year when total water levels at the Quinault Beach Resort and Casino exceed an elevation of 4.5 m NAVD88 – approximately the elevation of the dune toe and hence a proxy for possible erosion.

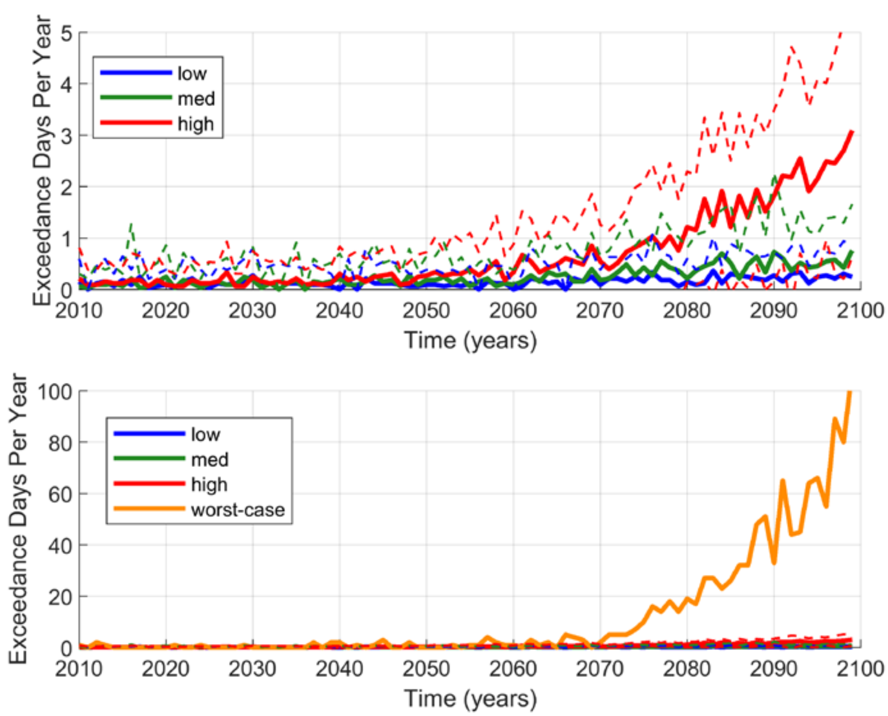

Figure 21 Exceedance days per year when total water levels at the Quinault Beach Resort and Casino exceed an elevation of 6.0 m NAVD88 – approximately the elevation of the dune crest and hence a proxy for possible overtopping and inundation.

2.3 Impact of Climate Change on Simulated Quillayute River Total Water Levels

Models for the Quillayute River were set up to explore the influence of climate change through increasing sea level and increasing winter river discharge on coastal flood probabilities. With increasing sea levels, flooding along the first 2.5 km of the Quillayute River shifts dramatically. For example, at river km 1.5, less than one day per year in present day, low, and medium impact climate scenarios changes to 3 and 95 days per year in high and worst case impacts scenarios, respectively (Figure 22). Flooding in the worst-case scenario could increase to one-third of the year in certain along-river locations (not shown). For all scenarios, river km 5 and upstream is not affected by changing ocean water levels. An increase to winter streamflow alters flooding the most between river km 3 and 4 (Figure 23), and minimally across other locations of the river.

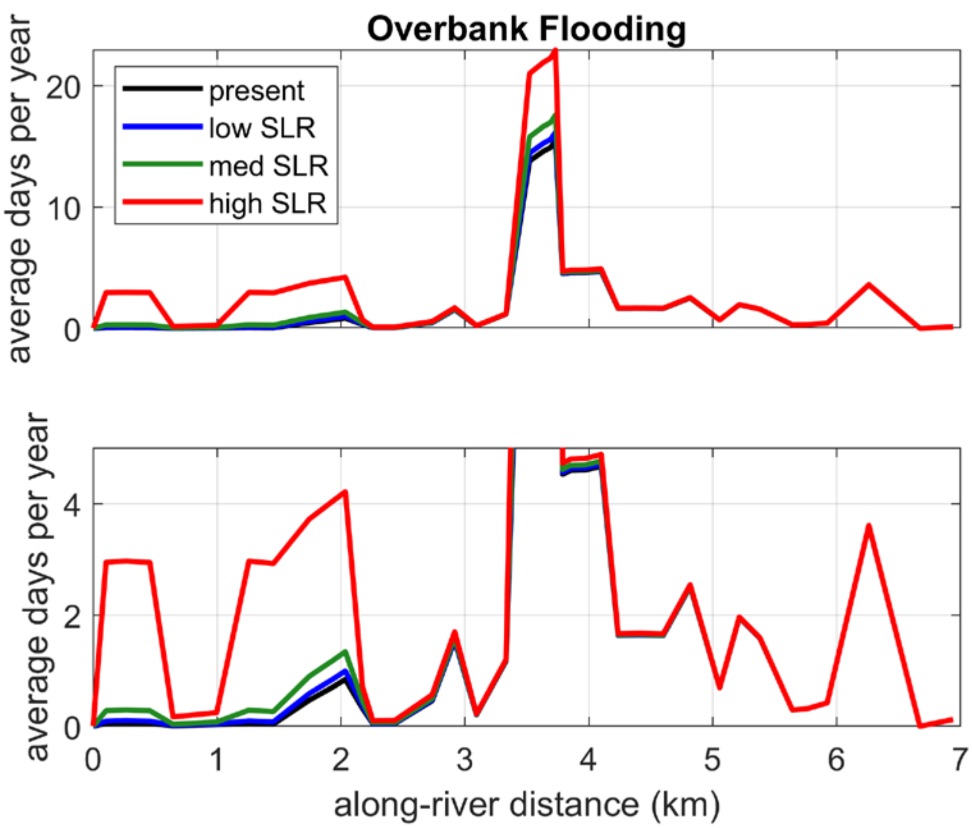

Figure 22 Average number of days per year of possible flooding as a function of river kilometer. For present-day climate, low sea level rise (SLR), medium SLR, and high SLR. Both panels show similar data but at different scale.

