Developing the RI Coastal Environmental Risk Index (CERI) to Inform State and Local Planning and Decision Making: Application to the Communities along the Southern RI Shoreline

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1. Introduction

The Coastal Environmental Risk Index (CERI), a method to assess the risk and damage to structures and infrastructure resulting from storm surges, including the effects of sea level rise, has been under development since 2016, with initial applications to Warwick, RI and Charlestown, RI; the first representing application to a protected area in Narragansett Bay, where surge amplification dominates flooding and the later to a coastal community along the southern RI shoreline where waves and erosion are critically important in estimating flooding risk. The applications to these two communities have been documented in Spaulding et al (2016, 2017a and b), Grilli et al. (2017) and Schambach et al. (2018). Application of the method to Barrington, Bristol, and Warren has recently been completed (Grilli et al, 2019). These towns were selected for application given the very low-lying topography of the area, the density of residences, and its exposure to storm flooding. The method has also been applied to the eastern end of Matunuck Beach (2015-2016) (Small et al., 2016), Misquamicut Beach (2016-2017) and downtown Providence (2017-2018) in recent senior design studies in Ocean Engineering, University of RI. In the most recent senior design project the method has been applied to assess the risk to waste water treatment facilities (WWTF) and selected above ground storage tanks (AST) in upper Narragansett Bay (2018-2019) (May 2019).
This report summarizes the application of CERI to the coastal communities along the southern RI shoreline from Little Narragansett Bay, Westerly, RI to the Narrow River, Narragansett, RI. Section 2 outlines the methodology used to generate the maps. Section 3 provides the results of the analyses. A summary and conclusions are given in Section 4. Information on CERI and its application can be accessed via the STORMTOOLS CERI web site (http://www.beachsamp.org/stormtools/stormtools-coastal-environmental-risk-index-ceri/). The papers, referenced above, describing CERI and its applications to date can also be found there.

Section 2 STORMTOOLS Coastal Environmental Risk Index (CERI)

An in-depth description of CERI is provided in Spaulding et al. (2016), while the presentation here focuses on providing an overview of the system and its basic building blocks. The goal of the STORMTOOLS CERI is to develop a methodology to assess the risks that structures and infrastructure face from storm surges, the combination of flooding and the associated wave environment, in the presence of sea level rise (SLR) and shoreline erosion/accretion. Figure 1 shows the basic framework for the STORMTOOLS CERI and its basic building blocks.

Each of the building blocks is described in more detail below.

Surge and waves (BFEs)

The flooding environment in CERI is characterized by the 100 year (also known as the 1% annual chance) flooding event that is adjusted for the sea level rise (SLR) value projected for the proposed design life of the structure of interest. The design life is specified in terms of the base flood elevation (BFE) (combination of inundation depth and the associated controlling wave height). BFEs are used to characterize the flooding risk to be consistent with the Federal Emergency Management Agency (FEMA) methods used in the Flood Insurance Rate Maps (FIRMS) and those embedded in the ASCE 7-16 Minimum Design Standards (ASCE, 2017), which have been adopted by the state of RI and the coastal communities were CERI is being applied in this study. Figure 2 provides a sketch from FEMA that shows the BFE in relationship to the still water elevation level (SWEL) (inundation level) and the underlying vertical reference to NAVD88. The RI Coastal Resources Management Council (RI CRMC) has formally adopted through its regulations the NOAA 2017 high curve (83% percentile) to estimate sea level rise for purposes of coastal planning and the review of proposed projects within its jurisdiction. The current NOAA projection is for SLR to be 3 ft by 2050, 5 ft by 2070, and 9 ft by 2100. (http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html).

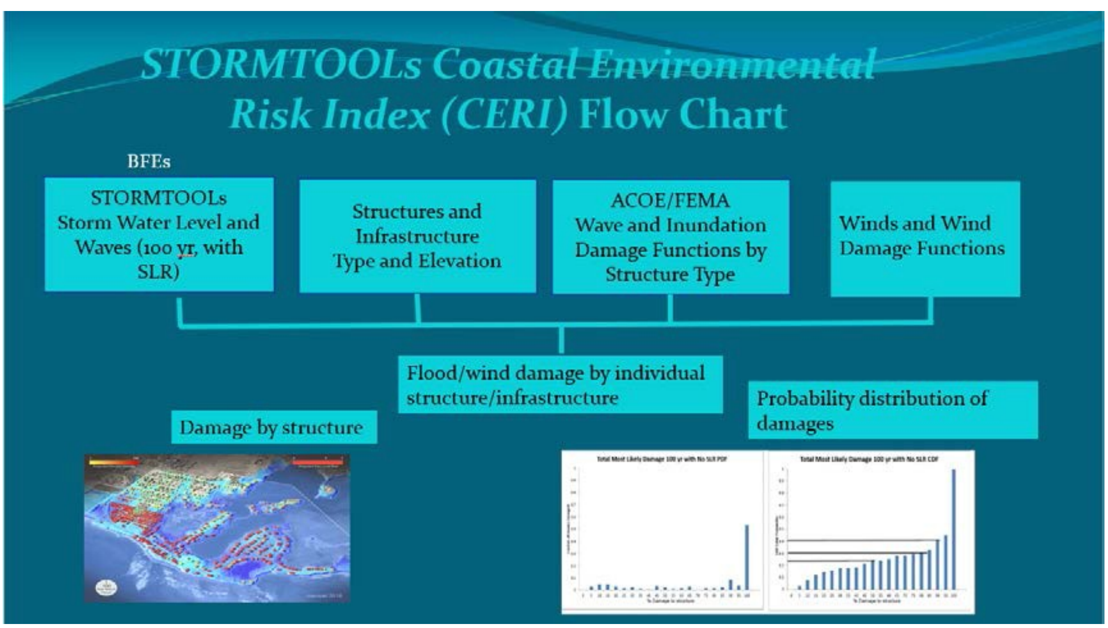


Figure 1 Flow chart for **STORMTOOLS** Coastal Environmental Risk Index (CERI)

Under the STORMTOOLS Design Elevation (SDE) maps initiative, maps of 100 year flooding for sea level rise values of 0, 2, 3, 5, 7, and 10 feet have been prepared for the coastal areas of the state (Spaulding et al., 2019). The maps were generated for Narragansett Bay and adjacent coastal waters and for the southern RI coastal line. The former reflects an area where wave heights and coastal erosion are limited, but surge amplification is critically important, while the latter area is dominated by high amplitude waves and coastal erosion is critically important.

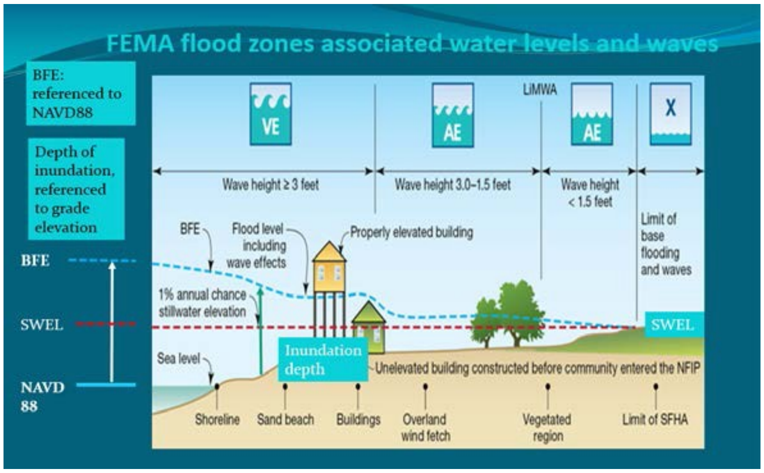


Figure 2 FEMA schematic of flood zones with associated water levels and wave conditions. The location of BFE and SWEL are clearly shown by the dashed blue and red lines, respectively. BFE and SWEL are referenced to NAVD88.

Given the focus of the present study, Figure 3 shows the maps for the southern RI shoreline for the cases of 0, 5, and 10 feet of SLR, reflecting the nominal values for today, 2070 and 2100, respectively. Details on the development of the SDE maps, including the modeling of the shoreline erosion for areas with significant wave heights is provided in Spaulding et al (2019). The SDE maps and supporting training material to facilitate their use are provided at http://www.beachsamp.org/stormtools-design-elevation-sde-maps/. The maps for southern RI are available at:
https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=3ba5c4d9c0744392bec2f4afb6ee2286.
The GIS-based online maps allow the user to determine the inundation and the associated controlling wave height that comprise the BFE at the area of interest. In addition, the user can also access FEMA FIRM BFE maps from the CERI application. The online map legend for the flood elevation values have been kept the same for all maps to facilitate inter-comparisons.

