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Abstract: Flood Insurance Rate Maps (FIRMs) are developed by the Federal Emergency Management Agency (FEMA) to provide guidance in establishing the risk to structures and infrastructure in the coastal zone from storm surge and coincidental waves. The maps are used by state agencies and municipalities to help guide coastal planning and establish the minimum elevation standard for new or substantially improved structures. A summary of the methods used and results of 2012 FIRM mapping are presented for Charlestown, RI; a coastal community located along the exposed, southern shoreline of the state. Concerns with the methods used in the 2012 analysis are put in context with the National Research Council's (NRC) 2009 review of the FEMA coastal mapping program. New mapping is then performed using state of the art, fully coupled surge and wave modeling and data analysis methods to address the concerns in the NRC review. The new maps and methodologies are in compliance with FEMA regulations and guidelines. The approach makes extensive use of the numerical modeling results from the recent US Army Corp of Engineers (USACE), North Atlantic Coast Comprehensive Study (NACCS 2015). Revised flood maps are presented and compared with the 2012 FIRM map to provide insight into the differences. The new maps highlight the importance of developing better estimates of offshore surge dynamics and its coupling to waves, dune erosion based on local observations, and the advancement in nearshore mapping of waves in flood inundated areas by the use of state of the art, two-dimensional wave transformation models.

Keywords: coastal flooding; inundation; waves; Flood Insurance Rate Maps (FIRMs); coupled wave and surge modeling; dune and shoreline erosion; base flood elevation

1. Introduction

Federal Emergency Management Agency (FEMA) leads the national effort for the development of Flood Insurance Rate Maps (FIRMS) for coastal flooding for the purposes of establishing the risk structures and infrastructure face from inundation and wave attack and setting the associated insurance rates. In most cases coastal municipalities also use these maps to guide coastal development and establish the minimum elevation standards. Additionally, the maps are regulatory, universally available, and developed within strict FEMA guidelines. This work is typically performed by contractors and organized by individual FEMA regions. The regions are given substantial latitude in establishing the methods used in the analysis, but all must follow FEMA guidelines; for example the Atlantic and Gulf of Mexico guidelines are provided in [1].

A Flood Insurance Study (FIS) was completed in 2012 for Washington County, RI [2] (Figure 1). The storm surge levels were estimated by linear interpolation of 100 year return period water levels from adjacent National Oceanic and Atmospheric Administration (NOAA), National Ocean Survey (NOS) water level stations [3]. For this study, data from the New London, CT; Newport, RI; and Providence, RI stations were used. The record lengths for the three stations are approximately 70 to 80 years. The 10-, 2-, 1-, and 0.2-percent-annual-chance flood water levels were determined by application of extreme statistics analysis (using L Moments) to the historical water level data at the three stations. One value of the water level for the selected return period was provided for each station. The water levels at intermediate locations, relative to the reference stations, were determined by linear interpolation. No estimates of values for other confidence levels (e.g., upper or lower 95%) were provided. The contractor used FEMA's Coastal Hazard Analysis and Modeling Program (CHAMP)/Wave Height Analysis for Flood Insurance Studies (WHAFIS) [4] to estimate the waves in the flood inundated areas. This program computes the wave crest elevations along representative transects using a 1-D wave action equation. Transects are selected by considering major topographic, vegetative, and cultural features with variable spacing of 30 m to hundreds of meters, depending on density of development and nearshore topography. WHAFIS is forced by an appropriate depth-limited wave height at the seaward end of each transect. The 100 year Still Water Elevation Level data (SWEL), empirically determined wave setup, and the wave height estimates are then assembled to provide estimates of the Base Flood Elevation (BFE) (Figure 2). The wave height is defined in terms of the wave crest (η_c) of the controlling wave height Hc, where Hc is the average of 1% of the highest waves. η_c is then equal to $0.7 \times H$c, where is related to the significant wave height by Hc = $1.66 \times H$s. The wave heights are then used to establish flooding zones (VE: 1% annual chance interval, wave heights higher than 3 ft (0.9 m); AE: 1% annual chance interval, wave heights lower than 3 ft (0.9 m) and X: 0.2% annual recurrence interval). Data from each transect are laterally interpolated to develop a 2-D map of the BFEs for the flooding zones.

The National Research Council (NRC) performed an in-depth review of the FEMA flood mapping program in 2009 [5]. Recommendations from their report on coastal flooding (References, page numbers are provided for each) include the following:

> *FEMA should use coupled 2-D surge and wave models to reduce uncertainties associated with the use of a 2-D surge model and the 1-D WHAFIS model. Before choosing which models to incorporate into mapping practice, an analysis of the impact of various uncertainties on the models should be undertaken.* [5] (p. 72)

> *FEMA should work toward a capability to use coupled surge-wave-structure models to calculate base flood elevations, starting with incorporating coupled two-dimensional surge and wave models into mapping practice.* [5] (p. 75)

> *Wave crests calculated by CHAMP/WHAFIS have not been sufficiently validated, creating potentially significant uncertainties in BFE (base flood elevations) estimates. Factors that contribute to the uncertainty of WHAFIS wave crest calculations include the following: (1) wave transformation is a 2-D process that cannot be represented in a 1-D model; (2) WHAFIS wave crests and BFEs are not 1 percent annual chance values (i.e., probabilistic wave conditions are not incorporated in the WHAFIS calculations); (3) surge and waves are completely decoupled, which may lead to over- or underestimates of the BFE; (4) the 540-square-foot rule for dune erosion (i.e., a dune exceeding a cross-sectional area of 540 square feet will not be breached in a 1 percent annual chance storm) has not been validated; (5) the approach for wave dissipation by vegetation, buildings, and levees has not been validated; (6) One-dimensional transects do not reflect 2-D terrain; and (7) the manual interpolation of 1-D results to two dimensions is subjective.* [5] (p. 71)

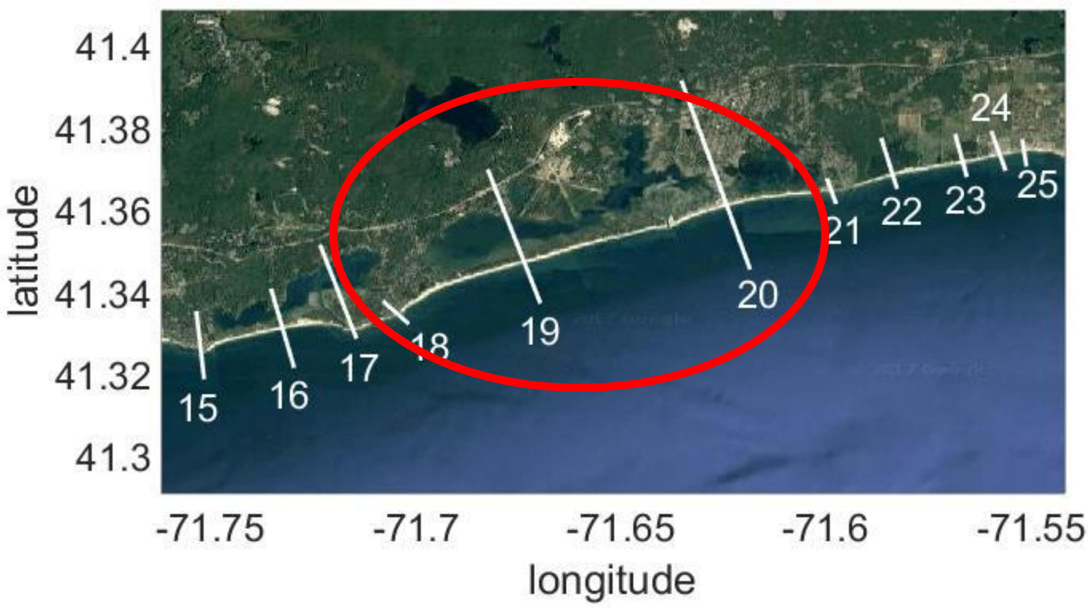


Figure 1. Location of the Federal Emergency Management Agency (FEMA) (2012) [2] Washington County, RI Wave Height Analysis for Flood Insurance Studies (WHAFIS) transects in the vicinity of the study area. The Charlestown study area is shown in the red circle. The FEMA transects of primary interest are numbers 19 (west) and 20 (east).

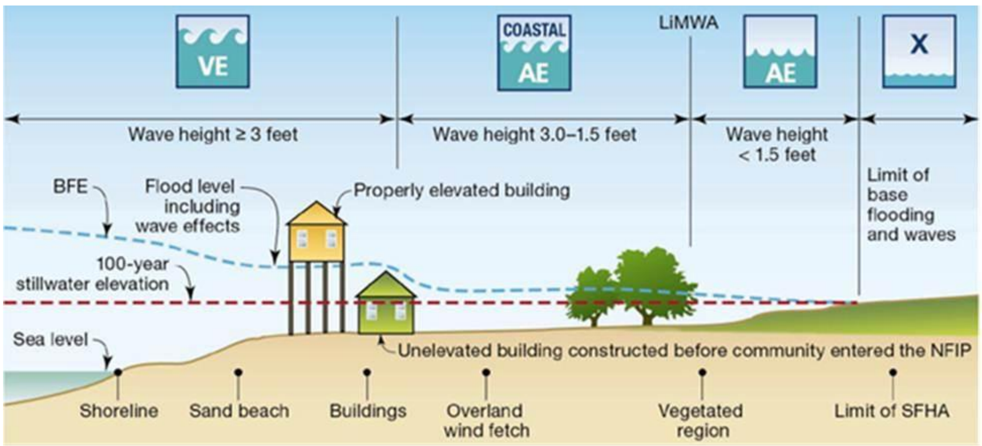


Figure 2. FEMA definition schematic for flooding and structures located on grade and elevated [6]. The still water elevation (SWEL) for 1% annual chance (100 year) is shown in the dashed red line and the Base Flood Elevation (BFE) in the blue dashed line. FEMA zones (VE, AE seaward and landward of the Limit of Moderate Wave Action (LiMWA)), based on wave heights, are also noted at the top of the figure.

It is clear from comparing the methods used in the 2012 flood maps performed for Washington County, RI, summarized above, that NRC's recommendations were not followed.

The goal of the present study is to develop FIRMs for a portion of the southern RI coastal line using state of the art methods, following the NRC recommendations. The town of Charlestown, RI has been selected for this application, since it is located along the exposed southern RI coastline, has a substantial barrier system, and is well suited to showing the impact of improving the approach used to flood mapping. In keeping with the FEMA guidelines, only models approved by FEMA for use in coastal flood mapping studies have been used in the present effort [7]. FEMA guidelines for coastal flood mapping for the study area have also been followed [1].