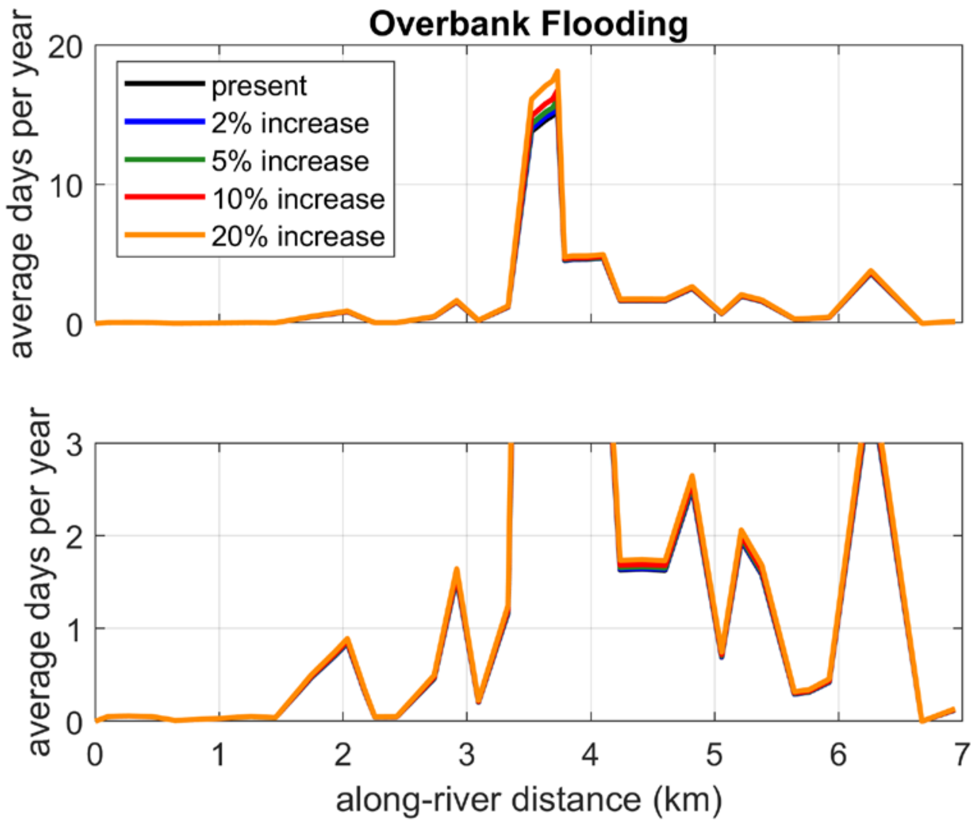

Figure 23 Average number of days per year of possible flooding as a function of river kilometer. For present-day climate, a 2%, 5%, 10%, and 20% increase in winter river discharge.

Objective 3: Assess the Impact of Present Day and Forecasted Future Coastal Flooding Events on Infrastructure in Several Communities within the Treaty of Olympia

3.1 Impact of Flooding on Infrastructure

One valuable application for the surrogate model approach developed in this project is the ability to produce more robust estimates of the 100-year flood event for Grays Harbor. The 100-year flood event is the most common engineering tool for determining flood risk in communities. This surface represents flooding that has a 1% chance of occurring in any given year. The 100-year flood event is often used for community development planning, flood insurance premiums, and many other applications. Therefore, any improvements to how this metric is computed can provide a wide range of benefits.

An example of the 100-year flood event results from this study is shown below in Figure 24. This is a unique application as many extreme flood inundation studies assume a spatially constant 100-year water level (known as a bathtub model as the assumption that water raises statically like a bathtub). In contrast, this approach is able to calculate spatial variability in this flooding surface. This is found to be a significant factor with some locations experiencing 100-year water elevations that are half a meter higher than other locations. Additionally, these results can be considered relatively more robust than traditional techniques since they are calculated using extreme events from 100-year simulated time series. Generally, 100-year flooding events are based on statistical extrapolations from short simulations or observed events. This results in significant uncertainty as a result of the extrapolation. This new approach therefore allows a significant reduction in this uncertainty, at least in terms of the present-day climate. Future projects could fully explore how this refined flooding estimate may affect specific infrastructure in and around Grays Harbor, WA.

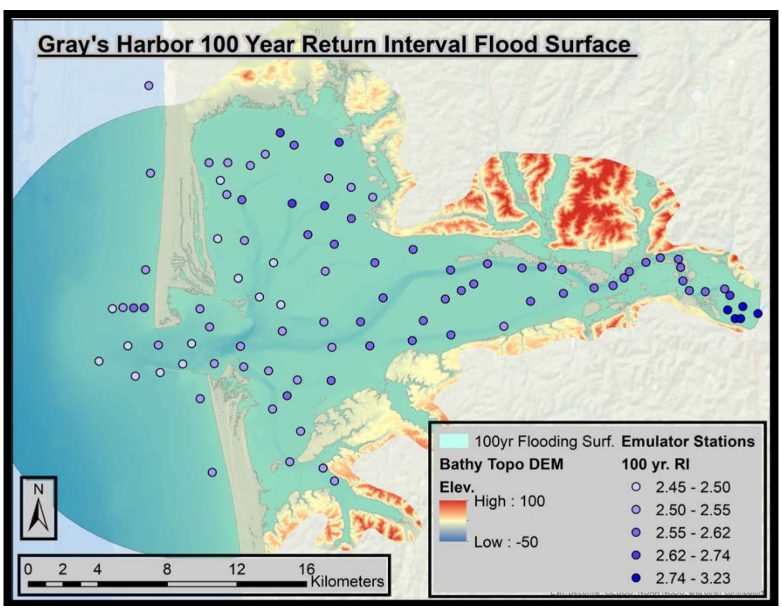

Figure 24 Example 100-year return flood surface produced from ADCIRC results. Vertical datum is relative to mean sea level.

