CHAPTER 4

Rhode Island's Exposure to Coastal Hazards

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4.1 Chapter Highlights

1. This chapter provides an overview of what is known to date about Rhode Island's exposure to coastal hazards associated with climate change. Exposure refers to a community's assets, including people, property, infrastructure, and the natural environment, subject to a hazard's damaging impacts. Coastal hazards considered here include storm surge, coastal erosion and sea level rise; other hazards including waves, storm frequency and intensity, debris damage, and wind are not included in this analysis. This chapter examines the exposure of the natural and built environment, focusing in particular on the coastal structures, features, and natural resources that are within coastal communities within CRMC's jurisdiction.

2. Salt marshes in RI and throughout southern New England are considered among the most vulnerable to SLR in the entire U.S. Accelerating SLR is outpacing accretion in RI, and as a result, salt marshes are showing signs of erosion, ponding, drowning, and vegetation shifts. These SLR impacts may work in synergistic ways with other human-induced and natural stressors to further degrade marsh condition.

3. A CRMC analysis of SLR and marsh migration suggested that RI is likely to face a substantial loss of coastal wetlands due to SLR, with south shore communities disproportionately impacted, under 1, 3, and 5-foot SLR scenarios. This analysis suggested that communities within Narragansett Bay may experience a net gain of new coastal wetlands through the process of marsh migration, although the authors caution that these results are likely overestimates of wetland gain.

4. A scientific study of the vulnerability of RI salt marshes to SLR revealed that south coast marshes are generally much more vulnerable to SLR. Marshes up Narragansett Bay are relatively less vulnerable although there are contrasting patterns of vulnerability among bay locations. This study found that low marsh elevation above mean high water and presence of tall *Spartina alterniflora* are indications of high vulnerability to SLR.

5. The Rhode Island south shore consists of a series of barrier spits alternating with headland bluffs which are largely erosional. By contrast the Narragansett Bay shoreline includes many hardened shorelines; it is estimated that 30% of the Narragansett Bay shoreline is hardened through shoreline protection structures, although a comprehensive inventory of the type and condition of shoreline protection structures has not been undertaken statewide.

6. Rhode Island has not experienced a significant shoreline change event with widespread overwash over the entire south shore since Hurricane Carol in 1954. More recent storms

(e.g. Hurricane Bob in 1991 and Superstorm Sandy in 2012) were smaller events and are not an indication of how future storms could change the Rhode Island shoreline.

7. The construction of new structural shoreline protection facilities on all barriers classified as undeveloped, moderately developed and developed and along all Type I waters is prohibited pursuant to Section 300.7 of the RICRMP. Shore parallel shoreline protection structures along eroding bluffs and dunes have numerous negative physical impacts to beaches directly in front of the structure as well as adjacent shorelines. They also have deleterious ecological impacts on adjacent structures, impact the loss of lateral shoreline access in front of these structures.

8. A Shoreline Change SAMP analysis revealed that the entire Rhode Island south shore is largely erosional, characterized by systematic retreat driven by storms and SLR. The south shore barriers in this region have an average annualized rate of shoreline change of 0.57 meters/year (1.9 ft/year). The stratified headlands in this region have an average annualized rate of shoreline change of 0.75 meters/year (2.46 feet/year). Some of the highest rates of change occur along the Matunuck Headlands, where the annualized rate of change exceeds 1.4 meters/year (4.7 feet/year) and total erosion since 1951 approaches 90 meters (300 feet).

9. A Shoreline Change SAMP analysis of projected future shoreline change suggested that the RI south shore could experience a total change of 89 meters (292 feet) by 2065 and 216 meters (708 feet) by 2100.

10. A CRMC-led assessment found that 27,431 (11.5%) of the residential structures in Rhode Island's coastal communities are exposed to the combined effects of sea level rise and storm surge under the Shoreline Change SAMP's Long-range Planning Scenario (a 7-foot SLR + a 100-year storm surge). Residential structures included in this assessment were single and multi-family homes, seasonal homes, mobile homes, camps, and other residential structures listed in the state's E-911 database. By percentage, the most exposed community is Barrington, with 64.4% (6,100) of its residential structures exposed.

11. With regard to residential structures, South Kingstown and Westerly are the state's top two most exposed communities under projected 3, 5, and 7-foot SLR scenarios. Warwick and Barrington are the top two most exposed communities to a present-day 100-year storm surge as well as 100-year storm surges when combined with the 3, 5, and 7-foot SLR scenarios. Evaluated together, by number of structures exposed, South Kingstown is among the state's top five most exposed communities under all of these scenarios.

12. 3,082 (18.9%) of the commercial structures in Rhode Island's coastal communities are exposed to the combined effects of sea level rise and storm surge under the Long-range Planning Scenario. Commercial structures in this assessment included all lodging, farm, and other commercial structures listed in the state's E-911 database. Providence has the highest number of exposed structures (993, or 23.2%) whereas Barrington has the highest percentage of its commercial structures exposed (70.8%, or 154 structures). Importantly, findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.

13. With regard to commercial structures, Newport, North Kingstown, Providence, and Westerly are among the top five most exposed municipalities under projected, 3, 5, and 7-foot SLR scenarios. Newport, Providence, Warren, Warwick and Westerly are the top five most exposed communities to a present-day 100-year storm surge as well as 100-year storm surges combined with projected 3, 5, and 7-foot SLR scenarios. Under all three combined SLR and storm surge scenarios, over 50% of the exposed commercial structures in the state's coastal communities are concentrated in just five municipalities: Newport, Providence, Warren, Warwick and Westerly.

14. 566, or 13.8%, of the public service structures in Rhode Island's coastal communities are exposed under the Long-range Planning Scenario. Newport has the greatest number of such structures exposed (110 structures, or 31.8%) whereas some communities have a greater percentage of their public service structures exposed (e.g. Warren at 55%, or 38 structures).

