PRESENT AND FUTURE VULNERABILITY TO COASTAL FLOODING AT GRINDLE POINT AND THE NARROWS

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Executive Summary

The Town of Islesboro, located on an unbridged Island in Penobscot bay, has begun an effort to enhance the island community's resiliency to the coastal effects of climate change and sea level rise. In particular, the Town is taking a closer look at the threat of coastal flooding at two locations on the island where critical transportation infrastructure is vulnerable to coastal storms and sea level rise. This effort is supported in part by a Coastal Communities Grant through the Maine Coastal Program of the Maine Department of Agriculture, Conservation and Forestry. With this support, the Town has contracted Ransom Consulting Inc. (Ransom) to study the present and future vulnerability to coastal flooding at these two locations, and provide assistance identifying adaptation measures that may be used reduce the coastal flooding risk.

The study combines high-fidelity numerical modeling of storm surge and wave conditions with recent local probabilistic sea level change projections to quantify the probability of present and future flooding from coastal storms at the two critical locations. The results are used to generate flood hazard maps showing a range of return period water levels and wave crest elevations that show how the likelihood of coastal flooding is expected increase in the future due to sea level rise and the increasing uncertainty with longer-term projections. Maps are provided which illustrate the changing hazard at five-year intervals over the next century. Examples are provided that show how the full spectrum of flood probabilities are expected evolve in the future, and how that evolution inform decisions on the timing and prioritization of adaptation measures at specific locations.

Storm surge and wave model data from simulations of historic extra-tropical storms (e.g. nor'easters) were obtained from the U.S. Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NACCS). These data were reviewed and compared to water level observations to assess the validity of the NACCS model result for application in Penobscot Bay. It was found that the NACCS model was too coarse in resolution to reflect the detailed bathymetry and topography at Islesboro, and that the NACCS model simulations tended to underestimate the peak storm tide levels for extra-tropical storms. However, the NACCS model does provide useful information on the coastal storm climatology for the region and the NACCS model data could be effectively used to provide boundary conditions for downscaled numerical modeling of detailed coastal storm water level and wave conditions for Islesboro. A high resolution tightly coupled storm tide-wave model was developed for Penobscot bay with detailed focus on Islesboro and a subset of the NACCS storms, representative of the extra-tropical storm climatology of the Maine Coast were simulated to provide detailed results for Islesboro.

An extreme value analysis was performed on the water levels and wave data generated from the downscaled modeling in order to quantify the flooding hazard at Islesboro due to extra-tropical events, which are expected to drive the majority of flood risk in the region from moderate to severe storm events. The current study does not directly consider the hazard related to tropical storms (e.g. hurricanes), which are less likely than extra-tropical events, but do pose a threat to the region. The currents study also does not directly consider extremes related to purely tidal events (e.g. sunny day flooding), which will have some impact on the future coastal flood hazard at the more frequent, but less severe end of the risk spectrum. As such, the information presented in this study can be considered as a guide for decision making related to moderate to minimally severe storm events, but other sources should be reviewed and future work should be undertaken to better characterize the extreme high and extreme low ends of the coastal flood risk spectrum.

This study presents the current federal scenario based guidance for sea level change planning as provided by the USACE and the National Oceanic and Atmospheric Administration (NOAA).

Localized probabilistic sea level rise guidance that is available in the recent climate science literature is also presented. Discussion is provided which investigates the differences between scenario based and probabilistic guidance, and synergies are identified where both types of guidance may be used together, including enhanced understanding of the need to evaluate the full range of possible sea level rise scenarios when projecting future coastal flooding risk. A Monte Carlo simulation method is employed to combine the localized probabilistic sea level change projections with the coastal flood hazard information, which also accounts for uncertainty in the analysis from various sources. A simple game that illustrates the Monte Carlo technique, is presented as an educational tool to help stakeholders and other interested parties more intuitively understand how sea level change will lead to increasing flooding risk in the future, and how the larger degree of uncertainty associated with longer term projections leads to non-linear increases in the flood risk.

The results of the analysis are used to identify where low-lying roadways at Grindle Point and The Narrows are most vulnerable to present and future coastal flood risk. The future flood hazard information is used to estimate precisely how the flood probabilities for specific sections of roadway will change in the future. In order to assess the risk due to flooding of these roads a qualitative set of potential consequences is identified for a range of possible flood levels, and future hazard information is used quantify the probability of those consequences. Presented in this way, the risk information can aid Islesboro in identifying and prioritizing adaptation actions to best reduce the risk. Based on the vulnerability assessment some general options for adaptation measures are suggested for future consideration. Discussion is also provided, which recommends that future work should evaluate the risk to other infrastructure in addition to low lying roadways, and the effort should be made to better quantify specific consequences of flooding so that the detailed future flood hazard information developed in this study can be applied in a more rigorous risk informed decision making process to help the Town determine the most beneficial courses of action when planning for specific infrastructure improvements.

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1.0 INTRODUCTION

1.1 Maine Coastal Program Grant

The Town of Islesboro (Town or Islesboro) was awarded a Maine Coastal Program Coastal Communities Grant in 2015 to complete a coastal flood vulnerability study at Grindle Point and The Narrows. Islesboro hired Ransom Consulting, Inc. (Ransom) to complete the flood vulnerability study and present the results to the island community. The results will help the Town make decisions that will potentially increase their resiliency to coastal flooding. This report summarizes the study and the results and is meant to help Islesboro plan their future for climate adaptability and flood resiliency.

1.2 Background

Islesboro is an unbridged island in Penobscot Bay with a year-round population of approximately 600 people. While island communities are usually more resilient than their mainland counterparts—due to typical experiences with longer and more frequent power outages, reduced access to emergency services, and weather dependent access to mainland resources—all coastal communities will likely experience an increase in the severity and/or frequency of coastal flood hazard with future sea level change, and thus require accurate actionable information in order to adapt and maintain resiliency in the face of climate change.

The island is long and narrow in geography, approximately fourteen miles long, and ranging from the width of a road to three miles wide. Island communities are inherently vulnerable to coastal storms, and Islesboro is no exception. At the narrowest point on the island, "The Narrows," the peak land elevation is approximately 9.8 feet[1]. Similarly, the elevation of the access road to Grindle point is as low as 8.5 feet. Because of their importance to the vitality of the island, these two locations were the main focus of this study.

Grindle Point and The Narrows are both vital locations to the island and its residents. The ferry terminal is located at Grindle Point. The ferry is the islanders' main means of getting on and off the island. It is used daily by commuters coming to and from the island to go to work and by more than two dozen magnet students travelling to the island for school. Grindle Point is also the location of the Quicksilver, Islesboro's taxi boat, and thus, represents the location of both public boat services to islanders. Additionally, it is the location used by many local lobstermen to access their fishing vessels, one of the island's major economic industries. The ferry terminal building, Grindle Point Lighthouse, boat landing, and portions of Ferry Road are all vulnerable to coastal flooding.

The Narrows is the link between "up-island" and "down-island." It is a narrow, low-lying strip of the land that connects up-island and down-island. The roadway at the narrows is low in elevation and sections of it are exposed to wave action from the east. Portions of the roadway are protected by a riprap revetment, which was constructed following major storms that occurred in the late 1970s. The ferry landing, Islesboro Fire Department, Safety Department, Health Center, emergency medical services, and airport are all located down-island. If the roadway at The Narrows were to become inundated or damaged, the residents on the northern half of the island would be disconnected from the ferry and all of the island's public services.

Given the importance of these two locations, the stakeholders for this project include all residents on the island, the Maine State Ferry Service (Maine DOT), mainland residents who commute to the island for

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[1] Elevations are estimated based on 2011 USGS LIDAR ground classified returns. All elevations in this report refer to the North American Vertical Datum of 1988 (NAVD88), unless otherwise specified.

work, and the magnet students who commute to the island for school. Additionally, any flooding at the Ferry landing may impact the Town's parking lot, the Grindle Point Lighthouse, the Maine State Ferry Service building, the ferry terminal itself, and the public docks, which are used by recreational boaters and lobsterman to access their boats. Island residents, who reside north of The Narrows, will also be especially vulnerable, as they may be disconnected from the ferry and the island's emergency services during an extreme storm event.

1.3 Objective

The objective of this study is to develop detailed coastal flood hazard information for two critical locations on Islesboro, using coastal hazard information from the U.S. Army Corps of Engineers (USACE) recent North Atlantic Coast Comprehensive Study (NACCS) and recent guidance on the probability of future local sea level rise. This study will help the community assess their vulnerability to present and future flooding events and identify appropriate adaptation solutions to mitigate increasing flood risks, while also providing an example of a detailed community level hazard analysis to be shared with other island communities.

2.0 NORTH ATLANTIC COAST COMPREHENSIVE STUDY

2.1 Overview of the NACCS

Following the wide-spread destruction caused by Hurricane Sandy in October 2012, Congress appropriated funding for the USACE to conduct an extensive study of the impacts of Hurricane Sandy, as well as a comprehensive study of coastal flood hazards from Maine to Virginia (the NACCS)[2]. The primary objective of the NACCS was to address the flood risks of vulnerable coastal populations throughout the North Atlantic Coastal Region. Although the impacts of Hurricane Sandy were minimal in Maine, Maine was included in the study so that state interests and local communities would have a consistent approach to identify local flood risk throughout the entire North Atlantic region. While the study provides a thorough assessment of the physical characteristics and probability of coastal storm impacts (storm surge and wave conditions), which are essential for effective flood risk management, it did not include any localized engineering calculations, which are needed for site-specific assessments of coastal flood hazards associated with overland flooding, wave run-up, or coastal erosion. Instead, the NACCS was intended to provide the basis needed to inform local studies of the coastal flood vulnerability, which is how it has been used in this study.

The NACCS used state-of-the-practice statistical methods to determine the magnitude and likelihood of the coastal flood hazard associated with coastal storms, including tropical cyclones (e.g. hurricanes) and extra-tropical cyclones (e.g. nor'easters). These statistical methods, known as the Joint Probability with Optimal Sampling[3] (JPM-OS) method for tropical storms, and the Composite Storm Set[4] (CSS) method for extra-tropical storms, represent the culmination of advances in coastal storm climatology, after more than a decade of effort from the USACE and the Federal Emergency Management Agency (FEMA) to modernize coastal flood hazard assessments for Atlantic and Gulf of Mexico coasts of the United States.

The NACCS also used leading edge advancements in high-fidelity numerical modeling to simulate the spatially variable physics of the tides, storm surge, and wave responses from extreme coastal storms. The NACCS employed the USACE's Coastal Storm Modeling System (CSTORM-MS), which couples together a sequence of numerical models including the Planetary Boundary Layer model (PBL) to simulate wind and barometric pressure fields, the WAM wave model to simulate deep ocean wave generation and propagation, and the ADvanced CIRCulation hydrodynamic model tightly coupled with the Steady-state WAVE spectral model (ADCIRC+STWAVE) to simulate the combined physics of tides, storm surge, wave transformation, and wave setup. CSTORM-MS was used to simulate the coastal ocean's response to 1050 synthetic tropical cyclones and 100 extra-tropical cyclones utilizing High Performance Computing (HPC) on the massive supercomputers housed at the USACE's Engineer Research Development Center (ERDC) in Vicksburg, Mississippi. The storms were simulated with and without the dynamic interaction of tides to estimate the non-linear interactions between tides and storm

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[2] Information on the NACCS can be found online at http://www.nad.usace.army.mil/CompStudy/. Also, please refer to the following USACE technical reports that describe the NACCS modeling and statistical analyses:
Nadal-Caraballo, N.C., J.A. Melby, V.M. Gonzalez, A.T. Cox. 2015. *North Atlantic Coast Comprehensive Study - Coastal Storm Hazards from Virginia to Maine*, ERDC/CHL TR-15-. Vicksburg, MA: U.S. Army Engineer Research and Development Center.
Cialone, M.A., T.C. Massey, M.E. Anderson, A.S. Grzegorzewski, R.E. Jensen, A. Cialone, D.J. Mark, K.C. Pevey, B.L. Gunkel, T.O. McAlpin, N.C. Nadal-Caraballo, J.A. Melby, J.J. Ratcliff. 2015. *North Atlantic Coast Comprehensive Study – Coastal Storm Model Simulations: Waves and Water Levels*, ERDC/CHL TR-15-. Vicksburgg, MA: U.S. Army Engineer Research and Development Center.

[3] FEMA, 2016. Guidance for Flood Risk Analysis and Mapping, Statistical Simulation Methods. U.S. Department of Homeland Security Federal Emergency Management Agency Guidance Document 77, November 2016.

[4] Nadal-Carabalo, N. J.A. Melby, B.A. Ebersole, 2012. Statistical Alanysis and Storm Sampling Approach for Lake Michigan and St. Clair. ERDC/CHL TR-12-9.

surge; and the storms were also simulated for a scenario with 1 meter of sea level rise to quantify non-linear effects that may occur with sea level rise. As such, the NACCS study provides the best available information on coastal flood hazard for the region, for today's climate and for the future with anticipated climate change.

2.2 NACCS Storm Selection for the Maine Coast

Because the NACCS focused on a relatively large region, the storm set developed to characterize the regional climatology contained many storms that do not impact the Maine Coast. From a local climatological perspective, it is not necessary for us to consider the full suite of NACCS storms for local statistical analyses in Maine. Also, the NACCS study generated tremendous amounts of model output data (on the order of petabytes, or millions of gigabytes), and it was not feasible for us to obtain all these data from the ERDC computer archives. For this reason, Ransom developed methods to select of sub-sets of the NACCS storm suite that would be representative of the local extreme storm climatology in Maine. The NACCS considered two types of storms, tropical cyclones (e.g. hurricanes, tropical storms, tropical depressions), and extra-tropical cyclones (e.g. northeasters). Because these types of storms differ in their physical characterization, the NACCS used different methods to develop representative storm sets for each type. Thus, we developed two different methods for sub-setting the NACCS storm sets and to determine a list of storms to request raw model data[5] from the USACE.

2.2.1 Tropical Storm Selection

Although tropical cyclones tend to dissipate before they reach the latitude of the Maine coast, and the direct impact of tropical cyclones in Maine is rare, the potential consequences of such an impact could be extensive. Therefore, in order to fully characterize the coastal storm hazard for Maine, it was necessary to determine a sub-set of the NACCS synthetic tropical cyclones that could impact Maine, and which influence the low probability but high impact end of the coastal flood risk spectrum.

After the NACCS study was complete, the USACE made some post-processed model data available through the Coastal Hazard System (CHS) website[6]. The post-processed data consisted of hazard curves, which illustrate the annual recurrence interval (or return period) water levels at approximately 18,000 locations, called "save points", along the North Atlantic coastline. The CHS also provided maximum water levels at each of these locations for each of the simulated tropical storm events. Ransom downloaded these data for a representative number of save points along the Maine Coast, and used these data to identify a sub-set of the NACCS tropical cyclones that had measurable impact on the extreme water level statistics in Maine. From this set of save points, storms were selected such that, at each site, all storms producing a peak water level greater than the 50-year return period water level were included in the sub-set. Because this constraint was applied at a range points across the Maine Coast where the individual tropical storm response varies, the resulting set for a single location also includes some storms that produced peak water levels below the 50-year level at individual stations. This resulted in the

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[5] "Raw model data" refers to the numerical model input and output files in their native formats. Raw model data are required for our purposes, because post-processed model data do not provide the level of detail needed to develop boundary conditions for local nested models.

[6] The CHS, http://chs.erdc.dren.mil, is no longer active. Instead the data are now available from the Northeast Regional Ocean Council, see: http://northeastoceancouncil.org/wp-content/uploads/2017/02/RPSASA_NACCS_15Feb2017.pdf

selection of a sub-set of 82 tropical storms[7], which are listed in **Appendix A.** The save point locations that were used to make this selection are shown in *Figure 1*.

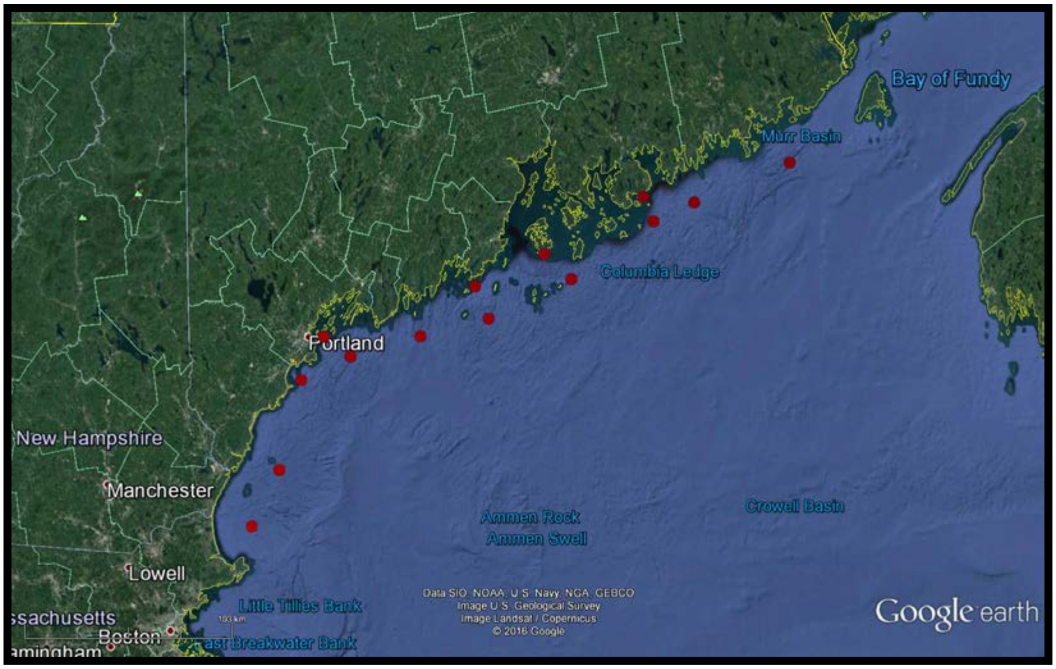

Figure 1. Location of NACCS Save Points Used to Select Subset of Tropical Storms

2.2.2 Extra-tropical Storm Selection

The NACCS utilized a set of 100 extra-tropical storms, which were selected from the history of actual events across the North Atlantic Region. The NACCS performed analysis on tide gauge data records, and synoptic weather data in order to identify this set of historic storms. To perform this analysis, the North Atlantic study area was divided into three separate regions, and storms were selected based on the observed impact they had within each of these regions. NACCS Region 1 includes Maine, New Hampshire, and Eastern Massachusetts; Region 2 extends from the south coast of Massachusetts to Delaware Bay; and Region 3 extends from Delaware Bay to the Virginia/North Carolina Border. For our purposes, it was necessary to include all storms that had their primary impact in Maine. Thus, a process of elimination was used to reduce the number of storms from the full NACCS set to a reasonable number that would be representative of the extra-tropical storm climatology in Northern New England. By process of elimination, all storms which had their primary impact in Region 3 were eliminated, and then lower ranking storms in Region 2 were eliminated, until a total of 45 storms remained[8].

[7] Ransom requested STWAVE input and output files for a total of 82 tropical storms. However, not all the NACCS simulations completed successfully so the files for some NACCS simulations were not available. For simulations without tides, (Base case) 77 of 82 storms were available. For simulations with tides, 75 of 82 storms were available. For simulations with tides and 1 meter sea level rise, 75 of 82 storms were available.

[8] Ransom requested STWAVE input and output files for a total of 45 extra-tropical storms. However, not all the NACCS simulations were completed successfully, so the files for some NACCS simulations were not available. For simulations without tides (Base case), 44 of 45 storms were available. For simulations with tides, 40 of 45 storms were available. For simulations with tides and 1 meter sea level rise, 41 of 45 storms were available.

2.3 NACCS Data Request

The selection of tropical storms resulted in a list of 128 storms for which Ransom subsequently requested raw model data from the USACE. With this manageable number of storms, the raw model data could fit on a standard two terabyte external hard-drive. In order to obtain these data, Ransom mailed an empty hard drive to the USACE ERDC and sent a list of requested model files. Ransom initially contacted the USACE in February 2016 to initiate this request. However, due to the time required by the USACE to develop a service contract with Ransom in order to obtain the data, and the effort required by the USACE to extract these data from their archives, Ransom did not receive the data until October 15, 2016. Unfortunately, this significantly delayed our efforts.

2.4 Validation of NACCS Model Results

Model validation is a procedure used to quantify model accuracy and evaluate model utility as a predictive tool. For our purposes, we are concerned with the accuracy of the model in simulating the maximum observed water levels associated with extreme storms. Because the NACCS included simulations of historic extra-tropical events, we are able to quantify the NACCS model error by comparing modeled water levels to historic observed water levels.

The NACCS model-simulated water levels were extracted from the raw STWAVE model input files that were provided by the USACE. The model data were extracted at locations corresponding to National Oceanic and Atmospheric Administration (NOAA) tide gauge stations in New Hampshire and Maine[9]. The NACCS Model accuracy was then validated by visual inspection of time series plots of the modeled and observed water levels during individual storm events. The model error is quantified by calculating the Root Mean Square Error (RMSE) and bias derived from the difference between observed and modeled storm peak water levels. The RMSE tells us how close the model is to predicting the observed value on average over many storms. The RMSE is always positive and smaller values indicate better accuracy.

The model bias tells us, on average, over many storms whether the model tends to over-predict or under-predict the observed value. Positive bias indicates that the model tends to over predict the observed peak water levels, while negative bias tells us the model tends to under-predict the observed peak water levels. The NACCS Model results can be adjusted to correct for the bias in certain circumstances. The RMSE, Bias, and number of storms compared at the NOAA tide stations are listed in *Table 1*. RMSE and Bias are calculated with the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(WSE_{mod} - WSE_{obs})^2}{n}}$$

$$Bias = \frac{\sum_{i=1}^{n}(WSE_{mod} - WSE_{obs})}{n}$$

Where WSE_{mod} is the modeled storm maximum water surface elevation, WSE_{obs} is the observed storm maximum water surface elevation, and n is the number of storms.

The validation results show a west to east trend of increasingly negative bias (under-prediction) in the peak water levels. At Bar Harbor, which is the closest station to Islesboro, the validation suggests that, on

[9] The NACCS STWAVE model grids did not cover the area including the Eastport, ME NOAA tide station so we were unable compare the model results to observations there.

average, the NACCS model under predicts the peak storm water level by more than 0.5 feet. A scatter plot comparing the model and observed storm peak water levels for Bar Harbor is provided in *Figure 2*.

On the scatter plot, a point is plotted for each storm corresponding to the observed peak water level on the horizontal axis, and the modeled peak water level on the vertical axis. If the NACCS model performed perfectly, all of the points would lie on a linear line with a 1:1 slope passing through the origin (red line). The scatter plots also include a best fit line that is determined by a linear least squares regression of the scatter points (green line). Comparing the best fit line with the 1:1 slope line indicates whether the model has a trend of greater error for more (or less) extreme events.

At Bar Harbor, the slope of the best fit line is less than 1, which indicates that the model tends to more significantly under-predict the more extreme events. For example, the NACCS model significantly under-predicts the peak water level from the two most extreme events observed at Bar Harbor. The February 7, 1978 blizzard (storm #37) is under-predicted by more than one foot, and the 1976 Groundhog Day storm (storm # 32) is under-predicted by nearly two feet, even though the average under-prediction is only about one-half foot.

This validation of the NACCS model suggests that the coastal hazard information provided by the NACCS may also under estimate the coastal flood hazard at Islesboro, so by themselves the NACCS results should be used with caution in this area. Fortunately, through downscaled modeling we are able to improve the model accuracy and adjust for model biases as needed. **Appendix B** includes additional scatter plots for the other tide stations in New Hampshire and Maine, as well as the time series comparisons for each storm at each tide station.

Table 1. Summary of NACCS Model Validation Against NOAA Tide Stations

NOAA Station ID	Station Location	RMSE (ft)	Bias (ft)	Number of Storms Compared
8423898	Fort Point, NH	0.66	0.52	7
8418150	Portland, ME	0.49	-0.16	39
8413320	Bar Harbor, ME	0.75	-0.56	30
8411250	Cutler, ME	0.79	-0.59	25

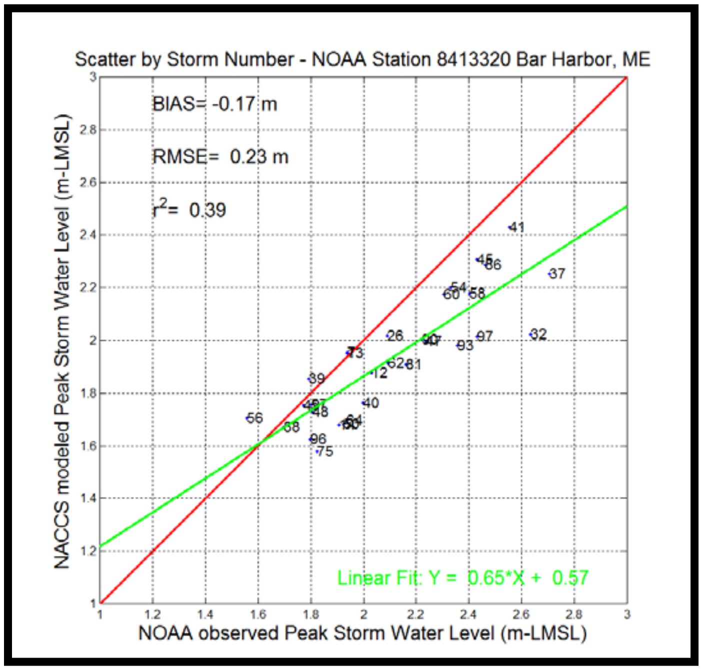

Figure 2. NACCS Data Peak Validation Scatter Plot for Storm Water Level Bar Harbor, ME

3.0 DOWNSCALED HYDRODYNAMIC-WAVE MODELING

This section describes the development of a coupled hydrodynamic-wave numerical model of Penobscot Bay to provide high fidelity simulation of astronomical tides, storm surge, and phase-averaged wave conditions for Islesboro. This model uses outputs from the NACCS model to provide the boundary conditions that drive high resolution downscaled (or "nested") simulations for Penobscot Bay. The downscaled Penobscot Bay model provides dynamic simulation results that are more detailed and accurate than the NACCS model, while also eliminating the local negative bias in the NACCS model results for the central Maine Coast.