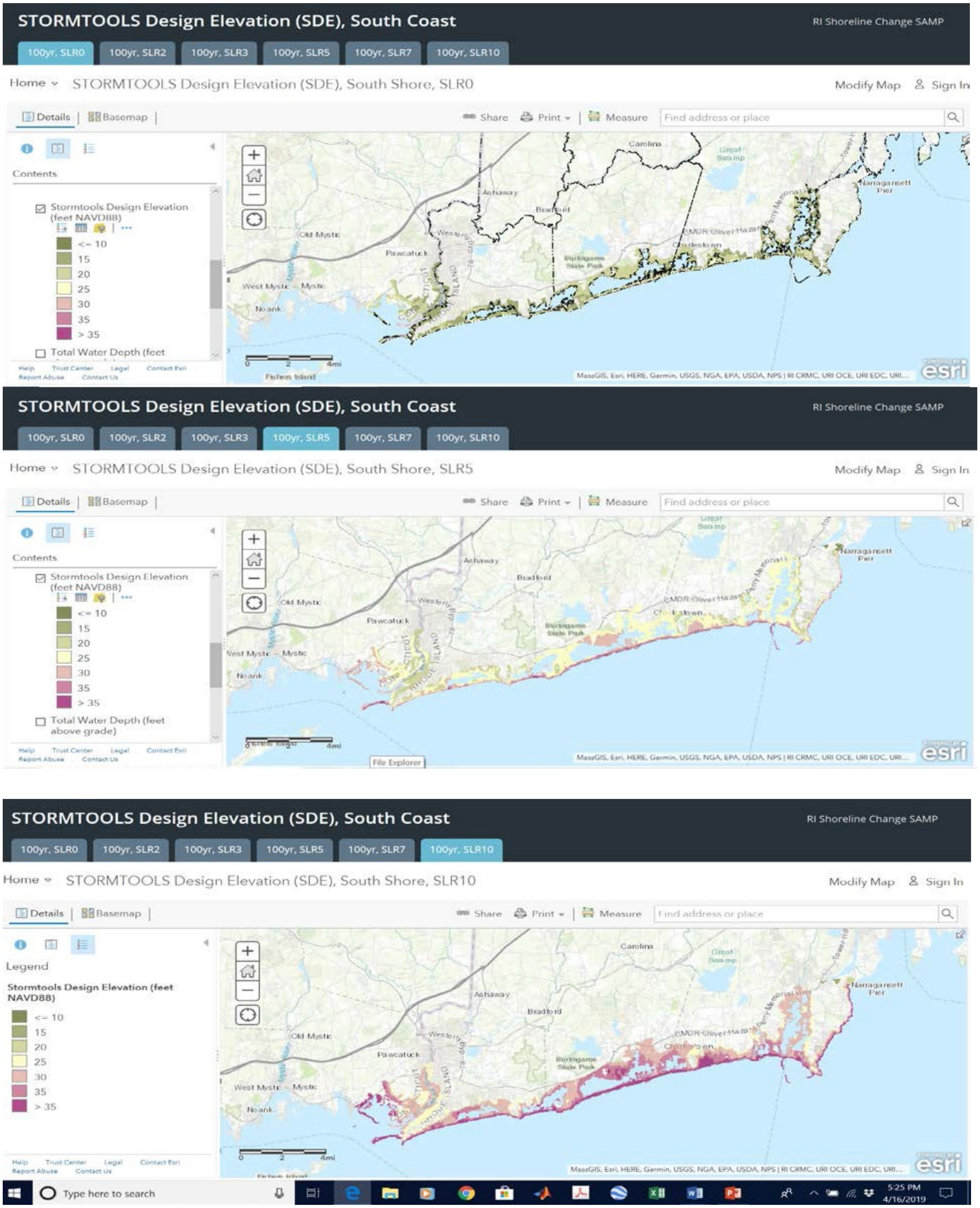


Figure 3 STORMTOOLS Design Elevation maps (BFE) for SLR values of 0 ft (upper panel) 5 ft (middle panel) and 10 ft (lower panel). Blue colored tabs at the top of each figure show the SLR value selected. The BFE values are provided in feet relative to NAVD88. The legend for each figure is shown at the left and is the same for all figures to facilitate inter-comparison.

Structure and infrastructure type and elevation

The structures in the study area have been characterized in terms of seven prototype categories as outlined in the Army Corp of Engineers (ACOE) North Atlantic Comprehensive Coastal Study (NACCS) (Cialone et al., 2015). This classification system has been selected to be consistent with the damage functions used in CERI to estimate structure and content damage (Simm et al., 2015). Figure 4, left side, shows all prototypes, while the right side of the figure shows the prototypes that dominate the southern RI shoreline communities (Prototypes 5, 6, and 7). Types 5 and 6 are residences without and with basements, respectively. A and B refer to single and two story residences, respectively. For Prototype 7 the structure is elevated on piles; A - open piles and B - enclosed piles. Photos of houses that typify each category, taken from RI shoreline communities, are shown in the figure. In addition to characterization of the structures by prototype class, the elevation of the first-floor elevation (FFE) must be provided. FFEs are typically 2 to 3 feet for structure types 5 and 6, and 9 feet for those that are pile supported (7). FFEs are typically measured relative to local grade at the entrance to the residence. For reference, stairs typically have a rise of 7.5 in (0.625 ft) per step (e.g., 3 steps is therefore about 2 ft).

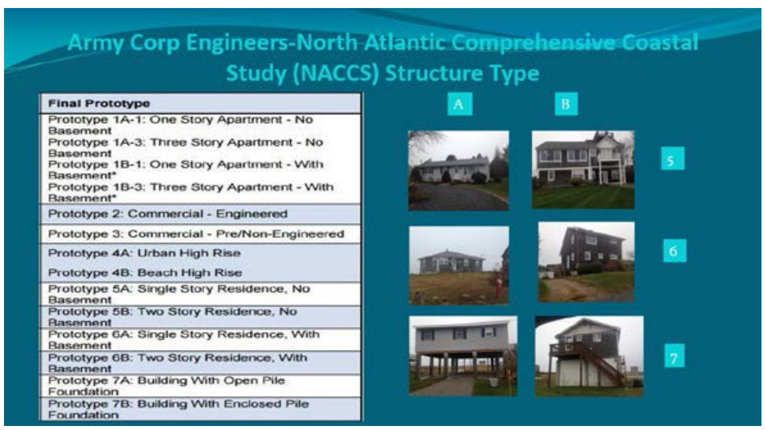


Figure 4 ACOE NACCS structure types (left side). Photographs of structure prototypes 5, 6, and 7, categories A and B are also shown (right side). 5 and 6 are residences, without and with basements; while A and B refer to single and two story buildings, respectively. Prototype 7 have pile foundations, A- open piles and B- enclosed piles.

The development of the structure database by ACOE NACCS prototype relied on four primary data sources (Table 1). Though each of the four towns organize and format their data differently the same general workflow was applied consistently for the study area.

Table 1: CERI input data and source

Dataset	Source	Role
RI E-911 Building Locations	RI Geographic Information System	Point locations for every structure in RI, along with the primary use category (residential, commercial, public, etc.).
Parcel Polygons	Town Database (local)	Base data set for the town to which all other information can be joined based on a common value.
Related Building Information	Town Database (cloud)	CERI-specific attributes such as the number of stories, the presence of a basement and whether the structure is elevated.
Digital Elevation Model	RI Geographic Information System	Determine if a structure is within the inundation zone and what approximate FFE will be.

A data request was submitted to each town's Planning Officer and the required information was delivered in both GIS (parcel) and Excel (building attributes) formats. Using a common ID field, the parcel and building datasets were merged.

The statewide E-911 points were separated by town and filtered to remove all structures outside of the inundation area to reduce file sizes. All structures at local elevations of 30 feet were retained in the database. An additional check was performed to remove duplicate points on a structure, common for residential duplexes, condominiums, and strip malls. Remaining points were tagged with a ground elevation value and the structure locations were spatially joined with the parcel/building information, resulting in a single point file for each town with all required attributes: XYZ location; E-911 use category; number of stories; basement area; and whether the structure was elevated on piles.

Table 2 shows the data groupings and queries used to assign the proper NACCS building prototype to each point. A listing of E-911 use categories can be found here: https://www.edc.uri.edu/projects/stormtools/E911_buildingtype.docx.

Table 2: NACCS Building Types as Applied to CERI Structure Database

Class	Description	E-911 Codes	Query
1A-1	1 story apt, no basement	R2; R4; R7	(NUMSTOR = 1) AND (BASEMENT = 'N')
1A-3	2+ story apt., no basement	R2; R4; R7	(NUMSTOR > 1) AND (BASEMENT = 'N')
1B-1	1 story apt with basement	R2; R4; R7	(NUMSTOR = 1) AND (BASEMENT = 'Y')

1B-3	2+ story apt with basement	R2; R4; R7	(NUMSTOR > 1) AND (BASEMENT = 'Y')
2	Commercial engineered	CL; P1-9; I1	n/a
3	Commercial non-engineered	CF	n/a
5A	1 story, no basement	R1; R3; R5; R6; C1; C9	(NUMSTOR = 1) AND (BASEMENT = 'N')
5B	2+ Story, no basement	R1; R3; R5; R6; C1; C9	(NUMSTOR > 1) AND (BASEMENT = 'N')
6A	1 story with basement	R1; R3; R5; R6; C1; C9	(NUMSTOR = 1) AND (BASEMENT = 'Y')
6B	2+ story with basement	R1; R3; R5; R6; C1; C9	(NUMSTOR > 1) AND (BASEMENT = 'Y')
7A	Elevated on open piles	R1; R2; R6; R7	n/a- field survey
7B	Elevated on closed piles	R1; R2; R6; R7	n/a - field survey

During the coding process, field checks were used to confirm the presence of elevated structures and to answer any building-specific questions that could not be answered from the available data. The database was modified as needed to reflect these surveys. The final output for CERI damage modeling was a comma delimited text file with the following format:

NAME – Town Name
LAT - Latitude
LON - Longitude
ELEV – Grade Elevation, feet NAVD88
FFE – First Floor Elevation (grade plus 2 feet in most cases; grade plus 9 feet for 7A/B)
NUMSTOR – Number of stories
BCLASS – NACCS Building Prototype

To give a sense of the structures at potential risk, the data base was used to estimate the total number of structures in each town that were located at elevations less than 30 feet NAVD88. This elevation was selected since it captures the envelope of area flooded for all SLR cases investigated. The data is summarized in Table 3. Each town is seen to have approximately one quarter of the total with South Kingstown, Narragansett, and Westerly having comparable numbers and slightly greater than Charlestown.