15. With regard to public service structures, Narragansett is among the top three most exposed communities under projected 3, 5, and 7-foot SLR scenarios. Providence, Newport, and North Kingstown are the top three most exposed communities to a present-day 100-year storm surge as well as 100-year storm surges combined with projected 3, 5, and 7-foot SLR scenarios. Under the Long-range Planning Scenario, the five municipalities of Newport, Providence, North Kingstown, Warwick and Narragansett together contain 65% of the coastal municipalities' exposed public service structures.

16. A RI Statewide Planning Program demographic study estimated that 6,945 individuals live in an estimated 3,321 occupied housing units that are exposed to a projected 7-foot SLR.

17. A RI Department of Environmental Management study found that 10 coastal wastewater treatment facilities are at risk of inundation under projected 1, 2, 3, and 5-foot SLR scenarios.

18. A RI Department of Health study which utilized conservative sea level rise projections found that by 2084, 20 drinking water utilities in the state may be impacted by sea level rise and 11 by coastal flooding.

19. A RI Statewide Planning Program transportation study found that up to 85 miles of road are expected to flood under a 5-foot SLR scenario, 70% of which are local roads which do not qualify for federal transportation funding.

20. A study commissioned by the RI Historic Preservation and Heritage Commission found that there are 1,971 National Register-listed or eligible assets located in FEMA-mapped flood zones, with 72.9% located in just the five municipalities of Newport, North Kingstown, Warren, Bristol, and Westerly. These results are conservative because this study did not consider SLR or changing future conditions.

21. Another Shoreline Change SAMP analysis examined areas of the RI coast which are particularly at-risk for the combined effects of storm surge, coastal erosion, and sea level rise. On the south shore, at-risk areas include the Matunuck Headland, where shoreline change exceeded 90 meters (295 feet) between 1951 and 2014. Areas of particular concern included Roy Carpenter's Beach and South Kingstown Town Beach, as well as the commercial and residential neighborhood east of the beach. Misquamicut was also identified as an at-risk area, including both the Misquamicut Headland and the Misquamicut Barrier. In Misquamicut, most of the revetments were damaged and many of the dikes failed during Superstorm Sandy in 2012; projected shoreline change for this area indicates that, over time, all but the largest such structures will likely fail. Shoreline change projections for both of these areas are extensive.

22. The Shoreline Change SAMP at-risk area analysis revealed that in Narragansett Bay, Barrington, Warren and Bristol are particularly exposed to the combined effects of storm surge, coastal erosion, and sea level rise. In this area, SLR and storm surge are the primary threats due to the low-lying nature of these communities. Low-lying residential and commercial districts, especially waterfront commercial areas, are projected to experience dramatic changes over time. Areas of Warwick were also identified as highly exposed to these hazards; for example, inundation associated with 5 feet of sea level rise and a 100-year storm surge could extend as far inland as the southern end of T.F. Green airport.

23. Storm surge, coastal erosion and sea level rise interact with each other, resulting in synergistic effects. For example, the combination of sea level rise and storm surge can accelerate the process of coastal erosion. Another such example is the way in which sea level rise increases the return period of storms, i.e. increasing water levels such that

today's 100-year storm will eventually become a 20-year ("nuisance") storm. These synergistic effects have not been fully examined by all of the tools and analyses incorporated into the Shoreline Change SAMP nor those developed by other agencies and organizations. Importantly this indicates that exposure assessments discussed in this chapter may underestimate the potential impacts to Rhode Island discussed herein, and points to the importance of long-term planning and adaptation.

24. The data and information included in this chapter are the best available to date, but scientific understanding of these issues is rapidly changing and additional research is needed on a wide range of topics. Some of these needs are being addressed by ongoing studies whereas others require future research.

4.2 Introduction

1. This chapter provides an overview of what is known to date about the exposure of Rhode Island's coast to coastal hazards associated with climate change. Exposure refers to a community's assets, including people, property, infrastructure, and the natural environment, subject to a hazard's damaging impacts. Hazards considered here include storm surge, coastal erosion and sea level rise.

2. CRMC policy, as reflected in Section 145 of the RICRMP, relies upon the "high" sea level change curve included in the most recent NOAA sea level rise (SLR) data. As of the time of this writing, the high curve included in the most recent NOAA analysis projects a maximum of 9.6 feet of SLR at the 83% confidence interval in Rhode Island by 2100 (NOAA 2017). However, scenarios developed for the Shoreline Change SAMP document, planning tools and analyses are based on earlier NOAA SLR analyses which projected up to 6.6 feet of SLR in Rhode Island in 2100 under the high curve (see NOAA 2012). NOAA's 2017 analysis also included an "extreme" curve which projected up to 11.7 feet of SLR at the 83% confidence interval in Rhode Island by 2100 (NOAA 2017). CRMC expects to update the Shoreline Change SAMP document, planning tools and analyses on an ongoing basis, using the most recent SLR scenarios, as resources allow. See the USACE sea level change curve calculator at http://www.corpsclimate.us/ccaceslcurves.cfm to view SLR projections for Newport under the full range of scenarios for both the 2012 and the 2017 NOAA analyses.