Section 2 provides an overview of the methods used in the analysis for estimating surge and waves. Results and discussion are provided in Section 3, conclusions in Section 4 and References at the end. Supplementary material is provided in Appendix A.

2. Methods

2.1. Surge and Tide Water Levels

The US Army Corp of Engineers (USACE) has recently completed a multi-year numerical modeling effort under the North Atlantic Coast Comprehensive Study (NACCS) [8], with a focus on the area impacted by Hurricane Sandy. In this study simulations were performed using fully coupled surge and wave models (ADCIRC, WAM, and STWAVE) for 1050 synthetic tropical storms and 100 historical extratropical storms, with a primary focus on the region from Cape Hatteras to Cape Cod. A high resolution (down to 50 m) unstructured grid was used to represent the area flooded during a storm. The surge model was validated with data from NOAA NOS water observation stations for hurricanes Gloria, Josephine, Irene, and Sandy and two extratropical storms in 1996 (storms #070 and #073) (see [8] for details on model validation). The wave model was similarly validated with data from offshore wave buoy observations [8]. Given constraints based on the volume of data generated, results of model simulations were archived at selected *save points* (approximately 18,000 in total for the study area and about 1000 in RI). These included peak water levels, peak wave heights and short time series of both for each storm event. The data were made available via ArcView on line or as GIS layers under the STORMTOOLS® initiative [9]. (The goal of STORMTOOLS is to provide access to a suite of coastal planning tools (numerical models, maps, etc.), available as a web/app service, that allows wide spread accessibly and applicability at high resolution for user selected coastal areas of interest. The approach is well suited for classic downscale modeling approaches used to investigate the impact of climate change on coastal and riverine processes and can readily take advantage of rapidly evolving cloud computing resources). Figure 3 shows the location of the save points along the southern RI coastline with the Charlestown study area circled in red. An analysis was performed to estimate the water level vs. return period for the tropical storms for surge only and surge and tidal (96 random tidal phases, linear superposition) [8]. Predictions are provided for mean and upper and lower 95% confidence interval values and are available at all save points.

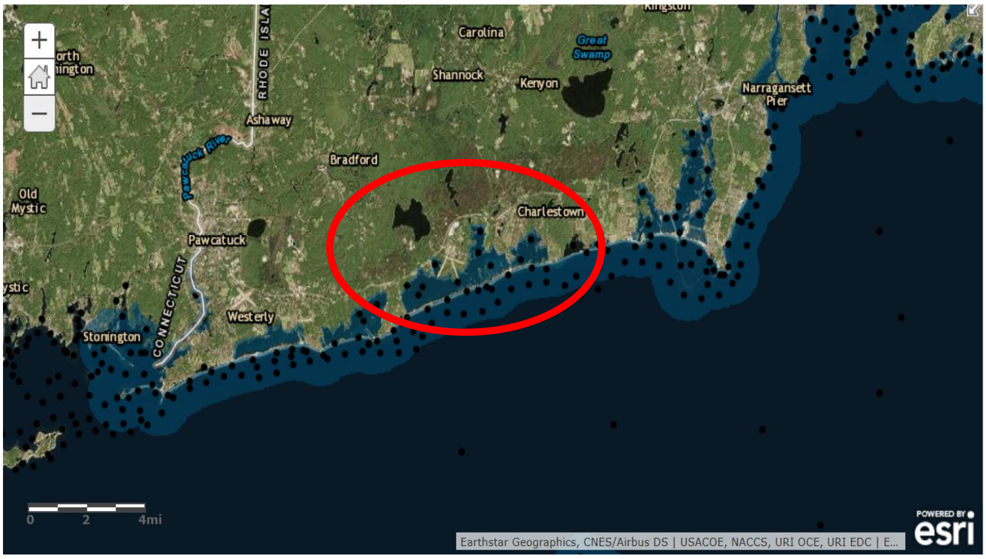


Figure 3. Location of *save points* along the southern RI coastline from the North Atlantic Coast Comprehensive Study (NACCS) study [8]. The location of the Charlestown study area is shown in the red circle.

Flood maps were generated from the NACCS simulations for selected return periods and are available at the STORMTOOLS web site [10]. The strategy utilized in this application is to apply extremal analysis at a primary water level station to determine the water levels for varying return period and then the results of hydrodynamic model simulations to determine the spatial scaling of the water levels for storms/return periods, referenced to this primary gauging station. As an alternate, water levels can be directly determined from the NACCS *save point* where return period information is available (e.g., Figure 3). Figure 4 shows the 100 year flooding contour map for the upper 95% confidence interval for the surge plus tide case for RI. The water levels (m, referenced to Mean Sea Level (MSL)) were spatially interpolated from the *save points* noted in part in Figure 3 to generate this figure. The spatial structure shows little variation in the west to east direction along the southern RI coastline and then increasing water levels with distance up Narragansett Bay. The amplification in the bay is almost linear with distance referenced to the mouth of the bay [9] and approximately constant in the cross bay direction.

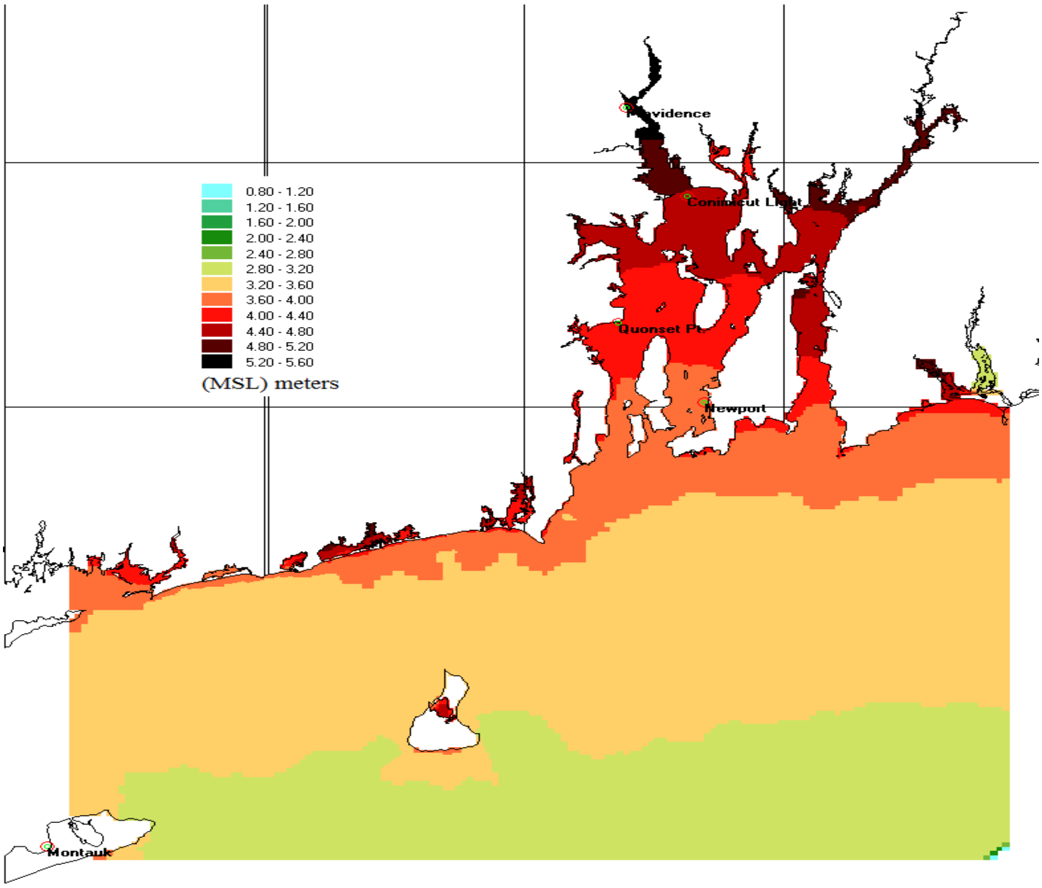


Figure 4. Water level contour map for 100 year, upper 95%, surge plus tide case, based on NACCS data.

Model predictions show a coupling between waves and surge, resulting in a wave setup along the coast. The pattern is most clearly observed by studying the local slope of the sea surface (Figure 5). The slope is largest in a small band along the southern RI coast line and is absent offshore and in Narragansett Bay. In the present application, the wave induced set up (order of 1 m) is predicted as part of the STWAVE application to the study area.

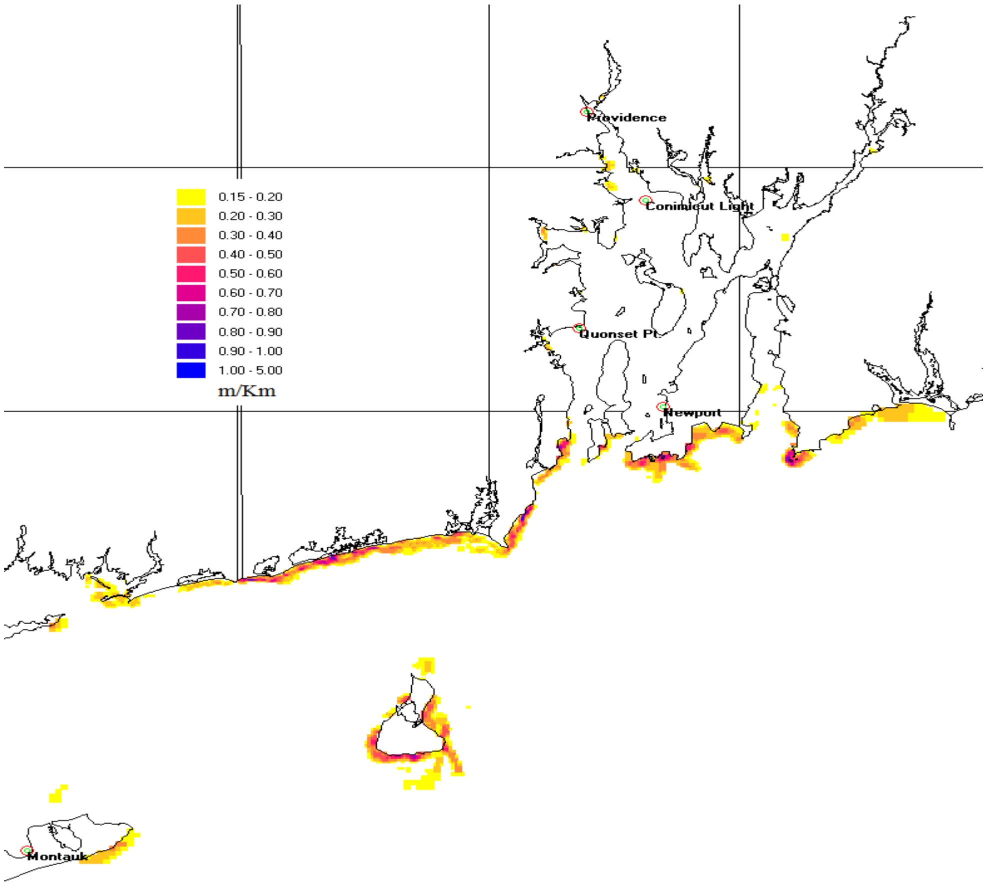


Figure 5. Contour map of the slope of water level (m/km) for NACCS 100 year, upper 95% surge plus tide case.

