STORMTOOLS Design **E**levation (SDE) Maps: including impact of sea level rise

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Abstract

Many coastal communities in the US use base flood elevation (BFE) maps for the 100-year return period, specified on FEMA Flood Insurance Rate Maps(FIRM), to design structures and infrastructure. The FIRMs are increasingly known to have serious problems in accurately specifying the risk coastal communities face, as most recently evidenced during hurricanes Harvey and Irma in 2017 and Florence and Michael in 2018. The FIRM BFE maps also do not include the impact of sea level rise, which clearly needs to be considered in the design of coastal structures over the next several decades given recent NOAA sea level rise (SLR) projections. Here, we generate alternative BFE maps (SDE maps) for coastal waters of Rhode Island(RI) using surge predictions from tropical and extratropical storms of the coupled surge-wave models from the US Army Corp of Engineers, North Atlantic Comprehensive Coastal Study (NACCS, 2015). Wave predictions are based on application of a steady state, spectral wave model (STWAVE), while impacts of coastal erosion and changes of geomorphology are modeled using XBeach. All methods used are consistent with FEMA guidelines for the study area and use FEMA approved models. Maps are generated for 0, 2 ft (0.6 m), 5 ft (1.5 m), 7 ft (2.1 m), and 10 ft (3.1 m) of sea level rise, reflecting NOAA high estimates at various times for the study area through 2100. Results of the simulations are shown for both the southern RI shoreline(South coast) and Narragansett Bay, to facilitate communication of projected BFEs to the general public. Risk maps can be generated from the SDE maps for each SLR case, where risk is ranked from low to high based on likely damages to the structures that are typically found in the study area. Example risk maps are presented for several coastal communities in Narragansett Bay to illustrate the approach.

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

1. Introduction

In most coastal states in the US, state and municipal building codes use the FEMA FIRMs generated during Flood Insurance Studies (FIS) to specify the flooding zones and the associated estimates of inundation depths and wave heights used in the design of structures and infrastructure. The later are normally expressed in the form of BFEs, relative to the NAVD88 datum, and represent the sum of the still water elevation level (SWEL) due to 100 yr flooding plus the controlling wave crest height. inundation and the controlling crest wave height for 100 yr return period (1% annual chance) flooding. The controlling wave crest height represents an estimate of the upper end of the wave spectra and is 1.12 times the significant wave height(Hs).The FIRMS also include 500 yr levels (0.2% annual chance), but represent flooding only; without the associated wave environment. FEMA further delineates the flood impacted area in terms of VE, AE, and X zones. The VE zone has a wave crest height greater the 3 ft (0.9 m), the AE zone has crest heights less than 3 ft (0.9 m), and the X zone is where flooding occurs from the 500 yr event, but not the 100 yr event. The AE zone is often divided in two sections, one where the wave crest height is above and the other below 1.5 ft (0.45 m). The dividing line is the limit of moderate wave action (LIMWA) and the zone between 1.5 (0.45m) and 3 (0.9 m feet is often referred to as the Coastal A zone. Any area that can be flooded during the 100 yr event is defined as the Special Flood Hazard Area (SFHA).

These BFEs are also included in the widely used in ASCE 7-16 (ASCE, 2017) (https://asce7hazardtool.online/, accessed on October 16, 2018) which sets the minimum design loads for structures and are often required or referenced in state and municipal building codes. Strong concerns have been voiced about the FEMA FIRMS being outdated and unreliable, particularly after flooding in Texas and Louisiana from hurricanes Harvey and Irma (https://www.bloomberg.com/graphics/2017-fema-faulty-flood-maps/). These have been highlighted in a recent review by the Office of Inspector General (OIG, 2017) and earlier by an in-depth technical review by NRC (2009) of the methods used in generating the maps. While the FIRMS have been explicitly developed for setting flood insurance rates, their use for design is being increasingly questioned since they do not address sea level rise (SLR), which is projected to be very significant (several meters) over the next 100 yrs. Design of structures that don't explicitly consider the risk from SLR put property owners, communities, governmental entities, insurance companies, businesses, and financial institutions at unnecessary risk.

The goal of this paper is to generate alternative BFE maps (SDE maps) which explicitly consider SLR for coastal communities in Rhode Island(RI) for both open coastal areas, where waves and erosion are important and for a protected bay where surge amplification dominates. The SDE maps are developed for the coastal waters of the state of RI, including the southern RI coastline (South Coast) and Narragansett Bay. The maps have been developed using methods that meet the FEMA guidelines (FEMA, 2007) for coastal mapping and employ models approved by FEMA (2017) for use in such investigations. This strategy is used to facilitate their adoption by coastal states and communities. The methods used in generating the maps have also addressed several of the fundamental weaknesses of the FIRMS for the study area.

2. Approach and study area

The maps are developed under the STORMTOOLs initiative (Spaulding et al, 2015) whose goal is to provide access to a suite of coastal planning tools (numerical models, maps, data sets, etc.), available as a GIS based, web service, that allows wide spread accessibly and applicability at high resolution for user selected coastal and inland areas of interest. They are called STORMTOOLS Design Elevation (SDE) maps in recognition of their use to support the design of coastal structures and infrastructure. The maps are also an integral part of the STORMTOOLS Coastal Environmental Risk Index (CERI) (Spaulding et al, 2016; Spaulding et al, 2017a, b), which assesses the risk that structures and infrastructure face from storm surges, including flooding and the associated wave environment, in the presence of sea level rise (SLR), and shoreline erosion/accretion, based on estimating damage to structures in the impacted area.

The study area selected for the development of the SDE maps are the coastal communities of RI including both the southern RI shoreline (South Coast) and Narragansett Bay. These areas were selected for application given the relatively low lying topography of the towns and the number of residential/commercial/municipal structures at risk from SLR and storm surge (Leporacci, 2015). They include all coastal areas in RI. Figure 1 shows the density of structures at risk for 100 yr storm, plus 7 ft (2.1 m) of SLR for RI. The locations of the structures were based on the RI E911 emergency response data base and partially verified with parcel level data from the coastal towns. The Narragansett Bay and southern RI coastline study areas are outlined by the red and blue circles, respectively. The division into open coastline and bay areas is in recognition of the fact that flooding dynamics are dominated by the amplification of surge levels with distance up the bay, with waves and shoreline erosion being secondary; while waves and shoreline erosion are critically important along the southern RI coast with very limited surge amplification.