3. As is noted throughout this chapter, some studies summarized herein were conducted at CRMC's direction in support of the Rhode Island Shoreline Change SAMP, and therefore use the SLR data described above, while others were conducted by other agencies, organizations and experts for other purposes. Readers are advised to use caution in interpreting study results reported herein or in trying to integrate, compare, or apply

results. Studies included here utilized a variety of different data sources, methods, and assumptions. Many different SLR and storm surge inundation scenarios were used, and in some cases either SLR or storm surge was not considered. Because of this inconsistency in data sources, methods, and scenarios, these studies cannot be directly compared. Additionally, scenarios projecting SLR or storm surges for specific locations should all be interpreted as underestimates in that they do not account for the approximately 1 to 2 feet of additional water depth above and beyond these projections that can be caused by an astronomical high tide plus the effects of storm-driven wind, which is above and beyond those projections.[1] Nor do they account for the effects of waves, storm frequency and intensity, debris damage, and wind. The effects of wind are not limited to the coastal environments but are relevant statewide; for further information please see the 2014 Rhode Island Hazard Mitigation Plan update at www.riema.ri.gov. Finally, studies summarized herein are, for the most part, statewide analyses that did not involve in-depth analysis of individual municipalities. CRMC encourages municipalities to conduct their own high-resolution site-specific analyses using available risk assessment tools (see Chapter 3) as well as the most up-to-date data.

4. This chapter examines the exposure of both the built and the natural environment, but is explicitly focused on the coastal structures, features, and natural resources that are within coastal communities within CRMC's jurisdiction. This information is designed to complement CRMC's existing regulatory program, particularly the RICRMP and the Salt Ponds Special Area Management Plan, which can be found at www.crmc.ri.gov. Where appropriate, this chapter directs readers to other federal, state and local agencies and programs charged with managing coastal structures, features and resources outside of CRMC's jurisdiction.

5. Importantly, this chapter is not exhaustive in characterizing the structures, features and resources of Rhode Island's coast which may be affected by coastal hazards and climate change, nor of the ways in which those structures, features and resources may be impacted. Additionally, scientific understanding of climate change, associated hazards, and their effects on coastal structures, features and resources in Rhode Island and elsewhere is rapidly changing. While the information included herein represents the best available data to date on Rhode Island's exposure to these hazards, there are multiple

[1] According to data available through the NOAA National Ocean Service, predicted water levels at Newport, Conomicut and Providence can be up to 1.6 feet higher than mean higher high water (MHHW) during an astronomic high tide; see https://tidesandcurrents.noaa.gov/tide_predictions.html. Wind setup can raise this number to 2 feet or more.

other such studies and assessments in progress. For further information on ongoing projects, please see Section 4.8.

4.3 Natural Environment

1. Rhode Island's natural environment is exposed in multiple ways to coastal hazards associated with climate change. This section summarizes what is known to date about the exposure of Rhode Island's coastal beaches, barriers, and headlands; coastal wetlands; and other coastal habitats. This section also highlights recent or ongoing restoration efforts targeted at these resources.

2. The Shoreline Change SAMP Planning Boundary encompasses a diverse range of natural resources and habitats and intersects multiple different ecosystems connecting inland areas with the waters of Narragansett Bay and Block Island and Rhode Island Sounds. While resources and habitats within the planning area and the surrounding ecosystems may be exposed to the impacts of climate change, the Shoreline Change SAMP focuses specifically on the natural environment located within the Shoreline SAMP Planning Boundary and in particular those shoreline features which are under CRMC's jurisdiction. Further, the Shoreline Change SAMP focuses specifically on the impacts of coastal hazards to these shoreline features. This information is designed to complement CRMC's existing regulatory program, particularly the RICRMP and the Salt Ponds Special Area Management Plan, which can be found at www.crmc.ri.gov.

3. This section refers to some studies that were not conducted by CRMC or as part of the RI Shoreline Change SAMP. Readers are advised to use caution in interpreting these study results or in trying to integrate, compare, or apply results. Studies included here utilized a variety of different data sources, methods, and assumptions, including different SLR and/or storm surge inundation scenarios. In some cases either SLR or storm surge was not considered.

4.3.1 Beaches, Barriers and Headlands

4.3.1.1 Overview

1. This section summarizes some of what is known to date about the exposure of Rhode Island's shoreline (beaches, barriers and headlands) to storm surge, coastal erosion and sea level rise. For CRMC's policies regarding these coastal features, see the RICRMP. The RI Shoreline Change SAMP process included multiple studies and mapping initiatives on these topics. In each case these studies and initiatives are either summarized or example findings are included in this chapter, and the reader is referred to the original source(s) of information for further information. Findings included here are the best available information at the time of this writing; however it is important to note that scientific understanding of these processes and their potential impacts on Rhode Island is rapidly changing.

2. It is important to note that Rhode Island has not experienced a significant shoreline change event with widespread overwash over the entire Rhode Island south shore since Hurricane Carol in 1954. While there have been smaller storms more recently (e.g. Hurricane Bob in 1991 and Superstorm Sandy in 2012), stakeholders and decision-makers should not rely on these recent storms as an indication of how future storms could impact and alter Rhode Island's coastal region.

4.3.1.2 Geologic Setting of the Rhode Island South Shore

1. The >30 km (18.6 mile) long Rhode Island south shore (RISS), bounded by the Napatree Point headland on the west and by the Point Judith headland on the east (see Figure 1), is a microtidal, wave dominated coastline in the classification of Hayes (1979) and Nummedal and Fischer (1978). Mean tidal range in the open ocean ranges from 0.8-1.2 m (2.62-3.9 ft). The shoreline is oriented generally east to west (70°) and consists of low, narrow barrier spits alternating with headland bluffs. The barriers are 1-8 km (0.6-5 mi) long, 200-300 meters (656-984 feet) wide, have foredune zones commonly 1-4 meters (3.3- 13.1 feet) in relief, and backbarrier flats dominated by overwash processes during major storms (Boothroyd et al., 1985). The headland bluffs range in relief from 1-25 meters (3.3-82 feet) and are fronted by sand or gravel beaches, but lack an aquatic habitat landward of the beach. The bluffs here are composed largely of Pleistocene-age glacial deposits (Boothroyd and McCandless, 2001; Boothroyd et al., 2003; Schafer, 1961, 1965; Smith, 2010). Napatree Point, Watch Hill, Weekapaug, Green Hill and Point Judith headlands are composed of glacial till, a poorly sorted mixture of gravel (including boulders), sand, silt and clay. The Misquamicut, Quonochontaug and Matunuck

headlands are composed of stratified deposits, comprising sand and gravel deposited by meltwater emanating from retreating Laurentide Ice Sheet during deglaciation.