2.2. Wave and Wave Set Up Modeling

Wave estimates for flood inundated areas were made by applying Steady-state spectral WAVE model (STWAVE) [11,12] to the study area, at a grid resolution of 10 m, with forcing on the offshore boundary (43 m depth) from an analysis of the NACCS wave data set. The domain included the area immediately offshore and the entire flood inundated area. The water level is the same as used for the inundation estimates presented in Figure 4. Figure 6 shows the mean 100 year wave heights for the surge plus tide case from NACCS generated by interpolating values at the save points to create a contour map. The figure clearly shows large waves propagating toward the southern RI shoreline from the southeast (SE). The amplitudes are dramatically reduced by breaking as they approach the Charlestown coast line. It is noted that the waves for the 100 year mean case are used in this analysis, rather than the upper 95% values selected for the water level. A review of the upper 95% wave heights show that they could not exist in much of the study area due to steepness limited wave breaking, thus the selection of the more reasonable mean values. Validation of the wave model with a long-term hindcast of waves in the study area is provided in Section 3.

The STWAVE model is a phase-average, steady state, spectral wave model and simulates depth-induced wave refraction and shoaling, current induced refraction and shoaling, depth and steepness-induced wave breaking, wind-wave growth, and wave-wave interaction and white-capping, that redistributes and dissipates energy in a growing wave field. The model does not include wave run-up as this is a time-dependent process. The dune that is present along the barrier system is assumed to be eroded based on Oakley's (2016) [13] analysis of a long-term (>30 years) time series of cross-shore beach profiles for the study area. Frictional losses from overland flows are addressed by assigning Manning roughness coefficients to each grid and depend on land cover and vegetation type. The land use was translated into Manning roughness based on standard hydraulic literature [14], as implemented by Wamsley et al. [15], resulting in a Manning coefficient map with variations from 0.02 in open water to 0.1 over woody wetlands. Manning roughness was specified based on a 30 m resolution map of ground cover provided by RI Geographic Information System (RIGIS) [16]. Table A1 provides the Manning coefficients by land type and use. Figure A1 shows its spatial distribution for the coastal area along the southern RI shoreline.

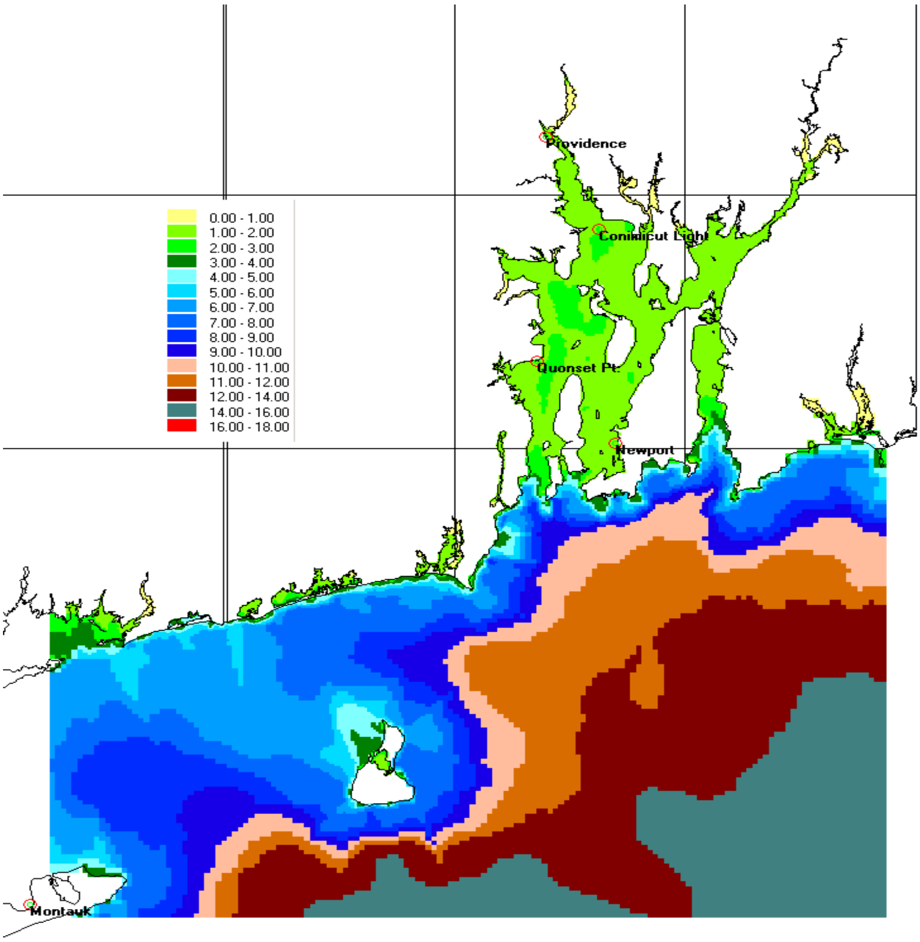


Figure 6. Contour map of the 100 year return period significant wave height (m, Mean Sea Level (MSL) referenced) for the mean surge plus tide case for RI coastal waters.

STWAVE was set up for the Charlestown study area, with the southern open, offshore boundary having a water depth of 43 m. The wave period at the location was set at 20 s and the wave height at 7 m based on the NACCS model wave predictions. Swell and wind generated gravity waves in shallow water are specified by a Texel, Marsen, and Arsloe (TMA) spectrum [11,12], with a direction of 170 degrees clockwise relative to North (waves from the SE). The model had a grid resolution of 10 m (Figure A2). The spectral peak enhancement factor was set at 3.3 and the directional spreading factor ($\cos^n$) at $n = 4$. The method is referred to as the NAST method in the following (referring to a combination of NACCS and STWAVE).

2.3. Digital Elevation Model (DEM)

To represent the topography and bathymetry in the flooded area, the wave analysis used the 2011 Laser Imaging, Detection, and Ranging (LIDAR) data Digital Elevation Model (DEM) for RI [16] and the flood maps to determine the water inundation depths. The data is available at 1 m horizontal resolution, NAVD88 benchmarked, with a vertical root mean square error (RMSE) of 15 cm. The DEM was benchmarked against 20 Blind Control Points (BCP) that were distributed throughout the state and performed as part of the 2011 LIDAR survey, with an RMSE—9.4 cm. A detailed comparison was also performed against elevation certificates, filed with the town, that were available for selected structures using the value of the Lowest Adjacent Grade (LAG) (Figure 7). After quality controlling the certificates, twenty three (23) were selected for analysis. The RMSE was 37.3 cm. The data were interpolated onto a 10 m grid for the wave simulations.

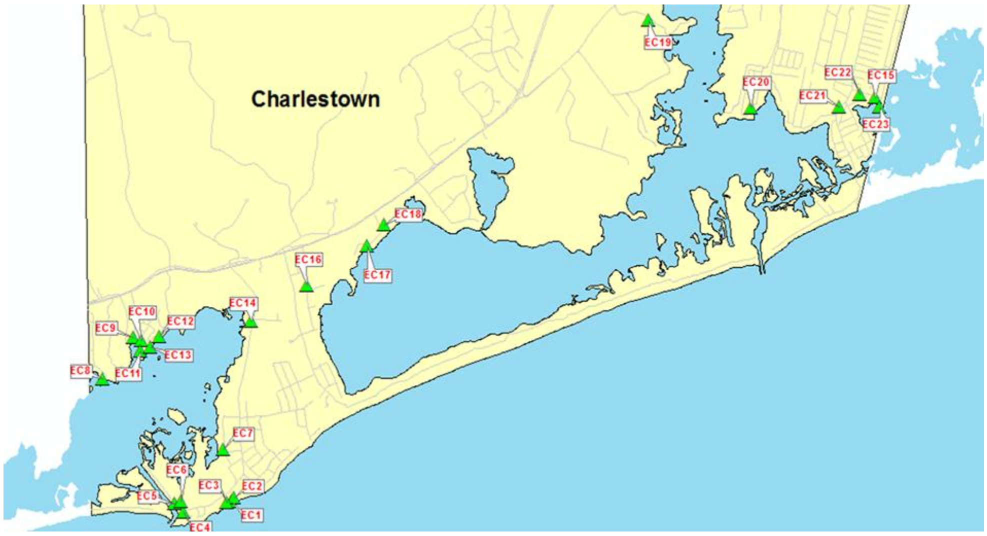


Figure 7. Location of elevation certificates for Charlestown, RI study area provided by the Town of Charlestown, RI.

According to the expected storm surge elevation (order of 4 m) and the fore-dune crest elevation (around 3.5 to 4 m), the 100-year storm is expected to overtop the dune. According to Sallenger [17], if overtopped, the dune should be flattened and the sand transported inland, creating wash-over fans. The current dune topography is therefore modified to reflect this erosion process and a 100-year storm dune profile is substituted for the current profile. The profile is based on Oakley's (2016) [13] analysis of historical aerial photographs following the 1938 Hurricane and Hurricane Carol (1954), long-term time series of cross-shore beach profiles for the study area, interpreted elevations for historic wash-over fans and slopes derived from modern wash-over fans using LiDAR. The resulting eroded profile reduces the dune crest elevation from its present value to 1.6 m (NAVD88) with a foreshore slope of 11%, and landward slope of 0.3% (300 m from crest) representing the wash-over fan; and after 300 m landward of the dune crest, reverts to the existing bathymetry.