100 yr water levels including effects of SLR

Following the approach presented in Spaulding et al (2016, 2017a, b), the 100 yr water levels for storm surge for the study area are estimated using predictions of unstructured grid, coupled, hydrodynamic and wave models (ADCIRC- STWAVE/WAM) for 1050 synthetic tropical storms and 100 historical extratropical storms performed as part of the US Army Corp of Engineers North Atlantic Comprehensive Coastal Study (NACCS) (Cialone et al, 2015). The results of the simulations and return period analyses are archived at approximately 1000 *save points* principally located near the coast of the entire state. The water level for the upper 95% confidence limit (CL), for the surge plus tidal case, is employed to address uncertainty in the estimates. Spaulding et al (2016) provide additional details including a comparison of the NACCS based return period analysis to that based on historical observations at the NOAA NOS water level stations at Newport (#8452660) and Providence (#8454000), RI (Zervas, 2013). The analysis shows that the surge water levels are approximately linearly amplified with distance from the mouth to the head of Narragansett Bay, but are approximately constant along the southern RI shoreline.

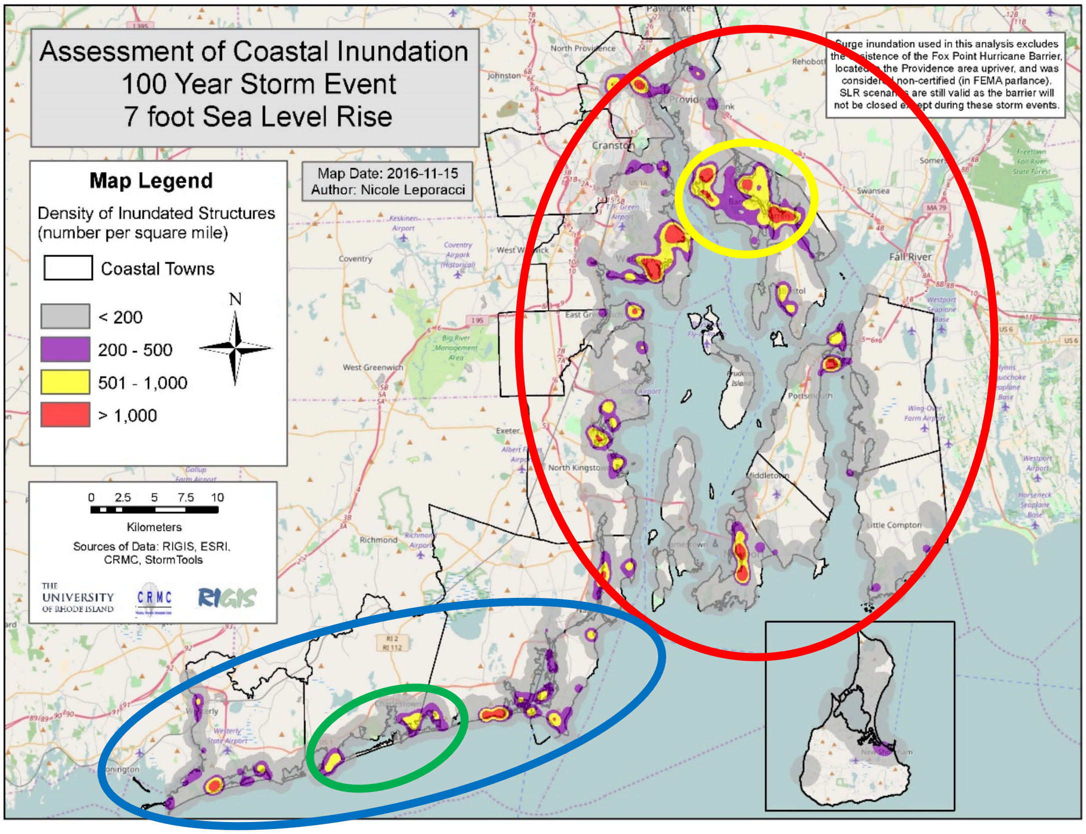


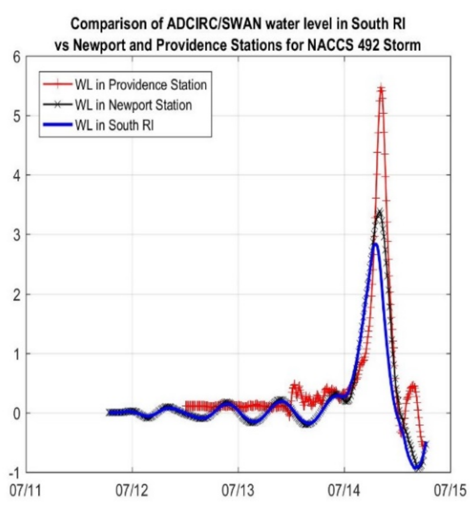
Figure 1 Density of structures inundated with 100 yr storm surge plus 7 ft (2.1 m) SLR for Narragansett Bay, RI based on STORMTOOLS. The red and blue ovals show the Narragansett Bay and southern RI shoreline study areas, respectively. The green oval shows the Charlestown study area and the yellow oval the towns of Barrington, Warren, and Bristol, (http://www.beachsamp.org/wpcontent/uploads/2016/11/Map_SLR7_100YR_Edited_11_15.jpg) (Accessed, October 26, 2017).

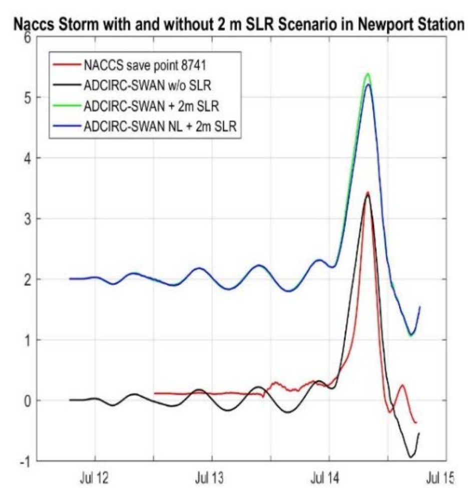
In the interest of simplicity it would be ideal if the surge water level in the presence of SLR could be approximated by the simple addition of the SLR value to the 100 yr flood levels (without SLR)(the so called linear superposition method). To evaluate this linear superposition method, simulations were performed for a much higher resolution grid, based on the original NACCS grid, but that more accurately captured the nearshore bathymetry and topography in RI. This ADCIRC-SWAN model, used in this analysis is the same as used in the NACCS, is described in detail and its application and validation to selected wind forced storm events in the RI study area are presented in Torres et al (2018). Simulations were performed with this higher resolution model for NACCS tropical storm #492. This storm was selected since it gave approximately the same water level as the 100 yr event (95% confidence limit) at the NOAA NOS stations at Newport and Providence, RI.