Table 3 Number of structures and percent of total that are located below 30 feet NAVD 88 for each town in the study area.

Town	Number Structures Below 30 ft NAVD88	Percent of Total

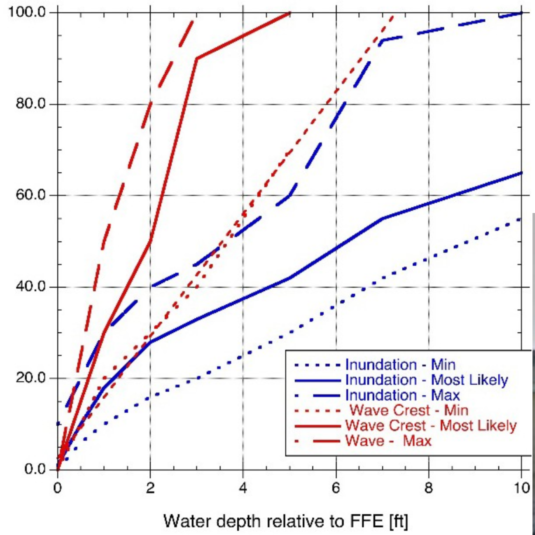
Narragansett	2616	26.5%
South Kingstown	2689	27.2%
Charlestown	2056	20.8%
Westerly	2524	25.5%
All Towns	**9885**	**100.0%**

A review of the data for southern RI communities potentially at risk from flooding with 10 feet of sea level rise is dominated by single/two story residences with and without basements (Prototype 5) (42%), Prototype 6 (47%) (total – 89%). Elevated structures (7A and B) account for only 5.6 % of the total. Commercial structures are quite limited and account for only a few percent of the total and are dominated by Westerly (Watch Hill area) and Narragansett (Port of Galilee).

Wave and Inundation Damage Functions

Damage (structure) functions from both waves and inundation are estimated using data from the NACCS study as summarized by Simm et al. (2015) for each structure type noted in Table 2. As examples, Figure 5 shows the damage functions for single story residence with no basement (NACCS Prototype 5A) (upper panel) and a residence on an open pile foundation (7A) (lower panel). These two cases were selected for presentation here given the fact that the former is the most dominant residence along the southern RI coast line, while the latter is the most typical for residences that are designed to reduce flooding damage. Minimum, most likely, and maximum structural damages are shown for both inundation and waves. Damages occur if the water/wave levels exceed the FFE of the structure. FFEs are typically a few feet for prototypes 5 and 6 and 9 feet for 7A/B. Following the NACCS protocol, CERI estimates the damage from inundation and waves and uses the value that results in the greatest damage. CERI provides a map of all structures in the study area in danger of flooding and characterizes their ACOE type classification and FFE. It is noted whether large waves (greater than 3 feet) are present, as they dominate the damage no matter the structure type. Given the large waves for the 100 yr return period (for all SLR cases) along the southern RI shoreline, wave damage dominates for structures located immediately along the coastline, while inundation damage becomes more prevalent as one moves landward, where waves have been dissipated by friction and breaking. This transition is graphically illustrated in Figure 2 by the transition from FEMA VE to AE zones.

5A, 1 STORY NO BASEMENT



7A, OPEN PILE FOUNDATION

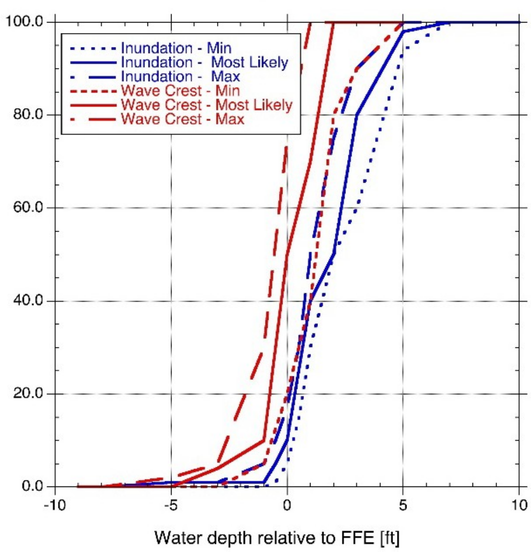


Figure 5 Damage (structural) functions for inundation(blue) and waves(red) for 5A (single story with no basement) and 7A (open pile foundation) residential structures are shown. A photograph of each structure type is provided. Damage functions for minimum, most likely, and maximum values are provided.

Section 3 Results

CERI was applied to the entire southern RI shoreline using the building blocks outlined above. Figure 6 shows the results for 100 yr no SLR for minimum, most likely, and maximum damages. The percent damage for each structure is provided. The legend gives the damage range from green (no damage) to red (greater than 75% damage). Given the resolution of the figure the maps look continuous but of course are not. The figure clearly shows the spatial distribution of structures in the study area, with most located on the various coastal headlands and interior shoreline of the coastal ponds. In general the further the structure is from the ocean the lower the damage. Damage is highest for the maximum case and lowest for the minimum case.

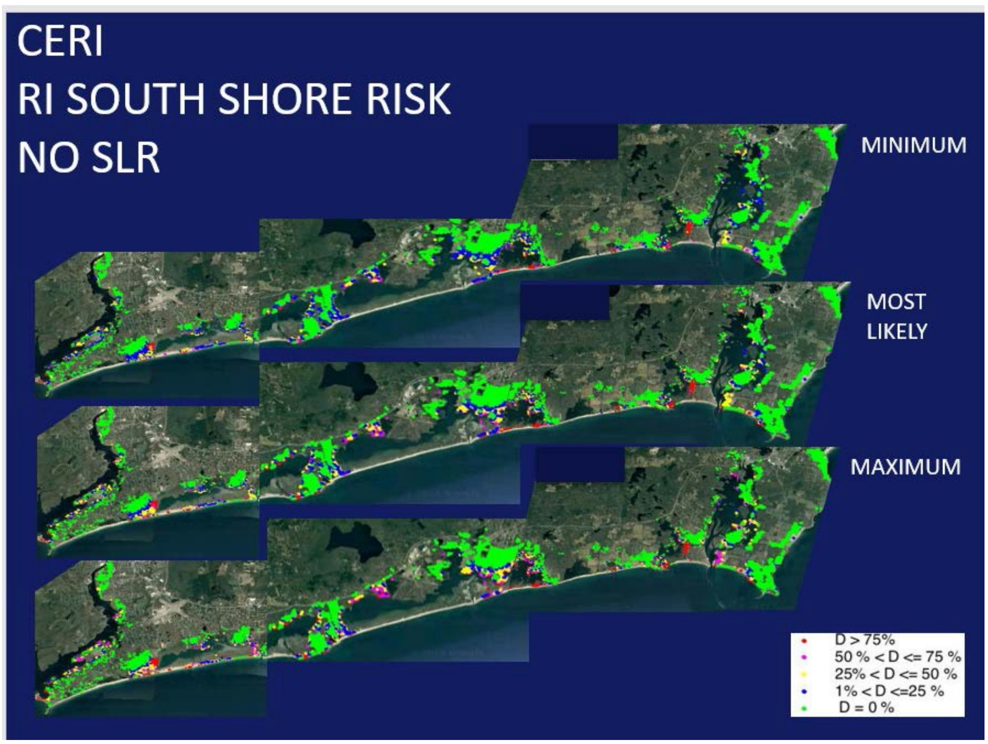


Figure 6 CERI predicted damage for the 100 yr surge, no SLR case for minimum, most likely, and maximum damage estimates.

Figure 7 shows example results for 100 yr surge with no, 5, and 10 feet SLR cases for all southern RI shoreline communities. (CERI results are available for all SLR cases at: https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=2a4ab310fecc4721935287e5a5f7ace4). These three cases are intended to show the impact of SLR on the results. Maps for the additional SLR cases are available at the previous web link. The legends are shown on the left and are the same for all SLR cases to facilitate inter-comparison. The dots represent the structure's damage and are color coded by percent damage. If the location of the structure is below mean sea level (MSL) for the SLR case selected, it is colored blue.