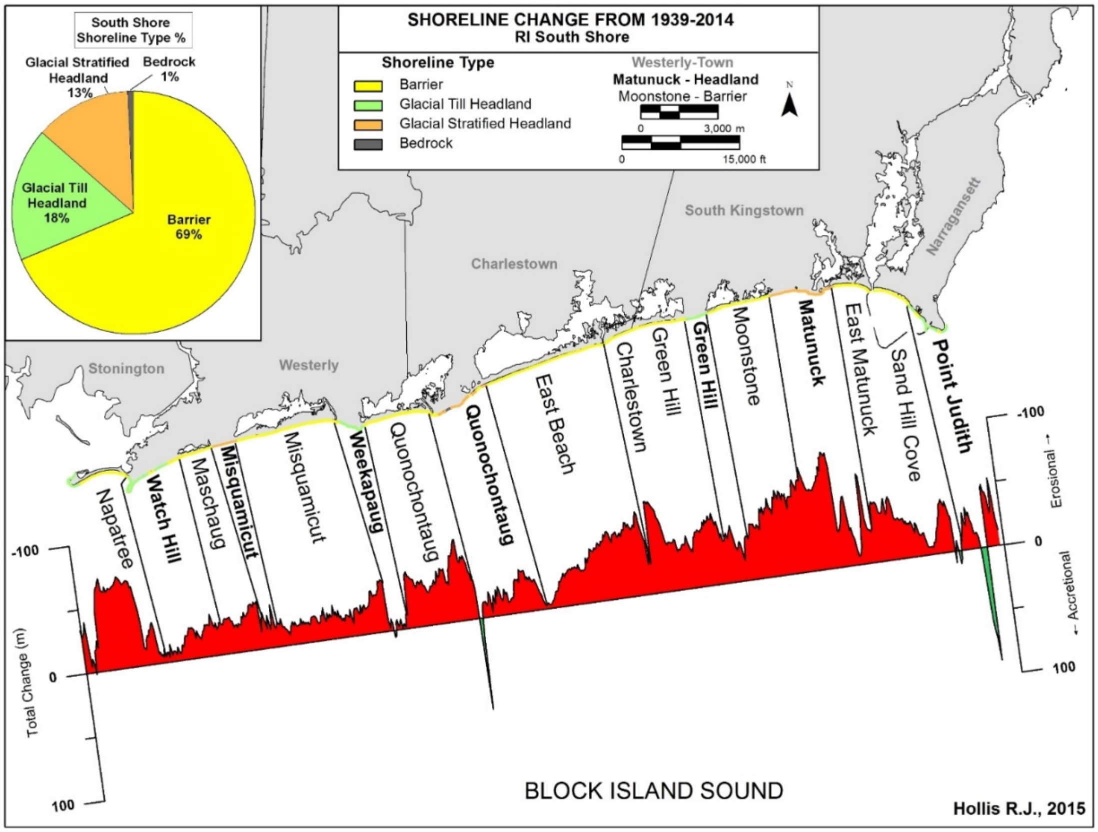

Figure 1. Shoreline type indicated as shoreline segments on the map as percentage (inset). Total shoreline change from 1939-2014 (m) along the Rhode Island south shore on the graph plotted parallel to shore. In this figure and subsequent figures, red indicates erosion and green deposition (Hollis et al. in preparation; Oakley, Hollis and Boothroyd 2016).

2. Over the long-term (decadal scale) the entire south shore is largely erosional (see Figure 1), with erosion rates ranging from near 0 to >1.5 meters/year (0 - 4.9 ft/year) (Boothroyd et al. 2016). Along the RISS, the barriers have an average annualized rate of shoreline change of 0.57 meters/year (1.9 ft/year). Coastal erosion does not occur slowly over time, rather it is the result of abrupt changes due to storms. For that reason, these annualized rates should be used with caution, and rates vary along the shoreline considerably in both space and time. The till headlands, often fronted by accumulations of boulders (i.e. Weekapaug and Green Hill), have generally lower erosion rates. The stratified headlands (Misquamicut and Matunuck), composed mostly of sand and pebble to cobble-sized gravel, have an average erosion rate of 0.75 meters/year (2.46 ft/year) comparable to (and even higher than) the barriers in some places. Some of the highest

rates of change along the RISS occur along the Matunuck Headland where the annualized rate of change exceeds 1.4 meters/year (4.7 ft/year), with total erosion approaching 90 m (300 ft) since 1951 (Boothroyd et al. 2016). See Figure 1 above.

3. Lagoons, called salt ponds in local terminology, are situated landward of the barriers. Small tidal inlets, both natural and maintained (locally called breachways) separate the spits. Natural inlets are shallow, less than 1 meter (3.3 feet) deep, and close intermittently as the longshore transport of sand tends to seal the inlet throat. Tidal range in all the lagoons is 7 to 10 centimeters (0.2 to 0.3 ft) (mean) and 16 centimeters (0.5 ft) (spring) due to the constriction of tidal-current flow through the inlets (breachways) (Boothroyd et al., 1985). The exception to this is Point Judith Pond which is connected to Block Island Sound through a relatively wider and deeper inlet and has a similar tidal range to that of the open ocean (Boothroyd et al., 1985). The maintained inlets have rubble-mound jetties and remain permanently open. The Pt. Judith Harbor of Refuge, at the east end of the RISS, is enclosed by a complex of breakwaters and functions as a large sediment sink (see Figure 1). Lastly, although the alongshore circulation picture is complex, potentially with several cells, data collected thus far suggest a net transport to the east from Watch Hill.