3. Results and Discussion

3.1. Surge and Tide Water Levels

To assess the performance of the NACCS model predictions for the study area, the model predicted water levels vs. return period were compared with data from the closest NOAA NOS water level station at Newport, RI (Station ID #8452660) [18]. This is the water level station closest to the Charlestown study area.

Figure 8 shows the mean and upper and lower 95% confidence limits for the water level vs. return period based on NACCS model predictions and NOAA historical observations. The water levels vs. return period for the mean value for NACCS surge only and the NOAA mean are in very good agreement. The NACCS is higher (typically about 30 cm) than the NOAA values for the surge plus tide case. The structure of the upper 95% is dramatically different between the NOAA and NACCS data. NOAA uncertainties are strongly asymmetric with return period, with the upper confidence deviating more from the mean than the lower confidence interval. This is a result of the limited length of the historical record (70 years) and the presence of several large storm events (1938 and 1954) in the record [18]. The uncertainty in the NACCS, as shown by the upper 95% confidence limit, is approximately independent of the return period. This is attributed by NACCS to the fact that the analysis is based on synthetic tropical storms rather than historical events [8]. For the most frequently used 100 year return period water level, the mean value for NOAA is 2.45 m, while the corresponding values from NACCS are 2.42 m (surge only) and 2.76 m (surge plus tide). The upper 95% water level from NOAA for this case is 3.46 m, compared with NACCS values of 3.58 m (surge only) and 3.93 m (surge plus tide). The estimates are hence reasonably comparable. FEMA guidance typically rounds up to the nearest 30 cm (1 ft).

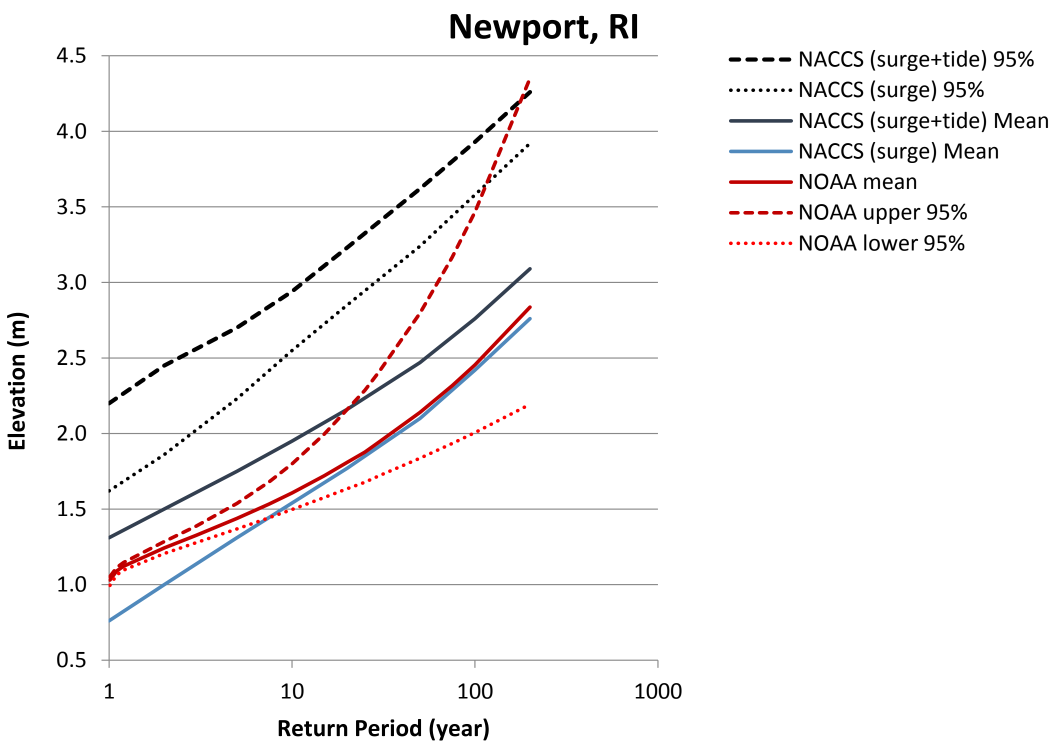


Figure 8. Surge elevation (meters, relative to NAVD88) vs. return period (years) for Newport, RI (Station ID #8452660). Estimates are provided from NOAA for the mean and lower and upper 95% confidence intervals and for NACCS for mean and upper 95% confidence intervals, for the surge only and surge plus tidal cases.

It is noted that the above analysis is based on a return period analysis using only the tropical storms from NACCS and for all data from the historical record. Employing all storms (e.g., tropical and extratropical storms) in the NACCS data, the return period analysis is essentially the same as the tropical storm case only. This is attributed to the fact that tropical storms provide the highest water levels and hence dominate the upper end of the low frequency tail of the distribution. This is consistent with the NOAA NOS historical observations at the site, with hurricanes responsible for the 6 of the top 10 surge levels [18].

Hashemi et al. developed an artificial neural network (ANN) model using the NACCS models predictions, which also serves to validate NACCS model predictions [19]. Model input included the tropical storm strength, forward speed, radius to maximum winds, and storm path used as input to the NACCS model. The ANN model predicted peak water levels at Newport and Providence for each of these events. Seventy percent (70%) of the storms (approximately 1000 tropical storms) were used to train the algorithm, with 15% utilized for validation, and 15% for testing. Model performance was very good for all three phases, with correlation coefficients greater than 0.92. The root mean square error (RMSE) was approximately 30 cm. The ANN model was then applied to predict the peak storm elevation for the largest tropical storms that have historically impacted the area (1938, 1944, 1954, 1991, 2011, and 2012) [18] using the same parameters as for the NACCS storms, but derived from the historical data. Predictions were again performed at Newport and Providence, RI. Model performance gave a RMSE = 32 cm for all storms except 2012 (Sandy). The ANN model under predicted the peak water levels for this storm by about 50 cm. This reduced performance is attributed to the fact that storms with characteristics like Sandy are extremely rare in the historical record and were not included in the NACCS synthetic tropical storm data base.

Model predictions, in another evaluation [9] were compared with a wide array of point observations collected during the 1938, 1954, and 2012 storms and reported by FEMA in their FIS for Washington County [2]. In this case the slope of the linear regression line from Newport to the head of the bay in Providence was based on the storm of interest. Figure A3 shows a comparison of model predictions to observations. While the data quality is typically quite variable, the analysis does well in capturing the amplification of the storm water levels with distance up the bay. The amplification is clearly strongly storm dependent and driven primarily by storm track, relative to the bay, and storm strength.

In the interest of developing conservative estimates of flooding and addressing uncertainties inherent in the modeling and extremal analysis methods, the NACCS surge plus tide, 95% confidence limit case is selected for this study.

Figure 9 shows the flood inundation levels (m) for the Charlestown study area for the 100 year storm event, assuming that the barrier dune is eroded. Inundation in the coastal pond (Ninigret and Green Hill Ponds) is masked in this figure. Note that either the spatial scaling method, noted earlier, or the selection of the data from the save points immediately offshore of the study area can be used to specify the flooding. In this case, the data from the NACCS save points have been used. Since the model used to generate the water level is coupled to a wave model, wave set up is inherently included at the save points closest to shore (Figure 5), but not in the spatially scaled values.

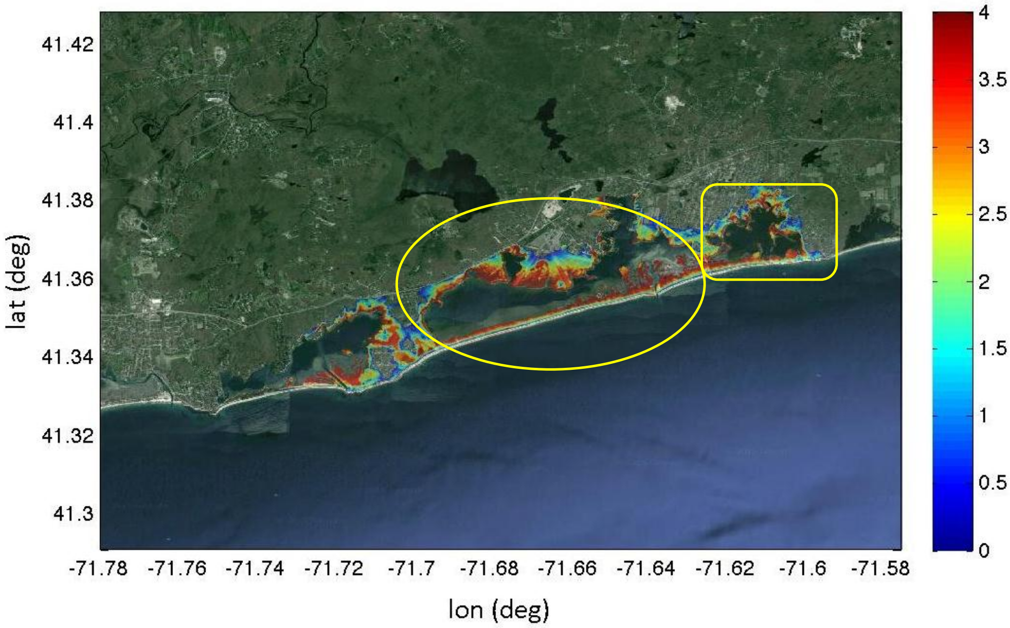


Figure 9. Inundation depths (m) relative to grade for Charlestown, RI for 100 year event [20]. Ninigret Pond is shown in the yellow oval and Green Hill Pond in the yellow box. The contour scale provided at the right of the figure is in meters.

3.2. Wave Modeling

An analysis was performed comparing extreme values for the 100-year wind and significant wave heights based on the US Army Corp of Engineers, Wave Information Study (WIS) [21] hindcast point #63079 (referred to as #79 in the text to follow) and an analysis of the NACCS peak wave heights for save point ID# 6859 for the synthetic tropical storms [8]. This is the *save point* in closest proximity to WIS#79. The WIS analysis is based on a hindcast of winds and waves from 1980 to 2012. A generalized extreme value (GEV) method was applied to both analyses, so the results are internally consistent for the method. The results are summarized in Table 1 for mean and upper and lower 95% confidence interval (CI) limits for wind speed and significant wave height and peak period.