Similarly, the 100-year (and other) return level event can be extracted along the Quillayute River and the drivers of these events can be assessed. The 100-year event is typically assumed to be driven by a specific forcing event, such as the 100-year rainfall or storm surge. However, for processes driven by multiple dimensions, different sizes and combinations of forcing conditions could potentially generate extreme flood magnitudes. The relative importance of both oceanic and riverine forcing to extreme water levels (WLs) emerges when averaging the magnitude of the drivers of the water level return levels at each transect from all seventy 500-year simulations (Figure 25). The magnitude of the average streamflow (Q) driving water level return levels gradually increases over river km 0–2 and then is consistent from river km 2 to 10. Downstream, between river km 0 and 0.25, the magnitude of the average still water level (SWL) driving water level return levels is consistent and then gradually decreases over a 1 km zone. This approach confirms the presence of an oceanographic-fluvial transition zone, where traditional methodologies for defining return level events based on a single driver are insufficient for defining water level return levels. Between river km 1 and 2, a range of SWL and Q conditions drive all return level events, and extreme water levels are driven by neither the individual SWL or Q return level event.

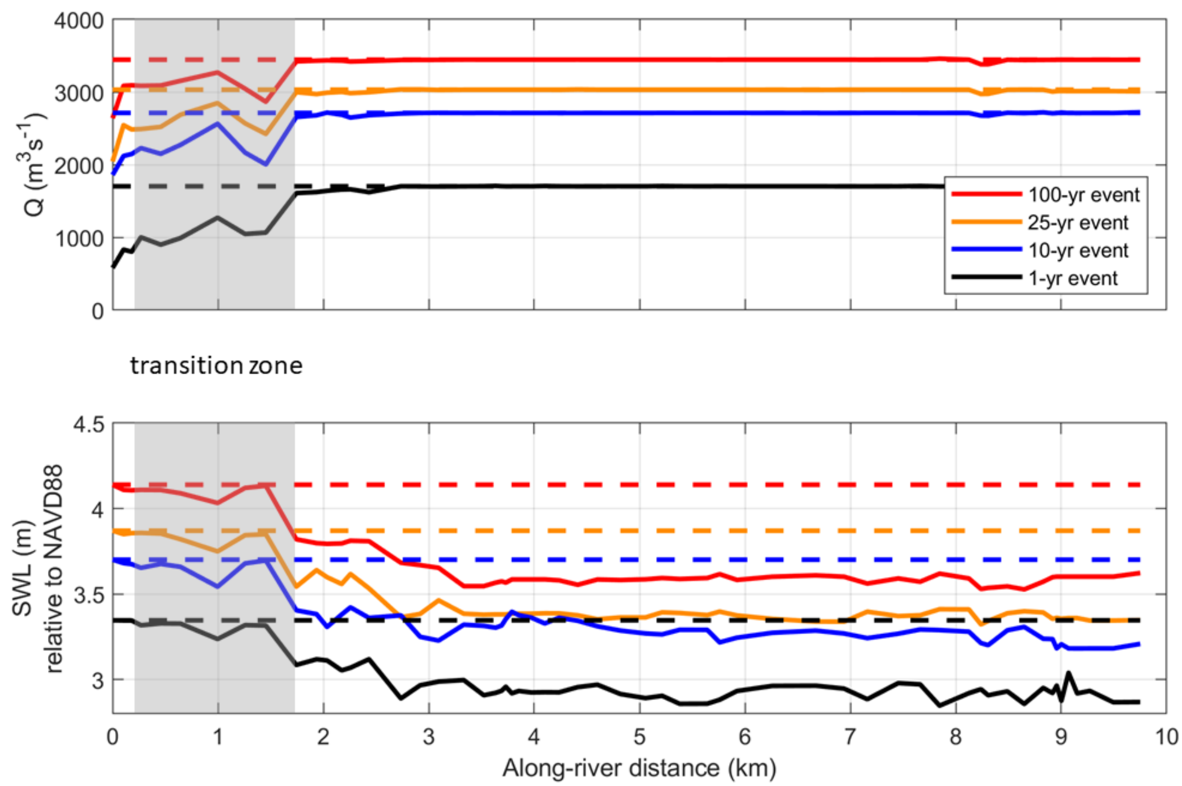

Figure 25 The average forcing condition driving along-river return levels at each transect where a) displays the Quillayute streamflow (Q) conditions and b) displays the still water level (SWL) conditions. The dashed lines depict the individual forcing conditions, where the along-river return level is assumed to be driven by either Q or SWL. Red, orange, blue, and black lines represent the 100, 25, 10, and annual return level event. The grey shaded area represents a transition zone, where the water level is driven by a combination of SWL and Q events.

The approach taken for the Quillayute River also allows consideration of flooding hazards along the river basin. As an example, the developed modeling setup can be used to assess important metrics such as the number of days per year that river stage exceeds bank elevation as a proxy for flooding potential (shown schematically for two locations in Figure 26). Figure 27 is an estimate of the average number of days per year in which the river elevation exceeds its banks for the present-day climate.