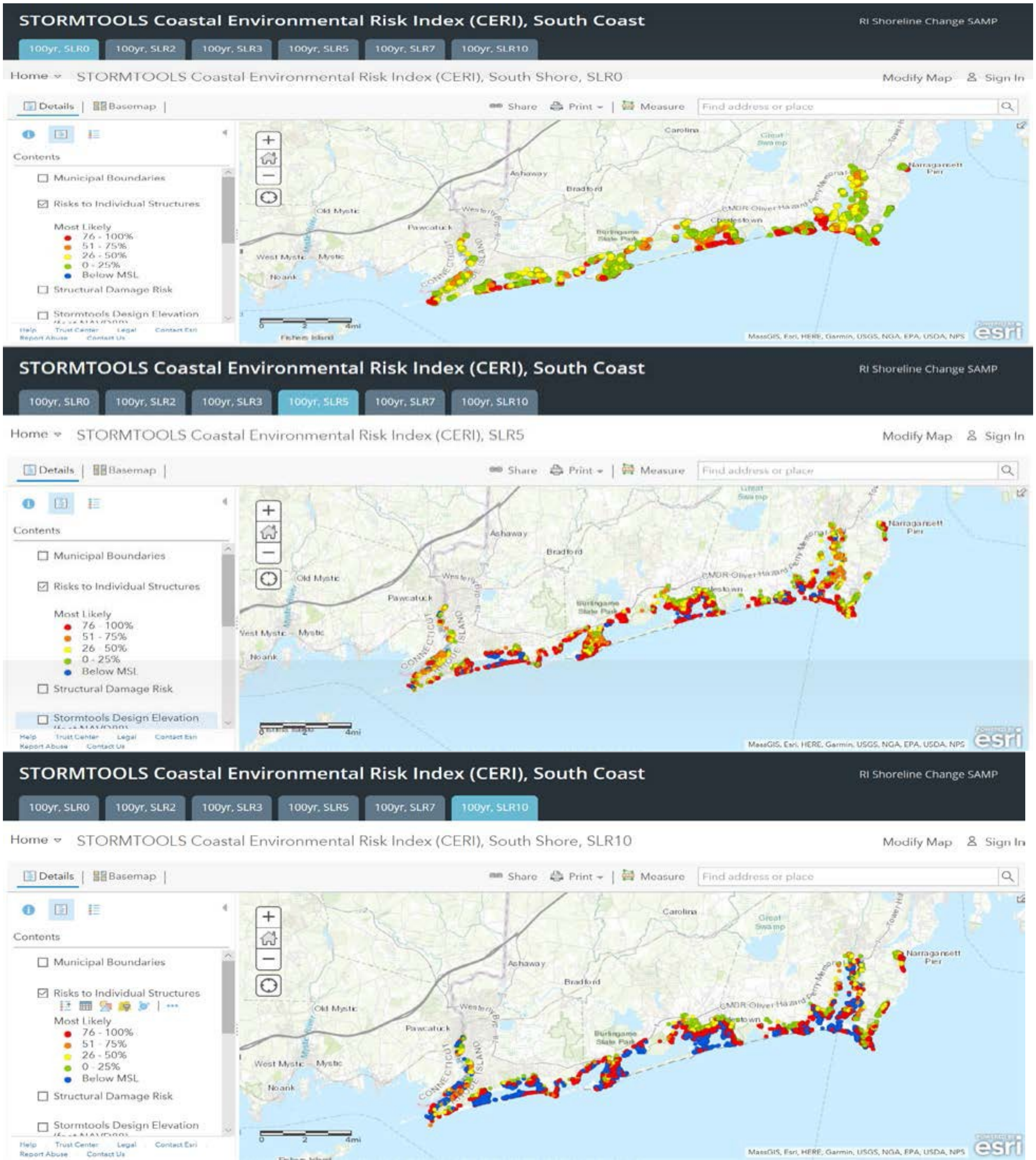


Figure 7 CERI predicted for 100 yr surge and varying SLR cases, none (upper panel), 5 ft (center panel), and 10 ft (lower panel) for southern RI shoreline. Legend shown on left.

Comparing the three panels shows that the damage increases with SLR as do the number of structures that are projected to be below MSL.

To give a better sense of the spatial resolution of CERI, Figure 8 shows a *zoomed in* version of a portion of the maps provided in Figure 7, in the vicinity of the Port of Galilee. The locations of the individual structures become more apparent with this higher resolution view. The progressive increase in damage with increasing SLR is clearly shown, as are the increase in the number of structures below MSL.

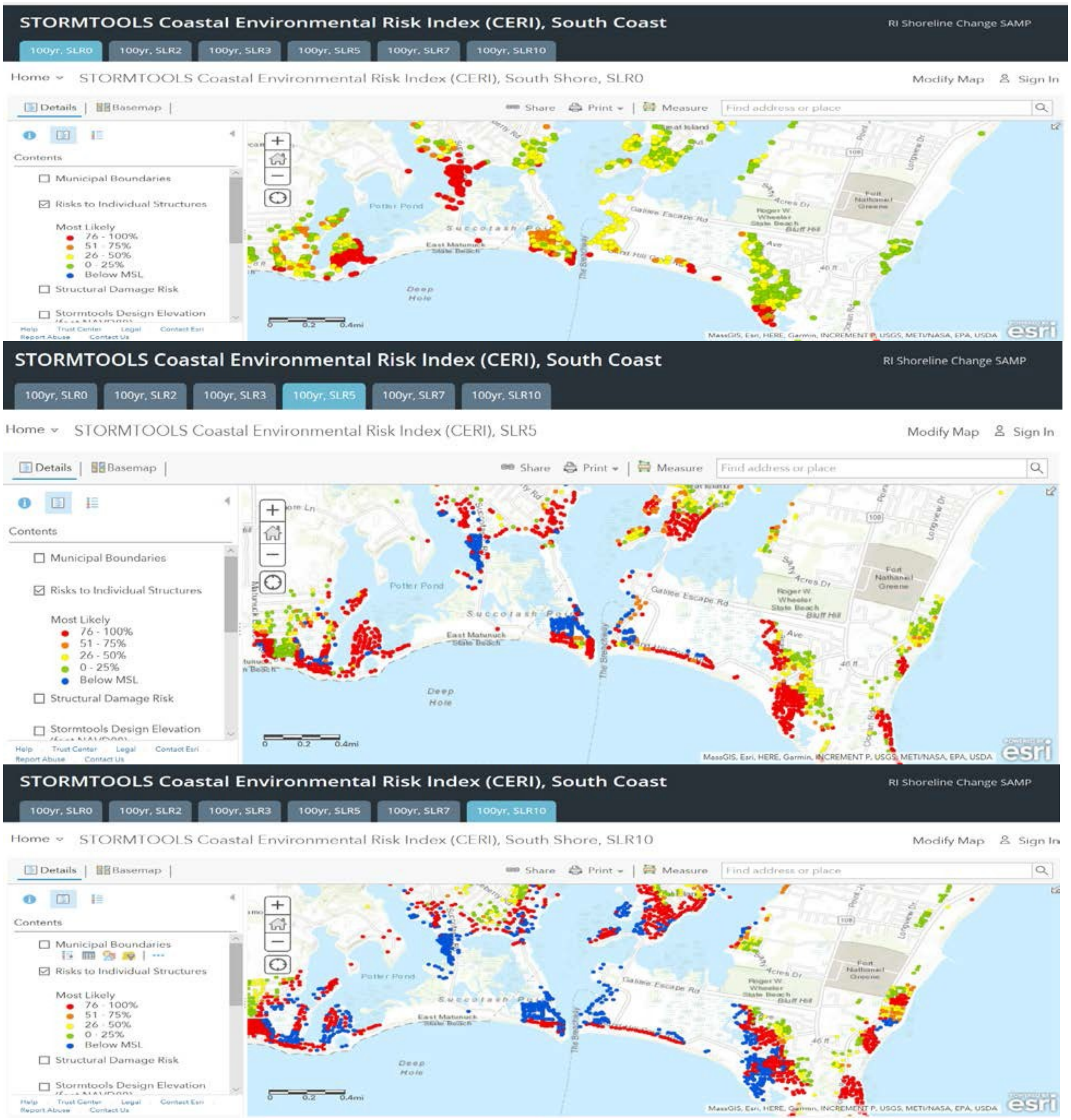


Figure 8 CERI predicted for 100 yr surge and varying SLR cases, none (upper panel), 5 ft (center panel), and 10 ft (lower panel) for the area in the immediate vicinity of the Port of Galilee. Legend shown on left.

Table 4 shows the number of buildings impacted by 100 yr storm for SLR values of 0 to 10 ft. Values are given for each town and summarized for all towns in the study area. This includes all structures that are predicted to be damaged. As noted earlier, the structures at most risk in the study area are single and two story homes, with and without basements (5 and 6 A&B). Narragansett and Westerly have the highest potential impact to commercial structures (Prototype # 2 and 3). The impact of SLR is to increase the number of structures at risk. The total number increases by about 30% with 2 ft of SLR, increases to 65% with 5 ft of SLR, and to 115% for 10 ft of SLR.

Table 4 Number of structures, by prototype class, impacted by 100 yr storm surge with SLR values from 0 to 10 ft for the Towns of Charlestown, Narragansett, South Kingstown, and Westerly, RI.