Table 1. Once in one hundred (100) year return period, mean and lower and upper 95% confidence interval (CI) limits for significant wave height and period and wind based on WIS hindcast data at station #63079 [20] and NACCS save point #6859 [8].

100 Years Return Period Based on Generalized Extreme Value [GEV] at WIS 79						
Variable	WIS Time Series			NACCS Synthetic Storms		
	100 Year Mean	Lower 95% CI	Upper 95% CI	100 Year Mean	Lower 95% CI	Upper 95% CI
Hs (m)	10.1	5.8	14.5	13.0	11.5	15.1
Ws (m/s)	32.8	24.5	41.0	39.3	33.9	47.9
Tp (s)	17.0	10.8	23.1	19.9	19.0	21.0

The significant wave heights, Hs, based on the NACCS data, are larger than the corresponding values using the WIS data for the lower (11.5 m vs. 5.8 m) and mean (13 m vs. 10.1 m) values, but comparable for the upper 95% confidence limit case (15.1 m vs. 14.5 m). The WIS based values likely underestimate the wave heights since the two largest hurricanes (1938 and 1954) to impact the area (1938 and 1954) are not included in the hindcast period. The 100-year wind speed mean and lower 95% are both higher for the NACCS values, than for the WIS based estimate and comparable at the upper 95% confidence interval. The wave and wind values are internally consistent with the higher winds giving larger and longer period waves. Based on this comparison the results from the NACCS study provide reasonable estimates of the 100 year wave height and period.

3.3. Simulations

Figure 10 shows the model predicted controlling wave height for Charlestown, RI, assuming the dune is eroded. Once again the wave heights in Ninigret and Green Hill Ponds (see Figure 9) are masked. The figure clearly shows that waves are subject to shallow water breaking on top of the eroded dune, thus reducing the wave heights on the landward side of the coastal pond. The wave field is seen to show strong 2-D effects with substantial variation in wave heights along the landward side of the ponds and the nearby flood inundated area.

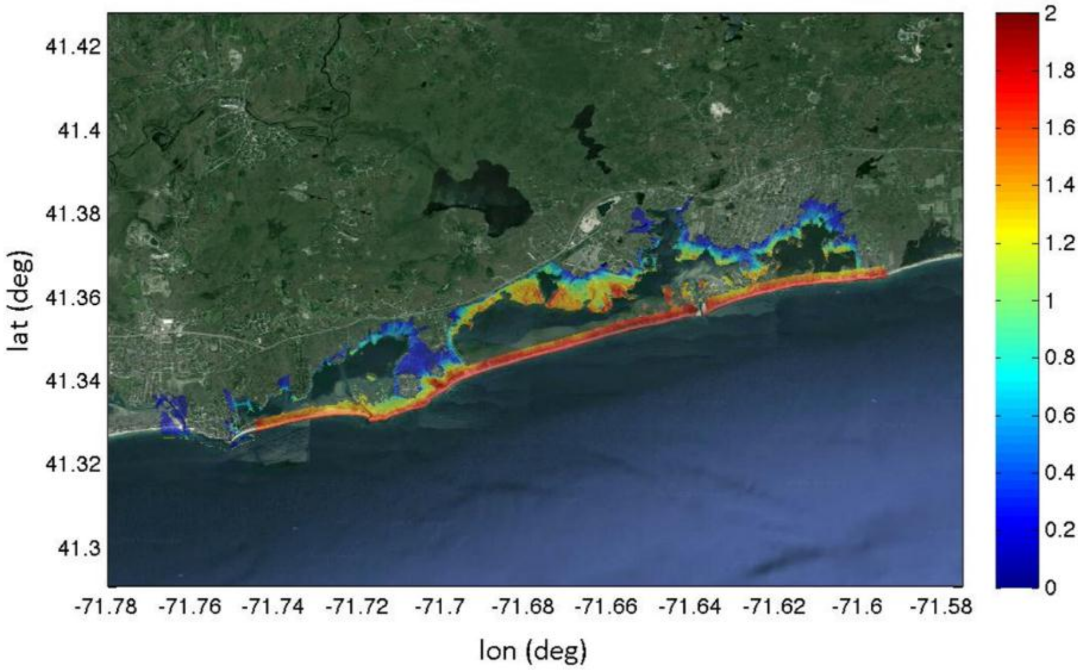


Figure 10. Controlling wave height (m) for Charlestown, RI, 100 year event, dune eroded [20]. The contour scale provided at the right of the figure is in meters.

Figure 11 shows the combination of the surge level (Figure 9) plus the controlling wave height (Figure 10) for Charlestown. This is essentially a map of the BFEs for the study area.

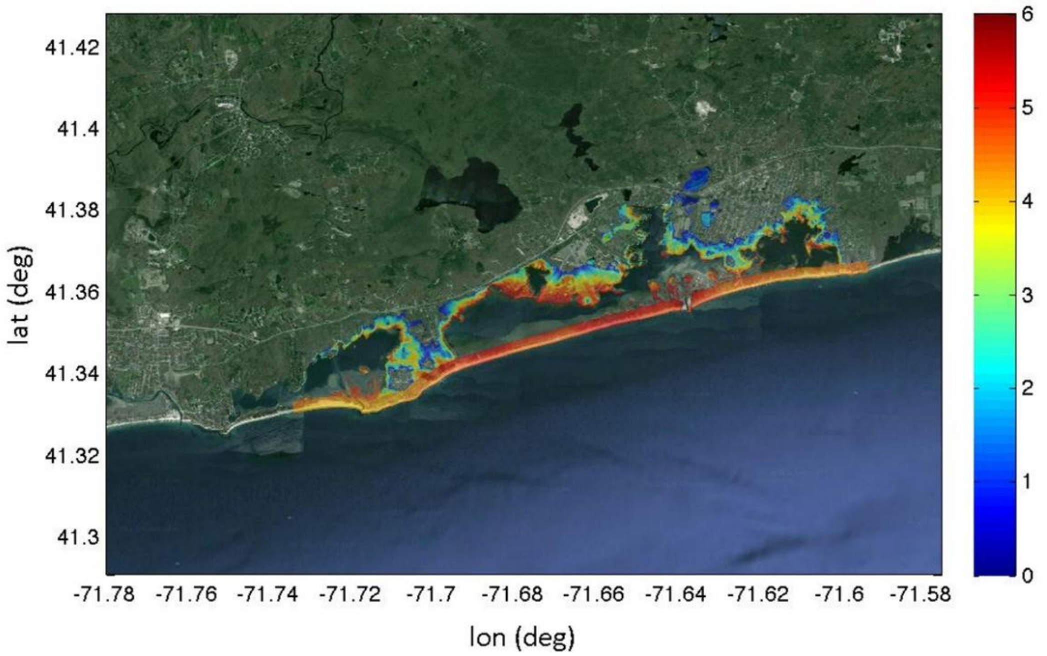


Figure 11. Total water depth (m) (inundation plus wave height) for Charlestown, RI, 100 year event, dune eroded [20]. The contour scale provided at the right of the figure is in meters.

In the interest of better understanding the impact of improvements in the modeling methodologies applied on the final FIRM maps, Figure 12 shows the FEMA predicted flooding zones for the Charlestown study area. The upper panel shows the total depth of water (m) (BFE-elevation of grade), while the lower panel shows the BFEs (m) relative to NAVD88. The latter is typical of the FIRM maps distributed by FEMA. Figure 13 shows the same set of maps using the results of the present study, referenced as NAST or URI Coastal Environmental Risk Index (CERI) [21].

Restricting attention to the area flooded, FEMA's (Figure 12) and the present study (NAST) (Figure 13) results show that the region impacted is slightly larger for the present study compared with FEMA's estimates. This is consistent with the fact that the SWEL in the present study is approximately 4.1 m compared with FEMA's value of 3.7 m; a difference of 0.4 m. This difference is consistent with the use of the upper 95% confidence interval value for the 100 year return period in the present study, compared with the mean value that FEMA used. The spatial variation in surge level along the southern RI coastline is limited and consistent between the two approaches.