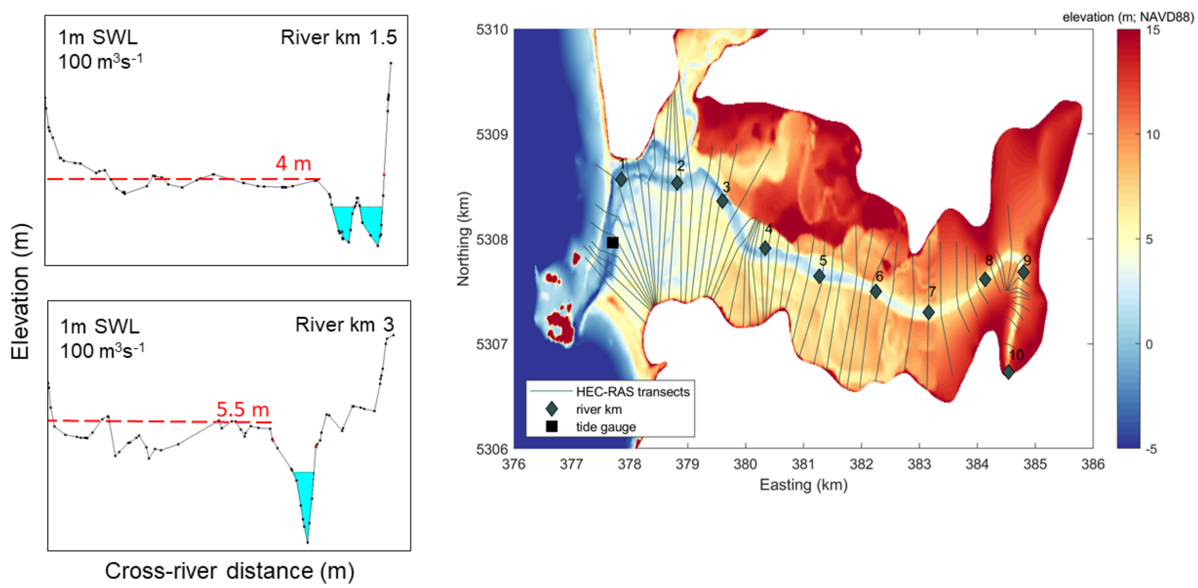

Figure 26 Example results from HEC-RAS modeling of the Quillayute River showing water surface elevations at model topography/bathymetry at River km 1.5 and River km 3 for low flow conditions.

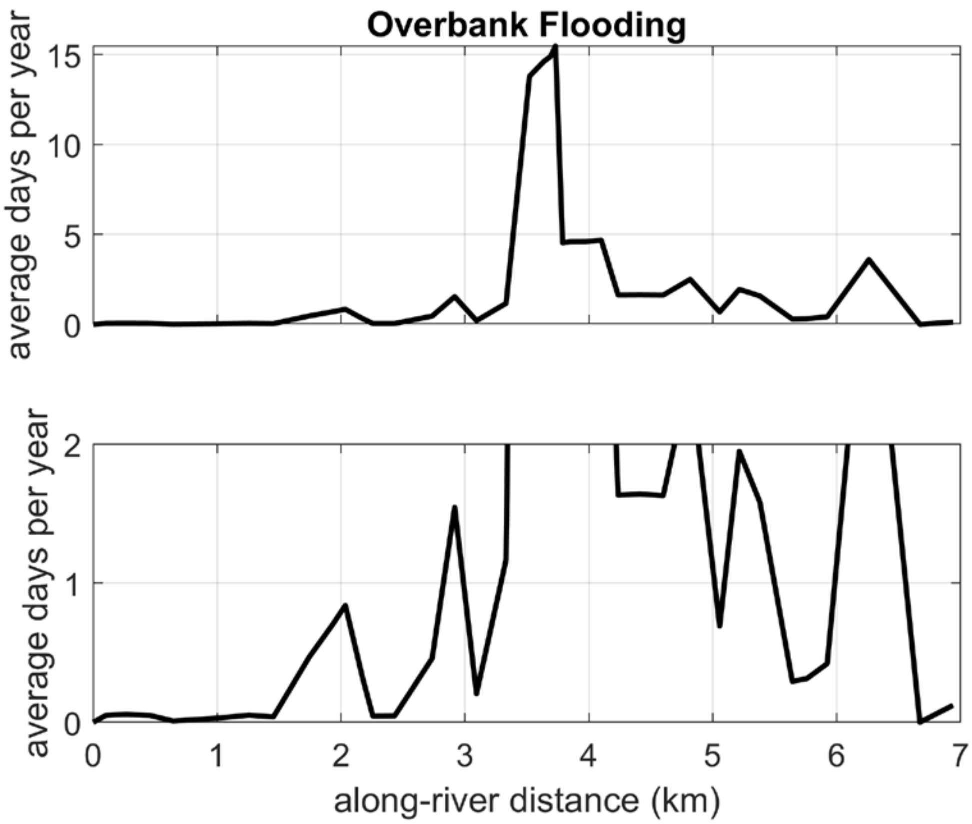

Figure 27 Average number of days per year of possible flooding as a function of river kilometer for present-day climate. The bottom panel displays the same results, but zoomed in.

We also evaluated the change in exceedance days per year at specific locations near the tide gauge as well as near river km 3.5 near the Thunder Field area (Figure 28). Here, we counted the number of days per year water levels exceeded 4m NAVD88 and 5m NAVD88, the approximate elevation of the bank on the Quileute Reservation side of each transect. Under low and medium climate change impact scenarios, the bank near the tide gauge is exceeded every few years, but not consistently. For the Thunder Field area, we see that while important, sea level rise has a lesser influence on flooding, which means increases to discharge will matter comparatively more for this location. For the worst-case scenario, sea levels flood the tide gauge area more than half of the year by mid-21st century and then every day of the year by the end of the 21st century (Figure 29). For this upper end SLR scenario, sea levels influence flooding at the Thunder Field area as well.