3.1 Modeling Software

3.1.1 Hydrodynamic Model

The ADvanced CIRCulation (ADCIRC)[10] model is a state-of-the-art numerical model that solves the Generalized Wave Continuity Equation (GWCE) form of the Shallow Water Equations (SWE). The SWE are set of mathematical equations that govern the motion of fluid in the ocean and coastal areas through laws of conserved mass and momentum. ADCIRC employs the finite element method on an unstructured triangular computational grid that allows for high spatial resolution in coastal areas. ADCIRC's capabilities include simulation of water level and current velocity driven by astronomical tides, and wind and atmospheric pressure induced storm surge. ADCIRC is applied in the 2-Dimensional Depth Integrated (2DDI) mode for storm surge simulations.

3.1.2 Spectral Wave Model

The Simulating Waves Nearshore (SWAN) model is a third-generation wave model developed at the Delft University of Technology in the Netherlands. It computes random, short-crested wind-generated waves in the spectral form for coastal regions and inland waters by solving the wave action balance equation. The unstructured version of SWAN has been developed to utilize an unstructured triangular numerical grid in the same format as ADCIRC.

3.1.3 Tight Coupling of Hydrodynamic and Wave Processes

The unstructured mesh version of the SWAN spectral wave model has been tightly coupled with the ADCIRC shallow water circulation model (ADCIRC+SWAN)[11]. The tight coupling results in a single software program that is capable of simulating the physical interaction of tides, storm surge and waves in integrally-coupled scalable computations. In the coupled model, ADCIRC computes winds, water level, and currents, which are passed to the SWAN model to force the propagation, generation, and transformation of the wave field; in turn SWAN computes the wave radiation stresses, which are passed back to ADCIRC to integrate wave setup and wave-induced currents into the hydrodynamic solution.

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[10] Luettich, R.A., J.J. Westering, N.W.Scheffner, 1992. "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries, Report 1, Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL". Technical Report DRP-92-6, Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.
[11] Dietrich, J.C., Zijlema, M., Westerink, J.J., Holthuijsen, L.H., Dawson, C., Luettich, R.A., Jensen, R., Smith, J.M., Stelling, G.S., and Stone, G.W. 2011. Modeling Hurricane Waves and Storm Surge using Integrally-Coupled, Scalable Computations, Coastal Engineering, 58, 45-65.

3.2 Model Configuration

3.2.1 Topography and Bathymetry

A large number of topographic and bathymetric data sets were synthesized for the development of the Penobscot Bay ADCIRC+SWAN model. This data synthesis involves converting datasets to a consistent horizontal and vertical datum (i.e. NAD83 and NAVD88), and merging the data such that more recent data are retained in favor of older data where datasets overlap. Ransom employed a number of custom software scripts to accomplish this task. The data were downloaded from various online sources including the NOAA digital coast archive for Light Detection and Ranging (LIDAR) data, NOAA's National Centers for Environmental Information (NCEI) GEODAS database for bathymetry data and the USACE New England Division website for hydrographic survey data. Once obtained, the data were converted to a consistent vertical datum using custom software scripts and the NOAA Vdatum, Version 3.4 software. Another custom software script was used to organize each dataset into a quad-tree data structure, which facilitates visualization of the data as Keyhole Markup Language (KML) super-overlays for viewing in Google Earth, and interpolation of the high-density LIDAR data to the model grid. Images showing the merged bathymetric data, and topographic LIDAR data are provided in *Figure 3* and 4, respectively. *Table 2* lists the NOAA hydrographic surveys used to provide bathymetric data for the model.

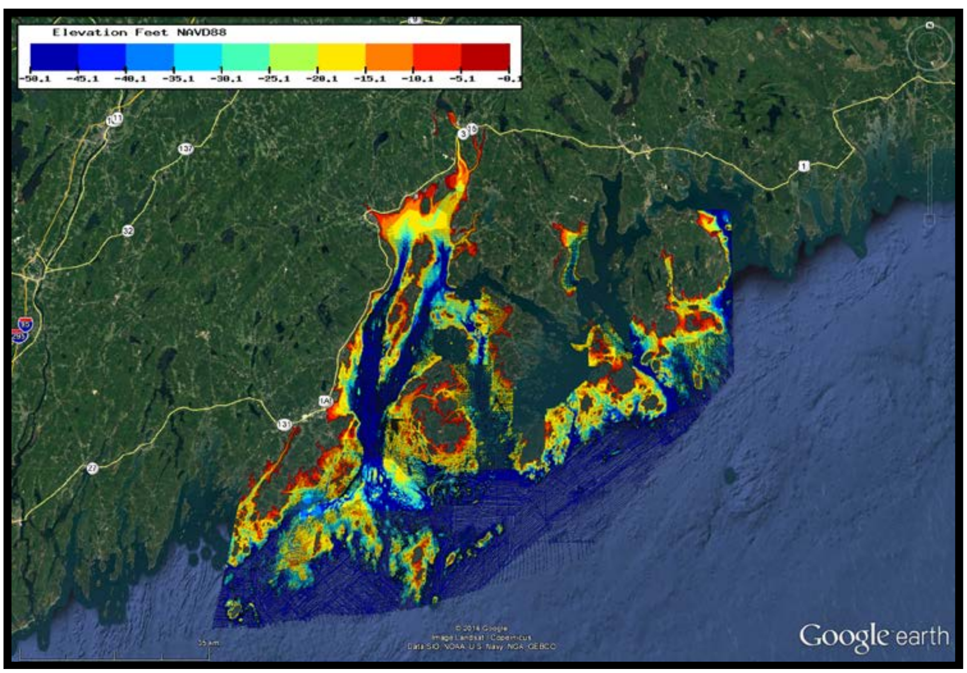

Figure 3. Merged Bathymetric Data for Penobscot Bay.

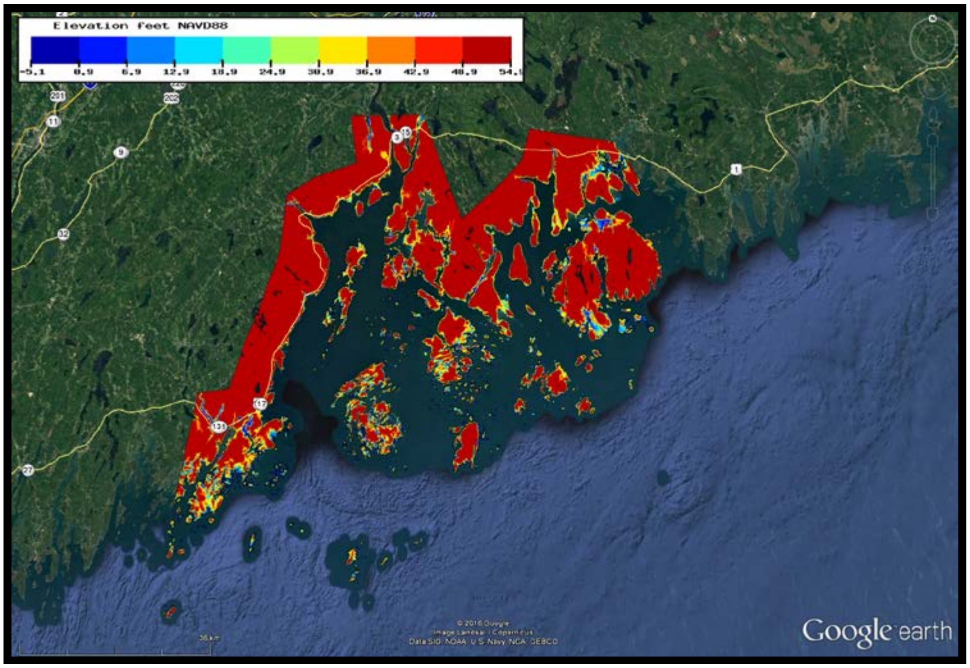

Figure 4. 2011 USGS “LIDAR for the Northeast”

Table 2. GEODAS Data Used In Development Of the Penobscot Bay Model

Survey ID	Original Datum	Year	Survey ID	Original Datum	Year	Survey ID	Original Datum	Year
F00253	MLLW	1983	H06982	MLW	1945	H08198	MLW	1955
F00407	MLLW	1994	H06984	MLW	1944	H08259	MLW	1955
F00448	MLLW	1998	H06992	MLW	1944	H08504	MLW	1958
H00983	MLW	1868	H07054	MLW	1945	H08513	MLW	1959
H01028	MLW	1869	H07055	MLW	1945	H08514	MLW	1958
H01029	MLW	1903	H07056	MLW	1945	H08667	MLW	1962
H01073	MLW	1870	H07057	MLW	1945	H08669	MLW	1962
H01142	MLW	1871	H07058	MLW	1945	H10097	MLW	1983
H01143	MLW	1902	H07150	MLW	1946	H10098	MLLW	1983
H01259	MLW	1873	H07151	MLW	1946	H10101	MLW	1983
H01261	MLW	1903	H07152	MLW	1946	H10109	MLW	1983
H01321	MLW	1875	H07153	MLW	1946	H10130	MLW	1984
H01401	MLW	1879	H07198	MLW	1947	H10131	MLW	1984
H01406	MLW	1878	H07199	MLW	1947	H10134	MLW	1984
H01434	MLW	1879	H07643	MLW	1948	H10136	MLW	1984
H01836	MLW	1888	H07772	MLW	1949	H10146	MLW	1984
H02763	MLW	1905	H07773	MLW	1949	H10157	MLLW	1985
H02782	MLW	1906	H07774	MLW	1950	H10173	MLLW	1985
H06564	MLW	1940	H07830	MLW	1950	H10177	MLLW	1985
H06675	MLW	1941	H07831	MLW	1950	H10178	MLLW	1985

Survey ID	Original Datum	Year	Survey ID	Original Datum	Year	Survey ID	Original Datum	Year
H06730	MLW	1941	H07832	MLW	1950	H10820	MLLW	1998
H06840	MLW	1943	H07833	MLW	1950	H10867	MLLW	1999
H06841	MLW	1943	H07834	MLW	1950	H10868	MLLW	1999
H06842	MLW	1943	H08029	MLW	1956	H01245A	MLW	1905
H06843	MLW	1943	H08030	MLW	1953	H01245B	MLW	1905
H06844	MLW	1943	H08031	MLW	1953	H01400A	MLW	1905
H06853	MLW	1943	H08109	MLW	1953	H01400B	MLW	1905
H06854	MLW	1944	H08110	MLW	1953	H01433A	MLW	1905
H06858	MLW	1943	H08114	MLW	1953	H01433B	MLW	1905
H06861	MLW	1944	H08167	MLW	1954	H01474A	MLW	1880
H06964	MLW	1944	H08168	MLW	1954	H01474B	MLW	1880
H06965	MLW	1944	H08169	MLW	1954	H01474C	MLW	1880
H06967	MLW	1944	H08175	MLW	1955	H01435A	MLW	1879
H06968	MLW	1944	H08176	MLW	1954	H01435B	MLW	1879
H06969	MLW	1944	H08177	MLW	1954	H01435B	MLW	1905
H01436B	MLW	1955	H08178	MLW	1954	H01436A	MLW	1905

3.2.2 Model Grid

The ADCIRC model grid was developed within the Surface Modeling System (SMS) software, developed by Aquaveo, Inc. The model grid consists of an unstructured triangular network of nodal points with variable spacing. The spatial resolution is increased around the areas of interest to provide more accurate representation of the nearshore geometry in those area. The grid spacing for the Penobscot Bay model ranges from about 20 meters near Islesboro to about 500 meters at the model's open ocean boundary. The extent of the model grid is shown in Figure 5 and the section with high resolution around Islesboro is shown in Figure 6. The topographic and bathymetric data were interpolated to the model grid to complete assignment of the model geometry. Bathymetric data were interpolated to the model grid using a triangulation and linear interpolation approach within the SMS software. LIDAR data where interpolated to the grid using a nearest neighbor approach coded in a custom software script. The topography/bathymetry for the entire model domain is shown in Figure 7. Close-up views of the topography/bathymetry for Grindle Point and The Narrows are shown in Figure 8 and Figure 9, respectively.

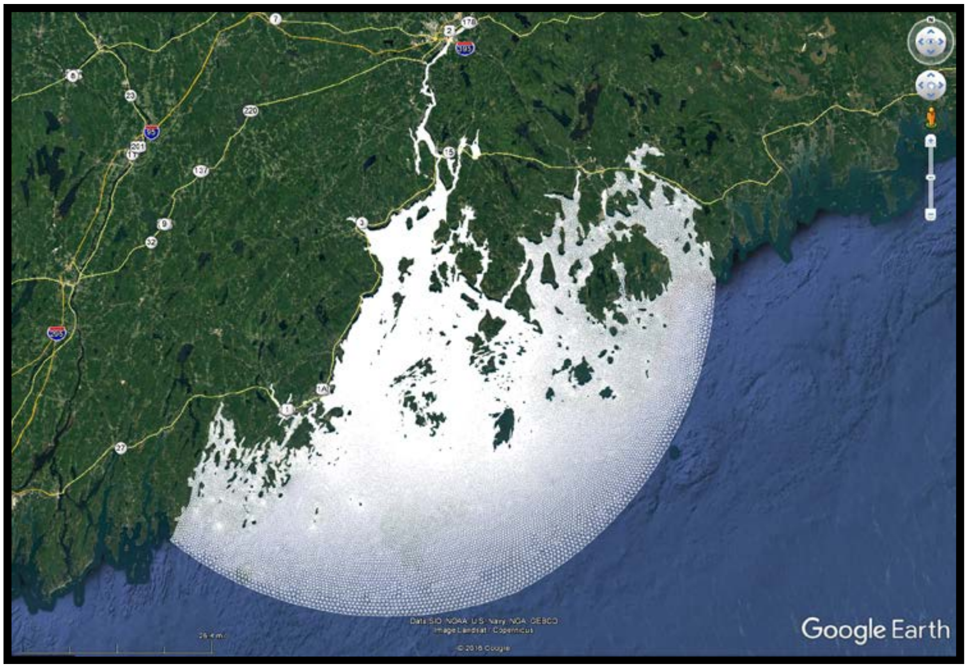

Figure 5. Penobscot Bay ADCIRC Model Grid

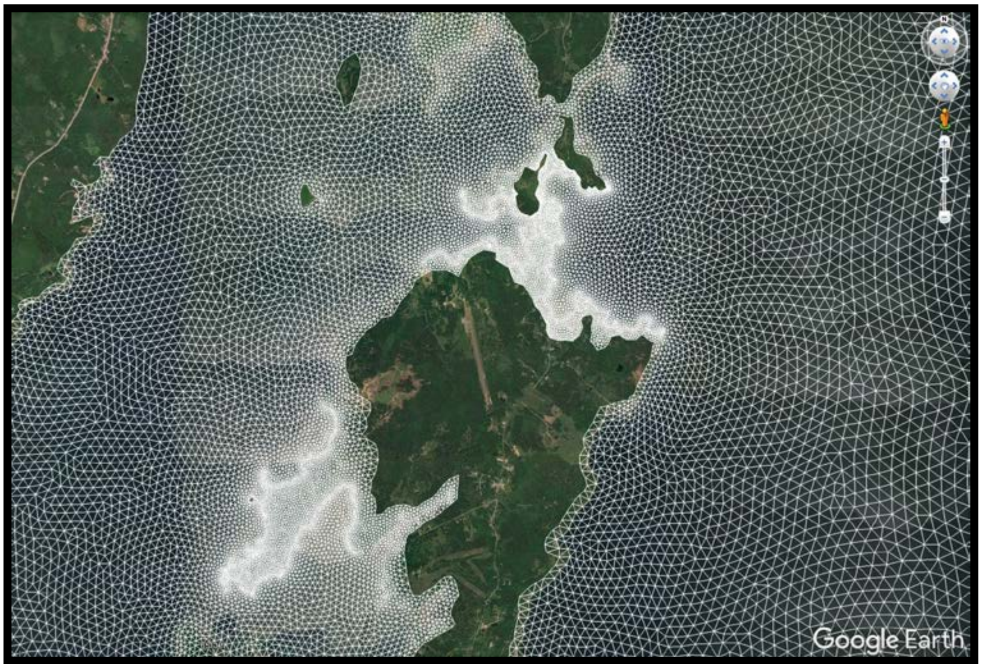

Figure 6. Close-up of Penobscot Bay Model Grid Showing Grid Resolution and Domain Extent at Grindle Point and the Narrows

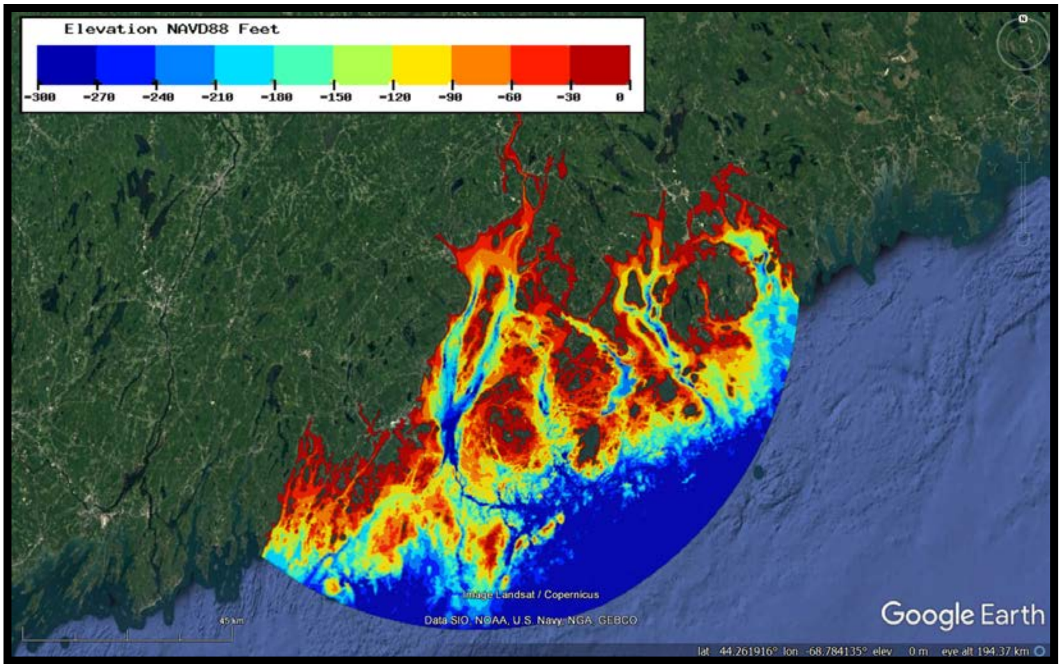

Figure 7. Penobscot Bay Model Topography/Bathymetry

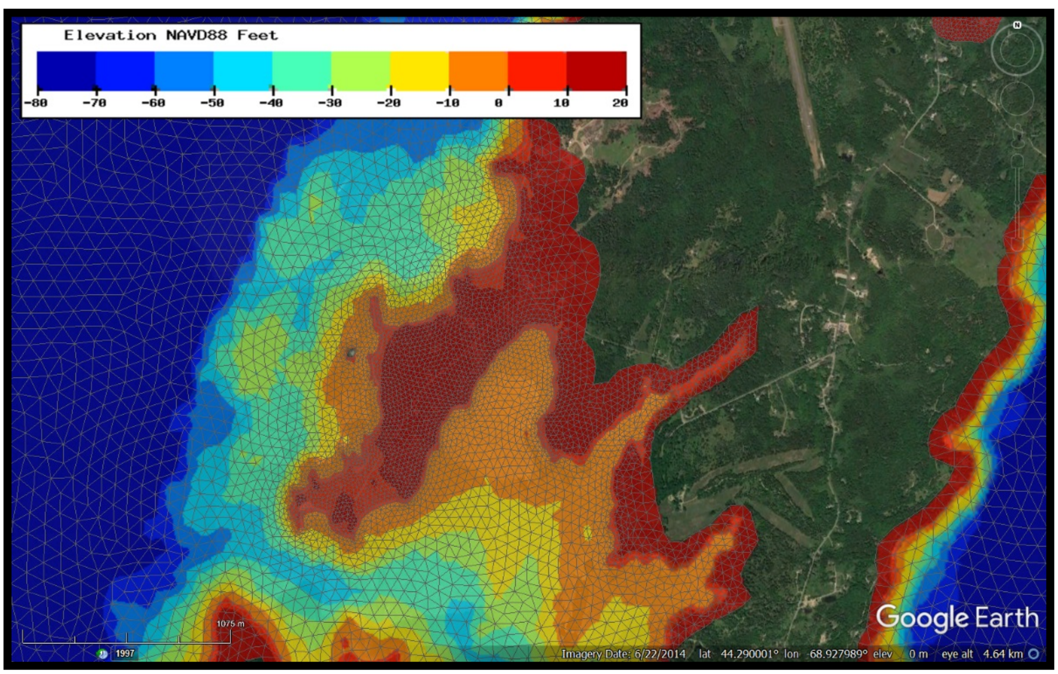

Figure 8. Close-up of Penobscot Bay Model Grid Showing Topo/Bathymetry and Grid Resolution at Grindle Point

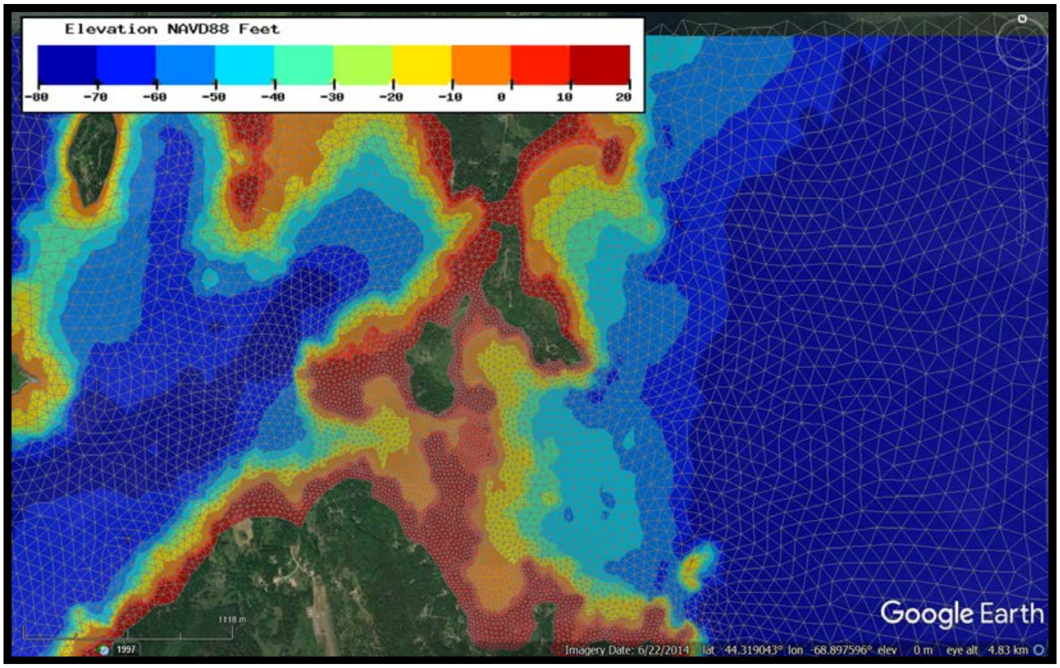

Figure 9. Close-up of Penobscot Bay Model Grid Showing Topo/bathymetry and Grid Resolution at The Narrows

3.2.1 Nodal Attributes

The model grid development also requires assigning nodal attribute values that specify frictional parameters in the model. The model was configured to use a Manning's friction coefficient (*n*), and wind drag reduction factors derived from land cover data. 2010 data from the NOAA Coastal Change Analysis Program (CCAP) for Maine were obtained from NOAA's CCAP website and used to determine the frictional values. Land cover data were also used to specify the Surface Directional Effective Roughness Length (SDERL) nodal attribute and the Surface Canopy Coefficient (SCC) nodal attribute. The SDERL is incorporated in the model to reduce the wind stress on the water surface based on upwind land surface roughness[12]. Twelve different SDERL values are applied at each node depending on the direction of the wind. The SCC is used to eliminate the wind stress in the model in dense forested areas where strong winds do not reach the ground, and on higher elevation floodplains, where wind stress on thin layers of water can cause instability and mass balance problems in the model. Table 3 lists the Manning's *n*, SDERL and SCC values for each CCAP land cover type. The Manning's *n* values applied in the Penobscot Bay model are shown in Figure 10, SDERL values are shown in Figure 11 thru Figure 22, and SCC values are shown in Figure 23.

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[12] The NACCS model did generally apply the SDERL nodal attribute, which means that the NACCS STWAVE wind fields we have used to specify the wind forcing in the Penobscot Bay model have already been subject to NACCS model SDERL. However, the portion of the NACCS model in Maine used SDERL values of zero for all directions. This means that the SDERL was effectively not applied in Maine for the NACCS model simulations and thus the application of the SDERL in the Penobscot Bay model does not create an inappropriate double counting of the wind reduction.