Figure 2a shows the model predicted water levels (WL) vs time for the south coast of RI (Charlestown), and at the Newport and Providence NOAA NOS stations. The amplification of the surge height with distance up the bay is clearly evident. Surge levels along the southern RI coastal line (not shown) are very close to the values at Charlestown, RI. Figure 2b shows the NACCS predicted water level vs time at NACCS save point #8741 (point closest to Newport), the results of simulations with the higher resolution grid for the 100 yr event, the 100 yr simulation results with 6.6 ft (2 m) of SLR simply added (linear approximation) and results of the high resolution simulation where sea level rise has been accounted for by changing the original bathymetry used as input to the coupled hydrodynamic and wave model. The latter case is based on the full simulation results and hence includes any non-linear (NL) interactions between surge and increased water depth due to SLR. Figure 2c is a repeat of 2b but at the Providence station. Results of the linear and nonlinear simulation using the high resolution model at the Charlestown location are shown in Figure 2d.

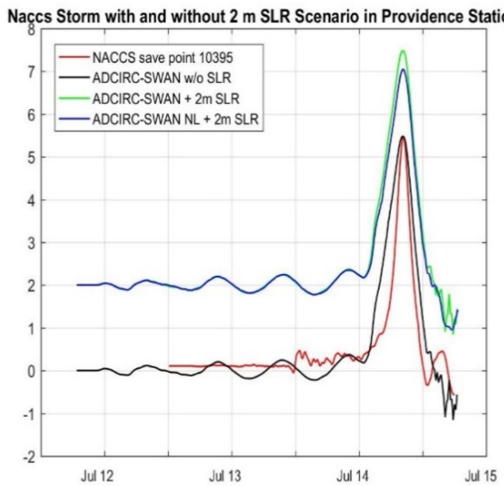
Table 1 shows the maximum water level at Newport and Providence, RI from NACCS storm #492 from the NACCS save point closest to these locations (#8741- Newport; #10395- Providence) based on the original simulations, as a result of the application of ADCIRC-SWAN high resolution model without SLR, with 6.6 ft (2 m SLR) simply added (linear superposition), and with 6.6 ft (2 m) SLR added to the initial bathymetry and non-linear simulations performed. The high resolution model is in excellent agreement with the original NACCS simulation for the peak water levels at Newport and Providence locations. The linear superposition method predicts slightly larger peak water levels than for the full nonlinear model; about 3.2% at Newport and 5.7% at Providence.

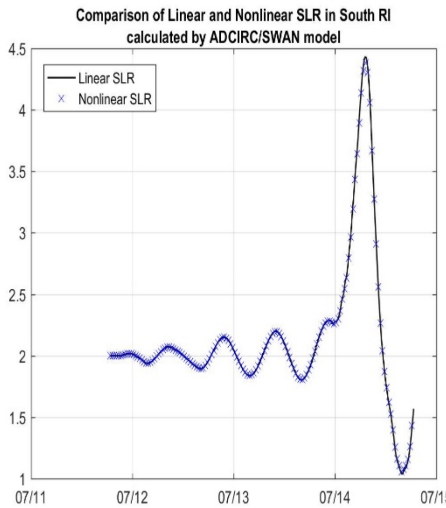
Figure 4 shows the spatial structure of the peak water level for the linear superposition method, the full non-linear results, and the percent difference between the two for the 6.6 ft (2 m) SLR case. The percent difference between the two increases with distance up the bay. There is in essence no difference along the southern RI shoreline (Figure 2c).





(a) (b)



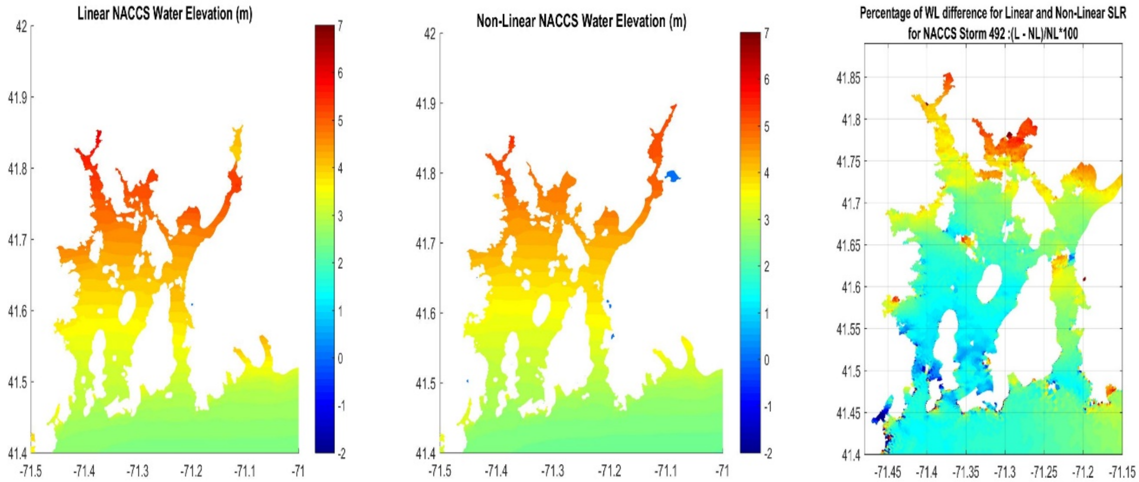


(c) (d)

Figure 2 (a) Water level vs time for NACCS storm # 492 at Providence, Newport, and Charlestown RI; (b) ADCIRC-SWAN predicted water level vs time for NACCS storm # 492 at Newport without sea level rise(SLR), with 6.6 ft (2 m) of SLR simply added on, and with 2 m SLR added to the initial bathymetry and simulations run with the full model, (c) same as in (b) but at the Providence station; and (d) results of linear(superposition) and nonlinear simulation at Charlestown.

Table 1 Maximum water level at Newport and Providence from NACCS storm $#492 for the save point closest to these locations (NACCS Save point # 8741- Newport; # 10395-Providence) based on the original simulations, as a result of the application of ADCIRC-SWAN high resolution model (Torres et al, 2018) without SLR, with 2 m SLR simply added, and with 2 m SLR added to initial bathymetry and non-linear simulations performed.

	Max Water Elevation (m)			
	NACCS at Save Point 8741/10395	ADCIRC-SWAN w/o SLR	ADCIRC_SWAN + 2m SLR	ADCIRC_SWAN Non-Linear with 2m SLR
Newport	3.43	3.38	5.38	5.21
Providence	5.46	5.48	7.48	7.05



(a) (b) (c)

Figure 3 Peak water level for NACCS storm #492 for Narragansett Bay for (a) linear superposition method, (b) full non-linear simulation results, and (c) percent(%) difference between the two for 6.6 ft (2 m) SLR.