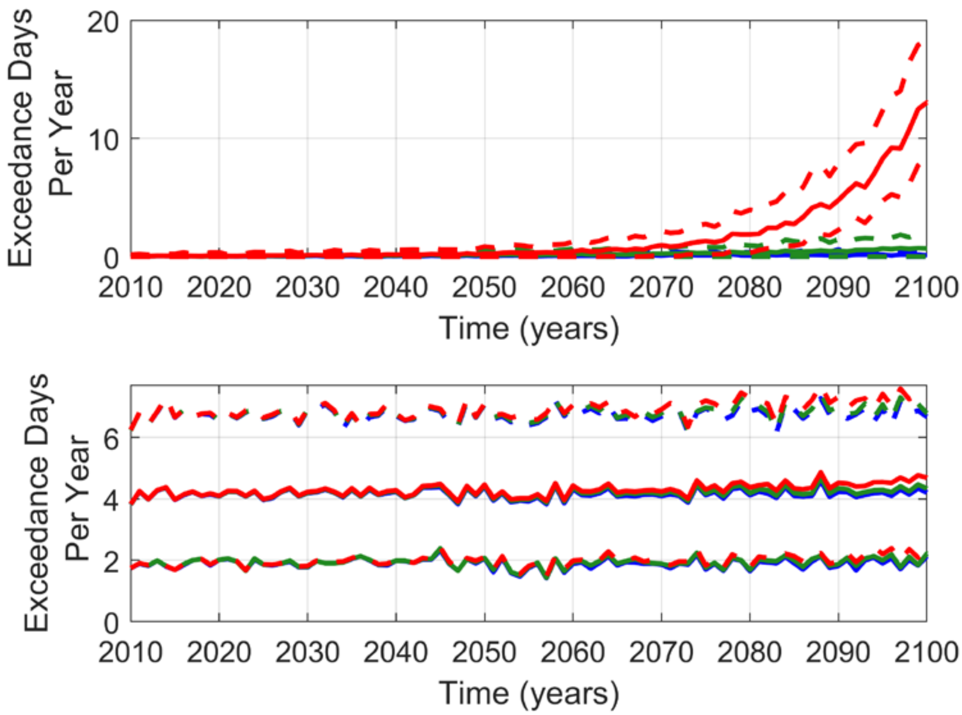

Figure 28 Average number exceedance days per year for the tide gauge (top) and Thunder Field area (bottom) during low (blue), medium (green), and high (red) sea level rise scenarios. The solid lines indicate the average while the dashed lines indicate bounds around the average.

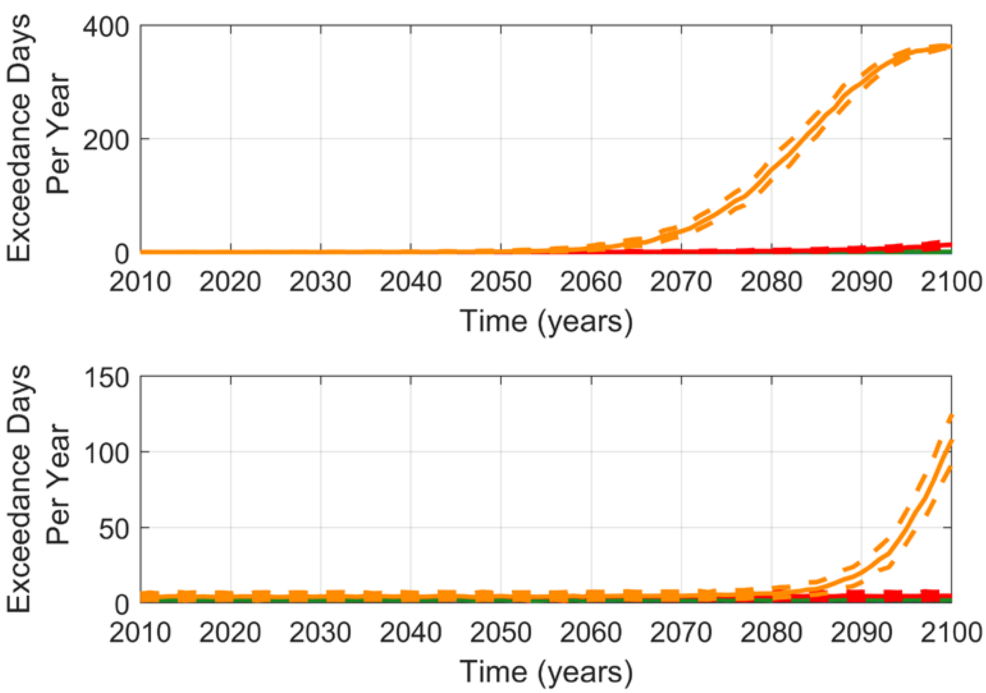

Figure 29 Average number exceedance days per year for the tide gauge (top) and Thunder Field area (bottom) during low (blue), medium (green), and high (red), and worst case (orange) sea level rise scenarios. The solid lines indicate the average while the dashed lines indicate bounds around the average.

3.2 Climate Change Impacts, Recommendations for Adaptation, and Suggestions for Future Research

As explored while emulating extreme water levels in Grays Harbor, analysis indicates that infrastructure along the bay will be exposed to significant flooding risk from climate change. That said, this risk will be sensitive to climate change impact scenario with characteristically different outcomes between the low and worst-case scenarios. Overall, the low climate change impact scenario is associated with modest impacts to infrastructure at the locations of interest. Nuisance flooding for the Quinault and Westport Marinas were projected to remain on the order of 10 days per year even by the year 2100. A similar result was found for extreme total water levels, including wave runup, at the beach fronting the Quinault Beach Resort and Casino (although with exceedance of the dune toe approaching 20 days per year). While this represents a change to the current hazard status quo, it might not be a drastic outcome.