Table 3. Nodal Attribute Values Based on CCAP Land Cover Type[13]

Land Cover Type	Manning's n ($s*m^{-1/3}$)	Surface Effective Roughness Length, Z0 (m)	Canopy Coefficient 1- Wind Applied 0 - No Wind
High Intensity Developed	0.120	0.300	1
Medium Intensity Developed	0.120	0.300	1
Low Intensity Developed	0.070	0.300	1
Developed Open Space	0.035	0.300	1
Cultivated Land	0.100	0.060	1
Pasture/Hay	0.055	0.060	1
Grassland	0.035	0.040	1
Deciduous Forest	0.160	0.650	0
Evergreen Forest	0.180	0.720	0
Mixed Forest	0.170	0.710	0
Scrub/Shrub	0.080	0.120	1
Palustrine Forested Wetland	0.200	0.600	0
Palustrine Scrub/Shrub	0.075	0.110	1
Palustrine Emergent Wetland	0.070	0.300	1
Estuarine Forested Wetland	0.150	0.550	0
Estuarine Scrub/Shrub	0.070	0.120	1
Estuarine Emergent Wetland	0.050	0.300	1
Unconsolidated Shore	0.030	0.090	1
Bare Land	0.030	0.050	1
Open Water	0.020	0.001	1
Palustrine Aquatic Bed	0.035	0.040	1
Estuarine Aquatic Bed	0.030	0.040	1

[13] The nodal attribute values for land cover types applied in the Penobscot Bay model are based on standard values that have been validated in numerous ADCIRC storm surge modeling studies. For example see: *Mesh Development, Tidal Validation, and Hindcast Skill Assessment of the ADCIRC model for the Hurricane Storm Surge Operational Forecast System on the US Gulf-Atlantic Coast.* Report prepared for National Oceanic and Atmospheric Administration/National Ocean Service, Coast Survey Development Laboratory, Office of Coast Survey. Prepared by Riverside Technology Inc. in association with AECOM.