These simulations show that the amplification factor decreases slightly with distance up the bay with no change along the southern RI shoreline. In the interest of developing conservative design elevation maps, the SLR value of interest is therefore simply added to the 100 yr surge.

Waves including effects of SLR

The analysis of wave heights (and the associated impact of coastal erosion) necessary to determine BFEs was performed using two different approaches. For Narragansett Bay where waves are quite limited, wave heights were estimated by applying STWAVE for a grid covering the bay area. For the southern RI shoreline where waves and coastal erosion are important simulations were performed using XBeach to determine the eroded dune profiles. The profile was then used to generate a eroded digital elevation model (DEM) which was then used as input to STWAVE for simulations of 100 yr wave conditions, with and without SLR. The methods for each location are provided in more detail below.

Narragansett Bay

Waves heights were estimated in Narragansett Bay for extreme storm events associated with an annual probability of exceedance of 1% (100-year storm) using the Steady State Spectral Wave model (STWAVE), a phase-averaged wave model (Smith et al, 2001; Massey et al, 2011). STWAVE was forced along the open boundary to the south (RI Sound) with significant wave heights of 10 m, a period of 20 sec, and a direction of 165 degrees referenced to N. These values were extracted from the NACCS save point wave data base located at the mouth of the bay. Wind forcing of 35 m/sec (100 yr) was assumed aligned with the central axis of the lower bay at 180 degrees to maximize the fetch along the lower East and West passages. STWAVE predictions employed a 15 m grid to optimize accuracy and computational efficiency and mapped on a 5 m grid. The DEM used the NOAA National Ocean Survey bathymetry merged with 2011 Lidar data and was available via RI Geographic Information System (RI GIS). The DEM has a horizontal resolution of 10 m across the ocean and 1 m on land. The vertical accuracy on land is approximately 15 cm, based on a comparison to the blind control points used during the 2011 Lidar survey and subsequent evaluations of the DEM using certificates of elevation made available for selected towns in the state. Simulations were performed for a no sea level rise as well as for four SLR scenarios: 0, 0.6, 1.5, 2.1 m, and 3.04 m. These SLR values span the likely range for RI (Newport and Providence) based on NOAA high estimates from mid-century through 2100 for the bay. They are available via the US Army Corp of Engineers (USACE) SLR calculator (http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html, accessed on October 18, 2018).

Southern RI shoreline (South Coast)

Schambach et al (2017) applied the geomorphological model XBeach to a section of the southern RI shoreline in Charlestown, RI (see Figure 1 for location, green oval). XBeach is a fully coupled hydrodynamic (wave action and horizontal mean flow) and morpho-dynamics (change in geomorphology and sediment transport) model that dynamically simulates processes that occurring during four erosion regimes as defined by Sallenger (2000) (swash, collision, over-wash, and inundation). A detailed description of the model is provided in Harter and Figlus (2017).

The model was applied to the Charlestown study area (approximately 10 km along shore and 7 km cross shore) including the dune and adjacent coastal pond using a nominal grid resolution of 10 m. The bathymetry/topography was provided using a merge data set which included NOAA bathymetric data and 2011 Northeast Lidar data for the land area. The land cover vegetation was obtained from RI GIS data base. The offshore boundary condition is specified in terms of water level and wave conditions during the event of interest. The lateral boundaries assume no flow and no along shore pressure gradient.

The model was applied and validated to tropical storm Irene, which impacted RI on August 11, 2011. Time series of water levels and waves during the storm were generated by Torres et al (2018) using the high resolution ADCIRC-SWAN models described above. The model was calibrated using the wave asymmetry and skewness parameter and resulted in a 6% mean relative error between simulated and measured subaerial eroded volumes from four cross transects (beach profiles) where measurements were made shortly (within several days) before and after the storm. The model was then applied to predict the shoreline erosion for the 100 yr storm event.

The forcing for the event was based on the NACCS data base with simulations performed using NAACS storm #457 as the 100-yr synthetic design storm (SDS). The SDS was selected based on the similitude of the return period of its water level and wave elevation to the NACCS estimated

100-yr significant wave height and surge elevations, at the closest NACCS save points from the grid offshore boundary. The predicted median eroded volume was 46 m^3/m for the entire barrier beach, in good agreement with FEMA's estimates, based on their protocol, of 50 m^3/m in their most recent Washington County FIS (FEMA, 2012). Model performance showed similar mean post storm reductions in dune crest heights to those generated by FEMA. The model showed large spatial variations in along shore eroded volumes, with the highest values where breaching and surge channels developed and the lowest where healthy back dune vegetation was present. Model results are broadly consistent with the data based approach performed as part of an earlier study to estimate storm damage to structures in the study area under the Coastal Environmental Risk Index (CERI)(Spaulding et al, 2016a).

In the current study, the method outlined by Schambach et al (2018) was applied to the entire southern RI coastline (Figure 1, blue circle). Time series of water level and waves necessary as input on the offshore boundary was similarly based on the 100-yr SDS. Values of water elevations and wave spectral parameters were extracted at many NAACS save points to accurately define four energy spectra placed at the offshore boundary conditions of the computational grid to cover accurately the larger domain. A JONSWAP wave energy spectrum was employed with a significant wave height varying between 7 to 9 m from Napatree Point, Westerly to Point Judith, South Kingstown,RI to capture the sheltering effect of Block Island on the western RI shoreline.

The model predicted changes in bathymetry and topography were then used to generate a revised DEM that reflected the 100 yr storm event. The STWAVE model was then used, employing the revised DEM, to simulate the wave conditions in the flood inundated area. The offshore boundary conditions for STWAVE were provided by simulations of the 100 yr storm event as noted above.

Results

The SDE maps (BFE maps with SLR) are shown for the Narragansett Bay and southern RI shoreline (South Coast) areas separately. The web links for the maps (accessed on October 16, 2018) are for

Southern RI shoreline (South Coast)

https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=3ba5c4d9c0744392bec2f4afb6ee2286)

Narragansett Bay

https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=9b85db9b7aaa400cac1a3cb404a96be8

The division into two separate viewers was done for convenience in organizing the results and based on the different methods used in their generation, as described above. Each is presented separately below.

SDE Maps South Coast, Southern RI shoreline

Figure 4 shows the user interface for the SDE maps for the southern RI shoreline. The map selected in this case is 100 yr surge with no SLR (highlighted blue tab at the top left of the interface). BFE maps for this case are shown in the figure; as is the legend to the left. To see the remainder of the legend one must scroll down the legend bar. The full legend has been inserted next to the figure. All water levels are provided in ft referenced to NAVD88. The highest water levels in this case are immediately along the shoreline (about 30 ft) and decrease with distance inland, as offshore waves are dissipated by breaking and friction. Most of the wave dissipation occurs immediately offshore of the coastal dune system. BFE heights decrease rapidly with distance landward as a result of wave breaking and frictional dissipation. Frictional dissipation is highest in the presence of due vegetation and more limited in its absence.