4.3.1.3 Geologic Setting of Narragansett Bay

1. The present geologic framework of Narragansett Bay (see Figure 2) is heavily dependent on the bedrock geology and the configuration of glacial processes, landforms and sediment type. Glacial deposits from the Late Wisconsinan deglaciation range from till to stratified deposits (gravel, sand and mud). The most prominent glacial features of western Narragansett Bay and adjacent watersheds are the large alluvial fans and deltas that drained into Glacial Lake Narragansett between 20,000 and 18,900 years before present (Oakley and Boothroyd 2013) These deltas are located primarily along the western shoreline of Narragansett Bay (i.e. the Warwick Plains delta north of Greenwich Bay) (see Figure 2) (Boothroyd and McCandless, 2003). Postglacial (Late Pleistocene to Holocene) sediment began accumulating as soon as Glacial Lake Narragansett, which occupied much of the bay and adjacent watershed during deglaciation (Oakley, 2012), drained and a rudimentary fresh-water drainage system became established on the newly emergent floor of the Bay. Holocene sediment accumulation accelerated as marine water entered the Bay and submerged the former glacial lacustrine environments (McMaster, 1984).

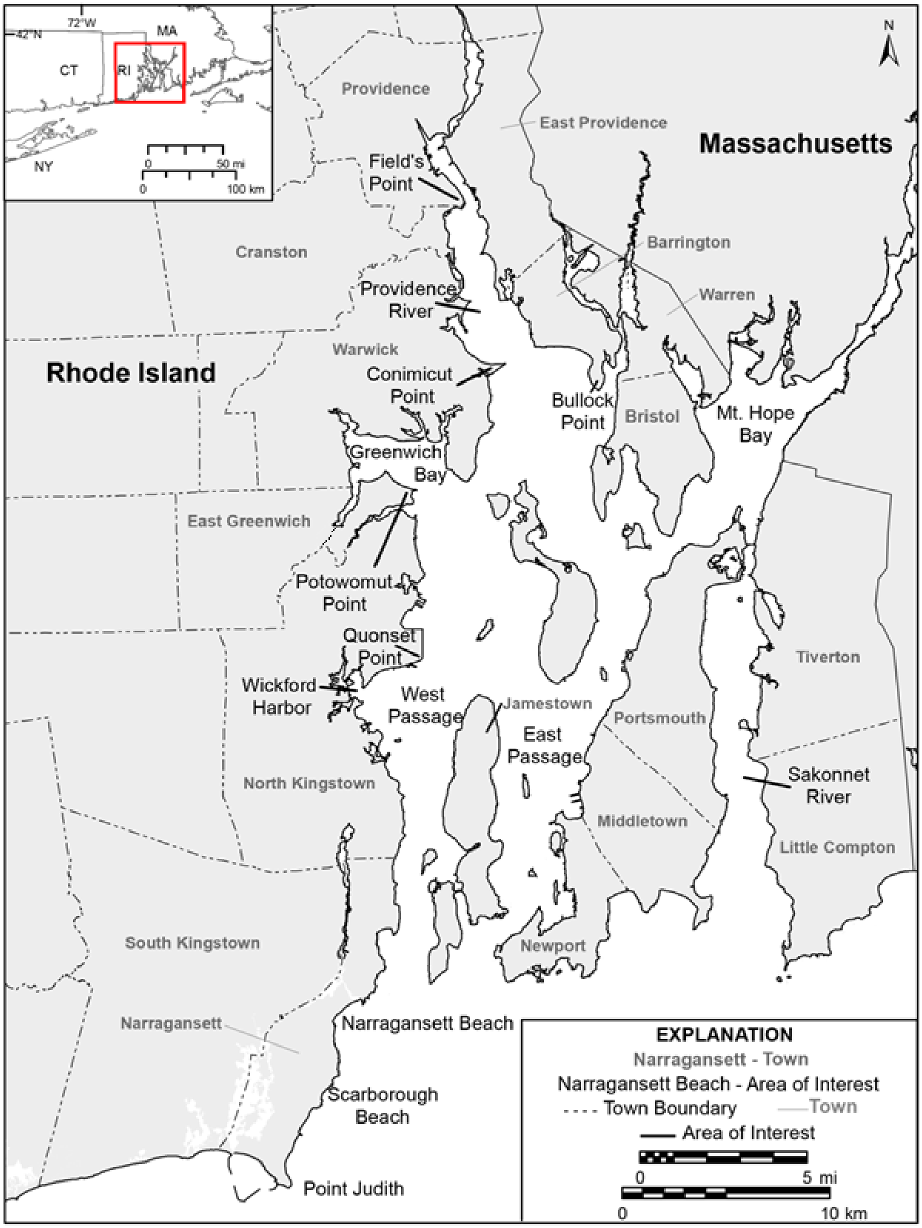

Figure 2. Location map of Narragansett Bay

2. Erosion of the Narragansett Bay shoreline contributed all sediment sizes to subtidal environments as the high-energy areas of the shoreline receded under the impact of storm events. The eroded silt and minor clay is deposited in the deeper, low-energy channels and basins along with organic silt-sized sediment formed from decaying plant material. The sand and gravel-sized sediment is deposited adjacent to the shoreline as depositional platforms and erosional terraces, and in coves as barrier spits and flood-tidal deltas. Shoreline types mapped by Boothroyd and Al-Saud, (1978) and summarized by Hehre (2007), comprise six main types (see Table 1).