		Building Class													
SLR Scenario(ft)	**Town**	**1A-1**	**1A-3**	**1B-1**	**1B-3**	**2**	**3**	**5A**	**5B**	**6A**	**6B**	**7A**	**7B**	**Town Total**	**Total All**
0	Charlestown	0	2	0	0	1	0	133	174	229	297	39	57	932	**3710**
	Narragansett	13	14	1	2	0	42	244	143	154	135	1	43	792	
	S. Kingstown	0	2	0	1	5	0	442	154	161	164	33	25	987	
	Westerly	5	14	1	4	33	0	275	170	203	165	14	115	999	
2	Charlestown	0	3	0	0	2	0	174	208	278	359	59	63	1146	**4749**
	Narragansett	16	16	2	3	0	52	301	190	220	198	1	54	1053	
	S. Kingstown	2	2	0	1	5	0	614	182	198	211	33	25	1273	
	Westerly	6	24	2	8	33	0	339	212	270	220	18	145	1277	
3	Charlestown	0	3	0	0	2	0	187	221	313	388	60	66	1240	**5285**
	Narragansett	16	38	2	4	0	66	326	213	256	232	1	64	1218	
	S. Kingstown	4	2	0	1	6	0	722	191	222	228	33	25	1434	
	Westerly	7	28	2	8	33	0	360	222	308	251	20	154	1393	
5	Charlestown	1	4	1	0	3	0	213	253	369	449	60	66	1419	**6144**
	Narragansett	16	52	3	4	0	73	371	252	296	286	1	73	1427	
	S. Kingstown	5	3	1	1	6	0	892	205	269	276	33	25	1716	
	Westerly	12	30	2	11	36	0	397	236	370	312	20	156	1582	
7	Charlestown	2	4	1	0	5	0	249	263	427	505	60	66	1582	**6917**
	Narragansett	16	55	3	8	0	74	421	291	338	332	1	75	1614	
	S. Kingstown	5	3	1	1	6	1	997	225	320	328	33	25	1945	
	Westerly	12	40	7	12	37	0	420	256	451	363	20	158	1776	
10	Charlestown	4	8	2	1	8	0	281	282	515	566	60	66	1793	**7945**
	Narragansett	19	65	4	12	0	83	473	338	415	405	1	79	1894	
	S. Kingstown	6	3	1	2	8	1	1048	250	445	426	33	25	2248	
	Westerly	13	41	12	20	39	0	451	269	545	439	20	161	2010	

To help put the results in context, Figure 9 shows the fraction of houses at risk of flooding with increasing SLR for the four coastal communities in the study area. The results for the application of CERI to the Towns of Barrington, Bristol, and Warren (BWB) are also shown for reference (Grilli et al., 2019). Application of CERI to BWB has recently been completed and represents the location with the most structures at risk of coastal flooding in the state. The values given in the figure are a fraction of the total structures in the potential flood zone and provided in Table 4. As an example, for Charlestown 65% of the structures in the flood risk area are at potential risk for the 5 ft SLR case. This corresponds to 1342 structures (2056 times 0.65). The figure shows that the risk increases approximately linearly with SLR. The risk is highest for Charlestown, lowest for Narragansett, and intermediate for South Kingstown and Westerly. The risk for the latter two towns is comparable to that for BWB.

The fraction of structures with damage greater than 50% versus sea level rise is provided in Figure 10. Figure 11 shows the predictions of the structures below mean sea level (MSL) vs SLR value. Once again, the actual number can be obtained by multiplying the value from these figures by the number of structures provided in Table 4. Results are provided for the four communities plus BWB. CERI predicts that the number of structures damaged increases for most communities with SLR until a SLR of 5 feet (Figure 10). For SLR values greater than this, the fraction impacted (50% damage) peaks and then declines with further increases in SLR. This behavior is a result of the loss of structures being below MSL elevation (Figure 11).

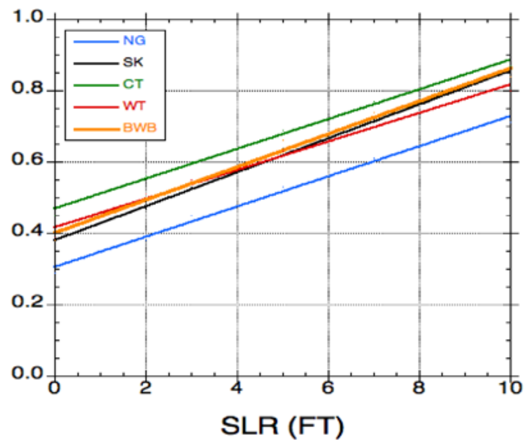


Figure 9 Fraction of houses (%) under 30 ft NAVD88 potentially in harm way (predicted damage larger than 0 %), assuming the most likely scenario for any SLR case between 0 to 10 ft, for Narragansett (NG), South Kingstown (SK), Charlestown (CT), Westerly (WT), and Barrington, Warren, and Bristol (BWB).

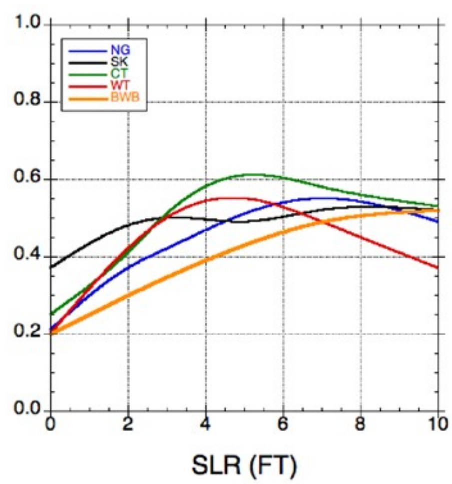


Figure 10 Fraction of houses in harm's way (damages >0; Figure 9) with damage greater than 50%, assuming the most likely scenario for any SLR case between 0 to 10 ft, for the towns of Narragansett (NG), South Kingstown (SK), Charlestown (CT), Westerly (WT), and Barrington, Warren, and Bristol (BWB).

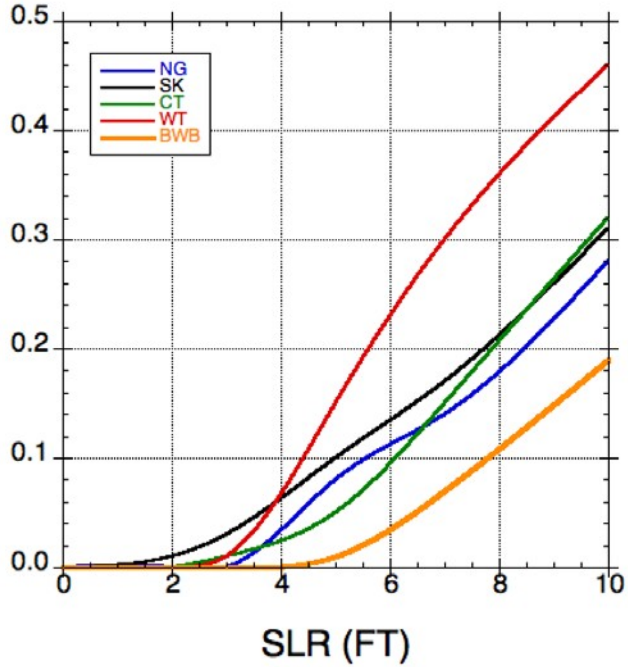


Figure 11 Fraction of houses experiencing some damages (Figure 9) predicted to be under MSL assuming the most likely scenario for any SLR case between 0 to 10 ft for towns of Narragansett (NG), South Kingstown (SK), Charlestown (CT), Westerly (WT), and Barrington, Warren, and Bristol (BWB).

To help communities assess what the risks are of constructing structures at various locations (not just the locations of current structures) a methodology to generate risk maps has been developed and implemented in the CERI framework. These maps assess the risk for building a structure at any location in the flood zone. They are based on assuming that the most common structure in the study area (single or two story residence with a basement, 5A) is located at each grid of the computational domain. The maximum damage function is selected to make sure the maps are conservative in their representation of the risk. CERI risk maps for the study area are shown in Figure 12 for 100 yr, 0, 5, and 10 feet SLR cases, upper, mid, and lower panels, respectively. These are shown to be consistent with the results presented in Figure 7. The risk maps show values ranging from moderate to extreme and locations where structures would be below MSL. Comparing the maps shows the risk level increases with SLR. The below MSL category grows substantially with increasing SLR particularly for the 10 foot value.

Figure 13 shows the CERI damage map by structure overlaid on the risk map generated by the methodology outlined above. The figure clearly shows the consistency between the two maps and that the risk map is in general more conservative than the actual damage map.