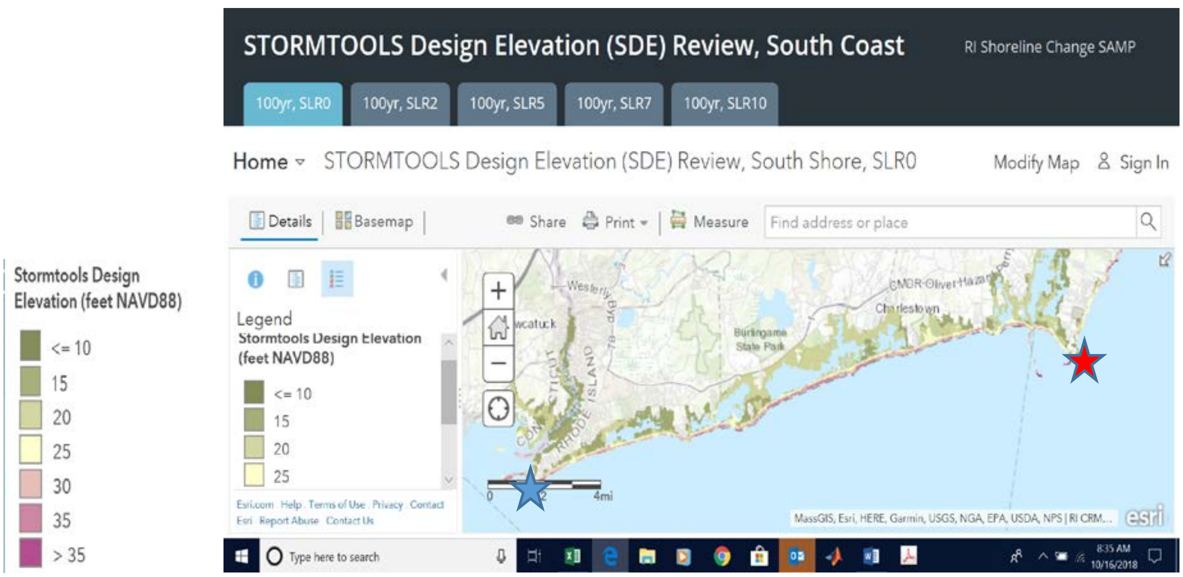


Figure 4 User interface for the STORMTOOLS Design Elevation(SDE) Maps, southern RI coast line(South Coast). The case selected is the 100 yr event with no SLR. Blue star- Napatree Point, Westerly and red star- Pt Judith, South Kingstown (https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=3ba5c4d9c0744392bec2f4afb6ee228. Accessed on October 16, 2018).

Figure 5 shows SDE maps for 0, 5 ft, and 10 ft of SLR. Maps are available for 2 and 7 ft, but not shown here. These maps have been assembled from individual images from the map viewer. In this case the background map was based on aerial photography, compared to the topographic map used in Figure 4. Background maps in the BFE map interface are user selected with six options (imagery, imagery with labels, streets, topography, dark and light gray).

The 100 yr flooding map shows the expected increase in BFE due to SLR. The BFEs for the SLR cases reflect the increase due to the increase in surge depth plus the increase in the controlling wave height given the greater underlying surge depth.

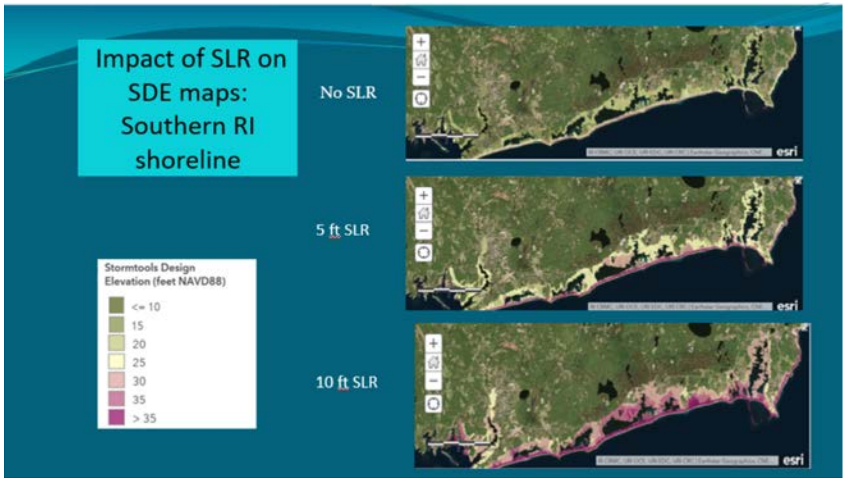


Figure 5 Impact of SLR on Narragansett Bay SDE maps, cases shown are 0, 5 ft, and 10 ft SLR. (Note that the background map in these figures use aerial photograph as a background compared to the topographic map shown earlier. Background maps are user selected.)

The user has the ability to zoom into an area of interest, either by using the zoom feature or entering the street address or latitude-longitude of the location of interest. Figure 6 shows the 100 yr, no SLR case for the Charlestown area, with Ninigret and Green Hill Ponds as the focus area. The upper panel shows the flooding levels relative to NAVD88, while the lower panel highlights the ability to interrogate the map and determine the BFE at a location of interest; in this case the BFE is 17.2 ft.

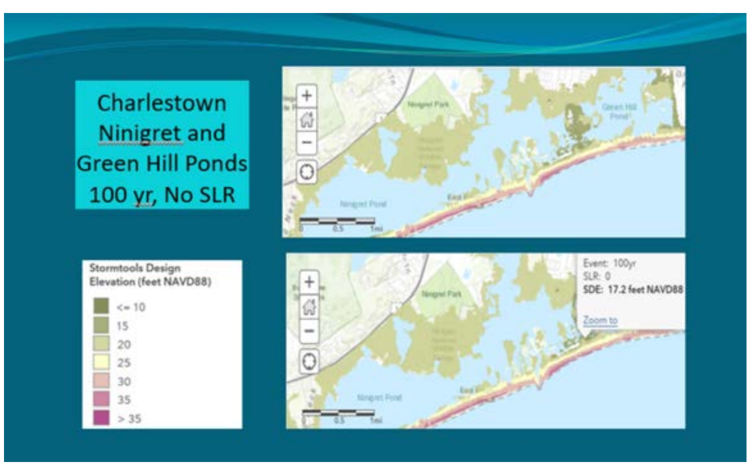


Figure 6 Flooding in Charlestown, RI in the vicinity of Ninigret and Green Hill Ponds for 100 yr, no SLR case (upper panel). The lower panel shows the same data but the point interrogation is used to determine the BFE at the location selected.