The low climate change impact scenario is 95% likely to be exceeded (see section 2.1). Therefore, impacts to flooding associated with climate change are likely to be greater than this outcome. The high climate change impact scenario, which is 5% likely to be exceeded, shows a very different outcome to infrastructure with nuisance flooding exceeding 150 days a year. This could drastically affect the functionality of these marinas with some form of adaptation being required. The fronting beach for the Quinault Beach Resort and Casino would likely become erosional with over 100 dune toe impact events a year. This said, overtopping projections remain low even for the high scenario at around 3 days per year by 2100. This result may change though as the beach profile adjusts to an erosional regime. Even this outcome is mild in comparison to the worst-case scenario which sees both marinas becoming continuously inundated (365 days a year) and overtopping/flooding of the Quinault Beach Resort and Casino approaching one-third of the year. While this outcome is unlikely, it is within the range of plausible future climates.

As shown by the wide range of uncertainty in future outcomes, appropriate adaptation measures will be very dependent on which scenario comes to pass. Traditionally, responses to climate change can be divided into groups of general strategies or grouping of adaptation measures such as “realign”, “protect”, and “restore” (e.g., Mills et al. 2018; Lipiec et al. 2018). A “realign” scenario involves changing human activities to suit the changing environment (e.g., relocation of people and infrastructure). A “protect” scenario involves resisting change through the maintaining/strengthening of current infrastructure, mainly through engineering solutions (e.g., shoreline armoring, seawalls, etc.). A “restore” scenario could involve implementing natural or nature-based solutions to accommodate environmental change (e.g., wetland restoration or dune building to reduce flooding). Each of these approaches most likely would bring out a set of tradeoffs that are highly dependent on the specific context of the application. While a detailed cost/benefit analysis of various adaptation measures was not part of the scope of this study, some general points can be made.

While our analysis suggests that overtopping of the beach fronting the Quinault Beach Resort and Casino will likely remain modest, this could change drastically if the fronting beach profile changes significantly. Projected increases in impacts to the dune toe could provide the mechanism for this to occur. Therefore, it is recommended that careful monitoring of the fronting beach be maintained (e.g., http://nvs.nanoos.org/BeachMapping). If the beach appears to be shifting towards an erosional regime, then further detailed research into adaptation measures may be warranted. Based on the significant hard infrastructure investment in the Quinault Beach Resort and Casino, relocation is unlikely. Therefore, some form of hard or soft (natural) protection may be necessary. The current location of the Resort is well set back from the shoreline providing with a healthy dune system. This potentially provides the opportunity for a natural solution although this will have to be explored more fully as the beach system changes.

With projected increases to flooding at the investigated Marina locations, likely some form of adaptation will be required (although the timing will be dependent on climate scenario). Realignment will likely be difficult due to the high cost of moving infrastructure, especially hard engineering structures. Rather a protective adaptation approach will likely be required through increasing armoring height and reinforcing the waterfront. Some infrastructure may be able to be moved back but a full analysis will be necessary to determine the optimal path forward.

For the La Push study site, results indicate that climate change impacts may significantly change the frequency with which the Quillayute River floods. Changes to high water levels will impact river stage as far as 5 km inland, most likely significantly worsening the existing Thunder Field erosion/avulsion threat (Figure 30). Assuming channel morphology stays similar, higher flows would increase flooding along some sections of the river and may influence more flooding closer to the river mouth. At the same time, changes in mean sea level will likely drive the oceanographic influence upstream. While we have characterized the spatial variability in driving processes to flooding in the present day, there is a high likelihood that changes in the future climate will shift the importance of these interacting processes. It is important to acknowledge that the un-stabilized nature of the Quillayute River means that its channel bathymetry and path are very likely to change moving forward. This is both a source of uncertainty in the results from this study (which uses a combined bathymetry from multiple channel geometries) as well as for future projections. Channel geometry and estuary bathymetry are first order controls on flooding processes so any changes in the Quillayute River would likely result in corresponding change to flooding vulnerability. Any considerations of adaptation measures should consider this significant source of uncertainty in its analysis.

While several Treaty of Olympia tribal communities experience compound flooding issues associated with both riverine and oceanographic forcing, our second modeling approach focused on the Quillayute River and the community of La Push due to the availability of data for sufficient model calibration and validation. Collecting relevant data to build similar models in the Quinault, Queets, and Hoh Rivers would be useful for a wide range of analyses. Installing tide gages, at least temporarily, at some of these streams will help to elucidate when river signals are influencing observed non-tidal residuals (see Serafin et al. 2019 [Appendix B] for details on an approach for quantifying this). Finally, developing sophisticated process-based models (e.g., CoSMoS, Barnard et al. 2014) for the region will allow for detailed exploration of extreme events in the present day as well as under climate change. Coupling models like CoSMos with stochastic approaches (so called hybrid modeling approaches such as those described in this report) is recommended.

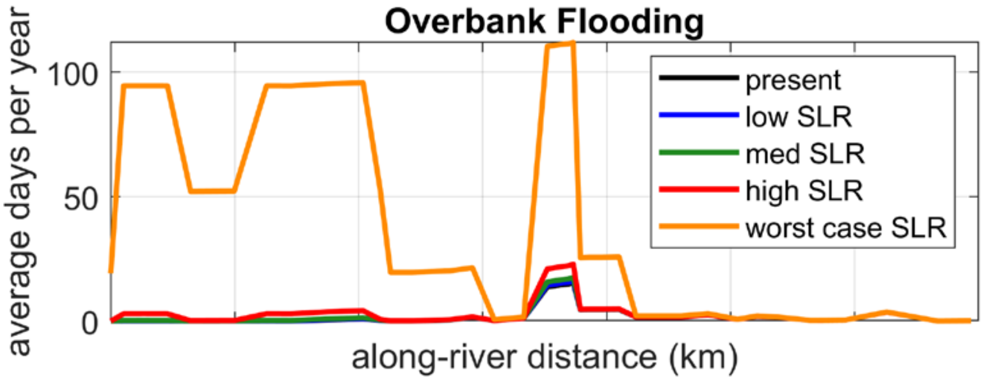

Figure 30 Average number of days per year of possible flooding as a function of river kilometer. For present-day climate, low sea level rise (SLR), medium SLR, and high SLR.