Table 1. Geologic shoreline types in Narragansett Bay (modified from Boothroyd and Al-Saud, (1978) and Hehre (2007))

Shoreline Type	**Percent-age of shoreline**	**Description**	**Example**
Beach plain and barrier spit	25%	Barriers are islands or spits comprised of sand and/or gravel, formed and maintained by wave or wind energy, extending parallel to the coast and separated from the mainland by a coastal pond, tidal water body, or coastal wetland. Beach plains have a wide berm backed by a coastal feature (e.g. bluff, foredune zone).	Rhode Island School of Design beach adjacent to the RI Country Club in Barrington
Stratified glacial deposits bluff	8%	Bluff composed of unconsolidated glacial stratified material that is subject to erosion during moderate storm events. Bluff is fronted by a narrow beach composed of sand and/or gravel.	Nayatt Point
Till bluff	23%	Bluff composed of till that is subject to erosion during moderate storm events. Bluff is fronted by a beach composed of sand, gravel, and boulders.	Warwick Point
Bedrock	13%	Outcrops of metamorphosed sedimentary, igneous and metamorphosed igneous bedrock. Often overlain by till deposits or backed by a by bluffs of either glacial stratified material or till that are protected from wave erosion by all but the largest storms Small, gravelly, pocket beaches are sometimes present.	Beavertail, Cormorant Point (Narragansett)
Discontinuous bedrock	1%	Discontinuous bedrock outcrops shelter areas of unconsolidated material between outcrops including, beach plains and barrier spits, glacial stratified material, and till.	Common Fence Point (Portsmouth)
Shoreline protection structures	30%	Characterized by physical alterations to shoreline including groins, jetties, revetments, bulkheads, and seawalls. If the structure is effective, the natural shoreline features are no longer dominant.	Various throughout Narragansett Bay

4.3.1.4 Physical Processes

Wind Speed and Direction

1. A comprehensive review of wind conditions for inland areas and coastal waters of the state can be found in work performed as part of the RI Renewable Energy Siting Partnership and the RI Ocean Special Area Management Plan. See Grilli et al. (2012) and Merrill et al. (2012) for the inland areas, and see Grilli et al. (2010) and Spaulding et al. (2010a and 2010b) for coastal waters. Only a high level summary is presented here.

2. Winds in the area are predominantly from the west, with winds from the northwest in the winter, the southwest in the summer, and the west in the transition seasons. Wind speeds are typically stronger in the winter from the northwest. Wind speed increases with distance offshore from the coast and decreases landward due to enhanced friction caused by the roughness of the land cover. Mean annual wind speeds increase from approximately 7 m/sec (16 mi/hr) for coastal stations to 8 m/sec (18 mi/hr) for offshore locations. Extreme wind speeds also typically increase with distance offshore increasing from 35 m/sec (78 mi/hr) nearshore to 39 m/sec (87mi/hr) offshore for the 100 year return period winds. Winds used for design of coastal structures are included in the state building code. The 100-year, 3-sec peak gust design wind speeds immediately adjacent to the Rhode Island coast are 49 m/sec (160.8 ft/sec) and decrease with distance inland.

3. The strongest winds observed in the area are the result of extratropical storms (nor'easters) generally occurring in late fall, winter, and early spring and tropical storms (hurricanes) in the summer and early fall. Of the two, hurricanes typically result in the strongest winds and the speeds are dependent on the storm strength; the higher the strength the stronger the winds. NOAA categories storms from Category 1 to 5, with increasing strength as the category number increases. Hurricanes with tracks to the west of the state result in the highest storm damage in Rhode Island given the superposition of the cyclonic storm winds being reinforced by the forward motion of the storm (Hashemi et al. 2016, 2015). The strongest storm Rhode Island has experienced in recent history is the 1938 Hurricane which was downgraded from a Category 4 to a Category 3 storm as it made landfall at the western end of Long Island Sound. The most recent storm to impact Rhode Island was Superstorm Sandy (2012), which reached the coast as a tropical storm and merged with an extratropical storm to generate a hybrid storm. The path of Sandy was quite unusual with a sharp turn to the northwest from its earlier shore parallel path.

4. Figure 3 illustrates how the most destructive area of a storm in the Northern Hemisphere is the right front quadrant. Applying this concept to Rhode Island, Figure 4 illustrates how

the most dangerous storms track to the west. Such storms have winds from the south or southeast in excess of 40 m/second (131 ft/second) (Wright and Sullivan, 1982). Figure 5 and Figure 6 show the tracks of historic hurricanes which have impacted Rhode Island (the hurricane of 1938, Hurricane Carol (1954), Hurricane Bob (1991) and superstorm Sandy (2012)) and illustrate how most of these storms tracked to the west of the state. The impact of a tropical storm depends on its path as well as the storm's strength, forward speed, and radius to maximum winds. The forward speed of a storm adds to the rotation speed of the storm, which is dependent on the storm's strength. With regard to Rhode Island, this leads to the right front quadrant being the location where the winds are strongest in the up-Bay direction. The strongest storm surges are also dependent on the radius to maximum winds and how far the center of the storm is from the area of interest. While the historic storms shown in Figure 5 and Figure 6 illustrate the right front quadrant issue, these storms differed with regard to other parameters. For example, the 1938 hurricane's strength was high (Category 3), forward speed was extremely high (60 mph), and the path and radius of maximum winds put RI in its bullseye. For Sandy, the storm was very weak (Tropical Storm) and forward speed was not very high, but the storm had a very large radius to maximum winds, thus its impact to RI.

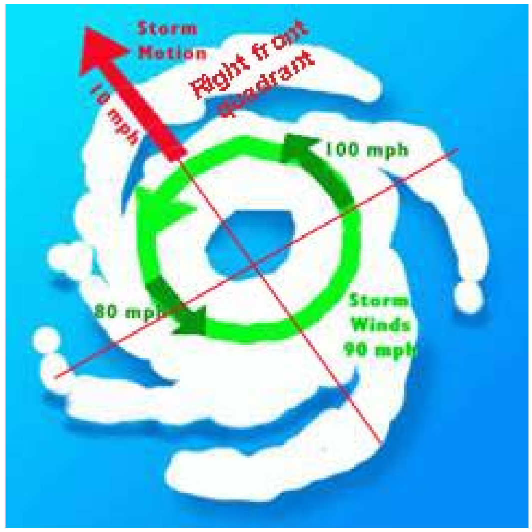

Figure 3. In the Northern Hemisphere, the right front quadrant of a storm is the most destructive area of the storm, with the strongest winds, seas, and resultant storm surge. (Source: University of Rhode Island, "Hurricanes: Science and Society," 2015; image adapted from the NOAA Atlantic Oceanographic & Meteorological Laboratory Hurricane Research Division.)