The interface also allows the user to compare and contrast the FEMA FIRMs and SDE maps. As an example selecting the same area in Charlestown, RI as shown in Figure 6 (see green oval in Figure 1 for its location along the coast), Figure 7 shows the SDE BFE map for this area in the upper panel and the FEMA FIRM BFE map in the lower panel. The FEMA BFE values are typically 3 to 4 ft lower than the SDE maps. The FEMA maps also lack the level of detail provided in the SDE maps. The unusual anomaly in the FEMA map(high water level) for Green Hill Pond is a result of the 1-D transect method used to generate the wave heights and its subsequent spatial interpolation to a 2-D map. A detailed presentation and discussion on the sources of the differences are provided in Spaulding et al (2017a).

Figure 7 Comparison of SDE (upper panel) vs FEMA (lower panel) BFE maps for the 100 yr, no SLR case. (Note: FEMA methodology includes flood depths over open water while SDE does not, thus the difference in the maps for Ninigret and Green Hill Ponds).

In addition to the information presented here (BFEs from the SDE maps, with varying SLR and FEMA FIRMs) also include the option to access maps of FEMA designated zones (V, A, LIMWA, and SFHA) for both FEMA FIRMs and SDE maps, transects long which FEMA made wave estimates, the various components of the SDE BFE including both surge and wave crest height, and SDE based water depths relative to local grade (this metric, depth of inundation, is different than BFEs which are typically referenced to NAVD88).

SDE Maps for Narragansett Bay

Provided below is a similar overview of the Narragansett Bay SDE maps that is comparable to that above for the South Coast.

Figure 8 shows the user interface for the SDE maps for Narragansett Bay. The map selected in this case is 100 yr surge with no SLR (highlighted blue tab at the top left of the interface). BFE maps for this case are shown in the figure; as is the legend to left. To see the remainder of the legend one must scroll down the legend bar. All water levels are provided in feet, referenced to NAVD88. The highest water levels in this case are found at the upper end of Narragansett Bay and are a result of the amplification of the surge height with distance up the bay (see Figure 3 as an example). Wave heights in the bay are generally quite limited given the protected nature of the bay and limited fetch distances. The large waves at the mouth of the bay propagating from offshore (9 m - significant wave height, 20 sec -peak period) decrease quite rapid in magnitude as they enter the East and West passages of lower Narragansett Bay. This transition from large offshore waves to much smaller fetch limited local wind generated waves is included in the STWAVE methodology used for modeling waves for the SDE maps.

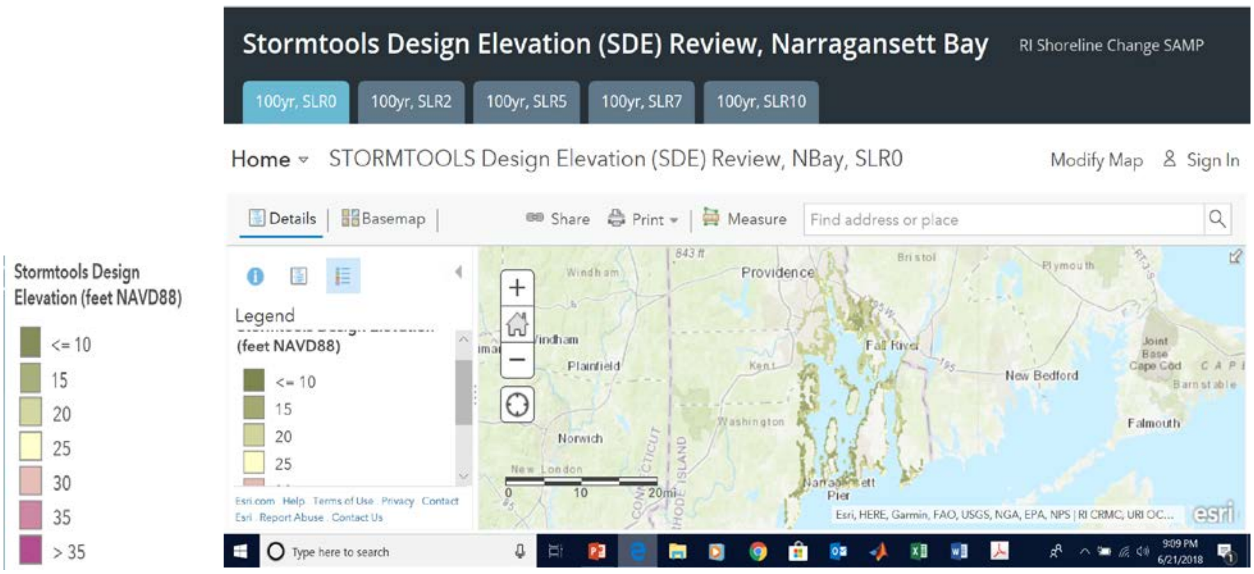


Figure 8 User interface for the STORMTOOLS Design Elevation Maps, Narragansett Bay The case selected is the 100 yr event with no SLR. (https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=9b85db9b7aaa400cac1a3cb404a96be8, accessed on October 16, 2018).

Figure 9 shows SDE maps for 0, 5 ft, and 10 ft of SLR. Maps are available for 2 and 7 ft, but not shown here. These maps have been assembled from individual images from the map viewer. The 100 yr flooding maps show the expected increase in BFE due to SLR. The BFEs for the SLR cases reflect the increase, due to the increase in surge depth plus the increase in the controlling wave height given the greater underlying surge depth. The wave contribution is generally quite small in the bay given the small wave heights.

Figure 9 Impact of SLR on Narragansett Bay SDE maps, cases shown are 0, 5 ft, and 10 ft SLR.

Figure 10 shows the 100 yr, no SLR case for the towns of Barrington, Warren, and Bristol as the focus area (Figure 1 yellow oval). The upper panel shows the flooding levels relative to NAVD88, while the lower panel highlights the ability to interrogate the map and determine the BFE at the location of interest; in this case the BFE is 14.1 ft. A closer look at the map shows that the south facing coastal areas, within the map window, have BFE amplitudes higher than those immediately landward. This is due to the largest wind fetch being along the central axis of the bay, with a direction toward the north.