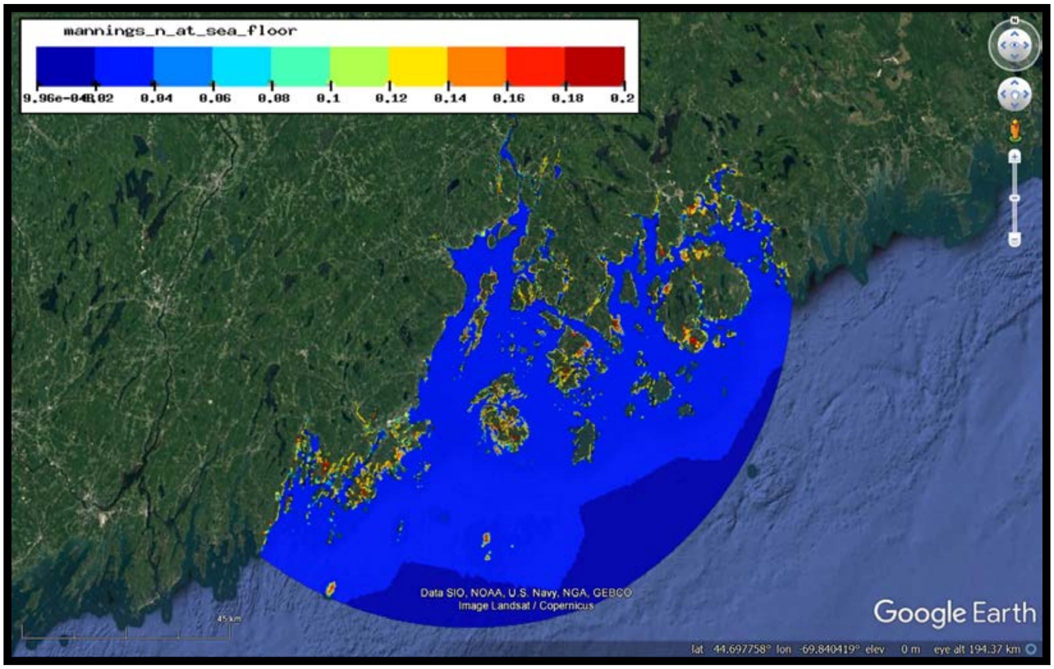

Figure 10. ADCIRC+SWAN Finite Element Grid Manning's *n* Specification

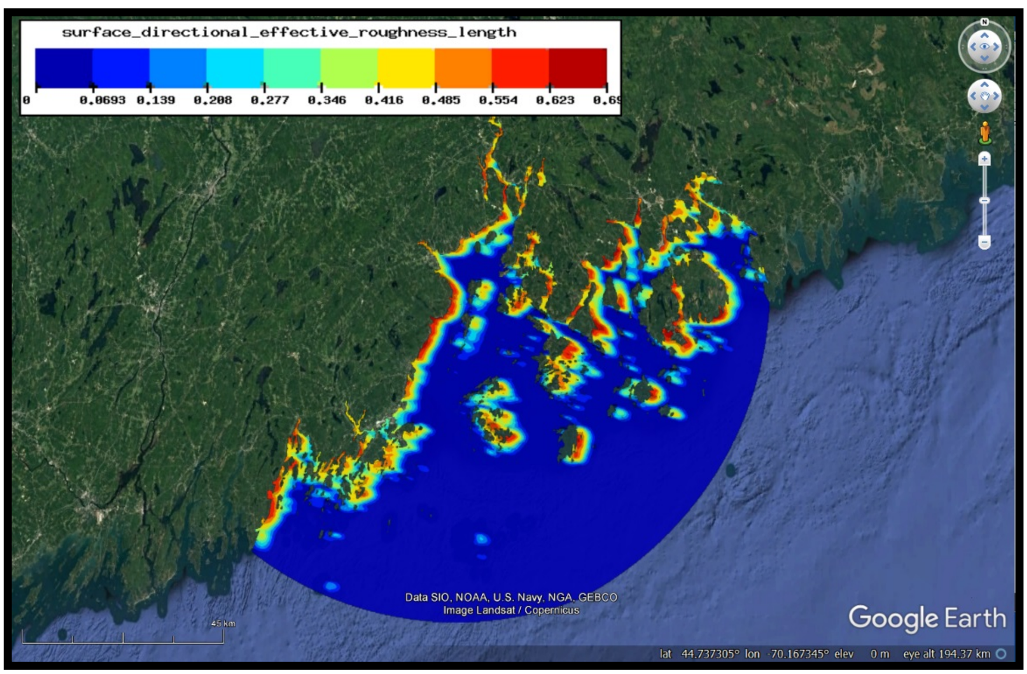

Figure 11. Surface Directional Effective Roughness Length, West wind

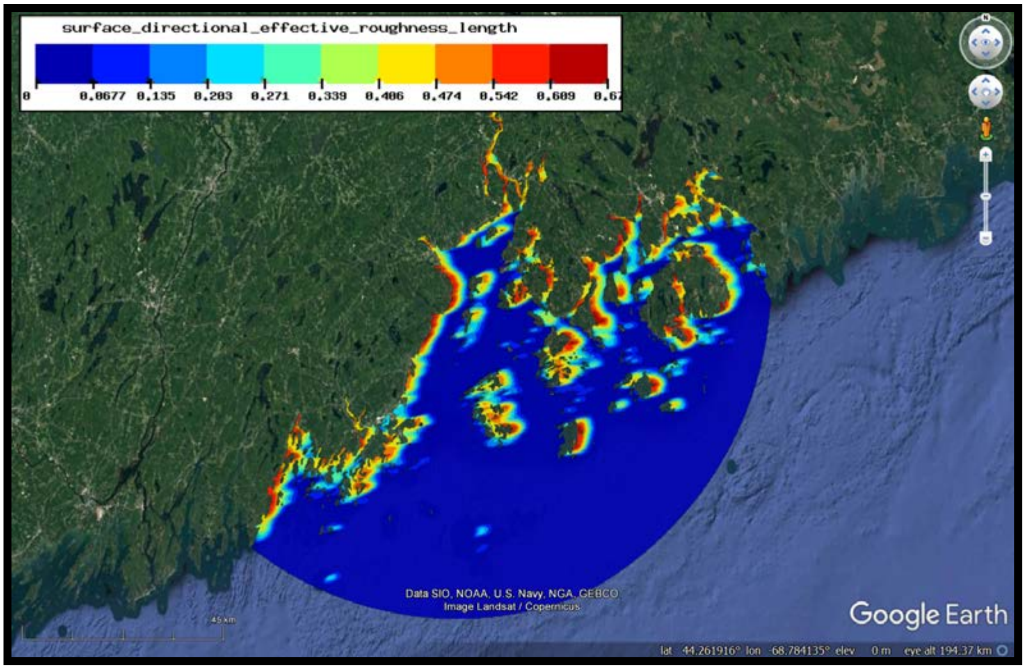

Figure 12. Surface Directional Effective Roughness Length, West Southwest Wind

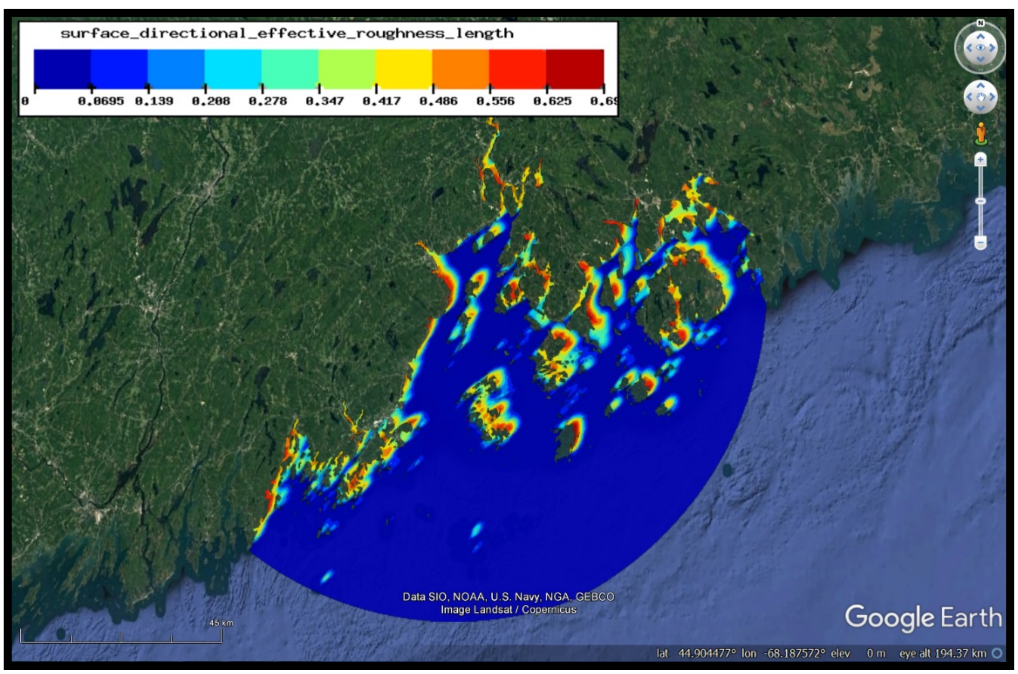

Figure 13. Surface Directional Effective Roughness Length, South Southwest Wind

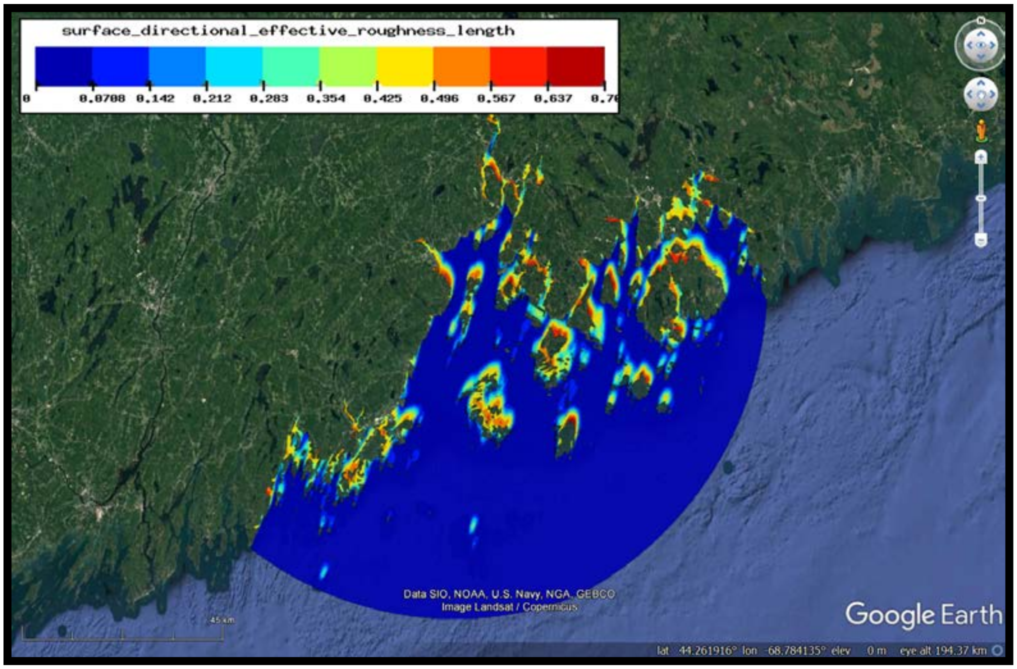

Figure 14. Surface Directional Effective Roughness Length, South Wind

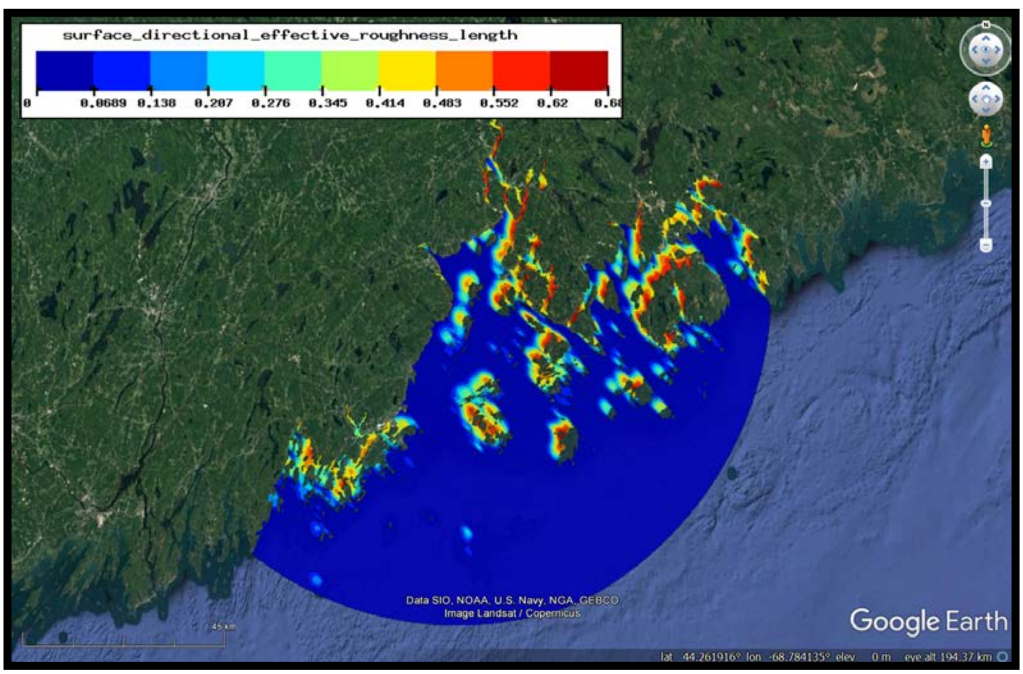

Figure 15. Surface Directional Effective Roughness Length, South Southeast Wind

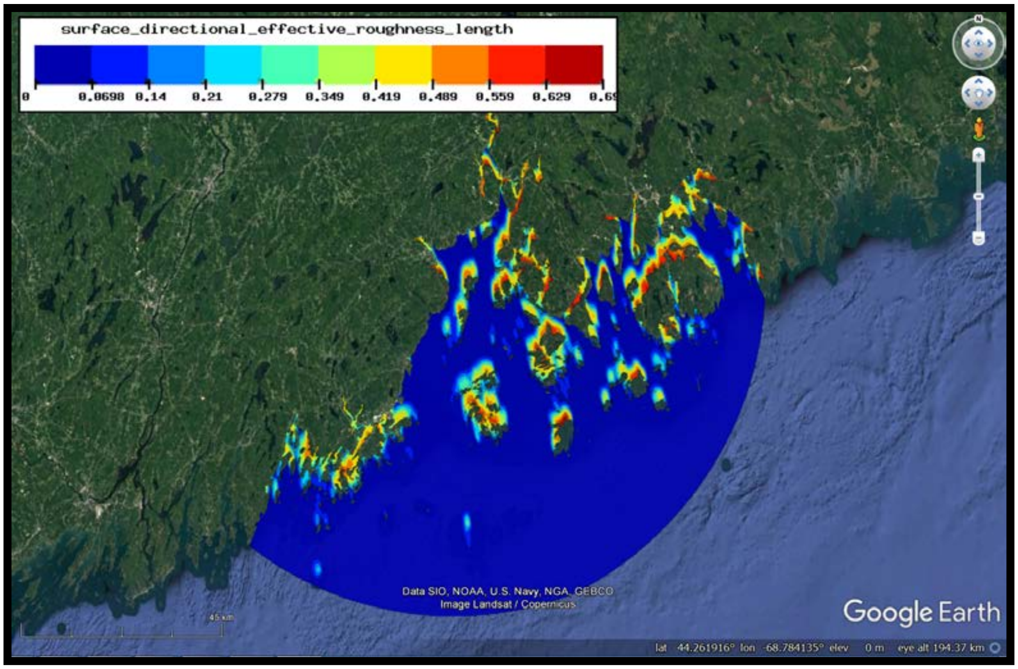

Figure 16. Surface Directional Effective Roughness Length, East Southeast Wind

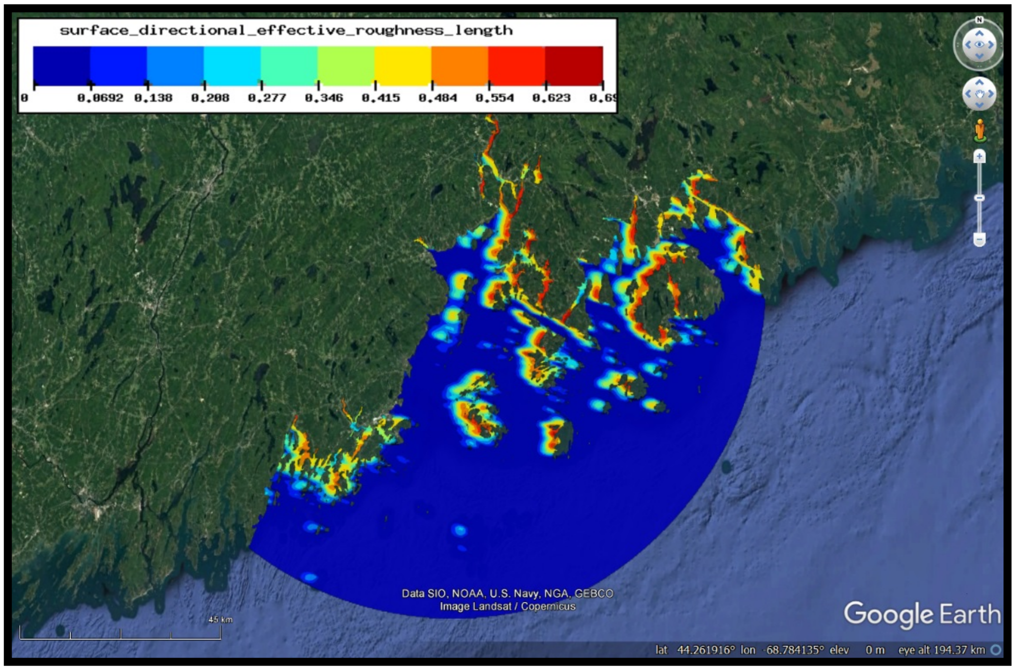

Figure 17. Surface Directional Effective Roughness Length, East Wind

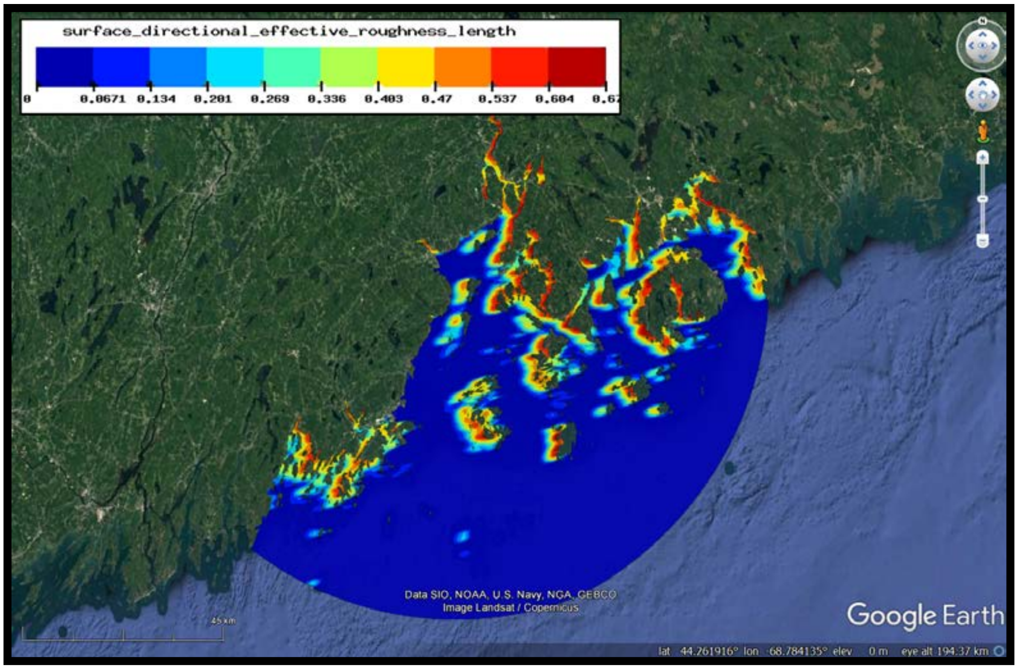

Figure 18. Surface Directional Effective Roughness Length, East Northeast Wind

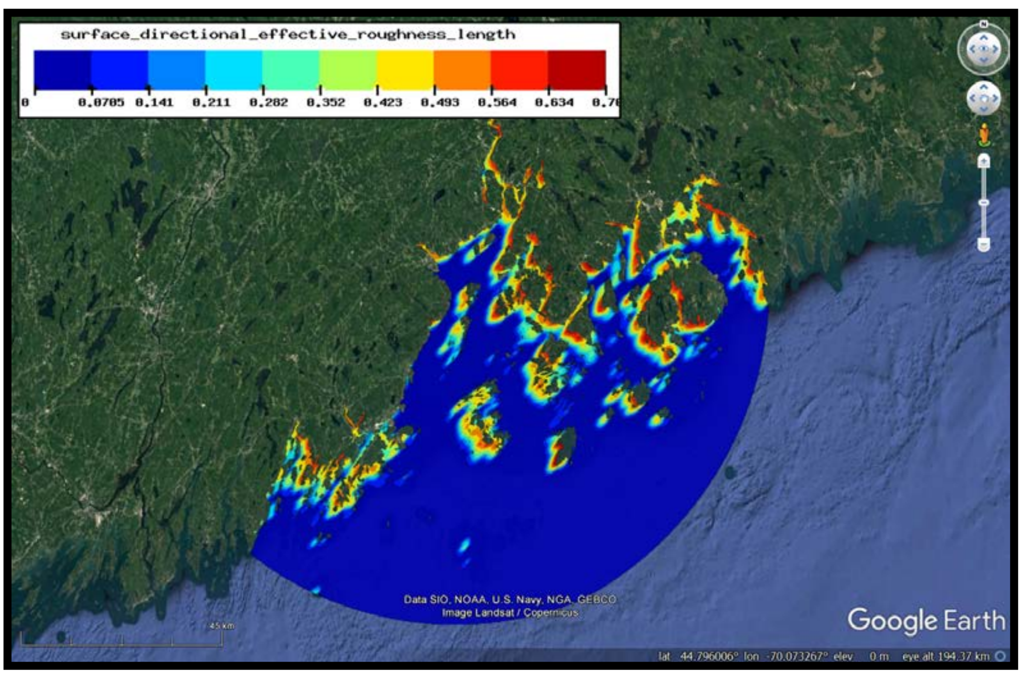

Figure 19. Surface Directional Effective Roughness Length, North Northeast Wind

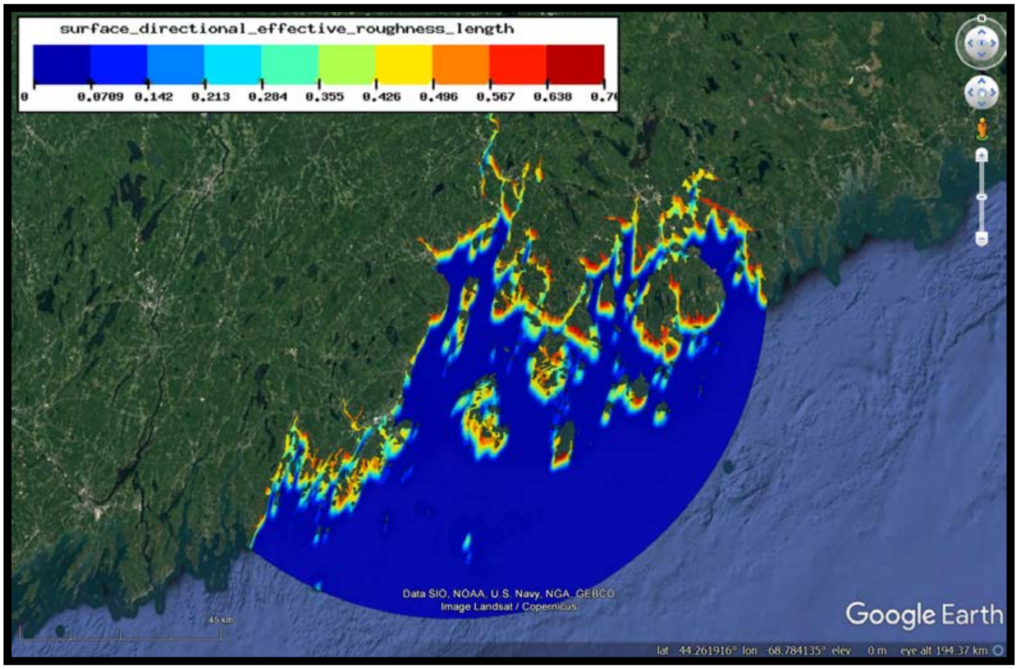

Figure 20. Surface Directional Effective Roughness Length, North Wind

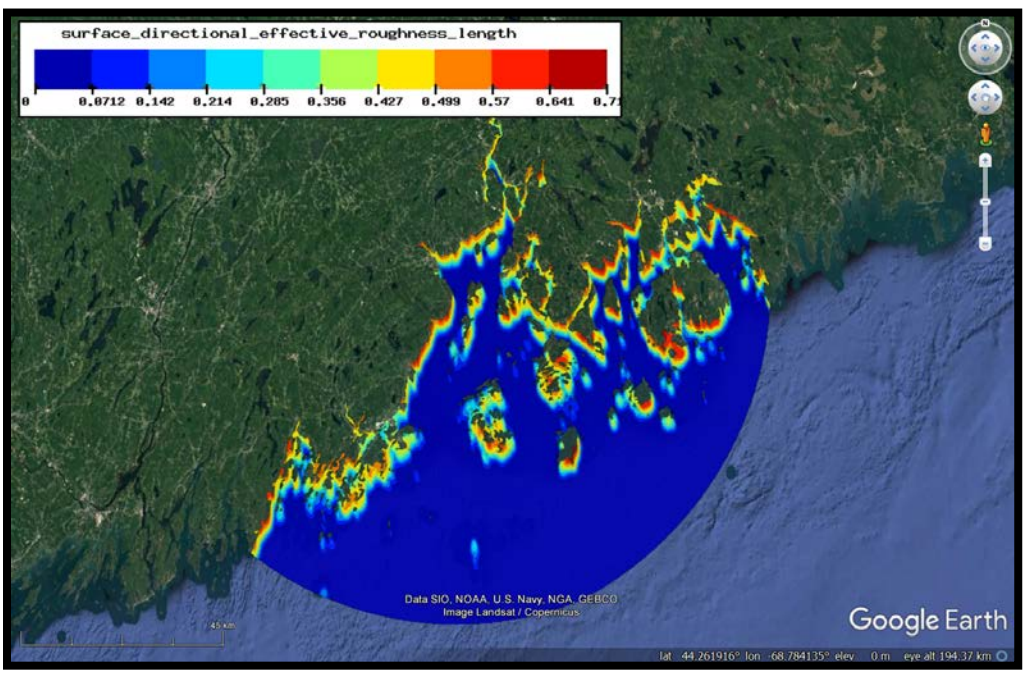

Figure 21. Surface Directional Effective Roughness Length, North Northwest Wind

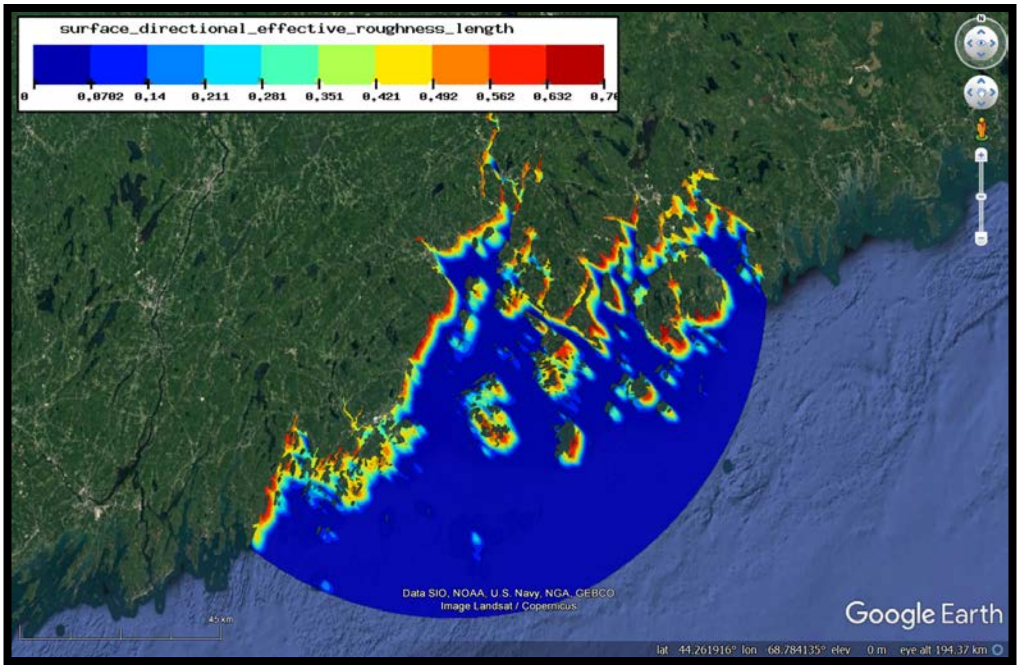

Figure 22. Surface Directional Effective Roughness Length, West Northwest Wind

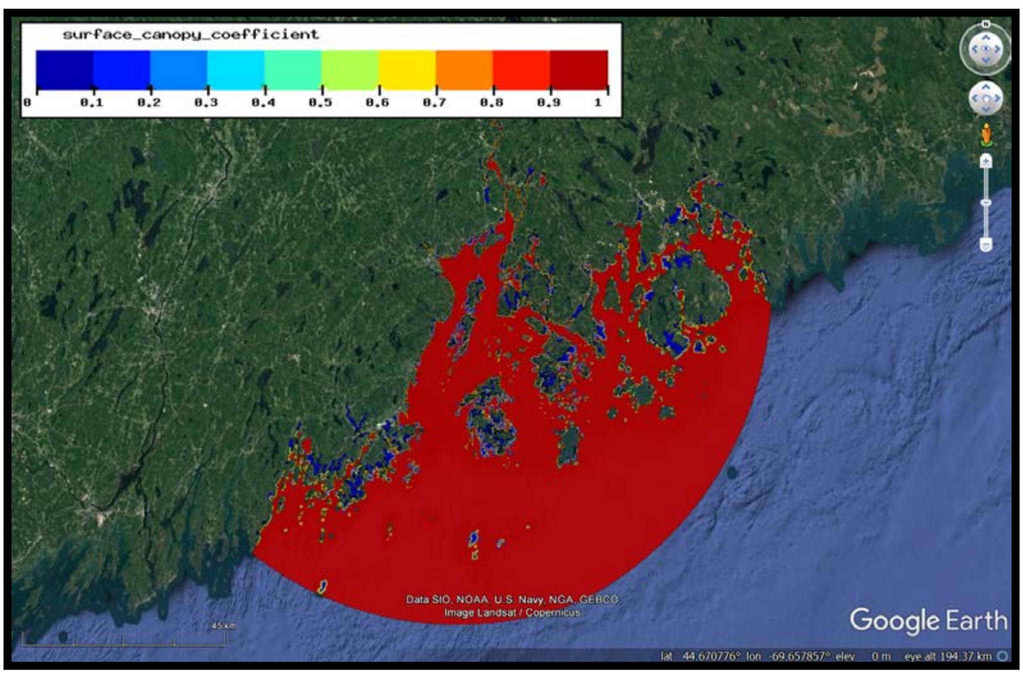

Figure 23. Surface Canopy Coefficient

3.2.2 Boundary Conditions

In order to configure the model to run for specific storm events, boundary conditions must be provided that specify time-dependent water levels and incoming directional wave spectra on the open ocean boundary. A time-dependent vector field that specifies the wind velocity and a scalar field that specifies the barometric pressure must also be specified across the entire domain. Water level and wave boundary conditions, and the wind velocity fields were extracted from NACCS raw STWAVE model inputs and outputs using a set custom software scripts developed for this effort. Atmospheric pressure data were not available from the NACCS STWAVE model files obtained from the USACE, so an alternative source of atmospheric pressure data were needed. Atmospheric pressure inputs were derived using the Northeaster Model method developed by Stone & Webster Inc. in the late 1970's[14]. The Stone & Webster method was modified to automatically derive pressure fields from National Center for Environmental Prediction (NCEP) National Center for Atmospheric Research (NCAR) Reanalysis data instead of employing the manual methods for synoptic paper weather maps originally employed by Stone and Webster. A set of input files for the ADCIRC+SWAN Penobscot Bay model was developed for all extra-tropical storms obtained from the USACE NACCS data that occurred during 1948 or later when the NCEP/NCAR reanalysis data are available.

3.3 Model Production Runs

A set of input files for the ADCIRC+SWAN Penobscot Bay model was developed for all extra-tropical storms obtained from the USACE NACCS data that occurred during 1948 or later when the NCEP/NCAR reanalysis data are available. These storms are listed in *Table 4*. Each of these storms were simulated to provide the maximum water level and significant wave height conditions for extreme value analysis and validation by comparison to observed high water marks. Full domain water level time series were also output from the model and reviewed to ensure model solutions are reasonable. Time series water level data at select stations, including the Bar Harbor Tide station, were output to provide for model validation against observed time series data.

Table 4. Historic Extra-Tropical Storms Simulated for Production Runs and Model Validation.

NACCS Storm ID #	Year	Month	Day
7	1950	11	25
12	1958	2	16
13	1960	2	19
14	1960	3	4
16	1961	4	14
26	1972	2	4
30	1973	1	29
32	1976	2	2
37	1978	2	7
39	1978	12	25
40	1979	1	21
41	1980	10	25
45	1983	11	25
47	1983	12	23
48	1983	12	29
49	1984	2	29

[14] Stone & Webster Engineering Corporation, 1978. Development and Verification of a Synthetic Northeaster Model for Coastal Flood Analysis. Prepared for the Federal Insurance Administration Department of Housing and Urban Development.

NACCS Storm ID #	Year	Month	Day
50	1984	3	29
54	1987	1	23
56	1988	11	2
57	1990	11	11
58	1991	10	30
60	1992	12	11
62	1993	3	14
64	1993	12	21
66	1994	3	2
68	1995	2	5
70	1996	1	8
73	1996	12	8
75	1997	4	19
79	2001	3	7
81	2003	12	18
86	2007	4	16
88	2008	12	22
90	2009	12	9
93	2010	2	26
96	2010	10	15
97	2010	12	27

3.4 Validation

The Penobscot Bay Model is validated by comparing model results from the production runs to available observed data. These include high water mark data throughout the model domain for two prominent historic storms, as well as time series observations at the Bar Harbor tide station for 27 of the production storms.

3.4.1 Groundhog Day 1976

Morrill et al. (1979)[15] reported high water mark data that were gathered throughout Penobscot Bay following an extra-tropical event that caused significant flooding on February 2, 1976. The report does not provide precise coordinates for the high water marks, but locations were estimated based on written descriptions of the locations and a map that was included with the report. Figure 24 shows our best estimate of the high-water mark locations, where maximum water level results were extracted from the storm simulation (NACCS storm ID 32). The observed high water mark data were originally reported relative to the NGVD29 vertical datum, but were converted to NAVD88 using the National Geodetic Survey (NGS) VERTCON program, prior to comparison to the model results. The report also provides a description with each high-water mark to indicate

[15] Morrrill, R. A. E. H. Chin and W. S. Richardson, 1979. Maine Coastal Storm and Flood of February 2, 1976. Geological Survey Professional Paper 1087. Report prepared jointly by the U.S. Geological Survey and the National Oceanic and Atmospheric Administration.

whether it appeared to have been caused by tidal surge only, wave action, or by riverine influence.

Figure 25 shows a scatter plot comparing the observed high-water mark elevations to the modeled maximum water level for all high-water mark locations. A line with a 1:1 slope passing through the origin is also shown on the scatter plot. If the model were to perfectly agree with the observations, the points would lie on the 1:1 line. Where a scatter point lies above the 1:1 line, it indicates that the model over-predicts the maximum water level, and where a scatter point lies below the 1:1 line, it indicates that the model under-predicts the maximum water level.

Figure 25 also shows computed the bias (or average error) and Root Mean Square Error (RMSE) in order to quantify the model performance for this storm. Overall, the bias of -2.23 feet indicates a significant under-prediction of the maximum water level, and the RMSE of 3.5 feet indicates variance in the error. However, upon inspection of the individual high water marks it is apparent the largest errors occur for the high water marks with riverine influence or wave action.

A similar scatter plot comparing the modeled maximum water level output to the tidal surge only high-water marks is shown in Figure 26. The latter comparison is more representative of the model error for Islesboro where the riverine influence is negligible. As shown in Figure 26, when only the tidal surge high water mark data are considered, the model has a relatively small bias of -0.08 feet, and the average magnitude of the error expressed as the RMSE is only 0.51 feet.

Figure 27 shows a comparison of the observed and modeled water level time series at the Bar Harbor tide station (station ID 8413320). This comparison shows that the model accurately simulates the observed peak water level at Bar Harbor for the Groundhog Day 1976 storm. When compared to the NACCS model validation described in our May 12, 2017 memorandum[16], it is apparent that the refined Penobscot Bay model provides a significant improvement in accuracy over the coarser NACCS model data.

From this comparison, we can conclude that the model may not give accurate results in the upper riverine dominated portions of the bay. It is likely this this error could be corrected by incorporating a river flux boundary condition into the model. However, riverine forcing was not included in the model for any of the production simulations, so model results north of Verona Island should be view with caution.

[16] Ransom Consulting, 2017. “Coastal Flood Vulnerability Study, Review of NACCS data”, Draft Memorandum to the Town of Islesboro, May 12, 2017.

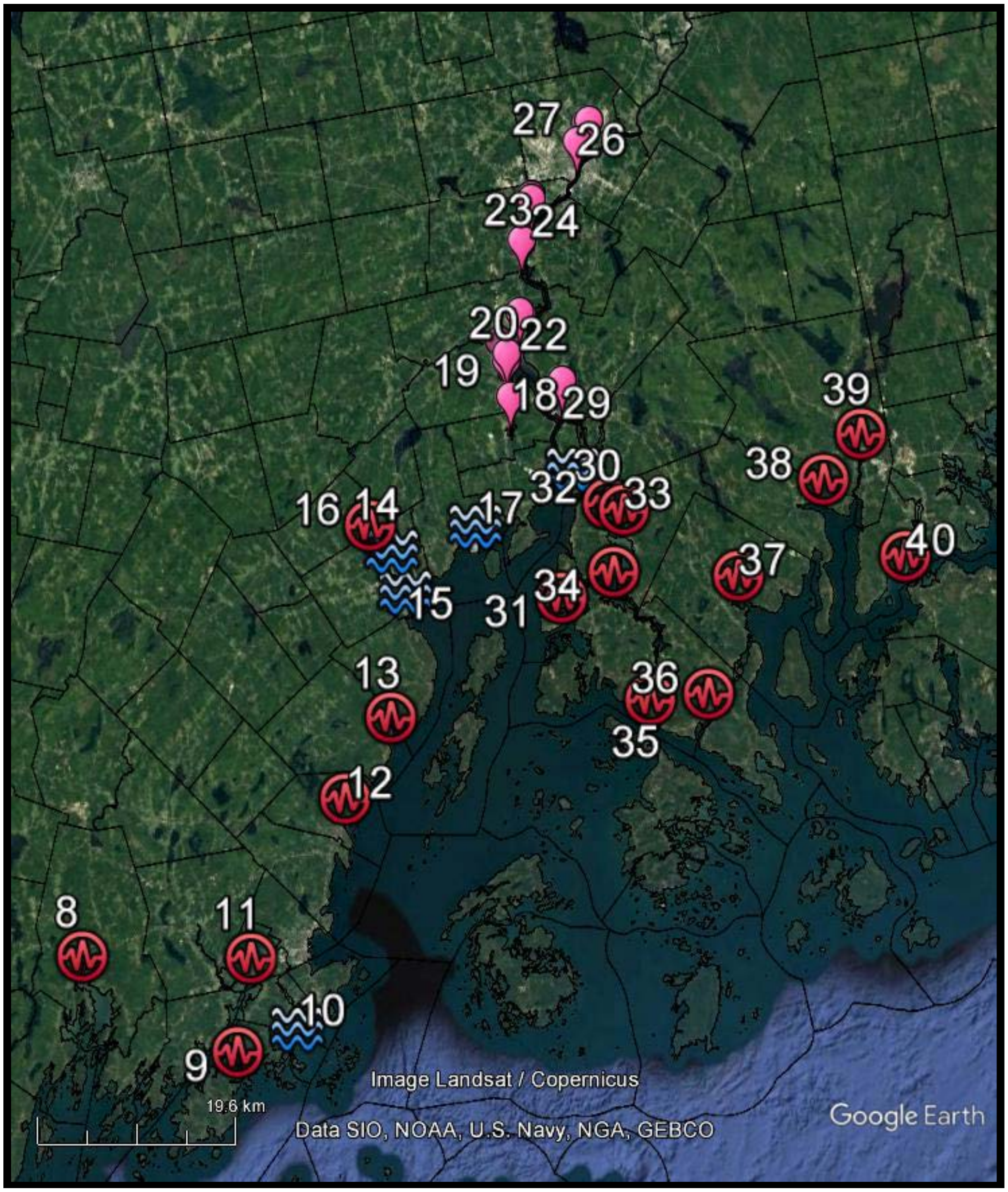

Figure 24. Location of High Water Marks from the Groundhog Day 1976 Storm.

Marks indicated with a red icon were identified as resulting from tidal surge. Marks indicated with a pink balloon icon were identified as having riverine influence. Marks identified with blue wave icon were identified as resulting from wave action.

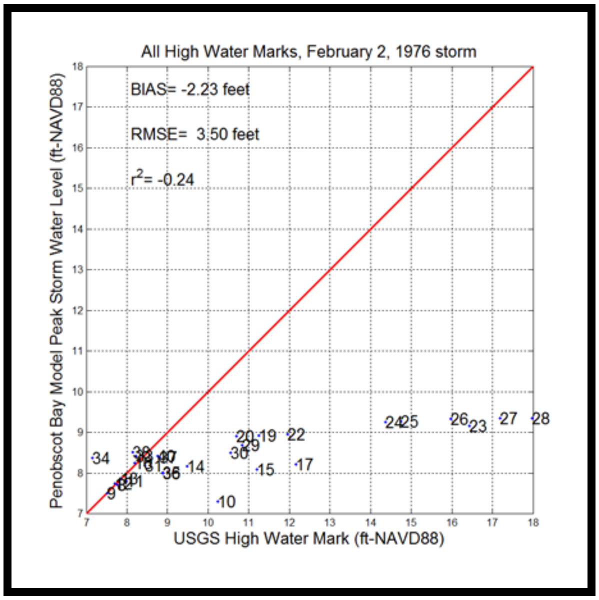

Figure 25. Comparison of all High-Water Marks to Modeled Maximum Water Level for the 1976 Groundhog Day Storm

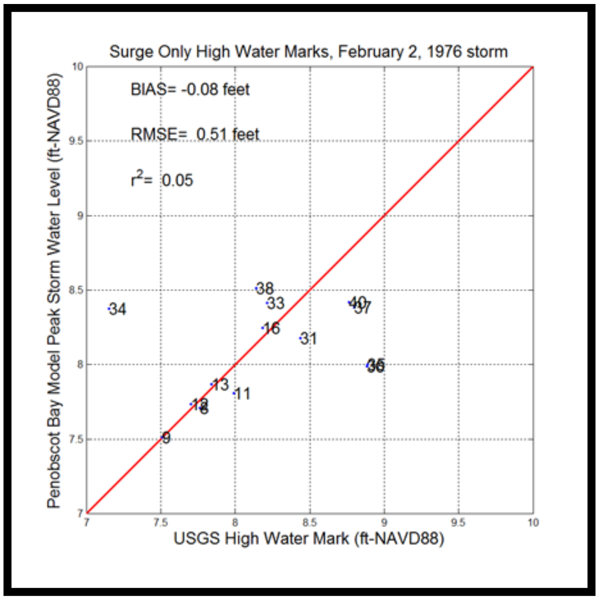

Figure 26. Comparison of Tidal Surge Only High-Water Marks to Modeled Maximum Water Level for the 1976 Groundhog Day Storm

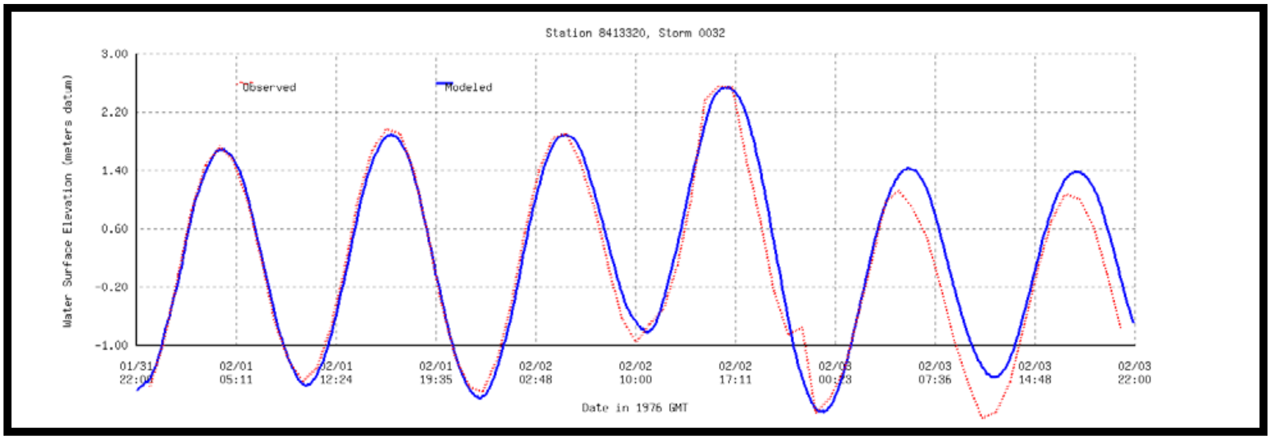

Figure 27. Groundhog Day 1976, Observed and Modeled Water Level Time Series at Bar Harbor

3.4.2 February 7, 1978 Blizzard

Gadoury (1979)[17] reported a number of high water marks throughout northern New England following the blizzard of February 7, 1978. All of the high-water marks that were reported within the Penobscot Bay model domain were identified as being caused by tidal surge. The location of the high-water marks is shown in Figure 28. *Location of High Water Marks from the February 7, 1978 Blizzard.* The observed high-water mark data were originally reported relative to the NGVD29 vertical datum, but were converted to NAVD88 using the National Geodetic Survey (NGS) VERTCON program, prior to comparison to the model results. Figure 29 shows a scatter plot comparing the observed HWMs to the modeled HWMs, as well as the bias and RMSE. The comparison shows a bias of -1.34 feet and a RMSE of 1.47 feet indicating under-prediction of the observed maximum water levels. This under-prediction is consistent with the NACCS model under-prediction of this storm, but is not as great in magnitude.

Figure 30 shows a comparison of the observed and modeled water level time series at the Bar Harbor tide station (station ID 8413320). This comparison shows that the Penobscot Bay model under predicts observed peak water level at Bar Harbor by about 0.4 feet. When compared to the NACCS model validation described in our May 12, 2017 memorandum[18], this shows a significant improvement in accuracy for this particular storm even though the peak water level is still under-predicted.

The Gadoury (1979) report also provided high water mark data from a storm that occurred January 9, 1978. This storm produced surge and wave condition that were comparable to the February 7 storm in many locations in Penobscot Bay. Unfortunately, the January 9 storm was not included in the NACCS storm set, so appropriate boundary conditions are not available for a simulation with the Penobscot Bay Model. Because the January 9, 1978 storm was not included in the storm set, the simulated maximum water level from the February 7, 1978 storm (or

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[17] Gadoury, Russell A. 1979. Coastal Flood of February 7, 1978 In Maine, Massachusetts, and New Hampshire, U.S. Geological Survey, Water-Resources Investigations 79-61 open file report. Prepared in cooperation with the U.S. Army Corps of Engineers and the Massachusetts Department of Public Works. U.S. Department of the Interior.

[18] Ransom Consulting, 2017. "Coastal Flood Vulnerability Study, Review of NACCS data", Draft Memorandum to the Town of Islesboro, May 12, 2017.

February 2, 1976 storm if it is greater) has been double counted in extreme value analysis for extra-tropical storms described later in this report. This is done to avoid under-prediction of the extreme water level probabilities that would result from missing a significant storm from the historic record. The results from the February 7, 1978 were also adjusted by adding 1.34 feet to the peak water level boundary across the model domain to account for the model bias for this particular storm prior to use in the extreme value analysis.