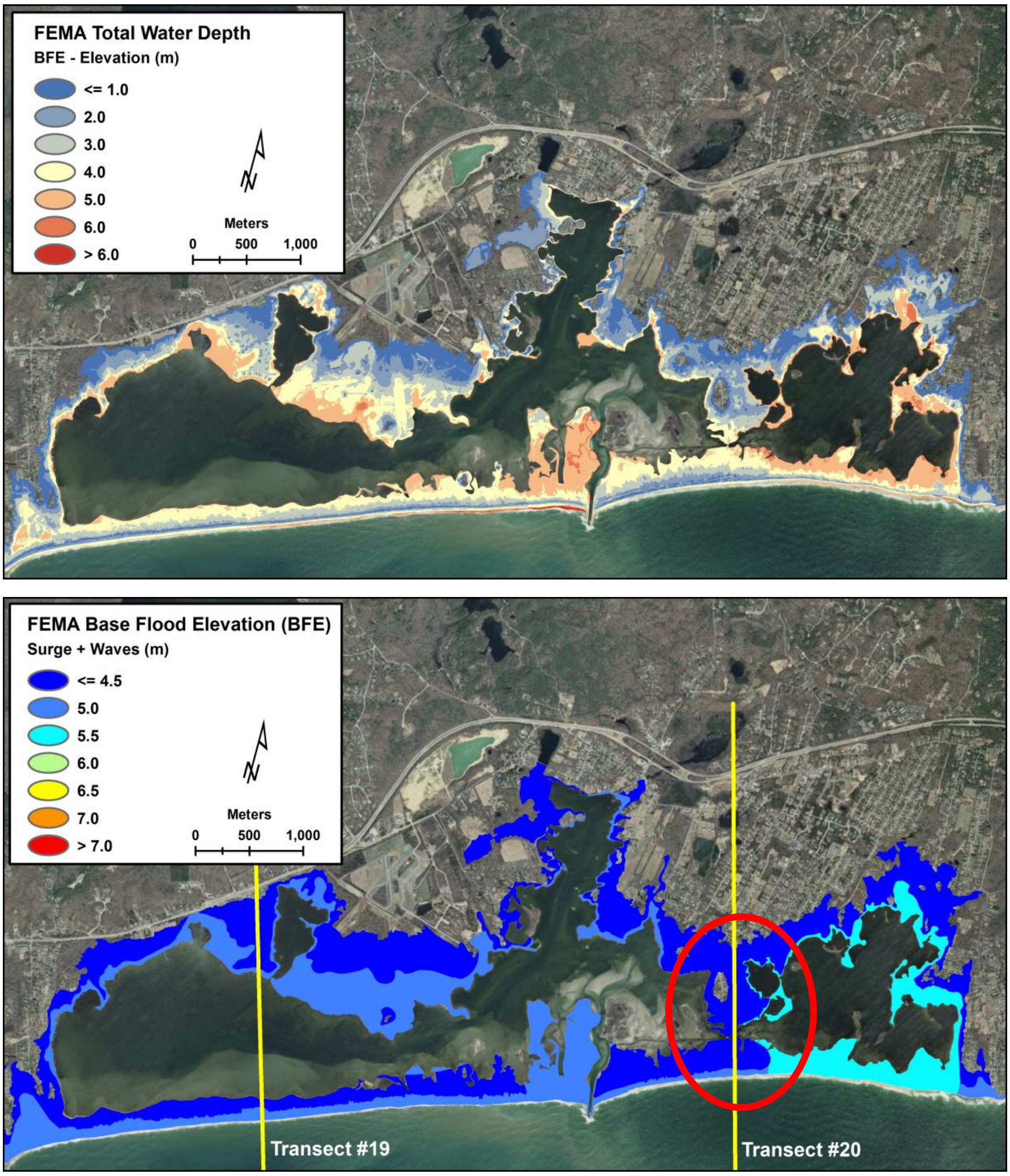


Figure 12. FEMA predicted total water depth (m) measured from grade to Base Flood Elevation (BFE) (**upper panel**) and BFE (m) relative to NAVD88 (**lower panel**). FEMA transect lines are shown in yellow, #19 (left) and #20 (right). Area of substantial increase in BFE near the shoreline from one side of transect #20 to the other (red circle).

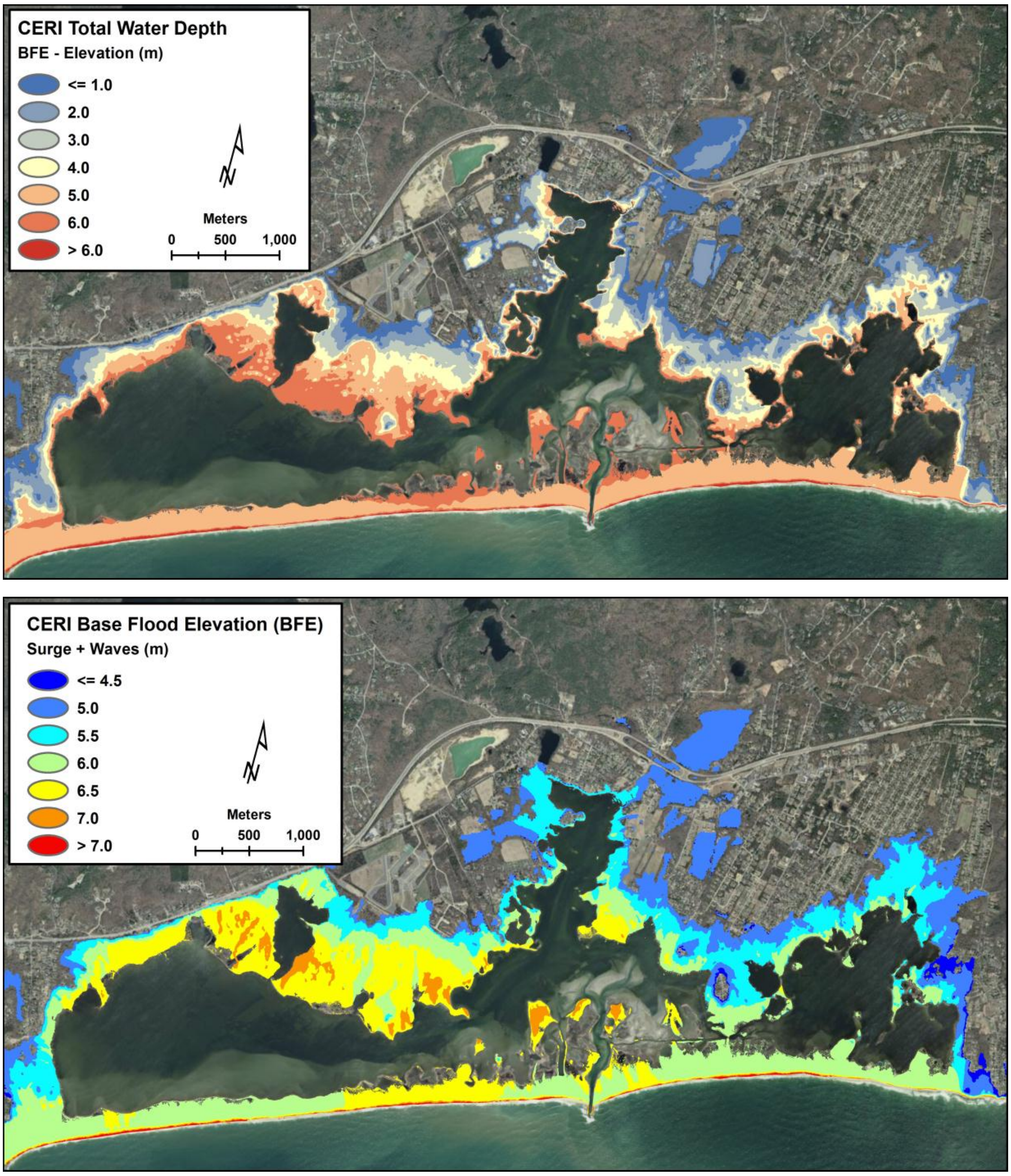
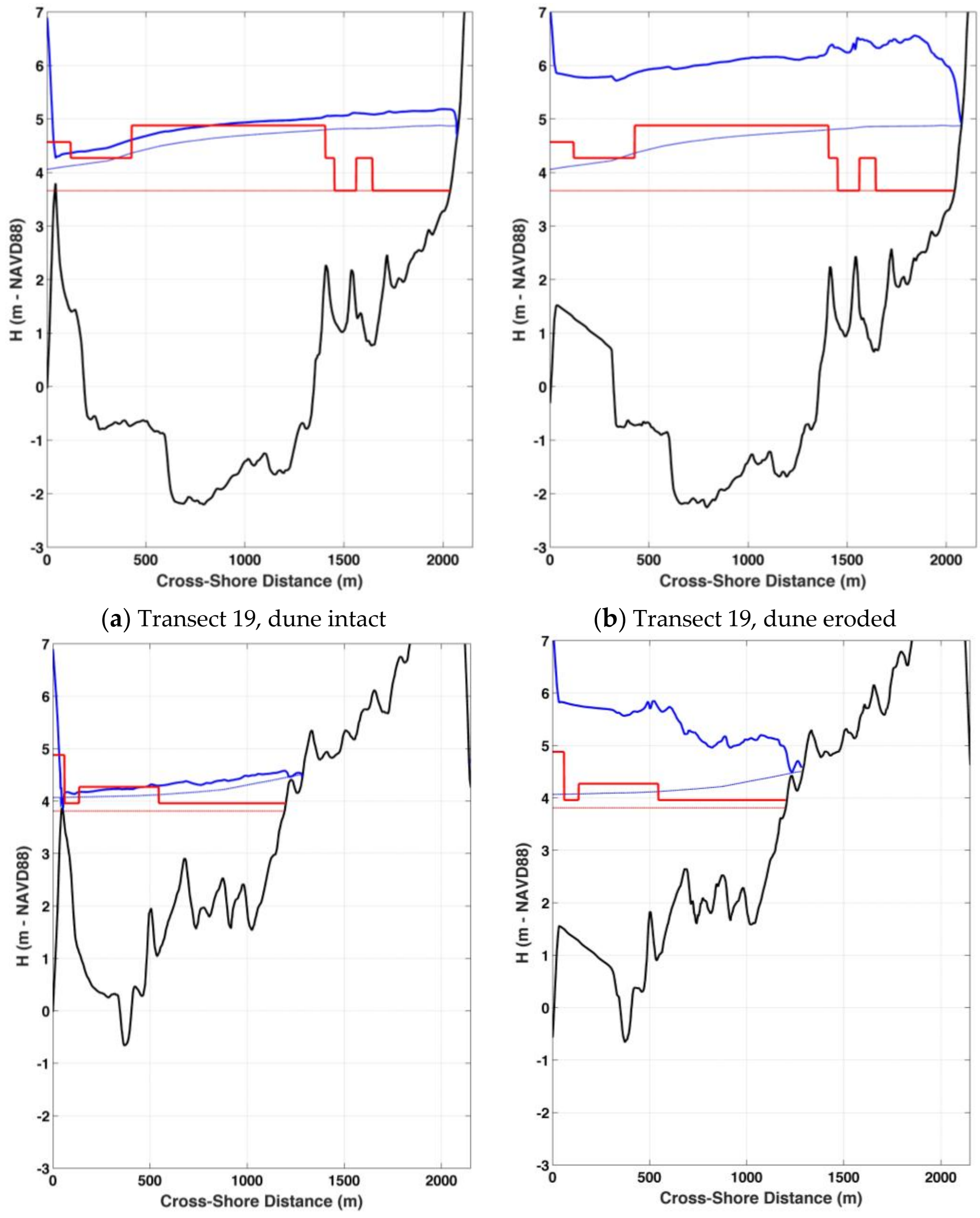


Figure 13. NAST/URI (CERI—Coastal Environmental Risk Index) predicted total water depth (m) measured from grade to BFE (**upper panel**) and BFE (m) relative to NAVD88 (**lower panel**).

To provide a more in-depth comparison between the results of FEMA and the current study (NAST), Figure 14 shows the predicted SWEL and BFEs vs. distance landward for transects #19 (upper panel, a and b) and #20 (lower panel, c and d). The location of the transects are shown in Figure 12 (lower panel). The length of transect #19, over the flooded area (2100 m), is about twice that of transect #20 (1200 m). Analyses were performed for the dune intact (left side, a, c) and dune eroded (right side, b, d) conditions. The FEMA dune erosion protocol was used by FEMA to generate their results, while the current study used observation based estimates of the eroded dune profile, as described earlier [13]. The FEMA erosion model assumes that a dune with a volume less than 540 square feet per foot of shoreline above the SWEL are eroded [1]. No dunes in the study area exceed this volume for either of the SWEL's (3.7 m or 4.1 m). The FEMA erosion model projects erosion from the toe of the dune, landward at a slope of 1:50 [22,23]. This does not match the observations in the study area for previous storm events. FEMA did not provide a dune intact case; hence the eroded dune case is shown. The topography is shown in black and based on the current DEM for the study area. The eroded dune profile shown in the figure is based on the present study approach. The plain bold blue line shows the NAST simulated total water elevation (Base Flood Elevation, BFE), and the light blue, dashed line shows the predicted still water elevation level (SWEL, combination of astronomical tide, storm surge, and static wave setup). For comparison, FEMA's inundation zones are shown in red, with the BFE shown in bold plain, and the SWEL in dashed, light red. The FEMA results are taken directly from the Washington County FIS [2]. Attempts were made to reproduce the WHAFIS predictions for these two transects but without success. Unfortunately, FEMA was unable to reproduce the results shown for each of these transects.