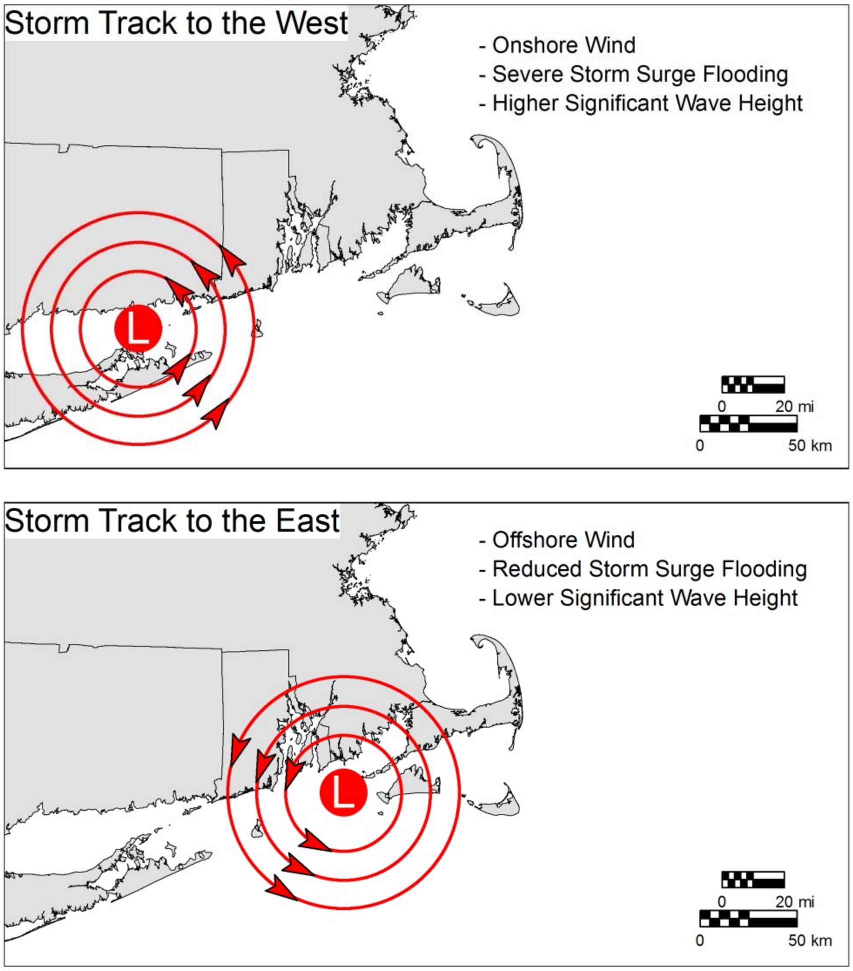

Figure 4. Wind, storm surge and wave height effects of westerly and easterly storm tracks (modified from Wright and Sullivan 1982)

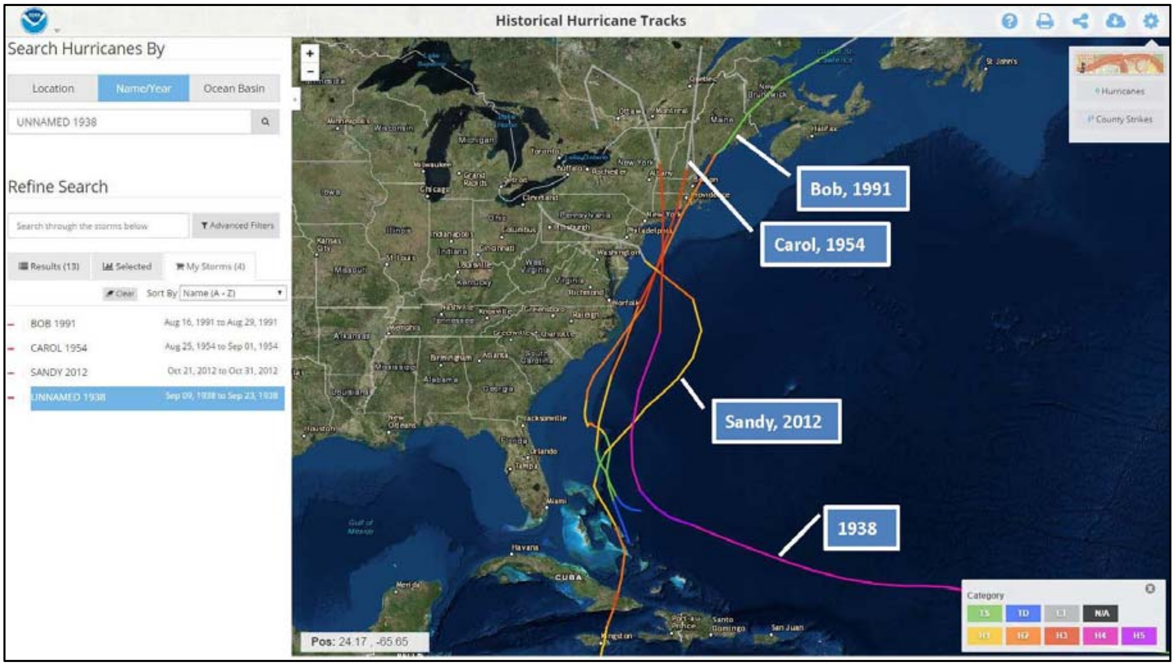

Figure 5. Map of historic hurricane tracks, Atlantic coast (Source: NOAA Digital Coast 2017, "Historical Hurricane Tracks," https://coast.noaa.gov/digitalcoast/tools/hurricanes.html)