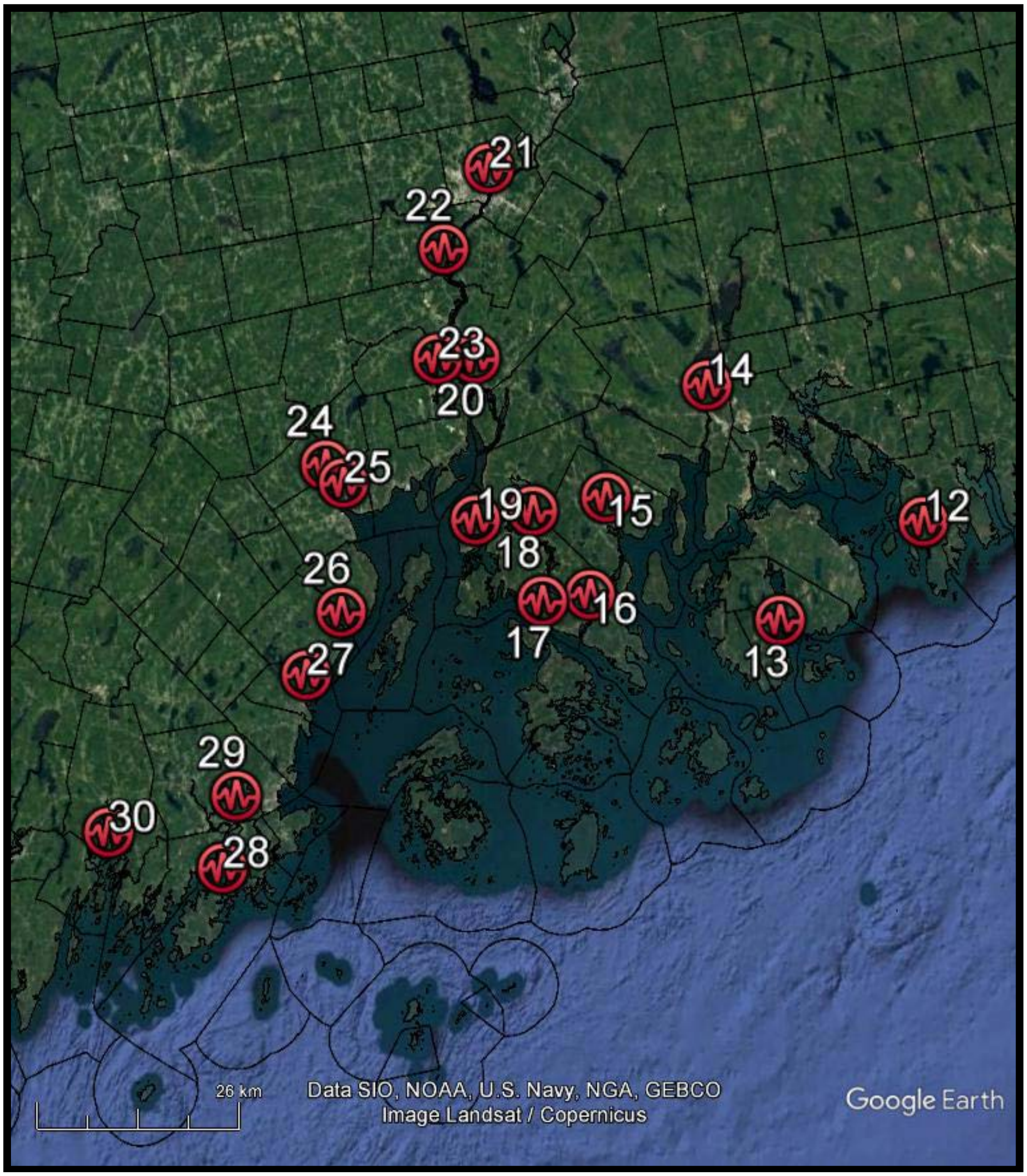

Figure 28. Location of High Water Marks from the February 7, 1978 Blizzard

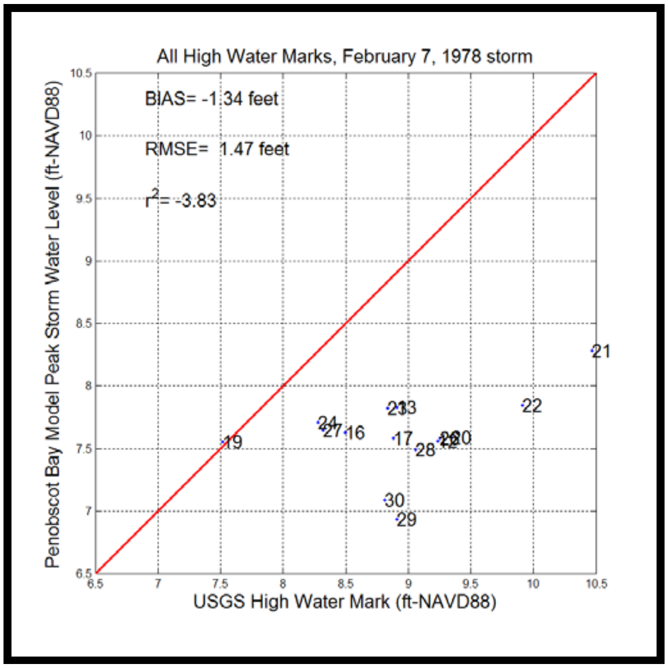

Figure 29. Comparison of Tidal Surge Only High-Water Marks to Modeled Maximum Water Level for the February 7, 1978 Storm.

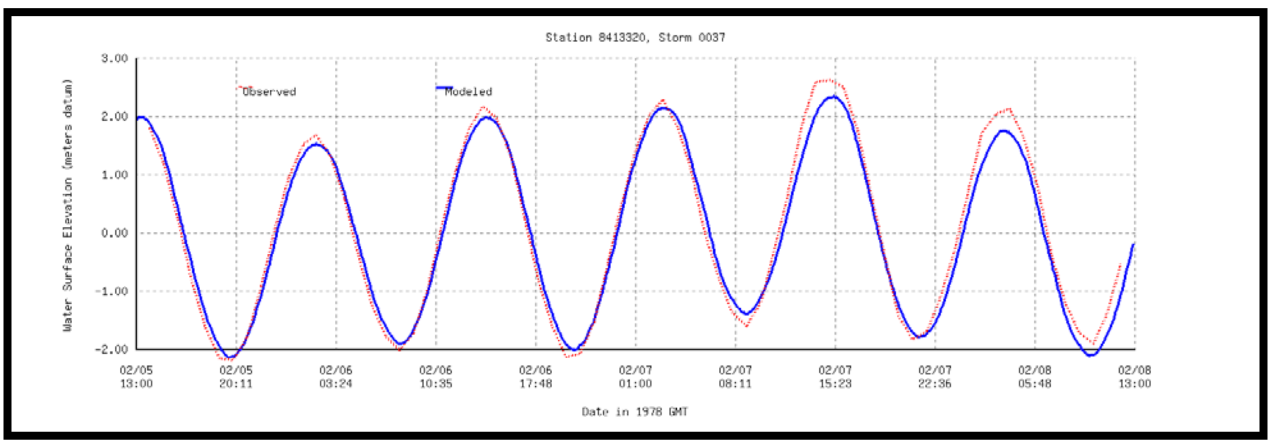

Figure 30. February 7, 1978 storm, Observed and Modeled Water Level Time Series at Bar Harbor

3.4.3 Bar Harbor Water Level Time Series

Model validation against high water mark data for particular storm events is useful for evaluating the variability of model performance across the model domain. However, validation against a single storm event is not necessarily representative of model performance for other events with different forcing conditions. In order to evaluate the performance of the model, it is necessary to compare the model output to observations for many storm events. Fortunately, hourly water heights at the National Ocean Service (NOS) Bar Harbor tide station are available for 35 of the 37-production simulation.

A scatter plot comparing the observed and modeled peak water levels at the Bar Harbor Tide station for each of these storm events is provide in *Figure 31*. On the scatter plot, a point is plotted for each storm corresponding to the observed peak water level on the horizontal axis, and the modeled peak water level on the vertical axis. If the model performed perfectly, all of the points would lie on a line with a 1:1 slope passing through the origin (red line). The scatter plot also includes a best fit line that is determined by a linear least squares regression of the scatter points (green line). The bias and RMSE were also determined for this comparison. The best fit line slope, bias, and RMSE are listed in *Table 5*. *Table 5* also lists the slope, bias, and RMSE from our review of the NACCS data described in section 2.4 of this report. From the comparison, it is clear that the Penobscot Bay model eliminates much of the under-prediction apparent in the NACCS model results, and provides an overall unbiased model for estimating peak water level conditions consistent with the historic extra-tropical storm climatology in the region. The validation also suggests a value of 0.56 feet, based on the RMSE, may be used to represent the contribution of modeling error to the epistemic uncertainty when performing extreme value analysis on the production run results. Modeled and observed water level time series at Bar Harbor for each of the production run simulations are provided in **Appendix C**.

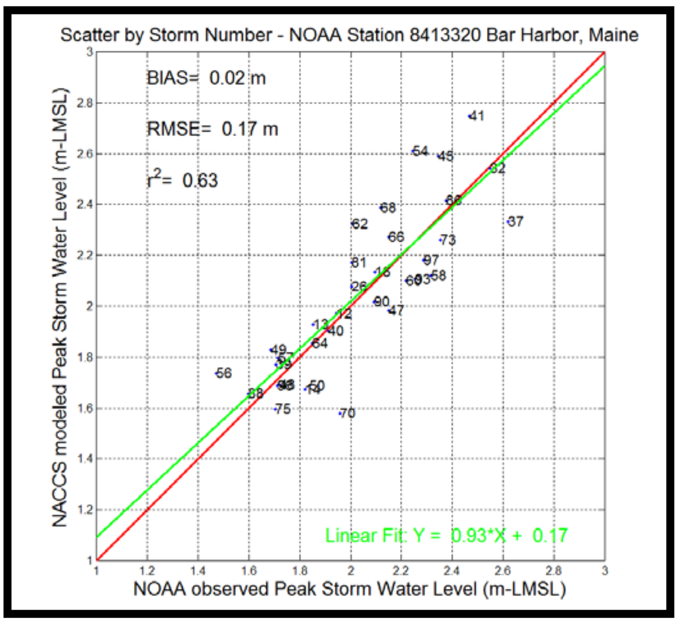

Figure 31. Scatter Plot Comparison of Modeled and Observed Peak Water Level at Bar Harbor for 35 out of 37 Production Simulation Storms.

Table 5. Comparison of Penobscot Bay Model Validation to NACCS Model Validation

	NACCS Model	Penobscot Bay Model
Bias (feet)	-0.56	0.07
RMSE (feet)	0.75	0.56
Best Fit Line Slope	0.65	0.93

4.0 COMBINED STORM SURGE AND SEA LEVEL RISE PROJECTIONS

4.1 Basic Hazard Statistics

When we discuss hazards within a probabilistic framework, we often talk about the likelihood of experiencing the hazardous condition in terms of an Annual Exceedance Probability (AEP). When the hazard is flooding, the AEP is often used to express the probability that the water will exceed a given elevation within any given year. For example, an event with an AEP of 10% has a 1 out of 10 chances of happening within a given year.

Another mathematically equivalent, but conceptually different, way of expressing the likelihood of a hazard is the Average Recurrence Interval (ARI), which also commonly called the “Return Period”. The ARI expresses how often, on average, the hazardous conditions is expected to occur given a sufficiently long period of time. For example, an event with an ARI of 10 years would be expected to happen once every ten years on average, which is approximately equivalent to an AEP of 10%.

It is important to understand that an ARI of 10-years does not mean that the event will reoccur precisely every 10 years, but rather, in the long run it will reoccur about every 10 years on average. For example, a 10-year event would be expected to occur about 10 times every 100 years, but within 100 years you may have multiple decades without a 10-year event and other decades that have multiple 10-year events. The concept of the ARI becomes more challenging and less useful when we consider that sea level rise tends to increase the likelihood of flooding in the future (e.g. the 10-year event of today is not the same as the 10-year event of tomorrow). For this reason it helpful to think about the coastal flood hazard in terms of an AEP that changes year to year with changes in the sea level, even when the hazard is commonly expressed in terms of ARI.

Table 6 lists the equivalent AEP for a range of common ARI values. For events rarer than the 10-year event, the AEP is practically equal to the reciprocal of the ARI expressed as a percentage (i.e. AEP=100*1/ARI), while more frequent events have AEP that is less than that. This makes sense if you consider that an event which occurs on average once a year, may happen twice or more in some years and not at all in others. The AEP for a given ARI is more precisely determined by assuming the coastal flood hazard may be represented as Poisson process, and applying the Poisson probability distribution, which expresses the probability of that a given number of events with some average rate of occurrence will occur within a given amount of time. The Poisson distribution is expressed:

$$P = \frac{(\mu t)^k * e^{-\mu t}}{k!}$$

> Where P is the probability of observing exactly k events in the time period t, with an average rate of occurrence μ; and e is Euler’s number (the base of the natural logarithm).

For example, consider an event with an ARI of 1-year, which has average rate of recurrence of 1 event per year. The probability of observing one or more 1-year event within 1 year is the compliment of (one minus) the probability of observing exactly zero 1-year events in 1 year. In that case:

$$1 - P = 1 - \frac{(1*1)^0 * e^{-1*1}}{0!} = 1 - e^{-1} = 0.6321$$

Table 6. Relationship Between Average Recurrence Interval (or Return Period) and Annual Exceedance Probability.

Average Recurrence Interval (ARI)	Annual Exceedance Probability (AEP)
1-year	63%
2-year	39%
5-year	18%
10-year	9.5%
20-year	4.9%
50-year	2.0%
100-year	1.0%
200-year	0.5%
500-year	0.2%
1000-year	0.01%

By quantifying the hazard in terms of ARI or AEP across the entire range of possible flood levels, from the relatively frequent events to the very rare, we can take a fully probabilistic approach to risk assessment. When the flood hazard is characterized in this way, it can be used as a basis for accurate Risk Informed Decision Making (RIDM). Within a RIDM framework the flood hazard information, in terms of probability, may be combined with an assessment of vulnerability to quantify the expected cost of flood damages and the benefits of proposed risk mitigation and adaptation measures.

4.2 Coastal Flooding Hazard Extreme Value Analysis

An extreme values analysis, based on the Peaks Over Threshold (POT) method of Goda[19], was performed to determine water level and wave height hazards from the maximum water level and wave height outputs from the Penobscot Bay model extra-tropical storm production simulations. The POT method involves fitting a record of extreme values (above a specific threshold) to set of standard extreme value probability distributions. Measures of the goodness of fit are then used to select the best fitting distribution for the data. Once the parameters of the best fitting distribution are identified, the water level (or wave height) for any ARI can be determined directly from the distribution. Goda's method involves fitting the set of probability distributions commonly known as the General Extreme Value (GEV) distribution, which includes the Frechet, Weibul, and Gumbel distributions. A fit of each distribution is attempted for a range of shape and scale parameters, and the best fit is identified as the one that yields the lowest Minimum Ratio of residual correlation coefficient (MIR). The threshold applied in the POT method is typically used to screen the data to select data points that are associated with extreme events from the same population (e.g. caused by extra-tropical storms). In our case, because the NACCS has already identified the storm events, we set the threshold just below the lowest maximum water level from the storm set and all storms are used in the POT analysis. The POT analysis was carried out for each node in the Penobscot Bay model, where a non-dry maximum water level was recorded in the model output for every storm in the extra-tropical storm set. Water level values associated with ARIs from the 2-year to the 2000-year were then determined for each "wet" node in the model. Figure 32. 10-year ARI Water Level through Figure 35 show the storm tide water level surface associated with the 10-year, 50-year, 100-year, and 500-year ARI, respectively. A similar POT analysis was carried out using the maximum significant wave height from the Penobscot Model output. Figure 36. 10-year ARI Significant Wave Height

[19] Goda, Yoshimi, 2010, Ransom Seas and Design of Maritime Structures, 3rd edition. World Scientific Publishing Co. Pte. Ltd. 27 Warren St. Suite 401-402, Hackensack, NJ 07601

through Figure 39 show the significant wave height surface associated with the 10-year, 50-year, 100-year, and 500-year ARI, respectively.

It must be noted that the extreme value analysis and vulnerability assessment presented in this report is based entirely on a population of historic extra-tropical storms, which does not include the possibility of rare tropical storm events that may occur. For this reason, the results of the extreme value analysis may under-estimate the hazard for very rare events (e.g. greater than 100-year ARI). Also, because the analysis is based on tidal dynamics that occurred specifically with a set of storm events, it does not fully consider the tidal contribution to extreme water levels that would occur during purely tidal non-storm events. As such, it may underestimate the water levels that may occur during more frequent “sunny day” flooding events that are not associated with high winds and wave conditions. Furthermore, the current analysis may only accurately represent the hazard spectrum from the moderate to somewhat rare events (e.g. 10-year to 100-year ARI).

Future work should consider contributions to the full hazard spectrum from both the rarer tropical storm events and the more frequent purely tidal events by incorporating a probability distribution derived from the JPM-OS tropical storm simulations into the analysis, as well as a probability distribution based harmonic analysis of the pure astronomical tide. For now, we assume that moderate to moderately severe storm conditions associated with extra-tropical storm events are the most important threat to consider when projecting increased risks with future sea level rise over the next 80 years. And thus, the extreme value analysis based on historic extra-tropical events provides us with a reasonable example of hazard information to use in the example analysis below, where it is combined with probabilistic sea level rise projections and used for site specific vulnerability assessments.