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The majority of citations for the methods developed are in Appendices A and B.

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Appendix A

The following is a reproduction of the publication:

Parker, K., P. Ruggiero, K. Serafin, and D. Hill. 2019. "Emulation as an Approach for Rapid Estuarine Modeling." *Coastal Engineering* 150: 79–93. https://doi.org/10.1016/j.coastaleng.2019.03.004.

Appendix B

The following is a reproduction of the publication:

Serafin, K., P. Ruggiero, K. Parker, and D. Hill. 2019. "What's Streamflow Got To Do With It? A Probabilistic Simulation of the Competing Oceanographic and Fluvial Processes Driving Extreme Along-River Water Levels." *Nat. Hazards Earth Syst. Sci. Discuss.*, in review. https://doi.org/10.5194/nhess-2018-347.

Appendix C

The following is a reproduction of the Executive Summary for Chapter 5: Coastal Hazards in "Climate Change Vulnerability Assessment for the Treaty of Olympia Tribes" (Dalton et al., 2016).

Coastal ecosystems and communities ***along the outer coast*** of the western Olympic Peninsula are currently at risk of erosion and flooding hazards driven by extreme total water levels (TWLs)—mean sea level combined with storm surge, high tide, seasonal and interannual variability in sea level, and ocean wave characteristics. Understanding the magnitude and frequency of these extreme water level events will better prepare coastal communities for dealing with both present day and future coastal hazards which effect critical shoreline habitats and infrastructure. TWLs along the shoreline of the Treaty of Olympia area are modeled for both present day conditions and future conditions under rising sea levels and increasing wave heights.

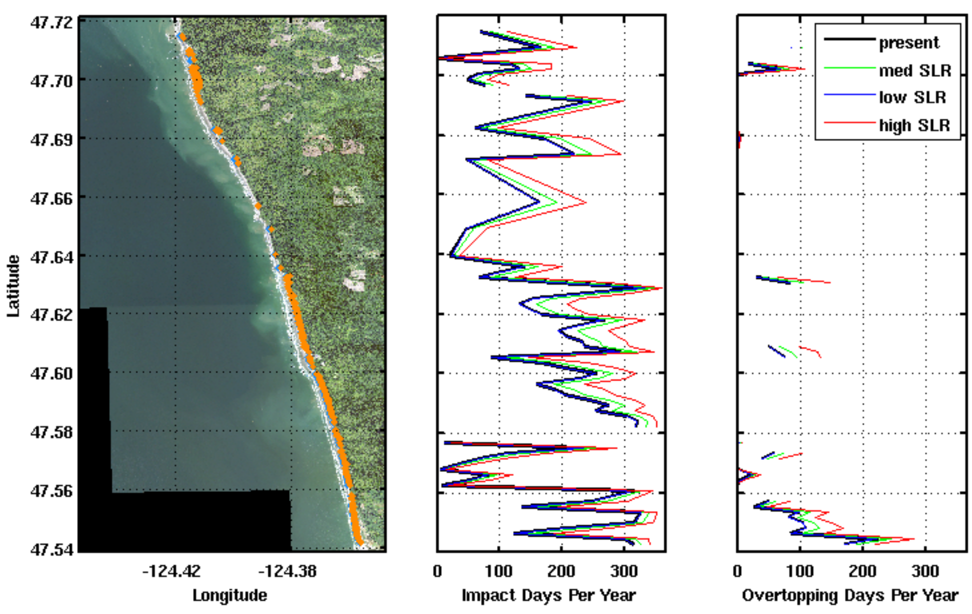
Along the Pacific Northwest coast, sea level is projected to rise by 4-56" by 2100, but local projections vary depending on the local tectonic setting. The central and southern Washington coast is uplifting at a slower rate than the northwest Olympic Peninsula, even subsiding in some areas, and thus is poised to experience the effects of sea level rise sooner than the northwest coast. In this analysis, sea level projections for 2050 range from -0.10 to 0.5 meters (-3.9" to 19.7") and the observed increasing wave height trend is allowed to continue to mid-century. Two types of high water events are analyzed: nuisance events (everyday hazards characterized by the average amount of days per year that the coastline experiences either overtopping or collision) and extreme events (such as the annual maximum event or the 100-year return level event).

The type of backshore[1] is important for characterizing TWLs and their impacts. By comparing elevations of TWLs to the elevation of the foremost backshore feature, we can estimate the risk of overtopping and inundating the backshore area and the risk of colliding with and eroding the backshore feature be it a bluff, cliff, dune, or engineered structure. The Hoh, Quileute, and Quinault coastlines, and surrounding beaches, consist of highly variable morphology including both low-sloping and steep beaches comprised of either sand or gravel and are backed by dune, bluffs, or cliffs. In general, however, the most characteristic morphology includes steep cliffs and bluffs, occasionally fronted by ephemeral beach berms. The number of days per year that these smaller fronting features experience impact (erosion) and overtopping (flooding) varies along the coastline (Table C1), as do extreme TWL return level events. These ephemeral features most likely act as a buffer to backing cliff or bluff erosion and critical habitat.

[1] The backshore is the region of the beach extending from the high water line to the landward extent of the beach. The most foremost backshore feature is therefore the first feature (dune, cliff, bluff, etc.) in which high water levels may impact.