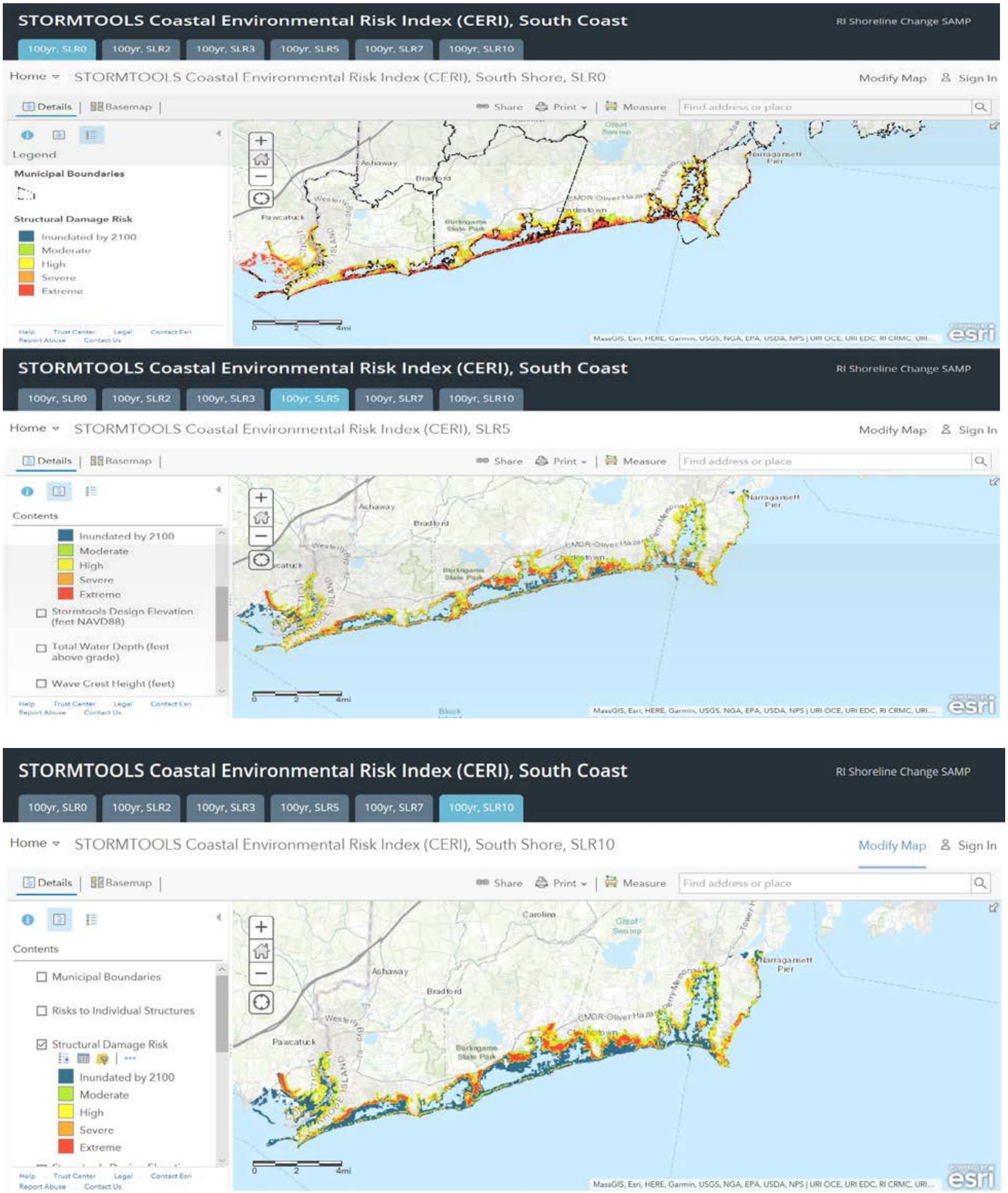


Figure 12 CERI predicted risk maps for 100 yr surge and varying SLR cases, none (upper panel), 5 ft (center panel) and 10 ft (lower panel) for the southern RI shoreline.

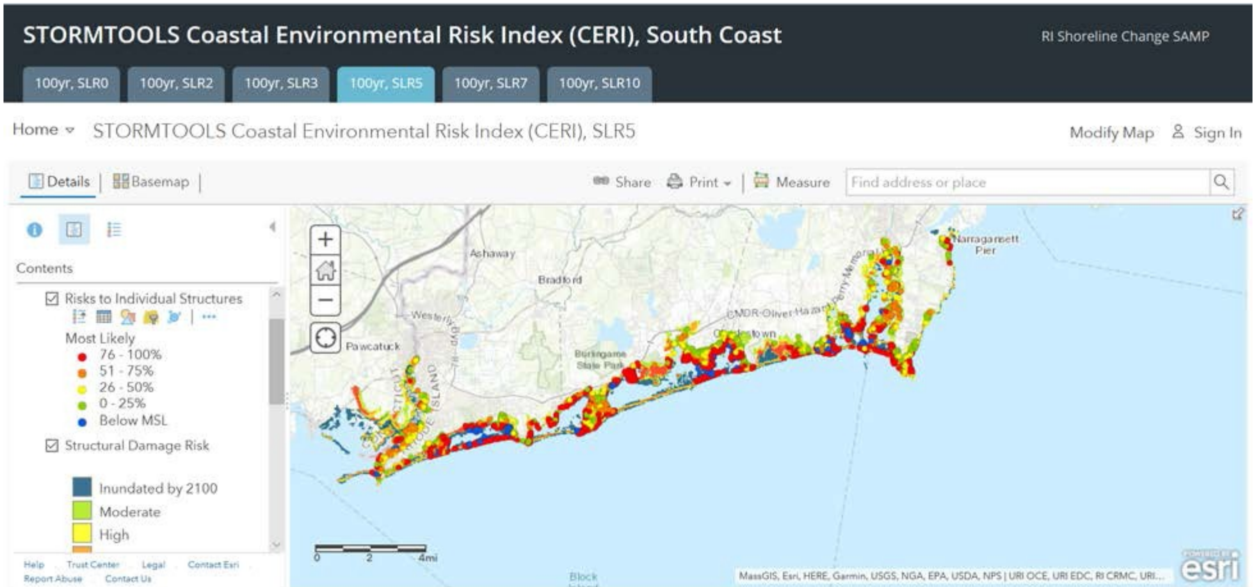
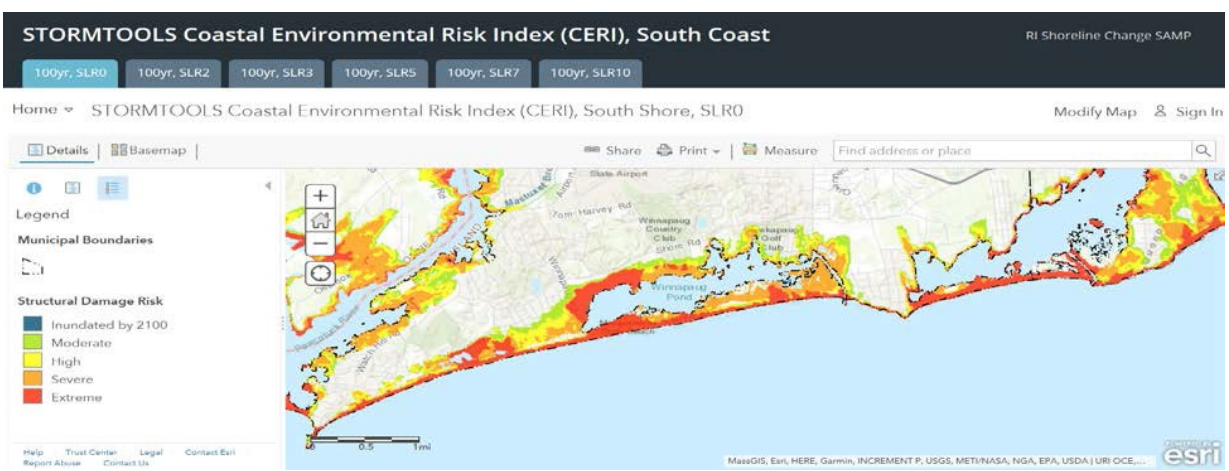


Figure 13 CERI predicted damage and risk maps for 100 yr surge with 5 ft of SLR.

Figure 14 shows the ability to obtain high resolution risk maps from CERI for a user selected area. In this case, the figure shows risk for the Misquamicut Beach – Westerly area for 0, 5, and 10 ft of SLR. The growth in the extreme area and the area that will be inundated by 2100 clearly increase with SLR.