(**a**) Transect 19, dune intact (**b**) Transect 19, dune eroded

(**c**) Transect 20, dune intact (**d**) Transect 20, dune eroded

Figure 14. Water elevation (m/NAVD88; BFE, plain; Still Water Elevation Level data (SWEL), dashed) versus landward cross-shore distance (m) along FEMA transects 19 (**a**,**b**) and 20 (**c**,**d**) for FEMA calculation (red) and NAST simulations (blue) assuming dune intact (**a**,**c**) or dune eroded (**b**,**d**); topography (black).

Table 2 summarizes the comparison between FEMA and present study results at the intersection of each transect and the shoreline. As noted above, the water elevation for the two transects, including the effects of wave setup, are comparable (FEMA—3.7 to 3.8 m vs. NAST—4.1 m). The critical wave crest values are however substantially larger for the present study (2.8–2.9 m) compared with FEMA (0.9–1.1 m). This is a result of assuming a constant offshore wind and unlimited fetch in FEMA's method versus using the results of offshore wind and wave simulations and return period analyses in the present study. One of the key problems here is that FEMA used a mean 100 year wind speed of 24.4 m/s derived from Quonset, RI airport. This station is located well inside Narragansett Bay and hence is not representative of offshore winds. For comparison, the mean 100 year winds offshore are 32.8 m/s and 39.3 m/s (Table 1) using the WIS and NACCS data, respectively.

Table 2. Comparison of the water elevation (NAVD88, m), critical wave crest height (m) and deep water significant wave height (m) at the intersection of the transect and shoreline for transects #19 and #20.

Transect	Shoreline Coordinates (deg)		Water Elevation NAVD88 (m)				Critical Wave Crest (m)		Deep Water Significant Wave Height (m) [Hs]	
			FEMA		NAST					
	Lat. N	Lon. W	SWEL + SETUP	BFE	SWEL + SETUP	BFE	FEMA	NAST	FEMA	NAST
19	41.338	71.670	3.7	4.6	4.1	6.9	0.9	2.8	4.0	7.0
20	41.346	71.619	3.8	4.9	4.1	7.0	1.1	2.9	4.0	7.0

For the dune intact case (Figure 14a,c), FEMA predicts a constant SWEL with distance along both transects. (FEMA values shown here assume that the dune in fact is eroded according to the specified dune erosion rules [4].). The NAST predictions are slightly higher and increase with distance landward. The increase in water level is about twice as large at the landward end of transect #19 as for #20. This increase in SWEL is associated with the water level setup resulting from the balance between wind stress and friction in the flood inundated area [24,25], inherent in the NACCS coupled surge and wave model (ADCIRC-STWAVE). The set up scales approximately linearly with transect length, and therefore is twice as large at the landward end of transect 19 compared with transect 20. WHAFIS does not include wind induced set up in flood inundated areas. The NAST BFEs show a similar shape to the SWEL, with slightly higher values. FEMA predictions show a stepped pattern, characteristic of the output of WHAFIS, with the BFEs generally decreasing with distance landward. (The stepping is a direct result of the FEMA results being rounded up to the nearest 30 cm (1 ft)). This behavior is controlled by wave breaking dynamics, given the lower SWEL in FEMA's method, compared with the NAST approach. The peak BFE values along each transect are comparable for both methods.

The SWEL and BFE results for the FEMA dune eroded case (Figure 14b,d) are the same as for the dune intact case. The FEMA SWEL is constant with distance along the transect, while the NAST results show the characteristic set up with distance landward, similar to the dunes intact case. This setup is the same as for the NAST dune intact case, showing that the presence of the dunes has little impact on flooding, since the dunes are overtopped in either case. The BFEs are however substantially larger for the dune eroded case, approximately 1 m greater, than the dune intact case. The NAST BFEs show an increase with distance landward for transect #19, until shallow water breaking reduces the wave heights at the landward end of the transect. The trend on transect #20 is in general a reduction with distance landward, reflecting shallow water breaking and the fact that water depths are much lower along transect #20 compared with #19.

Comparing NAST simulations for dune intact and eroded case shows that the condition of the dunes has little impact on the SWEL inundation levels since the dunes are overtopped in either case. The dunes however play a very important role in reducing waves and hence the BFE.

An attempt was made to compare the spatial structure of the BFEs generated by FEMA with those generated by NAST. In order to do this one needs to understand the procedure that FEMA used to translate the WHAFIS predictions along the 1-D transects to a 2-D map. The pattern of the FEMA BFEs suggests that they must be closely related to the inundation depths. This proved impossible to do however since the analysis has been done according to engineering judgement following FEMA guidelines [1]. The problem is compounded in the present case given the fact that only two transects were used in the analysis and their spacing exceeded FEMA guidance [1]. One clear indication of the level of the problem is the discrete increase in the BFE (over 1.5 m) on either side of transect #20 (see red circle in Figure 12, lower panel). The NAST simulation results highlight the importance of 2-D wave processes involved in wave propagation in flood inundated areas.

4. Conclusions

Flood inundation maps have been developed for Charlestown RI using state of the art, fully coupled high-resolution surge and wave models (ADCIRC, WAM, and STWAVE) applied to the study area as part of the NACCS. The model predictions were extensively validated with data from tropical and extratropical storms during the study. NACCS simulations were performed for 1050 synthetic tropical storms and 100 historical extratropical storms. Peak values were archived at selected save points and return period analyses performed for each storm data set. Additional validation, of the both water levels and wave heights vs. return period, with historical water level data at Newport, RI for the former and hindcasts (1980–2012) of wave conditions for selected locations off the coast for the later, from the USACE Wave Information Study (WIS) [20], were performed as part of this study to gain additional insight into model performance. The results are generally in reasonable to good agreement.

Simulations were then performed using STWAVE on a high resolution grid (10 m) of the flood inundated study area. The model was driven by offshore water levels, wave set up, and wave height, period, and direction along the open boundaries assuming a shallow water TMA wave spectral distribution model from the NACCS study with $\cos^n$ directional spreading. The model included wave dissipation based a comprehensive mapping of the roughness from both structures and ground cover. STWAVE predicted the 2-D wave transformation processes and explicitly considered dune erosion based on an analysis of a long historical record of beach profiles for the barrier system under study. The model clearly showed the importance of the dunes in preventing large waves from entering the coastal ponds and highlighted the 2-D nature of the wave field.

Key findings in the study include:

- FEMA and present study predict comparable SWEL for the study area. Present study values are slightly larger (4.1 m) than FEMA (3.7 m). This results in slightly larger inundated areas. The slightly larger values are attributed to the use of upper 95% confidence limit water levels used in the present study and the water level setup from the NAST simulations in the storm inundated area.
- The present study results show SWEL increasing with distance landward from the shoreline because of the balance between wind stress and frictional dissipation in flood inundated areas. FEMA's SWELs are independent of distance landward.
- FEMA (with eroded dunes) and the present study (with dunes assumed to be intact) predict comparable peak BFEs in the flood inundated areas. If the dunes are eroded FEMA results are substantially lower (about 1 m) than the present results. The primary source of differences is lower wave heights at the offshore end of the FEMA transects and differences in the eroded dune profiles. Attempts to obtain the FEMA bathymetry to use as input to WHAFIS for the two transects under study were not successful.
- FEMA results show strong evidence of the impact of the selection of the transects to represent wave conditions. As an example, for transect #20 the BFE shows a variation of almost 1.5 m from one side of the transect to the other at the dune crest line.

- It has proven impossible to recreate the 2-D structure of the wave field that FEMA has developed given the results for the two transects. It seems to be primarily controlled by topography. The transect spacing is too large to determine the spatial structure, and 2-D wave processes are not represented by the methods used (e.g., WHAFIS).
- The largest difference in the BFEs between the FEMA and present study methods is in the waves, particularly wave conditions at the shoreline and their subsequent 2-D spatial transformation. The present study predicts wave heights that are approximately twice as large as FEMA values. It has been impossible to determine which wave processes are critical in controlling the 2-D wave environment, but the initial indications are that they are caused by wave breaking along the eroded dunes, the specification of the eroded dune profile, and wave refraction and shallow water wave breaking on the landward edge of the coastal ponds and the nearby flood inundated areas.

The analysis presented herein implemented all of the NRC recommendations raised in their review of the FEMA coastal mapping program [5]. Thus, it represents an advancement over the methods used in the FEMA study [1,2].

Simulations for cases with dunes and with dunes eroded, including the effects of sea level rise for Charlestown are provided in [21]. Additional details on the application of the methods outlined here to other communities in Washington County, RI are provided in [26].

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Author Contributions: Malcolm L. Spaulding developed the idea for STORMTOOLS/CERI and its application to generate FIRMs. He led the project effort. Annette Grilli was primarily responsible for wave modeling. Implementation in GIS and providing access of the output was provided by Chris Damon. Grover Fugate advised on the design of the system to meet needs of coastal planners. Bryan Oakley was responsible for estimating erosion rates and the eroded dune profiles for Charlestown. Tatsu Isaji performed the water level analysis on NACCS data and Lauren Schambach performed the transect inter-comparisons.

Conflicts of Interest: The authors declare no conflict of interest in performing the study. The project sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the result.