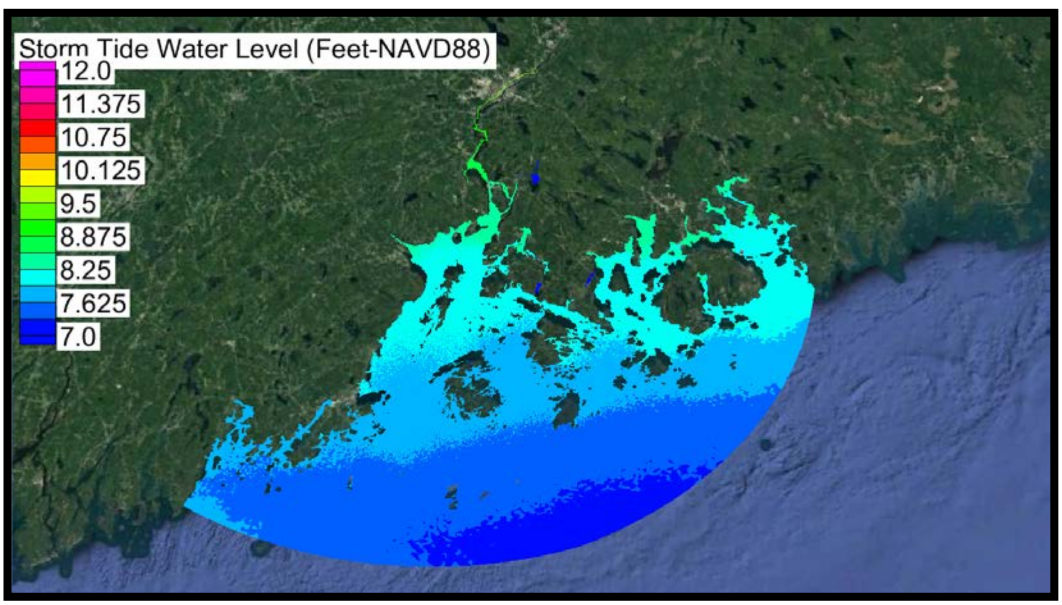

Figure 32. 10-year ARI Water Level

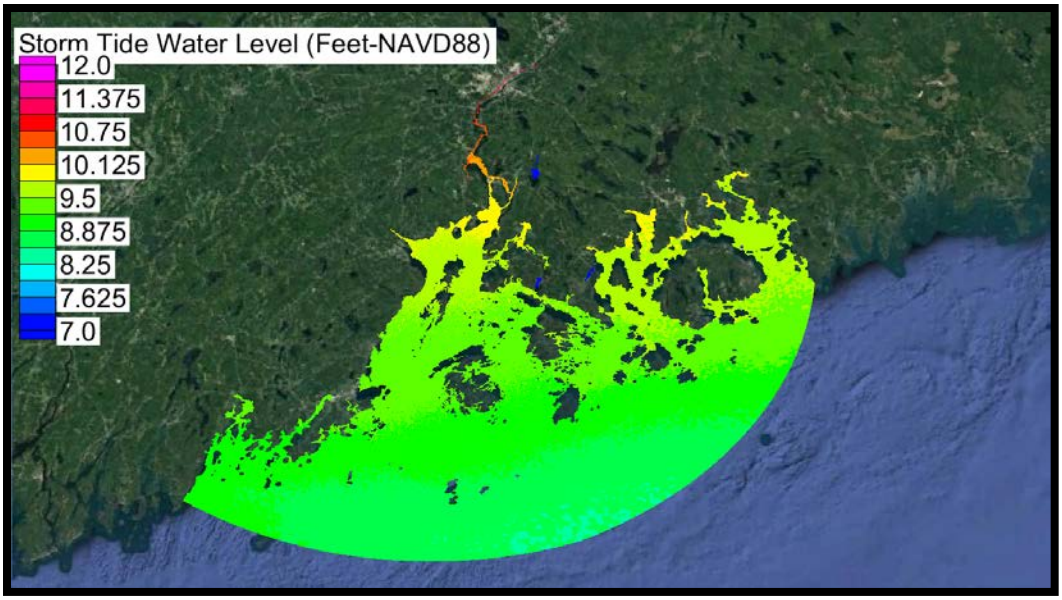

Figure 33. 50-year ARI Water Level

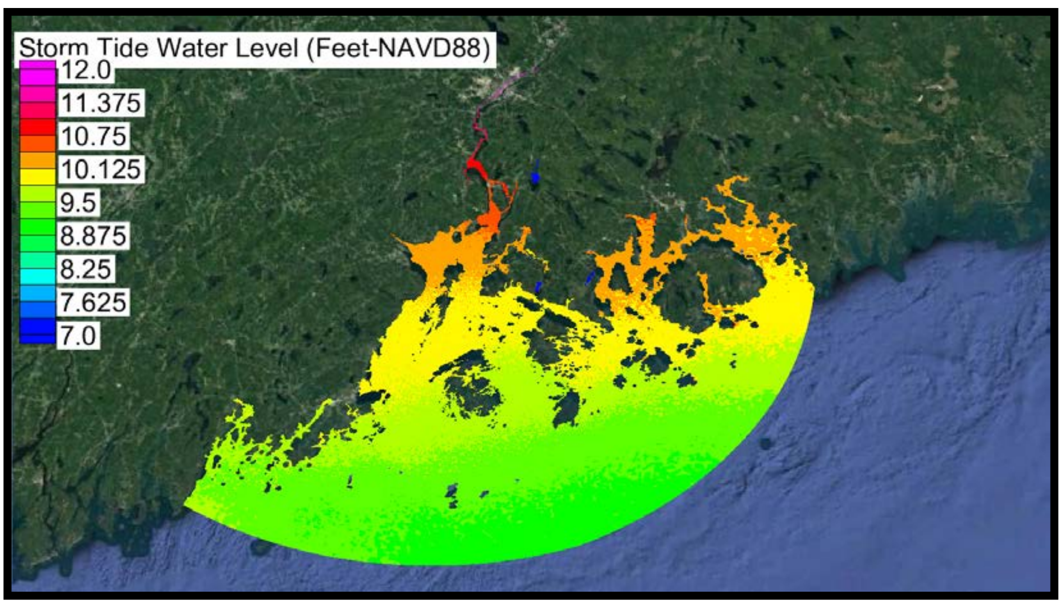

Figure 34. 100-year ARI Water Level

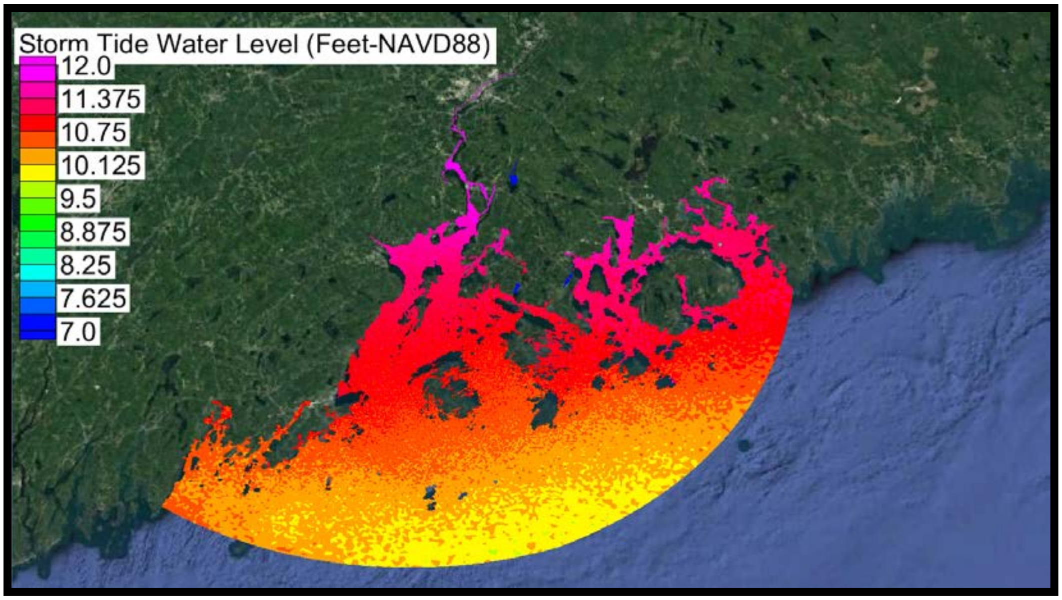

Figure 35. 500-year ARI Water Level

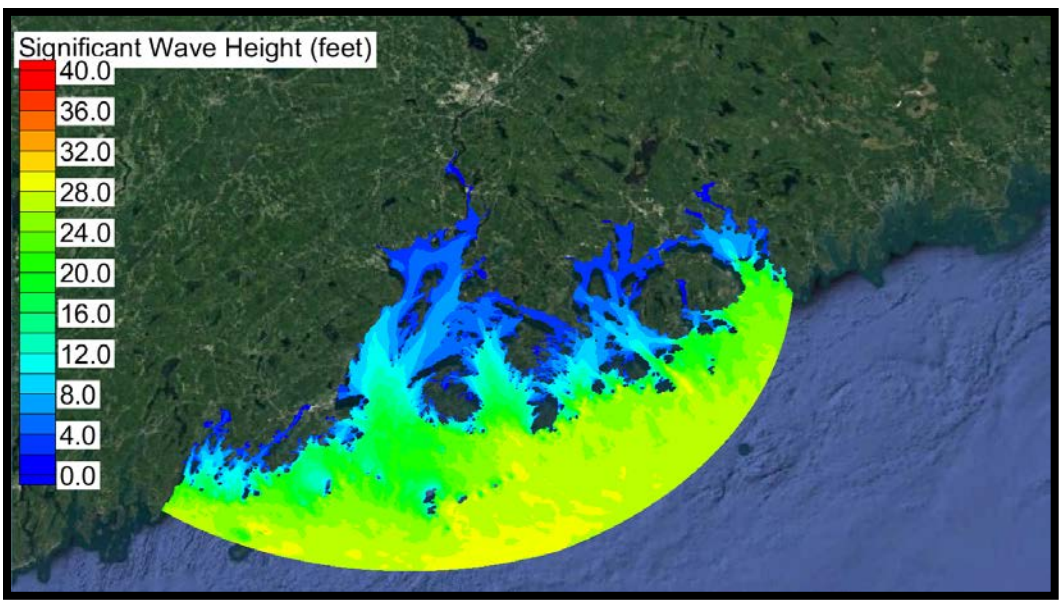

Figure 36. 10-year ARI Significant Wave Height

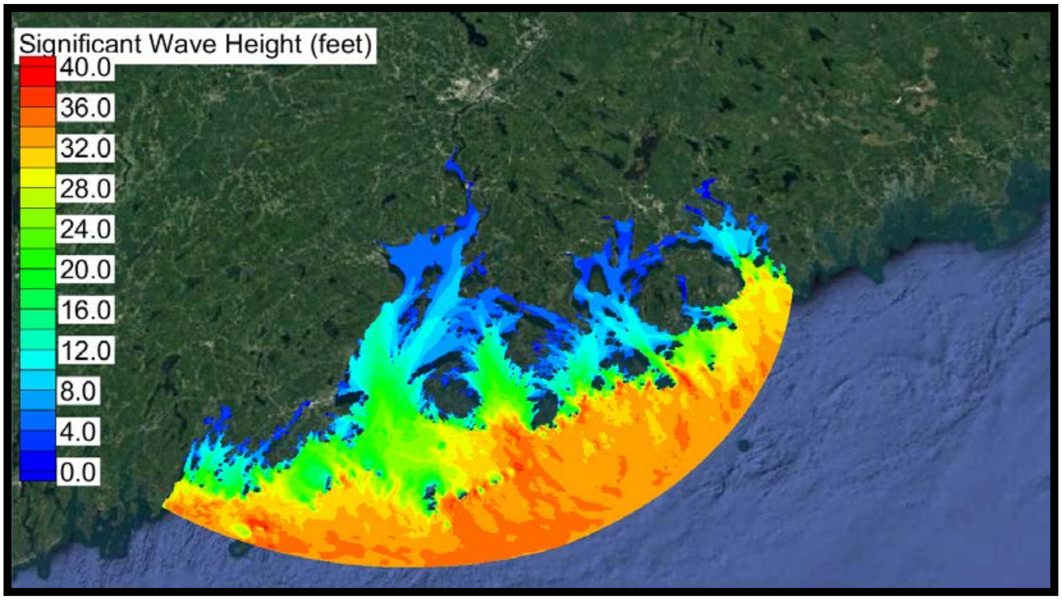

Figure 37. 50-year ARI Significant Wave Height

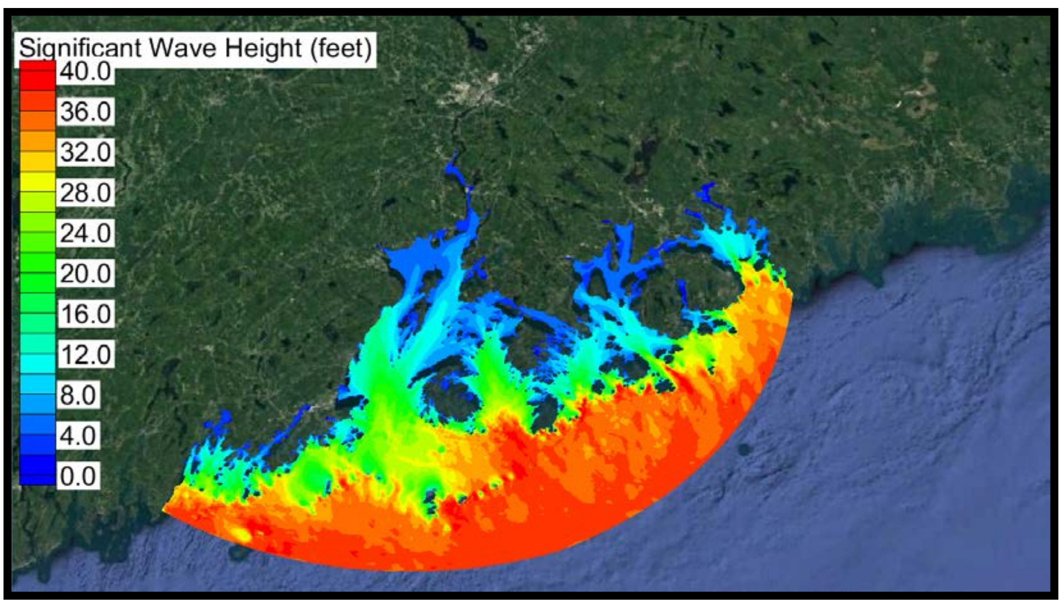

Figure 38. 100-year ARI Significant Wave Height

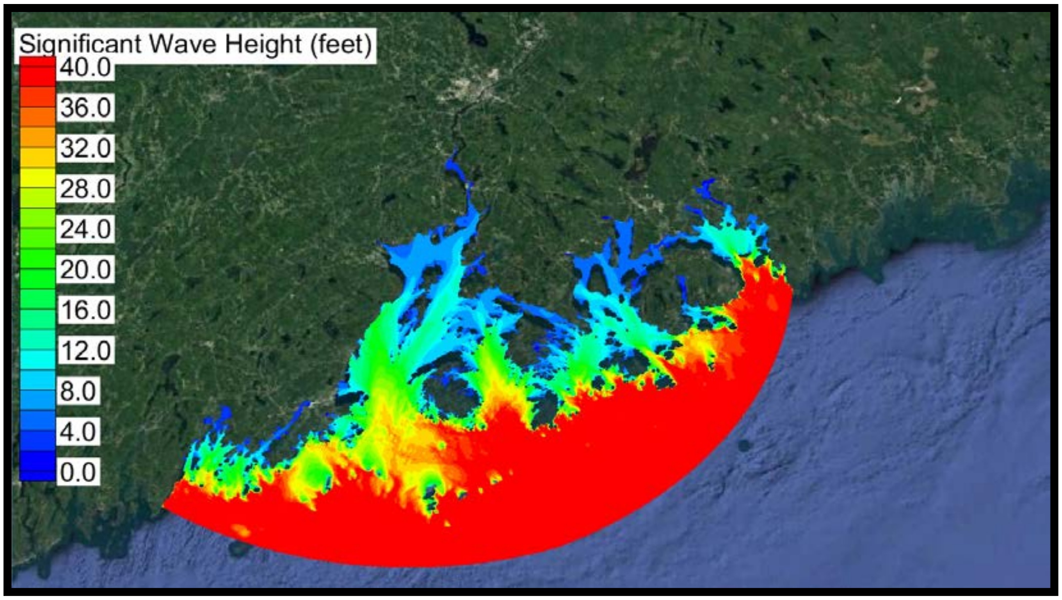

Figure 39. 500-year ARI Significant Wave Height

4.3 Sea Level Rise Projections

4.3.1 Scenario Based Guidance

Much of the current guidance for sea level rise planning recommends evaluating discrete sea level rise scenarios that cover a range of possible futures in order to encourage decision makers to consider multiple future conditions and identify robust solutions that will be functional for a range of highly uncertain future conditions[20,21]. Figure 40 shows a set of sea level rise scenarios for Bar Harbor based on recommendations from the USACE and NOAA and obtained from the USACE's online Sea-Level Change Curve Calculator (version 2017.55), http://www.corpsclimate.us/ccaceslcurves.cfm. The data used to plot the curves is also tabulated in *Table 7*. Following this guidance, Islesboro should consider the possibility that, by 2050 mean sea level could rise as little as 0.39 feet to as much as 2.11 feet higher than it was in 1992; and that by 2100 sea level could be anywhere from 0.72 feet to 6.68 feet higher than it was in 1992.

[20] Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K, Knuuti, R. Moss, J. Obeysekera, A. Sallenger, J. Weiss, 2012. Global Sea Level Rise Scenarios for the United States National Climate Assessment. National Oceanic and Atmospheric Administration Technical Report OAR CPO-1, Climate Program Office (Silver Spring, MD.

[21] USACE, 2014. Global Changes Procedures to Evaluate Sea Level Change Impacts, Responses, and Adaptation, Engineer Technical Letter No. 1100-2-1. Department of the Army, U.S. Army Corps of Engineers Washington, DC

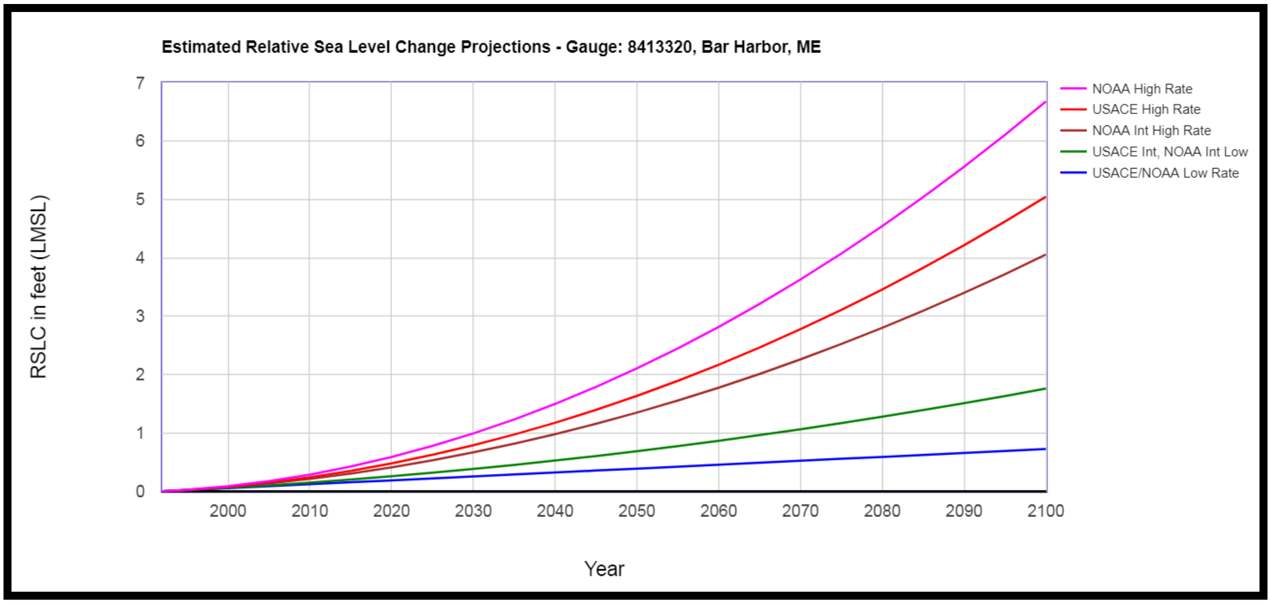

Figure 40. USACE/NOAA Local Sea Level Rise Scenarios for Bar Harbor, Maine

Table 7. USACE/NOAA Local Sea Level Rise Scenarios for Bar Harbor, Maine (feet)

Year	USACE/NOAA Low	USACE Low NOAA Int. Low	NOAA Int. High	USACE High	NOAA High
1992	0.00	0.00	0.00	0.00	0.00
1995	0.02	0.02	0.02	0.02	0.03
2000	0.05	0.06	0.07	0.08	0.09
2005	0.09	0.10	0.14	0.15	0.17
2010	0.12	0.15	0.21	0.24	0.29
2015	0.15	0.20	0.31	0.35	0.42
2020	0.19	0.26	0.41	0.48	0.59
2025	0.22	0.32	0.53	0.63	0.78
2030	0.25	0.38	0.67	0.79	0.99
2035	0.29	0.45	0.82	0.97	1.23
2040	0.32	0.53	0.98	1.18	1.50
2045	0.36	0.60	1.16	1.40	1.79
2050	0.39	0.69	1.35	1.64	2.11
2055	0.42	0.78	1.56	1.89	2.45
2060	0.46	0.87	1.78	2.17	2.82
2065	0.49	0.96	2.01	2.46	3.21
2070	0.52	1.06	2.26	2.78	3.63
2075	0.56	1.17	2.52	3.11	4.08
2080	0.59	1.28	2.80	3.46	4.55
2085	0.62	1.39	3.09	3.83	5.04

Year	USACE/NOAA Low	USACE Low NOAA Int. Low	NOAA Int. High	USACE High	NOAA High
2090	0.66	1.51	3.40	4.22	5.56
2095	0.69	1.63	3.72	4.62	6.11
2100	0.72	1.76	4.06	5.05	6.68

Curves like those presented in Figure 40 may intuitively suggest that sea level will follow a particular scenario into the future, but that is actually very unlikely. The scenarios should not be thought of as individual predictions of future sea level, but rather as limits that bound the range of possible future sea levels. This caveat is explained in the federal guidance, but many stakeholders may not be familiar with this detail, resulting in a tendency to focus on a particular scenario in the decision-making process rather than considering a full set of scenarios as recommended.

We know from observations that the mean sea level does not follow a smooth curve. In fact, it can vary quite a bit from day to day, month to month, and year to year. The shorter the time scale, the greater the variance. To put this in perspective, Figure 41 adds the observed mean sea level from the historic record at Bar Harbor to the sea level change scenario curves from Figure 40 showing the transition from what we know to what we try to predict. The observed mean sea level has been calculated at a range of time scales including the annual mean shown in yellow, the monthly mean shown in cyan, and the daily mean shown in black. The vertical datum for the mean sea levels is the mean level determined by averaging all hourly records during the National Tidal Datum Epoch[22] (NTDE) of 1983-2001. When observations and projections are compared side by side, it becomes apparent that projected sea level rise scenarios ignore the actual observed variability in the local mean sea level. Figure 42 shows the same data as Figure 41 but with focus on the present decade, where there is some overlap in the observed data and the sea level change scenarios that are projected from 1992. In Figure 42 we can see the projected scenarios do not even bracket the range of observations. For example, the annual mean sea level (yellow line) was actually higher than the NOAA High Rate in 2010, and then decreased over the following 5 years to a value lower than the Low Rate. The variability in the monthly mean is greater than the full range of scenario guidance out to about 2030, and the variability in the daily mean is greater than full range of scenarios out to about 2050. For this reason, the sea level change scenarios are not really indicative of the possible change in mean sea level that we should expect in the next few decades.

[22] The NTDE is a specific 19-year period over which tide observations are averaged to determine tidal datums, such as Local Mean Sea Level (LMSL), Mean Higher High Water (MHHW), Mean Lower Low Water (MLLW) etc. The NOAA National Ocean Service (NOS) considers a revised NDTE every 20-25 years in order to take into account long-term relative sea level changes caused by global sea level change, and the effects of land movement due to subsidence and/or glacial rebound. Then the NDTE is updated, older data which refer to the past NDTE are adjusted to the new NDTE.

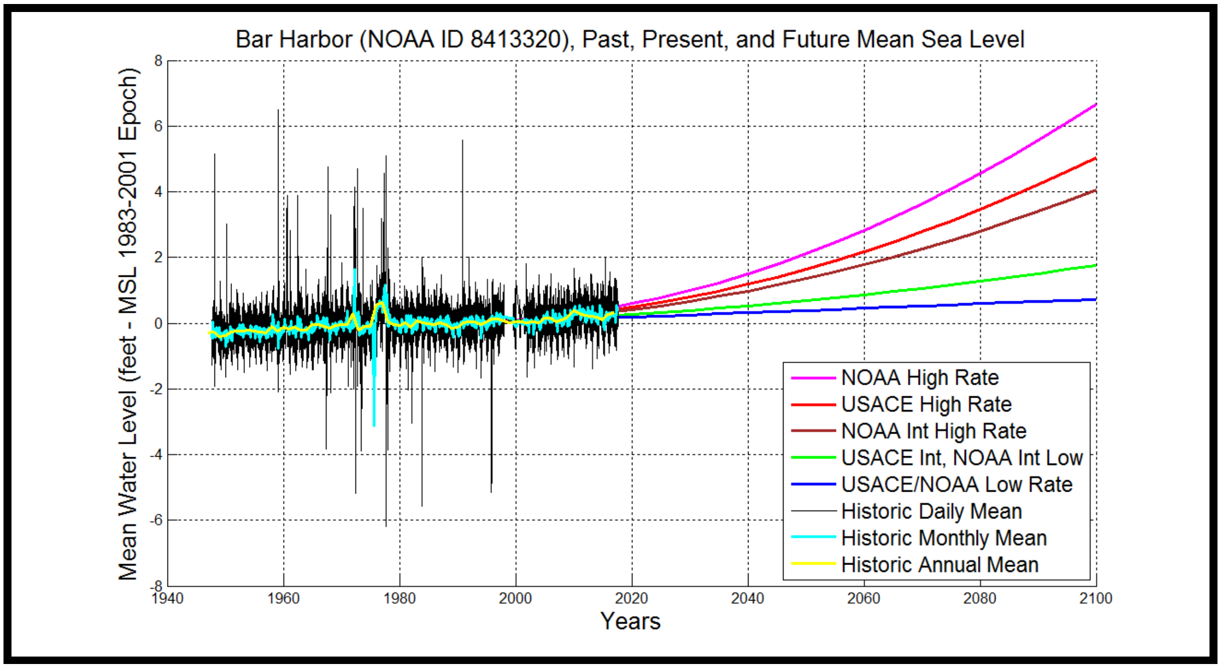

Figure 41. USACE/NOAA Local Sea Level Rise Scenarios and Historic Mean Sea Level for Bar Harbor, Maine

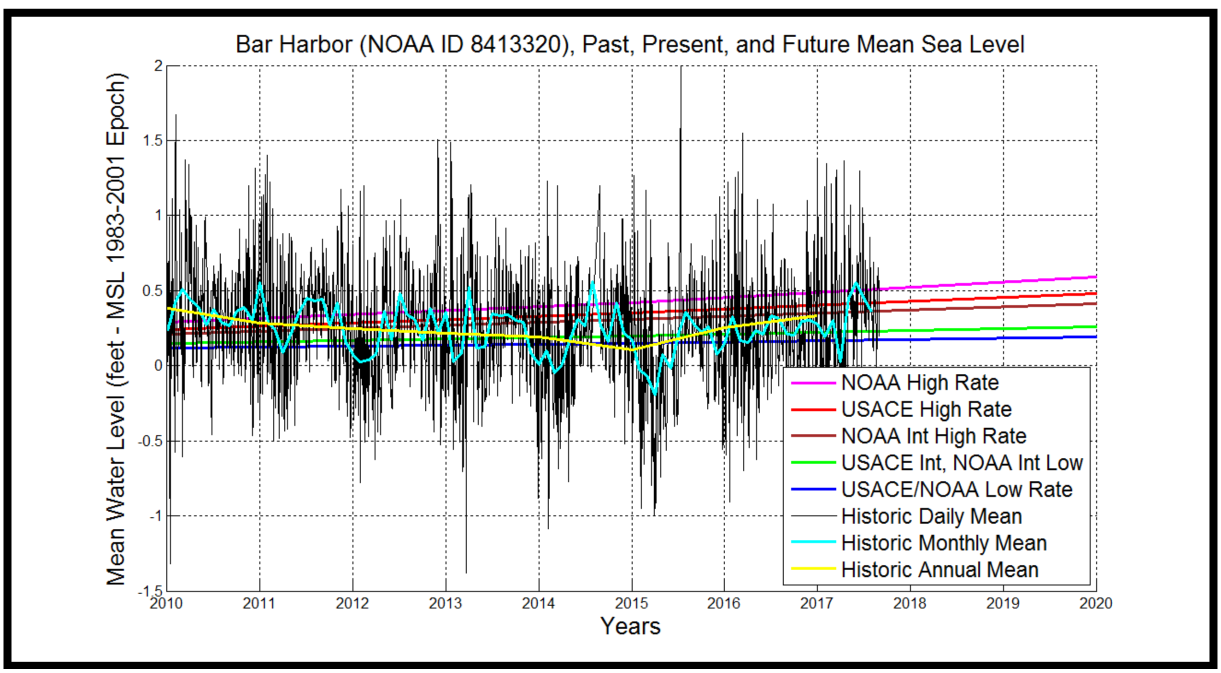

Figure 42. USACE/NOAA Local Sea Level Rise Scenarios and Historic Mean Sea Level for Bar Harbor, Maine

4.3.2 Probabilistic Sea Level Change

The scenario based approach to sea level change suffers from two inter-related problems. The first, mentioned in the previous section, is that it inadvertently inspires focus on individual scenarios, which are subject to prejudices of decision makers. The second problem is that it provides no information about how likely the various scenarios may be. So even when decision makers correctly consider a range of scenarios, they are at a loss when it comes to weighing the different scenarios against one another. They may inadvertently place too much weight on an unlikely outcome and/or too little weight on the more likely outcomes.

These problems can be alleviated by considering the mean sea level as a non-stationary random process. A random (or stochastic) process describes a variable that evolves through time in a non-deterministic way. This means that, even though values of the variable that are close in time may be close to one another, there is no way to precisely determine a future value based on the history of past values. Instead, a future value is characterized by a probability distribution that expresses how likely it is within a range of possible values, similar to the probability distributions for storm surge discussed in section 4.1 and 4.2. A random process is considered non-stationary if the parameters that describe its probability distribution (e.g. mean and variance) change with time. In the case of sea level, we clearly expect the mean to change, and the variance increases in future projections to account for increasing uncertainty. When we consider that the future mean sea level is non-stationary random process we are able to apply statistical model to offer guidance on the likelihood of future scenarios. This type of probabilistic information is necessary if we are to apply RIDM to planning for sea level rise adaptation, and mitigation of future coastal flood risk. This approach is also conceptually appealing because it does not preclude the possibility that sea level may actually decrease at times in the future; a circumstance that is clearly possible given observations presented in, and sometimes used by skeptics to discount scenario based guidance that increases sea levels into the future without any imposed limits.

Probabilistic sea level change guidance should not be thought of as a replacement for the scenario based guidance recommended by NOAA and the USACE. Instead it should be considered as a supplement to scenario based guidance that quantifies the likelihood of individual scenarios and allows application of RIDM. Probabilistic guidance for sea level change is not a new idea. For example, the U.S. Environmental Protection Agency (USEPA) saw the need for probability-based guidance on sea level rise over 20 years ago, and provided probability-based projections of global sea level rise for planning use[23]. Paris et al (2012)[19] mention probabilistic projections as another form of scenario guidance, but they do not pursue it, citing no accepted widely available method for producing probabilistic guidance at regional or local scales. The USACE also mentions probabilistic guidance, but then echo the same lack of accepted methods and large degree of uncertainty cited by NOAA.

More recently, Kopp et al. (2014)[24] provide localized actionable probabilistic information. For our study, we adopt their data to characterize probabilistic future sea level change at Bar Harbor. Their data provide cumulative probability distributions for local mean sea level at years 2030, 2050, 2100, and 2200 for three of the Representative Concentration Pathways (RCP) adopted by

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[23] Titus, J.G., V. K. Narayanan. 1995. The Probability of Sea Level Rise. United States Environmental Protection Agency, Office of Policy, Planning, and Evaluation, EPA 230-R-95-008, September 1995.

[24] Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi (2014), Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, *Earth's Future*, *2*, 383–406, doi:10.1002/2014EF000239.

the Intergovernmental Panel on Climate Change (IPCC) in their fifth assessment report[25]; these are shown in Figure 43. *Sea Level Rise Cumulative Probability Distributions for 2030 at Bar Harbor, Maine* thru Figure 46 respectively. The cumulative probability distributions show the probability that the future sea level will be less than the corresponding sea level rise value. For example, in Figure 43. *Sea Level Rise Cumulative Probability Distributions for 2030 at Bar Harbor, Maine*, for RCP 4.5, we see that there is a 60% probability that sea level rise by 2030 will be less than 20 centimeters (0.7 feet), or complementarily a 40% probability that local mean sea level will rise more than 20 centimeters (0.7 feet) before 2030. Using this information, we can evaluate the probability that future sea levels will be greater or less than the USACE and NOAA scenarios. Table 8 lists the probability sea level will be greater than the USACE and NOAA sea level rise scenarios at 2030, 2050, and 2100 based on the probabilistic guidance.

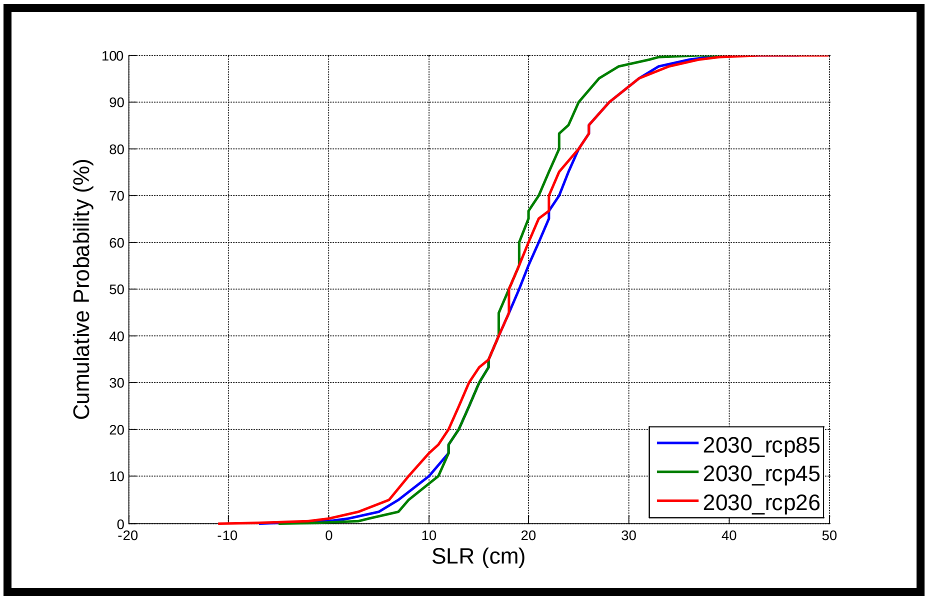

Figure 43. Sea Level Rise Cumulative Probability Distributions for 2030 at Bar Harbor, Maine

[25] Intergovernmental Panel on Climate Change (2013), Summary for policy makers, in *Climate Change 2013: The Physical Science Basis*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, pp. 3–29, Cambridge Univ. Press, Cambridge, U. K.