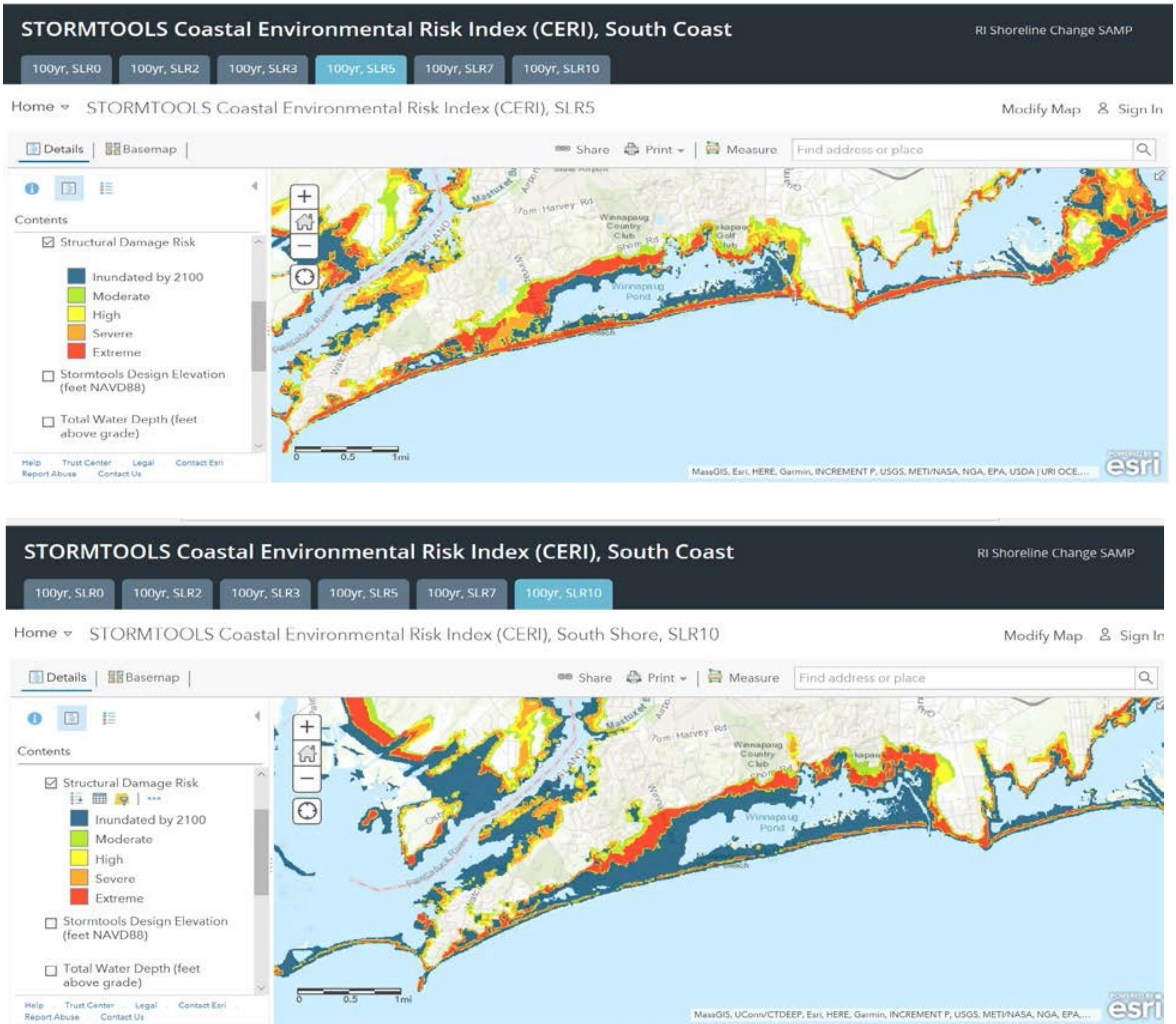


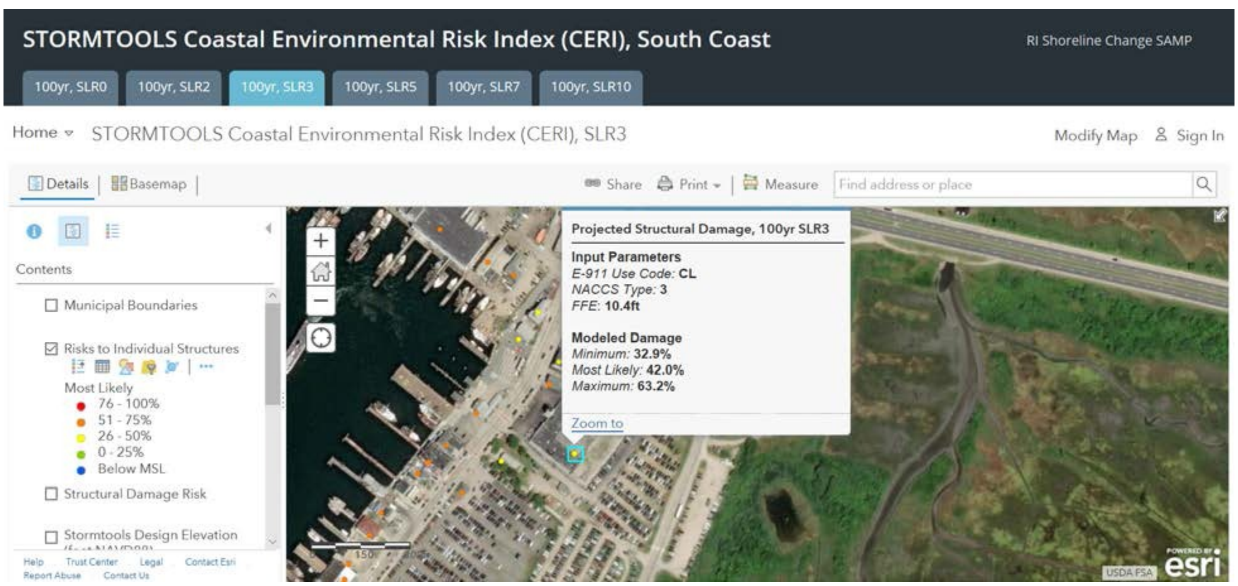
Figure 14 CERI predicted risk maps for 100 yr surge and varying SLR cases, none (upper panel), 5 ft (center panel) and 10 ft (lower panel) for the southern RI shoreline, high resolution map of Misquamicut Beach and Westerly area.

In accessing SDE maps and CERI results from their respective web sites, it is important to note that the user has access to more detailed supporting information. These additional data sets are noted in the summary below and selected examples provided.

SDE map:
https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=3ba5c4d9c0744392bec2f4afb6ee2286
CERI map:
https://crc-uri.maps.arcgis.com/apps/MapSeries/index.html?appid=2a4ab310fecc4721935287e5a5f7ace4)

Municipal boundaries
SDE maps expressed in the form of BFE relative to NAVD88, for SLR values varying from 0 to 10 ft.
SDE/BFE maps relative to grade elevation.
Inundation and wave components of SDE/BFEs.
FEMA FIRM BFEs relative to NAVD88.
FEMA Hazard Areas
FEMA Transects
CERI Structural damage risk
CERI Risk to individual structures

To highlight some of the additional data that is available, Figure 15 shows the damage to a structure located on the shoreline in Port of Galilee for 100 yr flood with 3 ft SLR (upper panel). Minimum, most likely, and maximum damages are provided. The E911 code, NACCS prototype number, and FFE are provided for the structure selected. The lower panel shows the risk map for the same area, ranking it as *severe*. As noted earlier, the risk map uses the maximum damage, which is consistent with the damage for the structure selected in the upper panel.



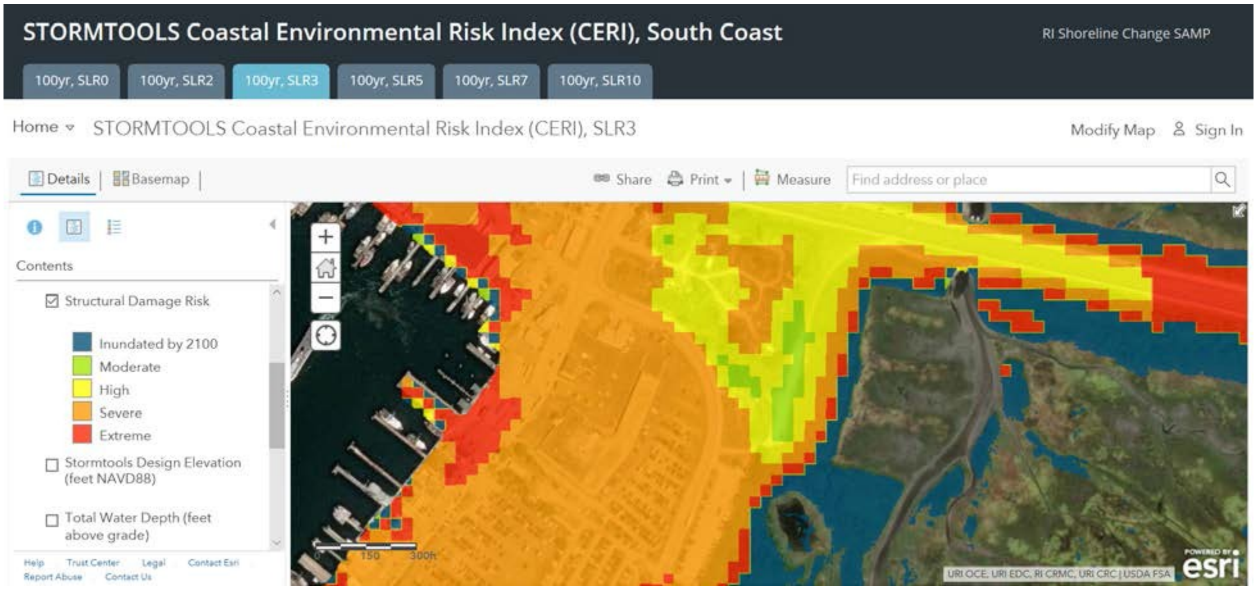
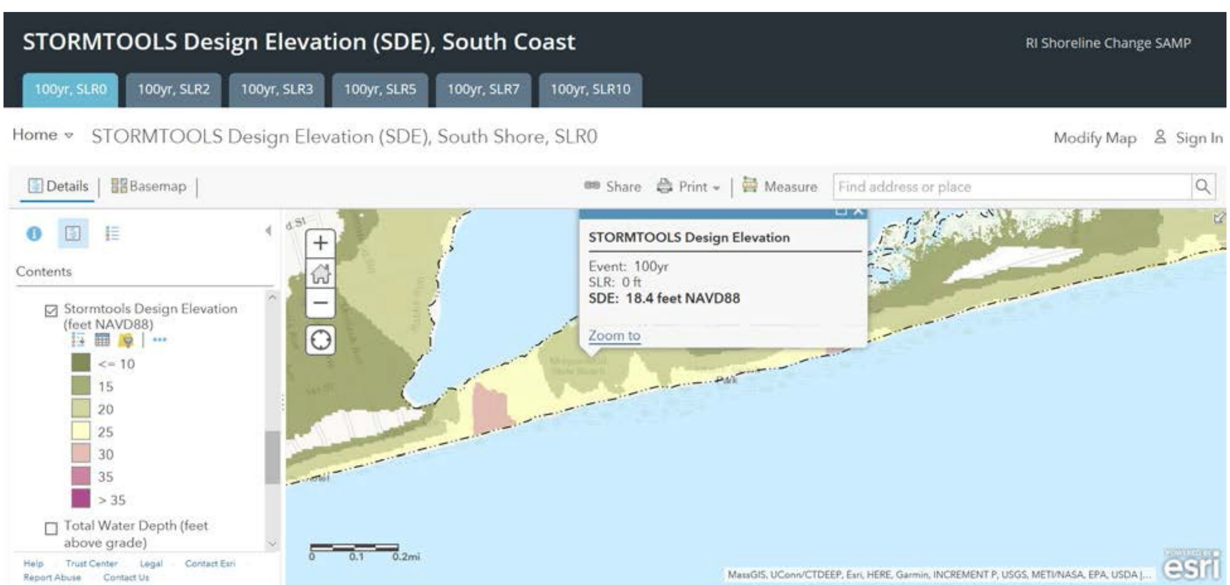