Acronyms

ADCIRC	ADvanced CIRCulation model
ANN	Artificial Neural Network
BCP	Blind Control Points
BFE	Base Flood Elevation
CHAMP	Coastal Hazard Analysis and Modeling Program
CERI	Coastal Environmental Risk Index
CI	Confidence Interval
CRMC	RI Coastal Resources Management Council
DEM	Digital Elevation Model
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Maps
FIS	Flood Insurance Study
HUD	Housing and Urban Development
LAG	Lowest Adjacent Grade
LIDAR	Laser Imaging, Detection, and Ranging
LiMWA	Limit of Moderate Wave Action
MSL	Mean Sea Level
NACCS	ACOE, North Atlantic Coast Comprehensive Study
NAST	North Atlantic Coast Comprehensive Study and STWAVE

NAVD88	North Atlantic Vertical Datum, 1988
NOAA NOS	National Oceanic and Atmospheric Administration- National Ocean Survey
OHCD	Office of Housing and Community Development
RI GIS	Rhode Island- Geographic Information System
RMSE	Root Mean Square Error
SAMP	Special Area Management Plan
SLR	Sea Level Rise
STWAVE	STeady state spectral WAVE model
STORMTOOLS	tools in support of storm analysis
SWEL	Still Water Elevation
TMA	Texel, Marsen, and Arsloe wave spectrum
URI	University of Rhode Island
USACE	US Army Corp of Engineers
WAM	Wavewatch III, Model
WHAFIS	Wave Height Analysis for Flood Insurance Studies
WIS	ACOE Wave Information Study

Appendix A

Table A1. Manning coefficients by land use category.

Land Use	Manning
Open water	0.02
Low intensity residential	0.07
High intensity residential	0.14
Commercial industrial transportation	0.05
Bare rock/sand/clay	0.04
Quarries/strip mines/gravel pit	0.04
Transitional (cleared forest)	0.1
Deciduous forest	0.12
Evergreen forest	0.15
Mixed forest	0.12
Shrubland	0.05
Grassland/herbaceous	0.034
Pasture/hay	0.03
Row/crops	0.035
Small grain	0.035
Fallow	0.03
Urban recreational grasses	0.025
Woody wetlands	0.1
Emergent herbaceous wetland	0.04

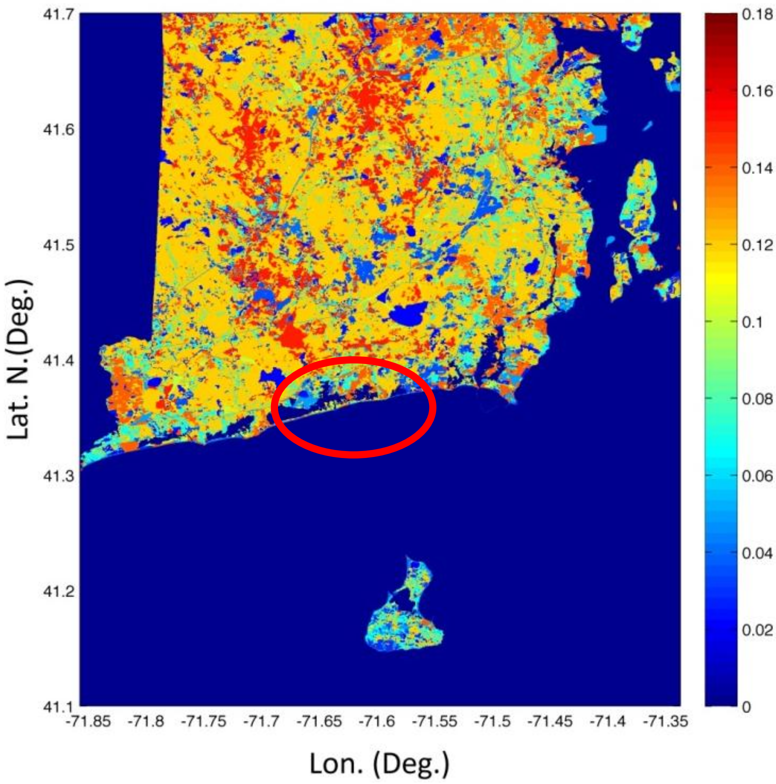

Figure A1. Map of the Manning coefficient associated to the land use and vegetation cover in Rhode Island [26]. A value of 0.02 is employed over ocean and open water. The study area is circled in red.

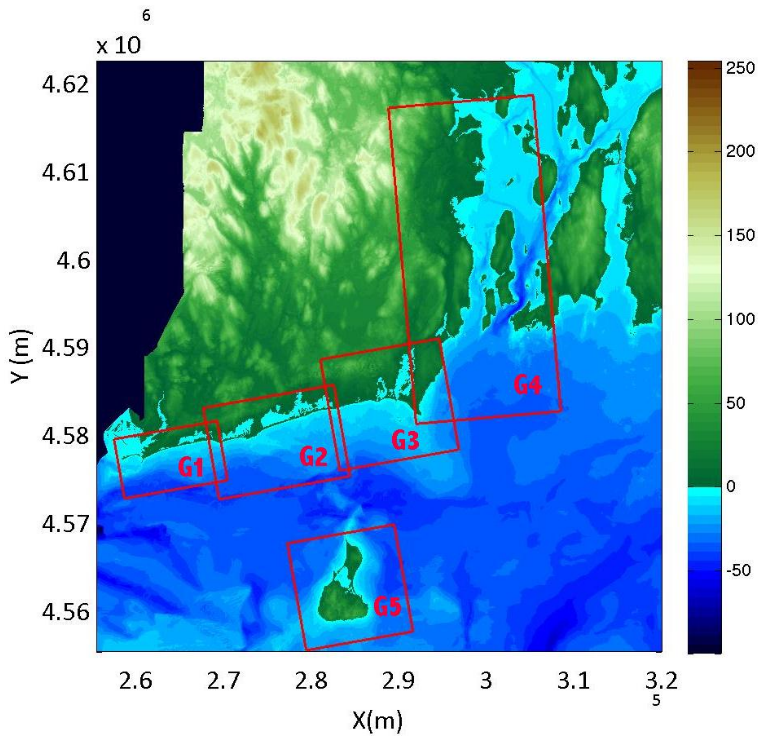

Figure A2. Bathymetry and location of the five computational grids used for STWAVE wave propagation modeling for inundated areas [26]. The G2 grid was used for Charlestown study area.

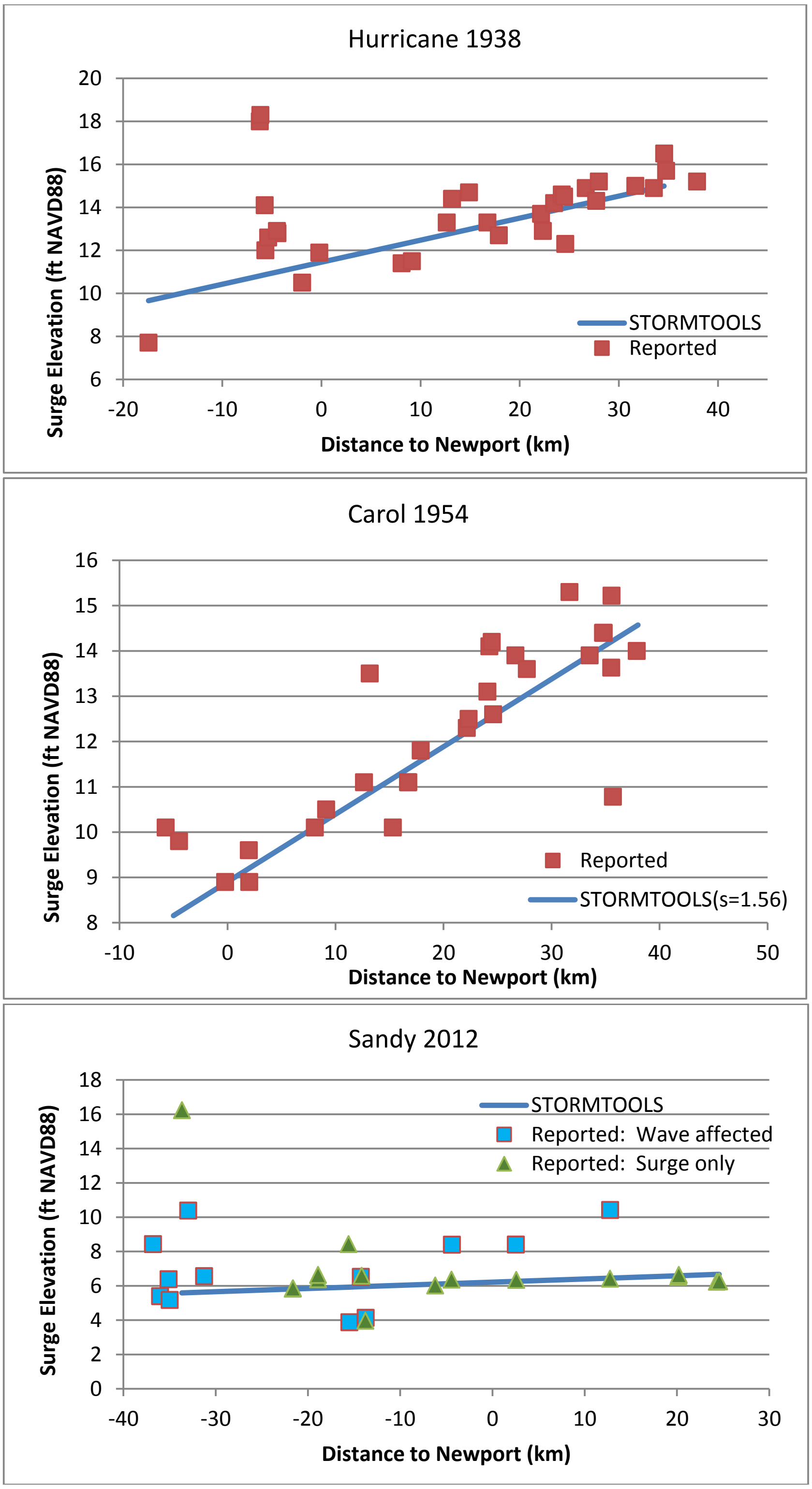

Figure A3. Peak storm surge water levels [2] for 1938, 1954, and 2012 hurricanes vs. distance up the bay referenced to Newport, RI. The data are fitted using a straight line with distance along the central axis of Narragansett Bay. Negative distances are to the west following the southern RI shoreline. (Figure 2, Spaulding et al. 2015 [9]). Data for 1938 and 1954 are based on observations collected during the event and provided in [2]. Data for 2012 were provided from temporary gauges deployed by US Geological Survey [27]. The slopes for the straight line fit to the data are 1.3 (1938), 1.56 (1954), and 1.1 (2012).

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