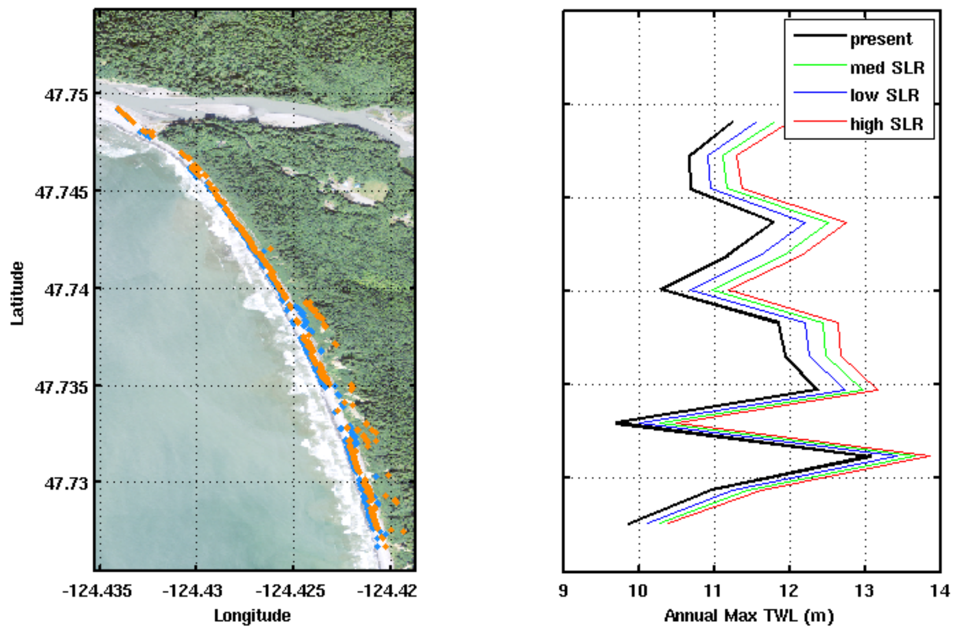
The beach segments from south of Ozette Lake to Rialto Beach, along the Quileute reservation, and Ruby Beach to the Queets River experience impact (erosion) regime on the leading backshore feature for at least half the year largely due to steep beach slopes and low dune toes. Most other areas along the Treaty of Olympia coastline experience impact days about a third of the year. In general, overtopping occurs much less often than the collision regime, but is most common near Kalaloch and some parts of the Taholah area where it occurs about 100 days per year. Under all sea level rise scenarios water levels increase along the coast, driving increases in number of impact or overtopping days per year (Table C1). The largest increases in impact days per year occur along the beach segment from Ruby Beach to the Queets River (Figure C1) and areas within the Cape Alava to Rialto Beach segment. The overtopping regime remains infrequent, due to the large amount of cliffs and bluffs backing the majority of the coastlines, but increases by a few more weeks per year along the Cape Alava to Rialto Beach segment and the Hoh Reservation coastline.

Figure C1 *Impact days per year (IDPY; middle) and overtopping days per year (ODPY; right) for Ruby Beach to the Queets River. Bolded black lines indicate the average (across 35 simulations) IDPY/ODPY computed using the present-day simulations while blue, green, and red lines indicate future simulations for low, medium, and high sea level rise, respectively.*



The annual maximum TWL event increases under all SLR scenarios for the Hoh, Quileute, and Quinault coastlines, but the Hoh coastline may receive the largest changes (Figure C2) likely due to the overall steeper beaches. Likewise, the steeper beaches from Ozette South may result in larger increases in the annual maximum TWL event compared with First Beach (Table C1). The southern Quinault coast segment experiences the smallest increase in the annual maximum event. However, even slight increases in water levels may matter more in locations with critical habitat or infrastructure (e.g., the Taholah area) rather than locations where little infrastructure or high backing cliff morphology exists.

Figure C2 *The annual maximum TWL for the Hoh reservation. Bolded black lines indicate the average (across 35 simulations) annual maximum TWL computed using the present-day simulations while blue, green, and red lines indicate the average annual maxima of future simulations (12 each scenario) for low, medium, and high sea level rise, respectively.*



Certain species with economic and cultural significance to the Treaty of Olympia tribes (e.g., surf smelt, razor clams, shorebirds) may be impacted by the projected future changes in extreme total water levels. While the projected changes in TWLs by 2050 are likely not severe enough to significantly threaten coastal habitat, some intertidal species may shift landward. For example, across all of the locations, the 3 m contour is inundated every day of the year during the maximum daily TWL under a high SLR scenario. The largest amount of change, on average, is in the southern extent of the Quinault area. While intertidal species, like razor clams and surf smelt, may have the ability to move vertically up the beach, snowy plovers and other back-barrier nesting species may face habitat loss as sea levels continue to rise.

Table C1 *Percent change (and standard deviation) in impact (erosion) and overtopping (inundation) days per year for present conditions and mid-21st century high sea level rise projections and increase in the average annual maximum TWL event for segments of the Treaty of Olympia coastline. The coastline segment is ranked by the average amount of Impact Days Per Year (e.g., on average, Quileute presently experiences the most IDPY and Southern Quinault experiences the least IDPY).*

Coastline Segment	**% Change in IDPY**	**% Change in ODPY**	**Average Increase in Annual Maximum TWL Event**
Quileute (Rialto Beach and First Beach)	+18% (±11%)	+35% (±31%)	+50 cm
Kalaloch (Ruby Beach to the Queets River)	+30% (±25%)	+55% (±34%)	+50 cm
Ozette (Cape Alava to Rialto Beach)	+25% (±36%)	+50% (±45%)	+60 cm
North Quinault (Northern Taholah to Queets River)	+18% (±15%)	+35% (±60%)	+50 cm
Middle Quinault (Point Grenville to Northern Taholah)	+17% (±40%)	+25% (±55%)	+50 cm
Second Beach	+54% (±10%)	+90%[1]	+43 cm
Hoh	+16% (±13%)	+27% (±12%)	+77 cm
Third Beach	+47% (±6%)	+43%[1]	+63 cm
Southern Quinault (Moclips to Point Grenville)	+65% (±33%)	+95% (±30%)	+30 cm

[1] Only one point was included in the analysis, so no standard deviation could be calculated.