Figure 15 CERI prediction of damage (minimum, most likely, and maximum) at a selected location in the Port of Galilee (upper panel) for 100 yr, 3 ft SLR case. A description of the structure is provided followed by minimum, most likely, and maximum damage. A risk map for the same SLR case and the same area (lower panel).

As another example, Figure 16 shows a comparison of BFE from the SDE and FEMA FIRM maps for a selected location on Misquamicut Beach for the 100 yr, no SLR case. The SDE maps predict a higher BFE compared to the FEMA FIRMS at this location. The spatial variations of the BFE at this location is much greater for the SDE maps compared to their FEMA FIRM counterpart. This reflects the high-resolution wave modeling used in the SDE maps compared to the simplified 1-D transect methodology used in the FEMA FIRMs (Spaulding et al., 2017a).



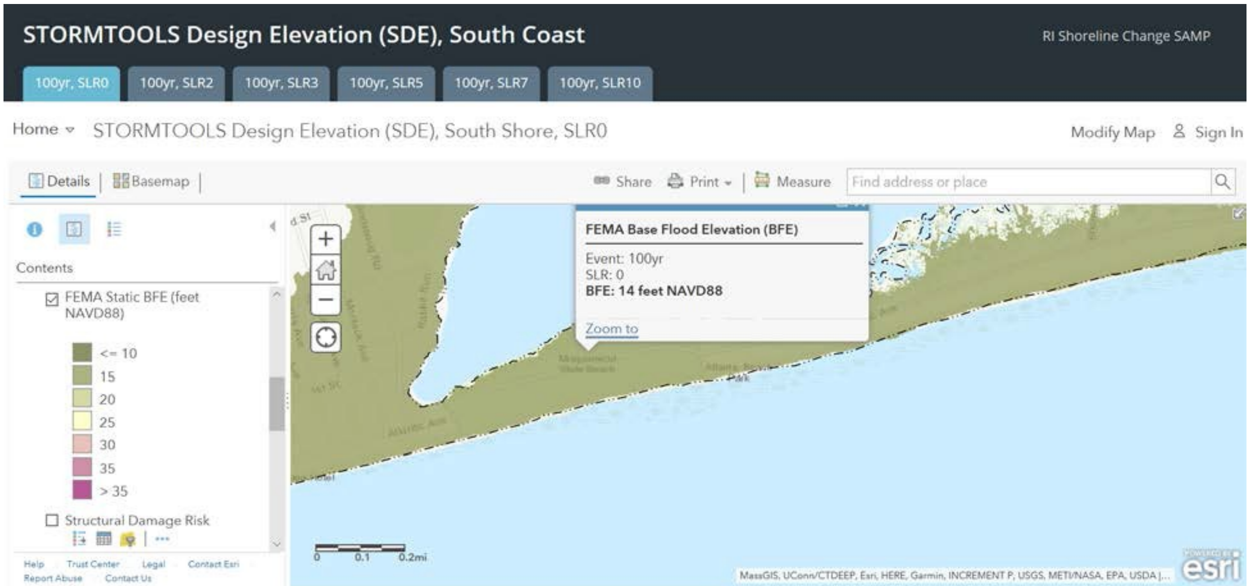


Figure 16 SDE and FEMA estimates of BFE for a selected location on Misquamicut Beach for 100 yr storm, no SLR.

Section 4 Summary and Conclusions

CERI has been applied to the southern RI shoreline extending from little Narragansett Bay in Westerly to the mouth of Narrow River in Narragansett (including the towns of Westerly, Charlestown, South Kingstown, and Narragansett). The application has used STORMTOOLS SDE maps to specify the BFE for 100 yr flooding, with SLR values varying from 0 to 10 ft. The SDE approach uses state of the art methods and the most recent results from the NACCS study. It also uses a validated, state of the art model (XBeach) to estimate coastal erosion along the southern RI shoreline.

The structures in the flood area have been characterized using a merger of E911 and parcel data sets provided by the town and verified by selected site visits. The first finished floor elevations have been generated based on the E911 and parcel data. Each structure has been assigned a classification according to the ACOE NACCS prototype protocol. Structures have been classified as apartments, commercial buildings, and residences (single and two story, with and without basements, elevated pile (open or closed) supported structures open or closed pile. Damages were calculated for each structure at risk of flooding using the ACOE NACCS damage functions. Damages were calculated for inundation and wave damage (minimum, most likely, and maximum). The estimate that generated the largest damage (inundation or wave) was selected based on the NACCS damage assessment protocol. In addition, flooding risk maps were generated for the study area for each SLR case. In this approach risk is estimated at each grid in the study area (not just at the locations of actual structures). These maps have proven helpful to assist municipalities in communicating risk to their constituents.

The results of this effort have been provided in the form of BFEs (STORMTOOLS Design Elevation, SDE) maps and risk to individual structures and generalized risk maps from CERI. All results are available via ArcView GIS and can be readily accessed by municipal staff and the public.

The analysis shows that the dominate type of structure at risk are residences (single or two story, with or without a basement) under the no SLR case. The without basement class accounts for 46% of the structures, while the more vulnerable, with basement, accounts for 40% for a total of 85%. Structures elevated on piles (open or closed) account for about 9%. The remaining are commercial buildings. The distribution of structures at risk (100 yr, no SLR) is roughly equivalent across town (with range varying from 800 to 1000) with a total for all four towns of 3710. The highest number at risk is in Charlestown and the lowest number is in Narragansett. Westerly and Narragansett have significantly more commercial structures at risk than the other towns but still a small number compared to the number of residential structures.

The number of structures at risk has shown to scale approximately linearly with SLR. 2 ft SLR results in an increase of 30% of structures at risk. For 3 ft this increases 42%, for 5 ft - 65 % and at 10 ft 114%. The predictions show that the number of structures that are more than 50% damaged increase with SLR reaching a maximum value when SLR is at 5 ft. The number of structures below MSL is quite limited until SLR reaches 5 ft and then increases rapidly for all towns.

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Author Contributions: Malcolm L. Spaulding developed the idea for STORMTOOLS/Coastal Environmental Risk Index (CERI), and the supporting STORMTOOLS Design Elevation (SDE) Maps, and its application to the southern RI shoreline. Annette Grilli was primarily responsible for inundation, wave, erosion, and damage modeling. Characterization of the structures at risk, implementation in GIS, and providing access of the output was provided by Chris Damon of the URI Environmental Data Center. Teresa Crean (URI, Coastal Resources Center) was the project manager and coordinated the effort to determine the building types for each community and to support project outreach to the communities. Grover Fugate, CRMC Executive Director, advised on project goals and outreach to meet the needs of state and community coastal managers and planners.

Acronyms

ASCE- American Society of Civil Engineers
ACOE- Army Corp of Engineers
BCLASS – NACCS Building Prototype
BFE- Base Flood Elevation
CERI- Coastal Environmental Risk Index
CI- Confidence Interval
CRMC- RI Coastal Resources Management Council
DEM – Digital Elevation Model
ELEV – Grade Elevation, feet NAVD88
FEMA- Federal Emergency Management Agency
FFE – First Floor Elevation (grade plus 2 feet in most cases; grade plus 9 feet for 7A/B)
FIRM- Flood Insurance Rate Maps
FIS- Flood Insurance Study
LAT/LON – Latitude/ Longitude
LIDAR- Laser Imaging, Detection, and Ranging
LIMWA- limit of moderate wave action
MESM- Master of Environmental Science and Management
MSL- Mean Sea Level
NACCS- USACE, North Atlantic Comprehensive Coastal Study
NAME – Town Name
NAVD88- North Atlantic Vertical Datum, 1988.
NOAA NOS- National Ocean and Atmospheric Administration- National Ocean Survey
NUMSTOR – Number of stories
OCM- Office of Coastal Management
PSM- Projects of Special Merit
RI GIS – Rhode Island- Geographic Information System
SFHA - Special Flood Hazard Area
SDE- STORMTOOLS Design Elevation maps
SLR- Sea Level Rise
STWAVE – STeady state spectral WAVE model
SWEL- Still water elevation level
STORMTOOLS- tools in support of storm analysis
URI- University of Rhode Island
XBeach – nearshore wave and geomorphological model

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