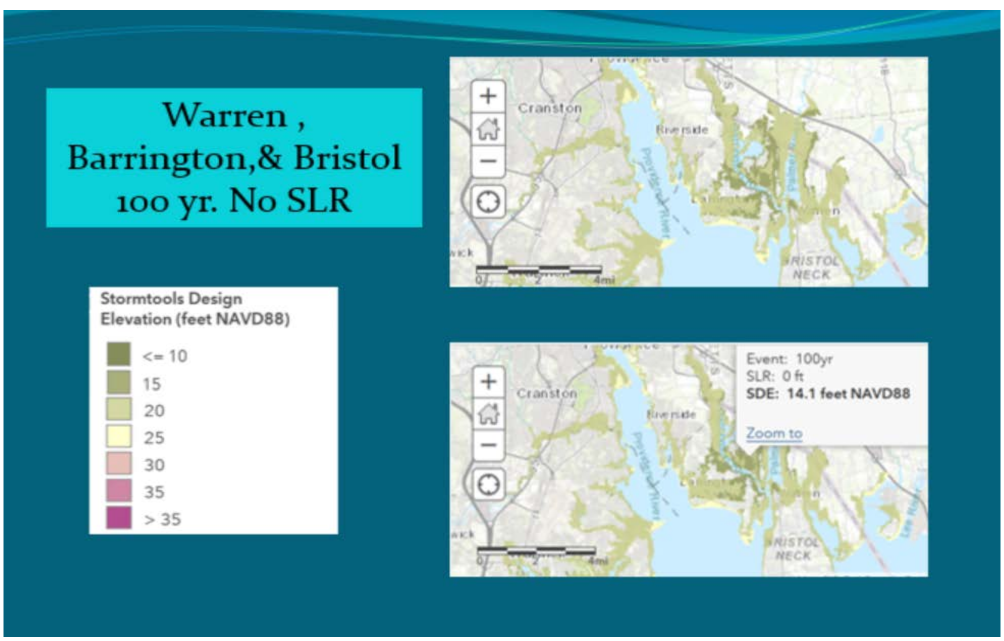


Figure 10 Flooding in vicinity of Barrington, Warren, and Bristol, RI for 100 yr, no SLR case (upper panel). The lower panel shows the same data, but the point interrogation is used to determine the BFE at the location selected.

The interface also allows the user to compare and contrast the FEMA FIRMs and SDE maps. As an example, Figure 11 shows the SDE BFE map for this area in the upper panel and the FEMA FIRM BFE map in the lower panel. The FEMA BFE values are typically several feet lower than SDE maps. The FEMA maps also lack the level of detail provided in the SDE maps. A detailed presentation of the sources of the differences for this general location in the bay are provided in Spaulding et al (2017b).

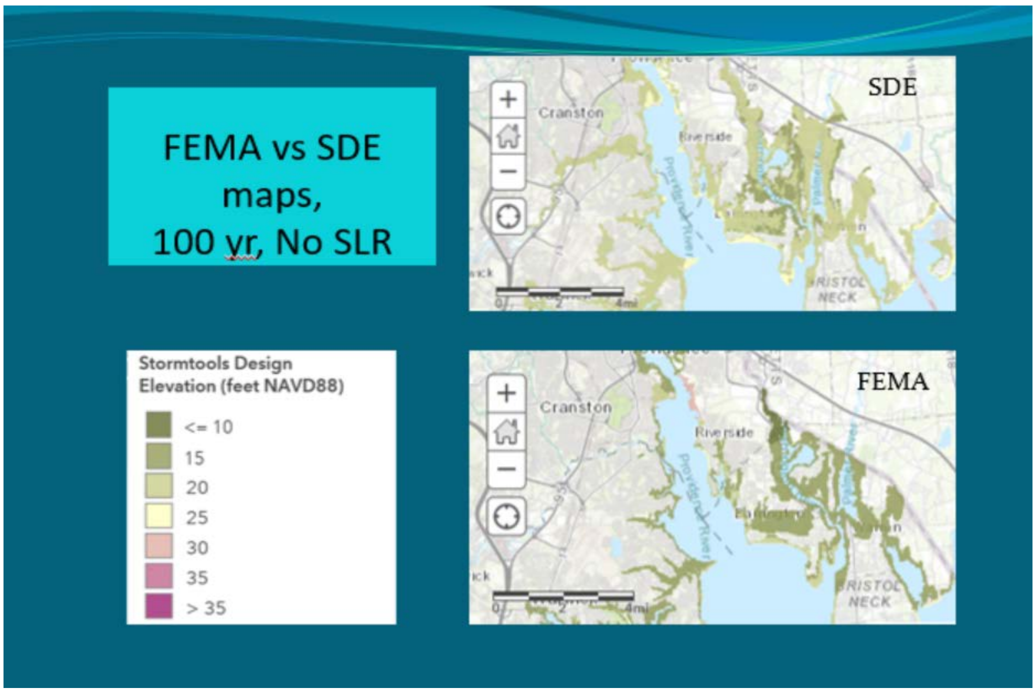


Figure 11 Comparison of SDE (upper panel) vs FEMA (lower panel) BFE maps for the 100 yr, no SLR case.

Extension to generate risk maps

The SDE maps summarized above are available via the STORMTOOLS web site (https://crc-uri.maps.arcgis.com/home/index.html) to facilitate access by the coastal community and regulators. While meeting the direct need to support the design of structures in the study area, they have proven to be less helpful for the general public to understand the risk. To address this need STORMTOOLs Coastal Environmental Risk Index (CERI) methodology(Spaulding et al, 2016) is being used in selected areas (complete: Charlestown, Warwick, Bristol, Warren, Barrington; in progress: Westerly, South Kingstown and Narragansett) to estimate the damage to structures if they are located at each grid point in the study area. To make maps that are conservative and allow the relative risk across the study area to be understood, structures were assumed to be single story homes with basements, the predominate type in most coastal areas (typically 80%

of the total). Figure 12 shows the risk (extreme, high, medium, and low) for no and 7 ft of SLR cases. The risk is extreme if the damage is 100 %, with corresponding lower risk levels with decreasing damage values. If the area is below mean sea level under the given SLR scenario, it is noted. It is predicted that the risk is extreme along the coast line for a good portion of the study area given its low elevation and the surge amplification with distance up the bay. At 7 feet of SLR most of the area at extreme risk at the no SLR case is now below mean sea level (MSL).