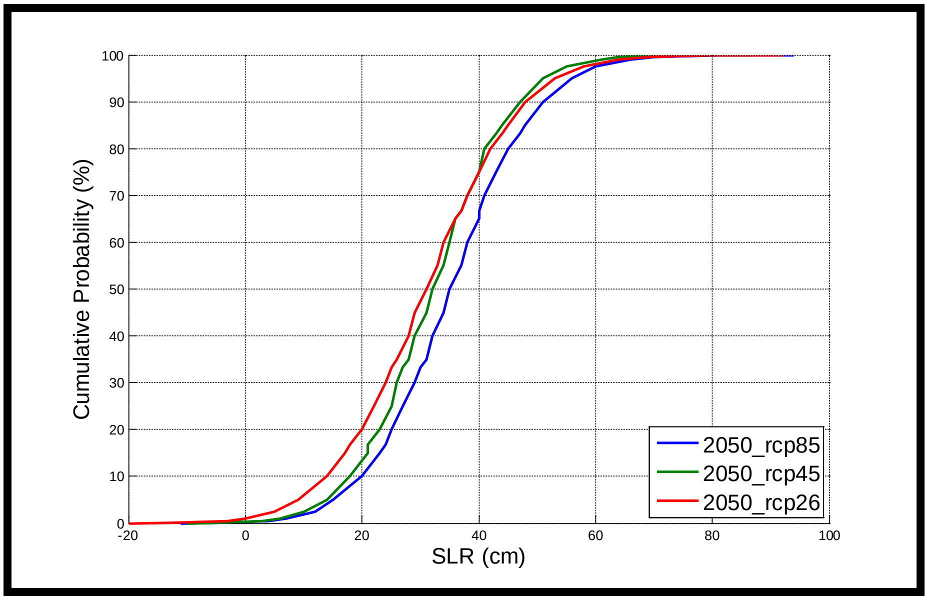

Figure 44. Sea Level Rise Cumulative Probability Distributions for 2050 at Bar Harbor, Maine

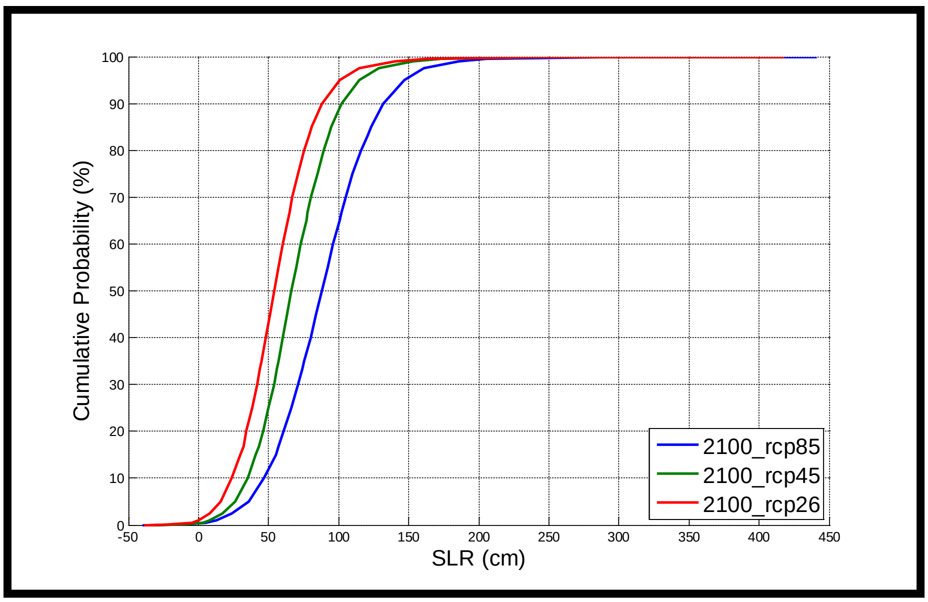

Figure 45. Sea Level Rise Cumulative Probability Distributions for 2100 at Bar Harbor, Maine

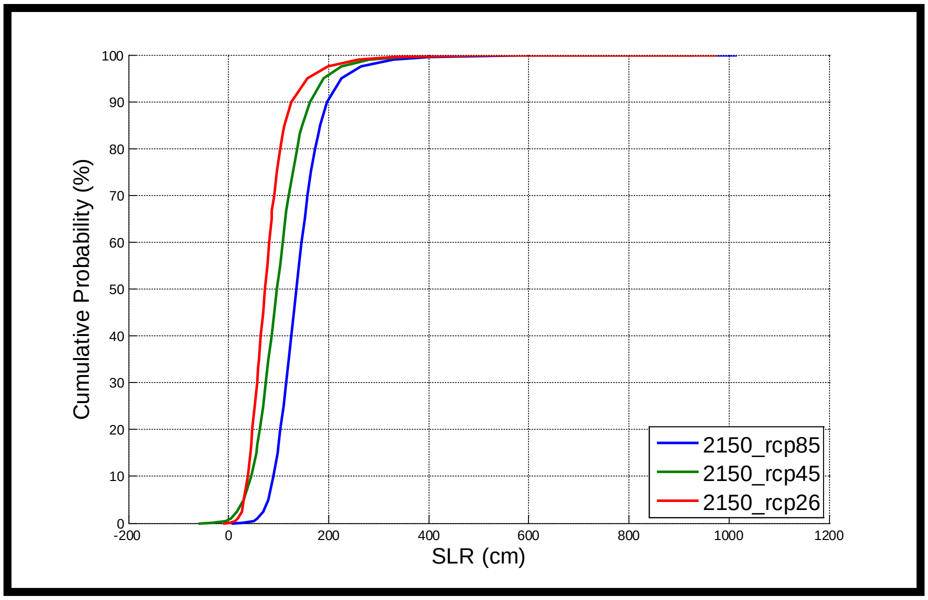

Figure 46. Sea Level Rise Cumulative Probability Distributions for 2200 at Bar Harbor, Maine

Table 8. Probability of Exceedance for USACE/NOAA Sea Level Rise Scenarios Based on Sea Level Change Cumulative Probability Distributions from Kopp et al. (2014) at Bar Harbor, Maine.

Year	Low Rate	USACE Low NOAA Int. Low	NOAA Int. High	USACE High	NOAA High
2030	94%	84%	38%	21%	4%
2050	96%	84%	25%	9%	1%
2100	96%	72%	5%	2%	1%

We can visualize the future sea level probability with greater detail by generating a large number of possible future sea levels and plotting the probability density (i.e. the relative probability that mean sea level will fall within a given time and height range. Samples of future sea levels can be generated randomly following the technique illustrated in Figure 47. This technique uses the sea level rise cumulative probability distribution curves to find a set of future sea levels that are consistent with the probabilistic guidance. Uniform values of probability (green squares) used to find corresponding sea level rise values (red squares). In practice, we use a random number generating algorithm that applies this technique to generate a large set of possible future sea levels. A new set of possible sea levels is generated for each year by linearly interpolating between the curves given by Kopp et al. (2014), while the three RCP scenarios are each given equal weight. Then the set of random possible sea levels is sorted into elevation bins, and the number of samples within each bin is counted to estimate the probability that sea level will fall within that bin in that future year.

Figure 48 shows the future sea level probability density overlaid by the NOAA and USACE sea level change scenario curves. Inspection of Figure 48 and the data in *Table 8* suggest that for the near future (to about 2050) sea level chance will most likely coincide with the intermediate to high scenarios, and that it is reasonably possible that sea level will rise more than the highest scenario. However, as we get toward the end of the 21st century the higher scenarios become much less likely and the range of possible future sea levels spreads out significantly.

It may be tempting to use this probabilistic guidance to identify a most probable scenario for planning purposes; for example, by projecting a scenario that follows the maximum probability density. However, the federal guidance explicitly advises against doing this, and we must also advise against it here. The identification and use of a most probable scenario is ill-advised because, given large degree of uncertainty in future projections, even the most probable scenario is very unlikely. Instead of using the probabilistic guidance to identify a most probable scenario, we recommend an approach to coastal hazard analysis that considers the full range of possible future sea level scenarios that is informed by the probabilistic information so that the results can be applied within a RIDM framework. This is accomplished through the Monte Carlo methods described in the following section.

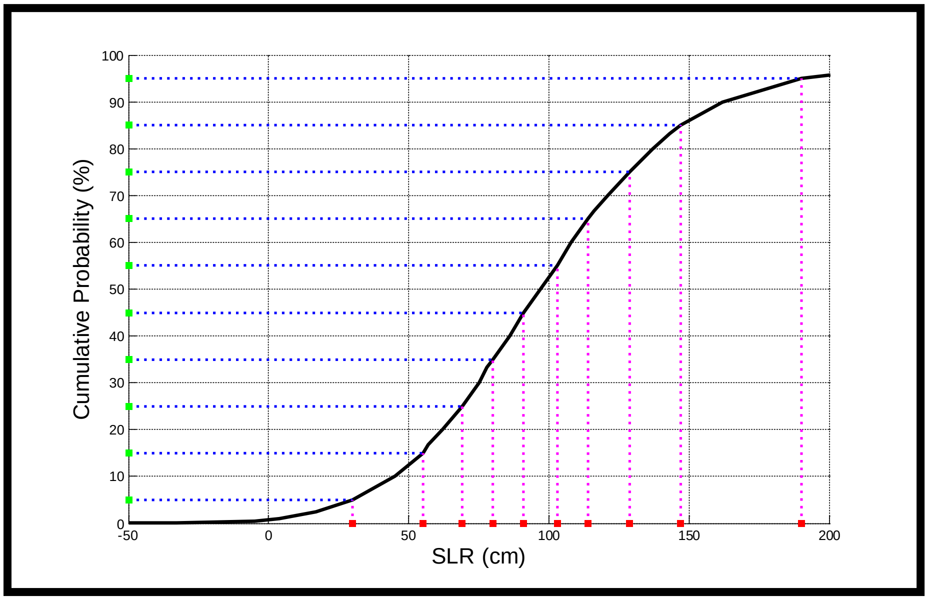

Figure 47. Sampling of a Sea Level Rise Probability Distribution.

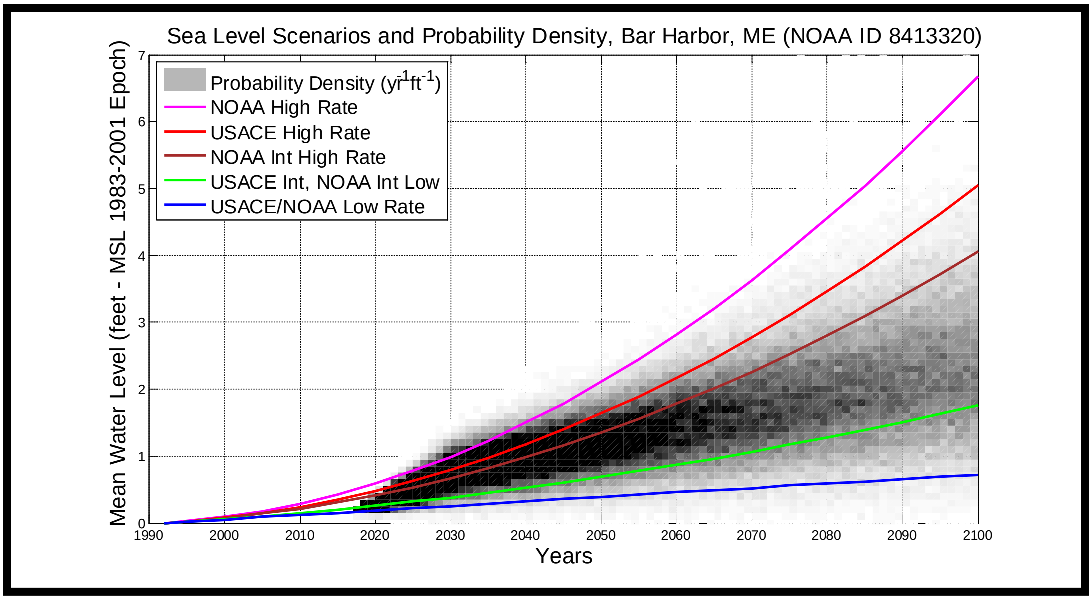

Figure 48. Comparison of NOAA/USACE Sea Level Rise Scenarios and Future Sea Level Probability Density, Bar Harbor, Maine.

4.4 Monte Carlo Simulation – Storm Surge Slot Machine

When considering coastal flooding hazards, we are ultimately interested in how much the sea level will rise within a relatively short time frame of only a few hours. Anyone who has spent more than a few hours along the Gulf of Maine coast has observed how much the sea level rises with each tide. In fact, the magnitude of sea level change that occurs twice on any typical day in the Gulf of Maine is greater than the worst-case mean sea level change that is expected by the end of the century. In section 4.2, we described the extreme value analysis to estimate extreme water levels in Penobscot Bay in terms of the AEP or ARI. Here we describe how a Monte Carlo simulation can be used to mathematically combine the probability of extreme water levels with the probability of sea level change to estimate the flood hazard in future years.

Monte Carlo simulation, named after the well-known gambling establishment in Monaco, is a technique that uses randomness to solve numerical problems. In this case, we combine a large number of random samples of storm tides with a large number of random samples of future sea level rise values to generate a large sample of possible future storm tides. We also add an additional term to the simulation to account for hydrodynamic model error and uncertainty due to possible Non-Linear Residual (NLR) interactions between rising sea levels and coastal storm surge. NLR is used to account for the fact that magnitude of storm tide, which is the difference between the peak water level and the current mean sea level, may increase or decrease with a change in the mean sea level.

To account for hydrodynamic model error, we draw random samples from a normal (Gaussian) distribution with a mean and standard deviation specified to approximate the model error. In this case the Penobscot Bay model validation is used, and we assume the error is unbiased with a standard deviation equal to the RMSE of 0.56 feet.

Uncertainty due to sea level change NLR, is also approximated with a normal distribution. For sea level change NLR, we apply a distribution with zero mean and a standard deviation of 0.66 feet. The NACCS points out that the magnitude of sea level change NLR depends on location and magnitude of sea level rise. For simplicity, we have assumed it is constant and have taken a value that is generally conservative based on the proof of concept analysis provided with the NACCS. A more detailed study of sea level change NLR would be possible with additional modeling of Penobscot Bay and could be performed in the future to better understand its contribution to future flood hazards. The Monte Carlo simulation is executed with the following steps to determine the ARI curves for future storm tide water levels. For each step, random sampling is performed as illustrated in Figure 47..

For a future year that we would like to know the coastal storm hazard:

1. Randomly select a maximum storm tide from the storm tide ARI/AEP curve;

2. Randomly select a sea level change value from the sea level rise cumulative probability distribution for the future year. If necessary, find values from a year before the year of interest and a year after the year of interest and linearly interpolate to get the value for the year of interest;

3. Randomly select an error value from the uncertainty cumulative probability distribution curve;

4. Sum the values from steps 1 thru 3 and record one possible future annual maximum storm tide level for the year of interest;

5. Repeat steps 1 thru 4 20,000 times to generate 20,000 possible annual maximum storm tide values for the future year; and

6. Sort the values from step 5 into elevation bins, count the number in each bin and empirically determine the ARI curve for the future flood hazard.

To illustrate the Monte Carlo procedure, and in keeping with the gambling analogy, we have developed the Storm Surge Slot Machine (S3M). S3M is an educational game of chance designed to give the players a sense of the range possibilities and the degree of uncertainty with future coastal flood hazards. S3M can be played with any number of players. The game play is simple, requiring only a pair of dice and a set of playing cards, which are analogous to the cylinders in a slot machine. The playing cards are based on the cumulative probability distributions used in the Monte Carlo analysis and may be developed for a specific site. A ruler and notepad are also recommended to aid in play. Playing instructions and playing cards based on the hazard analysis at Grindle Point are provided in **Appendix D.**

4.5 Present and Future Flood Hazard Maps

When probabilistic projections of sea level rise are mathematically combined with the flood hazard data through Monte Carlo Simulation, the resulting future hazard curves express the hazard considering all possibilities for sea level rise. In this case it becomes meaningless to discuss any particular sea level rise scenario because the hazard curve contains all possible scenarios. In other words, where the results show a flood level associated with a particular ARI for a particular future year (e.g. the 100-year flood level for the year 2067), the level shown represents the future hazard considering all possibilities of sea level rise up to that future year. Because the sea level rise probability information used in this analysis has been developed by experts in the area of climate science and sea level rise processes[26], this approach places the choice of what sea level rise scenarios and how likely each of those scenarios are into the hands of those

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[26] Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi (2014), Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, *Earth's Future*, *2*, 383–406, doi:10.1002/2014EF000239.

experts, allowing the community stakeholders to focus on identifying the vulnerabilities within their community and the adaptation measures that may reduce their risk.   In contrast, current scenario based guidance may ask stakeholders to consider very unlikely scenarios in their decision-making process (e.g. a 100-year flood plus the NOAA high projection for 2100) without providing any understanding of how unlikely the scenario may actually be.

A Monte Carlo simulation, described above, was carried at all nodal locations in the Penobscot Bay Model, where we have determined storm tide ARI curves. This allows us to produce two dimensional maps showing the coastal flood hazard. Two types of results have been generated from the modeling and statistical analysis. The first type shows the Total Water Level (TWL). The TWL is the peak storm tide water level that occurs during a storm event including the effects of the astronomical tides, wind and atmospheric pressure driven storm surge, and wave setup. The TWL is fairly constant within a relatively small area, but may vary considerably over larger regions. The TWL does not include the height of individual wave crests, or the height of wave run-up on the shoreline.

The second type of result is the Critical Wave Envelope (CWE). The CWE is the elevation of the highest 1% of wave crests that occur during a storm including the effects of astronomic tide, wind and atmospheric pressure driven storm surge, wave setup, and high frequency wave fluctuations. The CWE may vary significantly within a relatively small area due to variations in nearshore bathymetry and wave exposure during storm events. The CWE does not include the height of wave run-up on the shoreline. Areas subject to a CWE that is significantly greater than the TWL may be subject to damaging wave action as well as inundation.

TWL and CWE values corresponding to a range of AEP for present and future sea level conditions have been determined to characterize the flood hazard. The TWL and CWE were evaluated in detail for two critical locations on Islesboro: Grindle Point and the Narrows. High resolution images showing overlays of the TWL and CWE for a representative subset of future years and hazard levels are provided in **Appendix E**. **Appendix E** provides image overlays at Grindle point and the Narrows for the 10-year, 50-year, and 100-year TWL for 2017, 2037, and 2067. Overlays are also provided electronically in compressed Keyhole Markup Language (kmz) format for the 5-year, 10-year, 20-year, 50-year, 100-year, and 500-year TWL and CWE every 5 years from 2017 to 2117. The kmz formatted files allow for easy viewing of the hazard information with the Google Earth software.

The results for the TWL and CWE at a given location tells us how likely coastal flooding is at that location, and how much more likely it will become in the future considering all possibilities of sea level rise.

5.0 RECOMMENDATIONS

5.1 Vulnerability and Timing for Future Action

In order to assess the vulnerability to future flooding at a particular location, we must consider the probability of flooding as well as the potential consequences. The information provided above quantifies the probability of the flood hazard, but in order to assess risk we must also identify the consequences associated with the range of possible flood hazard conditions. Inspection of the flood hazard maps and LIDAR data at The Narrows and Grindle Point show that both location are probably most vulnerable to flooding of low lying roadways.

Here we take a simple approach to assess the risk by based only on the TWL flooding hazard, and classifying the consequences of flooding based on the flood depth over the roadway. With exception of the east facing side of the roadway at the Narrows, which is currently protected from wave action by a riprap revetment, the low-lying sections of road at Grindle Point and The Narrows are sheltered from severe wave action and the potential for damaging wave run-up. Considering this, we suggest the flood consequence classification presented in *Table 9*. This classification scheme is based the assumption that wave action over the roadway will be limited by the depth of flood water, and progressive damage to the roadway might result from breaking wave heights greater than 1.5 feet, which is the wave action limit used by FEMA to delineate the Limit of Moderate Wave Action (LiMWA) in coastal flood zones.

There are also other potential vulnerabilities at these locations that should also be evaluated when sufficient information is available to better characterize the consequences of the flood hazard on specific infrastructure. For example, if we can determine the design criteria (wave height, water level, stone size, etc.) that were used in the design of the riprap revetment that protects the roadway at the Narrows it would be possible to estimate the level of damage that might occur under to the revetment a range of possible future flood conditions. Other portions of the roadway at The Narrows that are not currently protected by the riprap revetment may also be subject to erosion and wave run-up hazards. Also, at Grindle point, a detailed survey of the lighthouse, ferry terminal building, various riprap revetments and other infrastructure would allow us to better assess the level of damage that would occur under different flooding conditions for that infrastructure. Furthermore, if the consequences can be more precisely quantified (e.g. cost of damage in dollars, number of residents effected) the quantity at risk can be determined and RIDM can be applied in the decision-making process to identify preferred adaptation and risk mitigation measures.

The discussion that follows is relevant to consequences due to the TWL exceeding the roadway elevations at the Grindle Point and The Narrows. In both of these locations sections of the roadway are protected from wave action by riprap revetments. The analysis presented here does not consider the potential hazard and damaging conditions at the roadway that might result from wave run-up and overtopping of the roadways and/or erosion that may expose currently unprotected sections of the roadways to direct wave attack. No attempt has been made here to evaluate the stability of these protective structures during present and future storm conditions. However, the potential for damage and failure of these structures does represent a significant hazard, which should be evaluated when considering options for adaptation and risk mitigation. As such, we strongly recommend that future work be undertaken to evaluate the potential for erosion at unprotected sections of the roadways, characterize the condition of existing erosion protection structures, evaluate their performance under the range of possible storm conditions, and revise the vulnerability assessment if necessary. Hazard analysis information developed as part of this study will be useful for making those evaluations.

Table 9. Assumed Levels of Consequence for TWL Flooding of Roadways with Depth Limited Wave Action.

Level of Consequences	Depth of Flooding	Wave Action	Description of Consequences
Minor	Less than 1.9 foot	Minimal Wave Height <1.5 feet	Road impassable for a few hours, but likely passable by heavy rescue vehicles. Minor roadway damage possible. Minor disruption to island residents. Minor economic impacts
Moderate	Between 1.9 feet and 3.8 feet	Moderate Wave Height <3.0 feet	Road impassable for a few hours to a day. Rescue vehicle access limited for a few hours. Moderate damage to roadway. Moderate disruption to island residents. Moderate economic impacts
Severe	Greater than 3 feet	Severe Wave Height >3.0 feet	Road impassable for multiple days, moderate to severe damage to roadway, sections of road require complete re-construction. Major disruption to Island Residents. Major economic impacts.

5.1.1 Grindle Point

Figure 49 shows the 2011 USGS LIDAR data at Grindle Point. From the topographic data we see the access road to Grindle Point has two low spots where the elevation is as low as 8.5 feet. Given the TWL consequences classification scheme this means that minor consequences would occur if the TWL exceeds 8.5 feet, moderate consequences would occur if the TWL exceeds 10.4 feet, and severe consequences would occur if the TWL exceeds 12.3 feet.

Figure 50 shows the TWL ARI hazard curves for Grindle point derived from the Monte Carlo simulation described in Section 4.4. The curves Figure 50 indicates the probability that the TWL will exceed a possible range of elevations during the present year, and for each future decade until 2117. It is noteworthy that future sea level rise is expected to cause the hazard associated with rarer events to increase faster than the hazard associated with more frequent events. For example, the 10-year TWL is expected to increase about 1.7 feet from 2017 to 2117 while the 100-year TWL is expected to about 2.3 feet over the next century. The greater increase in the more extreme hazards reflects the fact that increasing uncertainty in future sea level rise leads to greater risk in the future. This fact may not be apparent with scenario based sea level rise guidance, and is often ignored in planning studies that apply uniform sea level rise values to a present-day hazard curve to estimate future risks. In contrast, the Monte Carlo approach allows us to quantify how much the risk will increase due to increasing uncertainty in the future.

To evaluate the vulnerability of the roadway at Grindle Point, we can use present and future hazard curves to determine how the probability of minor, moderate, and severe hazards will increase in the future, as well as the probability of experiencing a minor, moderate, or severe flooding event between the present year and any future year. The flooding probabilities at Grindle Point for minor, moderate, and severe critical elevations are shown Figure 51 Figure 53 respectively. These figures present the probability of flooding in two ways. The blue line on the figure shows the probability that the critical elevation will be exceeded within each future year.

The red line shows the probability that the critical elevation will be exceeded at least once in any year up to and including the future year. This information can be used to estimate when in the future the levels of consequence become likely. Stakeholders may review this information in light of an acceptable level of risk tolerance to help them decide when action is necessary.

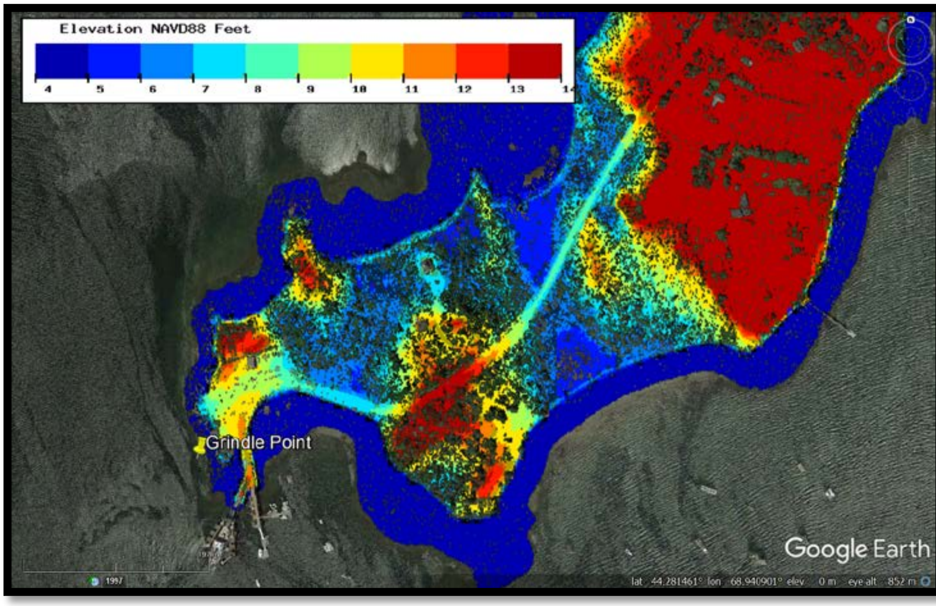

Figure 49. 2011 United States Geological Survey USGS LIDAR Overlaid on Aerial Imagery of Grindle Point.

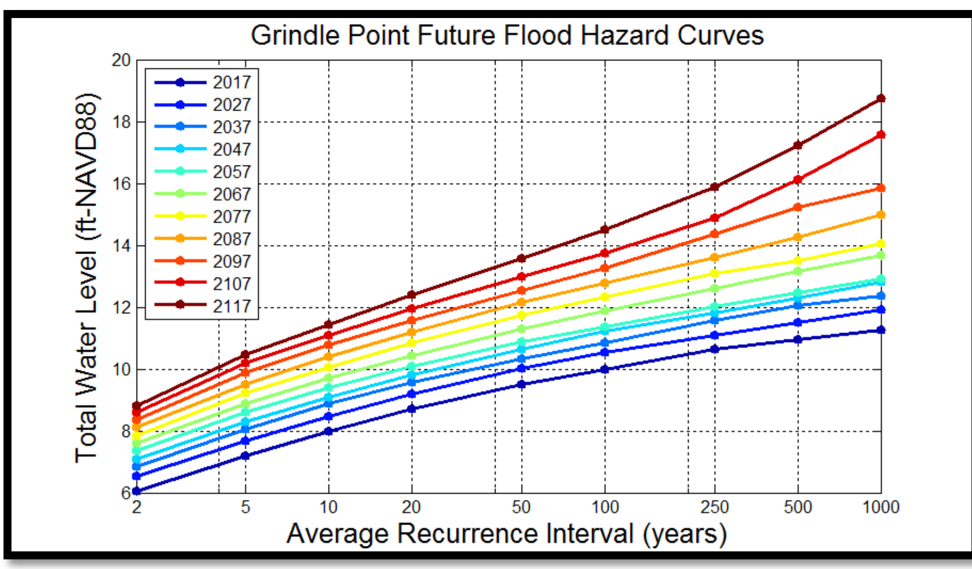

Figure 50. Total Water Level Flood Hazard for Present and Future Conditions at Grindle Point

5.1.1.1 Minor Consequences at Grindle Point

Figure 51 suggests there is nearly a 10% chance of experiencing minor consequences from roadway flooding at Grindle Point in the present year, and that the probability will increase to 20% 2060, and nearly 40% by 2100. When we consider that probability increases over many years, we see that there is about a 50% chance of seeing minor consequences sometime in the next decade, and minor consequences are almost certain (about 90% chance) to occur at least once before 2040.

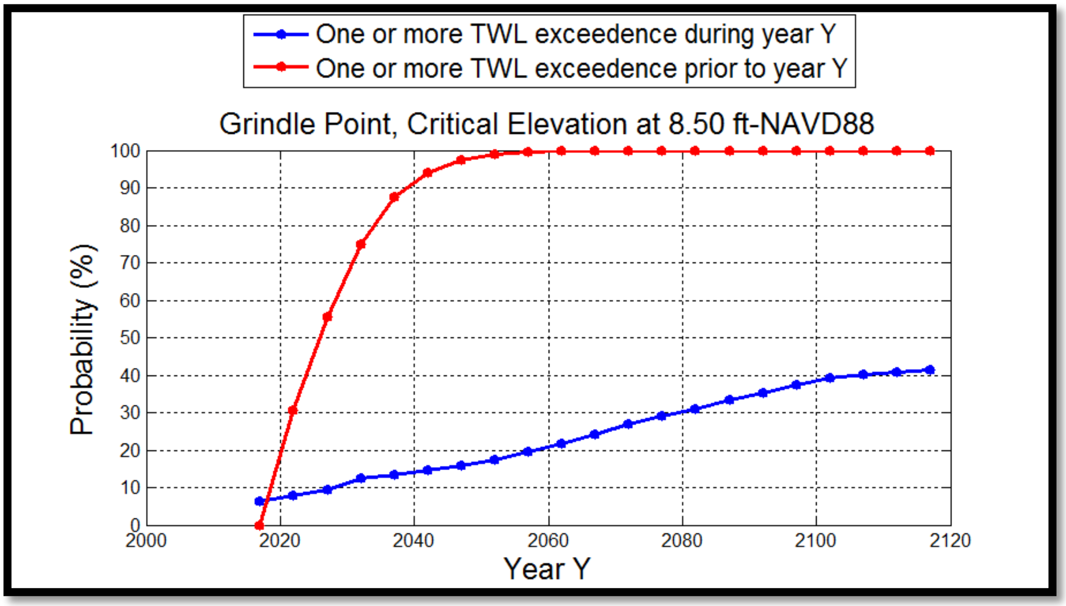

Figure 51. Present and Future Probability of Minor TWL Hazard at Grindle Point

5.1.1.2 Moderate Consequences at Grindle Point

Review of Figure 52 suggests that there is currently a less than 1% chance of experiencing moderate consequences in a given year. The annual chance will increase to about 5% by 2060, and there is more than a 60% chance of having experienced moderate consequences at least once by that date. It is nearly certain (90% chance) Grindle Point will experience moderate flooding consequences at least once before 2080, at which time the annual chance of moderate consequences will increase to nearly 10%.

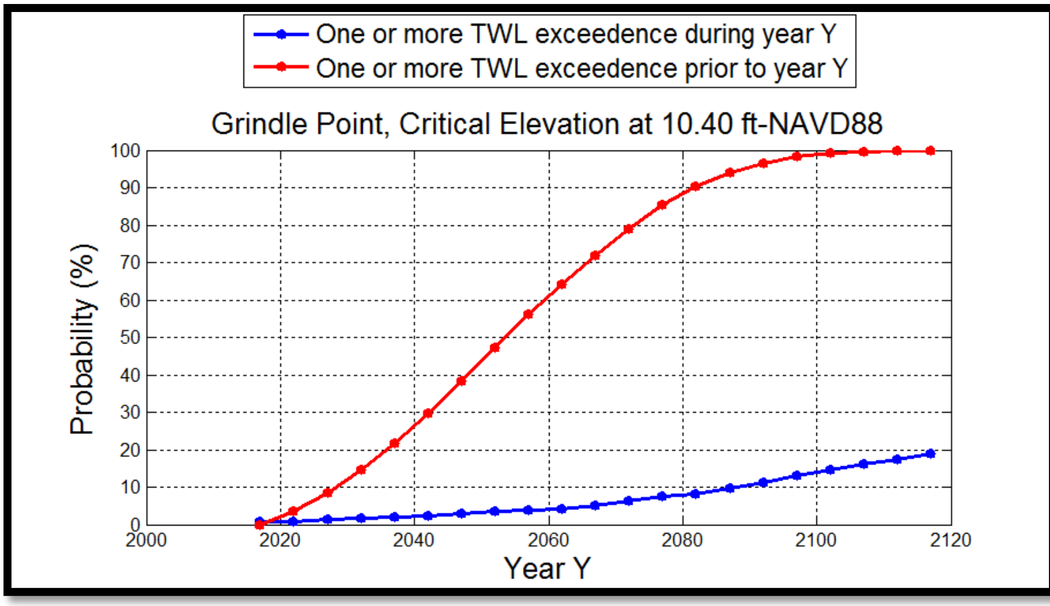

Figure 52. Present and Future Probability of Moderate TWL Hazard at Grindle Point

5.1.1.3 Severe Consequences at Grindle Point

Figure 53 illustrates the probability of severe consequences of roadway flooding at Grindle Point. There is currently a very small annual probability of Severe Consequences at Grindle Point, but by 2100 that annual chance will increase to about 4%, and the chance of experiencing severe consequences at least once in the next century is about 75%.

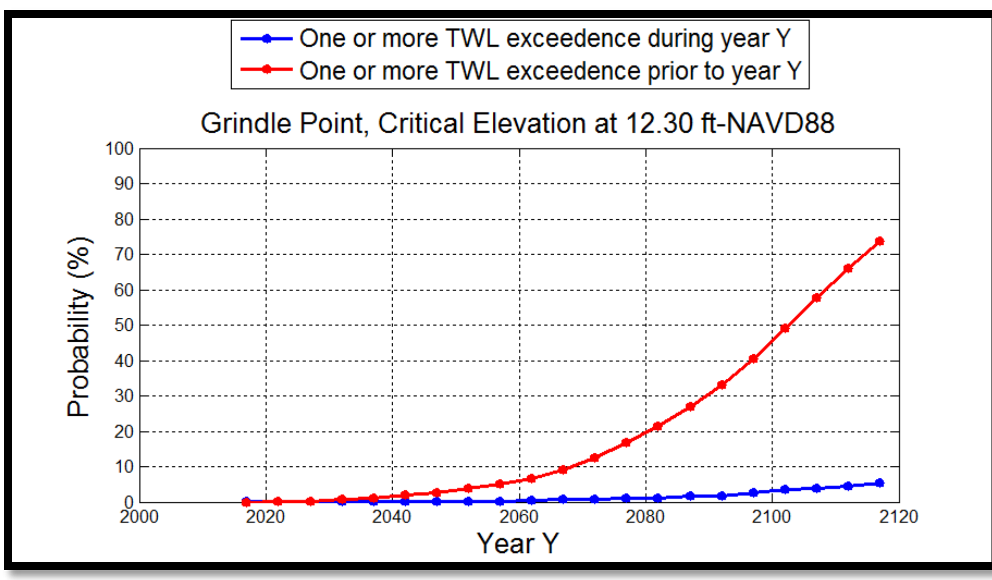

Figure 53. Present and Future Probability of Severe TWL Hazard at Grindle Point Figure

5.1.2 The Narrows

Figure 54 shows the 2011 USGS LIDAR data at The Narrows. From the topographic data, we see there is a section of the roadway north of the revetment that has a minimum crown elevation of about 9.8 feet. Given the TWL consequences classification scheme this means that minor consequences would occur if the TWL exceeds 9.8 feet, moderate consequences would occur if the TWL exceeds 11.7 feet, and severe consequences would occur if the TWL exceeds 13.6 feet.

Figure 55 shows the TWL ARI hazard curves for The Narrows derived from the Monte Carlo simulation described in Section 4.4. The curves on Figure 55 indicate the probability that the TWL will exceed a possible range of elevations during the present year, and for each future decade until 2117. It is noteworthy that future sea level rise is expected to cause the hazard associated with rarer events to increase faster than the hazard associated with more frequent events. For example, the 10-year TWL is expected to increase about 1.7 feet over the next century, while the 100-year TWL is expected to about 2.3 feet during the same time frame. The greater increase in the more extreme hazards reflects the fact that increasing uncertainty in future sea level rise leads to greater risk in the future. This fact may not be apparent with scenario based sea level rise guidance, and is often ignored in planning studies that apply uniform sea level rise values to a present-day hazard curve to estimate future risks. In contrast, the Monte Carlo approach allows us to quantify how much the risk will increase due to increasing uncertainty in the future.

To evaluate the vulnerability of the roadway at The Narrows, we can use present and future hazard curves to determine how the probability of minor, moderate, and severe hazards will increase in the future, as well as the probability of experiencing a minor, moderate, or severe flooding event between the present year and any future year. The flooding probabilities at The Narrows for minor, moderate, and severe critical elevations are shown in Figure 56 thru Figure 58, respectively. These figures present the probability of flooding in two ways. The blue line on the figure shows the probability that the critical elevation will be exceeded within each future year. The red line shows the probability that the critical elevation will be exceeded at least once in any year up to and including the future year. This information can be used to estimate when in the future the levels of consequence become likely. Stakeholders may review this information in light of an acceptable level of risk tolerance to help them decide when action is necessary.

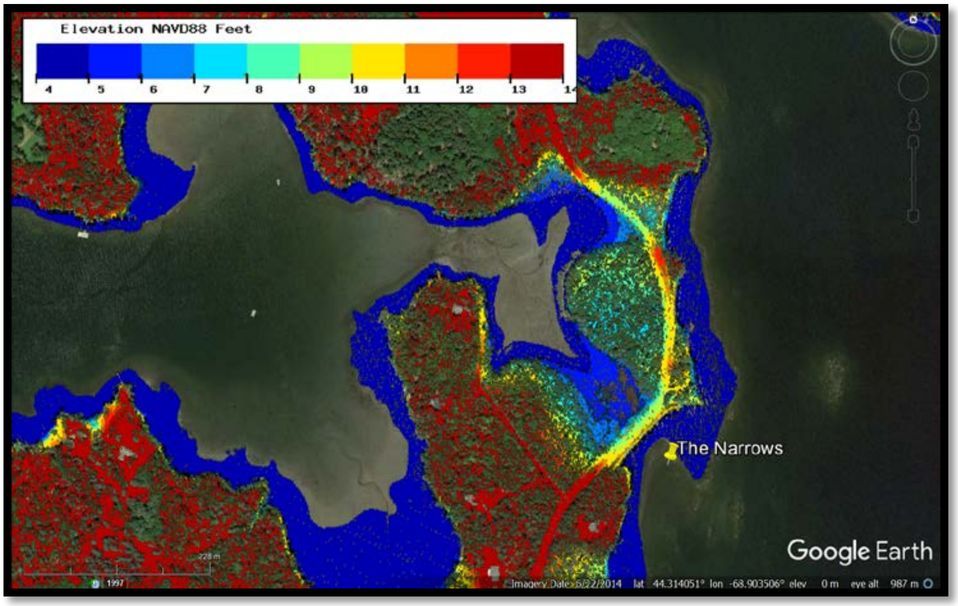

Figure 54. 2011 United States Geological Survey USGS LIDAR Overlaid on Aerial Imagery of The Narrows.

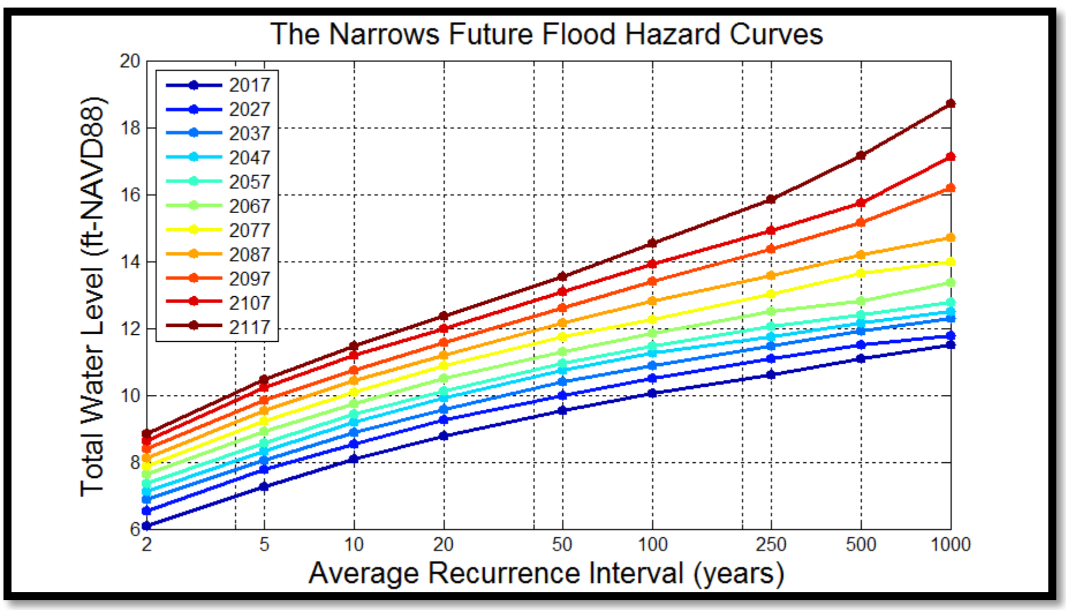

Figure 55. Total Water Level Flood Hazard for Present and Future Conditions at The Narrows

5.1.2.1 Minor Consequences at The Narrows

Figure 56 shows the probability of experiencing minor consequences from the TWL flood hazard at the Narrows. We see that there is presently between a 1% chance and 2% chance of experiencing minor consequences at the Narrows in the present year. The annual probability will increase to about 10% by 2070, and increase to just over 20% by 2100. There is about a 50% chance of experiencing minor consequences at least once prior to 2045, and it is near certain (90% chance) that minor consequence will be experienced at least once before 2070.

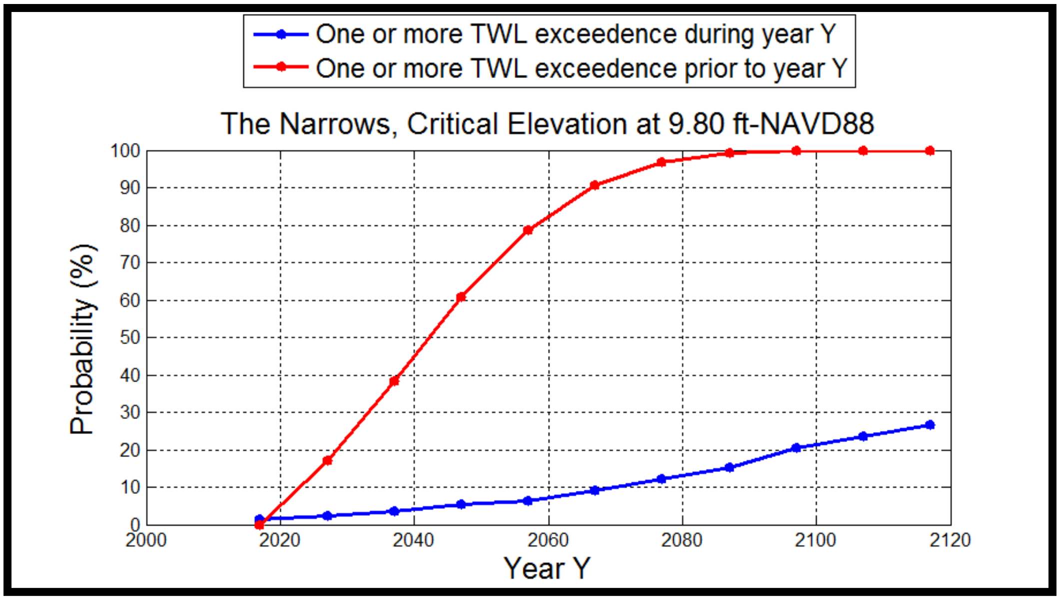

Figure 56. Present and Future Probability of Minor TWL Hazard at The Narrows

5.1.2.2 Moderate Consequences at the Narrows

Figure 57 shows the probability of moderate consequences at the Narrows. We see that there is presently very little annual chance of experiencing moderate consequences, but the annual chance will increase to about 5% by 2100. The probability of experiencing moderate consequences at least once reaches 50% by about 2085.

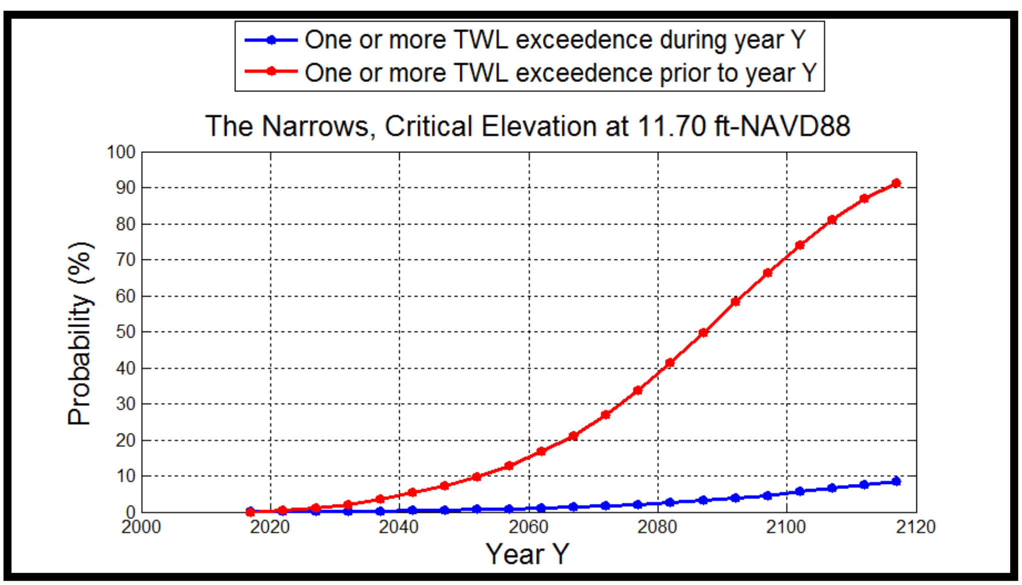

Figure 57. Present and Future Probability of Moderate TWL Hazard at The Narrows

5.1.2.3 Severe Consequences at the Narrows

Figure 58 shows the probability of severe consequences due to TWL flooding at The Narrows. It is presently very unlikely to experience severe TWL flooding at the

Narrows. However, there is about a 30% chance of experiencing severe consequences at least once prior to 2117, and by the end of the century the annual chance of severe consequences is approximately 1%.

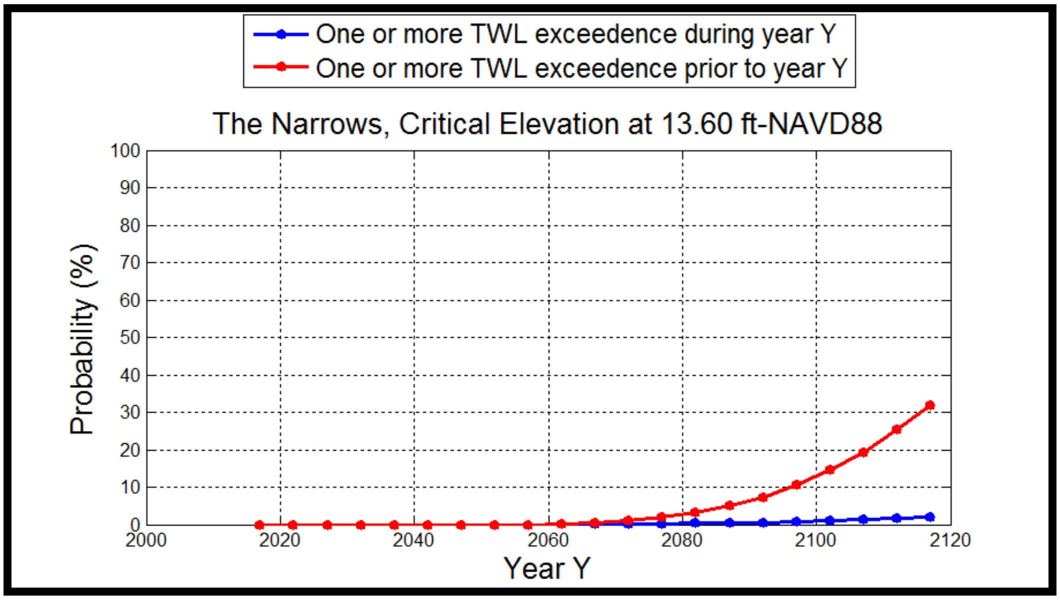

Figure 58. Present and Future Probability of Severe TWL Hazard at The Narrows

5.2 Adaptation Options for Future Consideration

Options for adaptation to future sea level change fall broadly within three categories: protect, accommodate, and retreat. Actions that may be undertaken to adapt also go hand-in-hand with actions that may mitigate present risk. Measures to mitigate risk may include traditional structural measures, such as hardened seawalls, non-traditional natural and nature-based features such as marsh creation, as well as non-structural interventions including policies, warning systems, etc. For Islesboro, it is likely that a combination of all these features may provide the best benefit, in terms of risk reduction and efficient use of limited resources. Thus, it is recommended that Islesboro consider a range of possible actions when planning for sea level change adaption. Adaptation planning should also be flexible and allow for evolution as guidance on sea level rise changes in the future and experience is gained with adaptation efforts.

5.2.1 Accommodate

Accommodation means essentially living with the change. Accommodation is already happening and any plan for sea level rise adaptation at Grindle Point and the Narrows will likely include some degree of accommodation in the near future, at least. Accommodation may include non-structural features. For example, Islesboro may draft policy to locate emergency response equipment up-island, north of The Narrows, during events which could potentially cause moderate inundation of the roadway. A warning system could be developed to identify trigger points that would require this action. Considering the timing of future hazards accommodation might be a reasonable option for adaptation for the next 20-30 years or so, until the likelihood of moderate to severe flooding at the Narrows becomes too great.

5.2.2 Protect

Protection typically involves some type of structural measure to maintain current function in the face of rising sea levels and increasing flood hazards. This may include traditional structural measures, such as elevating the roadways and constructing revetments to protect them. It may also include the use of natural or nature-based features. For example, Adaptation options for Grindle Point may consider elevating the low lying sections of the roadway and building new revetments or enhancing existing ones to reduce the risk to minor to moderate flooding consequences. In addition, where the road to Grindle point is presently protected by wetland areas, plans to protect and enhance those wetlands may also help to protect the roadway and mitigate the risk of severe flooding consequences.

5.2.3 Retreat

In the long term, it is possible that Grindle Point will become its own island, as will the northern and southern portions of Islesboro that are presently connected by The Narrows. While the previously mentioned protection options may result in bridges or significantly raised causeways to keep things connected, another alternative would be to abandon the low lying roadways all together and seek out locations for a new ferry terminal, or even two new ferry terminals. The costs for retreat and relocation of the ferry terminal would likely be considerable, but it may be worth considering if suitable sites can be identified and costs for protection options are on a similar order of magnitude.

APPENDIX A

NACCS Extra-Tropical Storms, Maine Coast Sub-set, Storms with Base+Tide Results

Present and Future Vulnerability to Coastal Flooding
at Grindle Point and the Narrows

Ransom Consulting, Inc.
Project 151.06112

APPENDIX B

Islesboro Coastal Flood Vulnerability Study, Review of NACCS data Memorandum NACCS Model Validation Scatter and Time Series Plots

Present and Future Vulnerability to Coastal Flooding
at Grindle Point and the Narrows

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APPENDIX C

Scatter by Storm Number

Present and Future Vulnerability to Coastal Flooding
at Grindle Point and the Narrows

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APPENDIX D

Storm Surge Slot Machine

Present and Future Vulnerability to Coastal Flooding
at Grindle Point and the Narrows

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APPENDIX E

Hazard Maps

Present and Future Vulnerability to Coastal Flooding
at Grindle Point and the Narrows

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