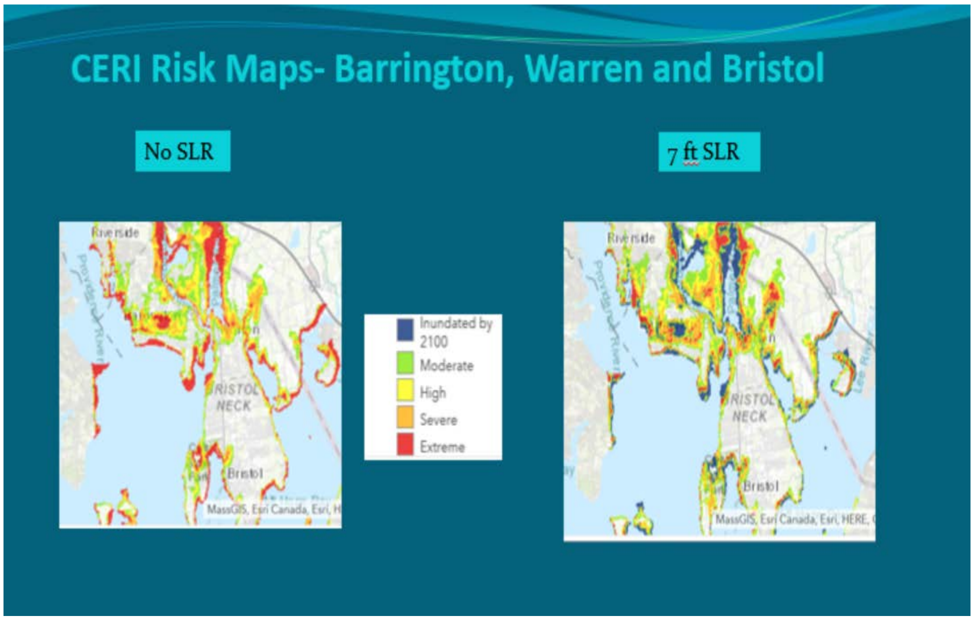


Figure 12 SDE risk map for Barrington, Warren, and Bristol, RI for no and 7 ft of SLR. The scale of risk (0 to 100) is provided in the center ranking from moderate to high. If the area is blue it is below mean sea level for the case selected. (https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=63fc6b8970ce4ef5902c307f2c8e36e2, Accessed October 16, 2018)

3. Conclusions

A method to generate BFEs including the effects of SLR (SDE maps) has been developed and applied to a protected low lying coastal communities inside Narragansett Bay and to wave impacted, erosion prone southern RI shoreline (South Coast). The approach implemented uses FEMA approved models and guidelines, but addresses weaknesses identified in the development of the FEMA FIRMS for the study area. The strategy to develop the maps is based on extensive state of the art hydrodynamic and wave modeling studies performed as part of the US ACOE North Atlantic Comprehensive Coastal Study, simulations with a fully coupled high resolution surge and wave model (ADCIRC-SWAN) with and without the effects of SLR, application of XBeach to southern RI coast line to determine the geomorphology of the eroded shoreline and dune system and the application of STWAVE to predict the impact of SLR on storm wave heights for areas along the southern RI shoreline and Narragansett Bay. The underlying methodology and its application have been documented in the publications provided in the reference list by the authors. The approach taken in developing the maps has been conservative in the approaches used and decisions made in the mapping methodology as a way to address the uncertainty in the predictions. The two most important assumptions are (1) the use of the upper 95% confidence level value for the surge water levels, compared to FEMA's approach which uses the 50% confidence level and (2) the assumption that linear superposition of SLR values on 100 yr surge can be used to represent surge levels in the presence of SLR. As shown in the paper, this is a conservative assumption since fully coupled simulations shown the surge level predicted by non-linear methods gives values slightly lower than linear superposition approach.

The Narragansett Bay study area is impacted by the amplification of the 100 yr surge as it progresses up the bay (amplification of about 1.35, between Newport and Providence), but experiences relatively low wave heights given the protected location from offshore waves. Wave heights are largest when the fetch distances are greatest and on the south facing portions of the coast given that winds that give the largest wave heights come from the south. Sea level rise is shown to slightly decrease the 100 yr surge levels and increase the wave heights. The methods employed here assumes that SLR has no additional impact on the surge level beyond raising the mean water level by the selected value of the SLR.

The southern RI coast line (South Coast) shows very little variation in the 100 yr surge height from Napatree Pt. to Point Judith. Wave heights are very large (7 to 10 m significant wave heights, 20 sec- peak period) along this coastline as it borders on the open ocean with strong winds and unlimited fetch distances. The presence of the large waves results in substantial nearshore erosion with overtopping or breaching of the dunes and flooding of the adjacent coastal ponds. While large waves break at the top of the eroded dune line the decrease in dune height allows substantial waves to propagate into the adjacent ponds.

A methodology was developed to generate risk maps using the CERI framework and based on the SDE maps. An application to towns of Barrington, Warren, and Bristol for no and high SLR, cases was performed by assessing the damage to structures that are typical of the area. These risk maps have proven to be useful to help the public understand the risk of building in these selected case coastal communities. Risk maps for other RI coastal communities are available via the SDE web site address given above, under the CERI initative.

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Author Contributions: Malcolm L. Spaulding developed the idea for STORMTOOLS/Design Elevation (SDE) Maps and the application to generate alternative BFEs that include the effects of sea level rise. Annette Grilli was primarily responsible for inundation, wave, and erosion modeling. She and Spaulding, co-led the project. Implementation in GIS and providing access of the output was provided by Chris Damon. R. Hashemi and S. Kouhi Anbaran led the effort to determine the impact of linear vs nonlinear approximations to sea level rise on storm surge water levels. Grover Fugate advised on the design of the system to meet the needs of coastal managers and planners.

Acronyms

ADCIRC- ADvanced CIRCulation model
ASCE- American Society of Civil Engineers
BCP- Blind Control Points
BFE- Base Flood Elevation
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
JONSWAP- JOint North Sea WAve Project
LIDAR- Laser Imaging, Detection, and Ranging
LIMWA- limit of moderate wave action
MSL- Mean Sea Level
NACCS- USACE, North Atlantic Comprehensive Coastal Study
NAVD88- North Atlantic Vertical Datum, 1988.
NOAA NOS- National Ocean and Atmospheric Administration- National Ocean Survey
OIG- Office of Inspector General
OHCD- Office of Housing and Community Development
RI GIS – Rhode Island- Geographic Information System
SFHA - Special Flood Hazard Area
SDE- STORMTOOLS Design Elevation maps
SDS- Synthetic Design Storm
SLR- Sea Level Rise
STWAVE – STeady state spectral WAVE model

SWEL- Still water elevation level
STORMTOOLS- tools in support of storm analysis
SWAN - Simulating WAves Nearshore
URI- University of Rhode Island
USACE-US Army Corp of Engineers
XBeach – nearshore wave and geomorphological model

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