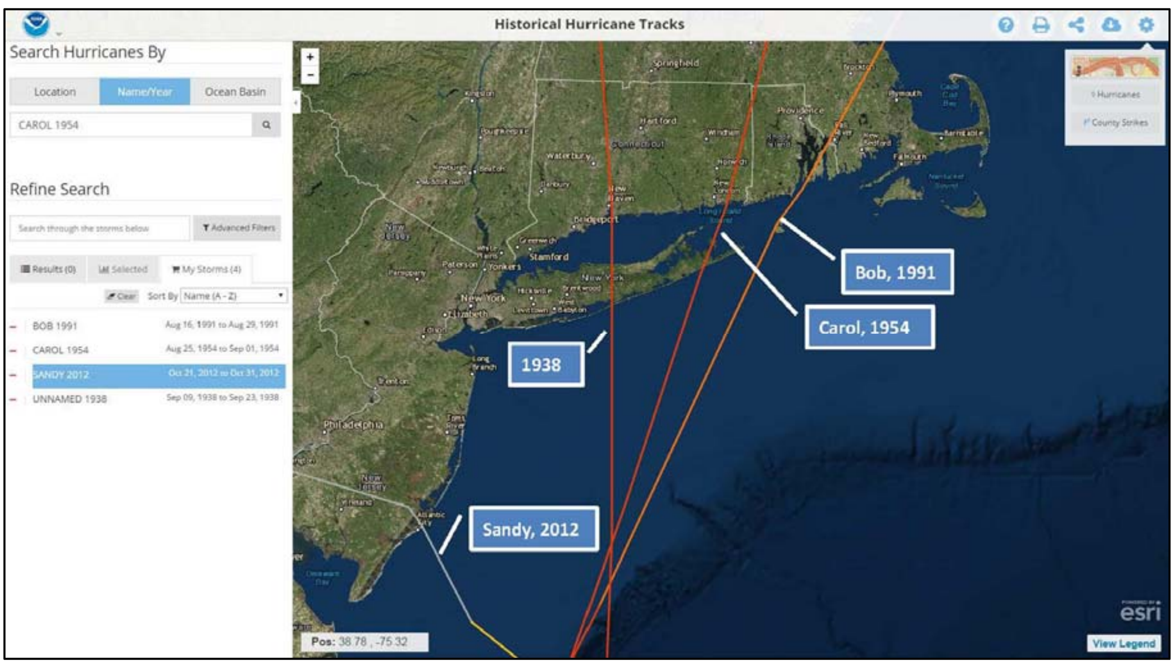

Figure 6. Map of historic hurricane tracks, northeastern U.S. (Source: NOAA Digital Coast 2017, "Historical Hurricane Tracks," https://coast.noaa.gov/digitalcoast/tools/hurricanes.html)

Circulation in Narragansett Bay and RI Coastal Waters.

1. A recent comprehensive review of the circulation in Narragansett Bay is presented in Spaulding and Swanson (2008), and in Codiga and Ullman (2010) and Ullman and Codiga (2010) for RI coastal waters (RI and Block Island Sound). Grilli et al (2010) have also performed detailed, high resolution hydrodynamic modeling of the Block Island and RI Sounds, Buzzards Bay, and adjacent coastal waters. Only a high level summary is presented here.

2. The circulation in RI waters is dominated by semi-diurnal tides, with a periodicity of 12.42 hrs. On flood/ebb, the tide propagates from offshore toward coast/from the coast toward offshore and bifurcates in RI Sound, with flooding/ebbing to the west/east into Block Island (and eventually Long Island Sound), to the north/south into Narragansett Bay, and to the east/west into Buzzards Bay. The mean tidal range along the southern RI coastline is approximately 1 m (3.3 ft), comparable to the value at the NOAA NOS Newport gauging station of 1.06 m (3.08 ft). The greater tidal range at Newport is 1.17 m (3.84 ft); greater tidal range is defined as the difference between Mean Higher High Water(MHHW) and Mean Lower Low Water(MLLW). The mean tidal range increases approximately linearly with distance up Narragansett Bay and reaches a value of 1.35 m (4.43 ft) at Providence. The greater tidal range at Providence is 1.48 m (4.86 ft). The tides hence are amplified by approximately 28% with distance up Narragansett Bay as a result of the standing wave nature of the system.

3. Tidal currents in RI waters are typically quite modest (below 50 cm/sec at peak values) given the relatively low tidal range and lack of strong geographic constraints, with the exception of currents at tidal inlets where higher velocities have been observed. Tidal currents (typically two dimensional) in the bay display an unusual double peak flood, single peak ebb behavior due to the resonance of harmonics (over-tides) of the principal semi-diurnal. This behavior is absent in offshore waters. Stratification of the water column is typically quite limited. Density-induced (fresh water) currents are typically observed in areas close to river discharges, such as where the Seekonk/Blackstone River discharge into the Providence River and the Taunton River discharges into Mt Hope Bay. Wind driven flows are strongly dependent on the wind forcing events, both in terms of dynamics of the event and its passage relative to the tides.

Storm Surge

1. The strongest variations in water level and currents are caused by storm winds from either extratropical (nor'easter) or tropical (hurricanes) storms. The surge resulting from these events is superimposed on the existing tides and hence the tidal stage can make a

significant difference in the surge heights. As an example, if the peak surge of 1 m (3.3 ft) arrives at low tide, the peak water level at Newport is no higher than the water level at high tide. If it occurs at high tide, the water level effectively doubles to 2 m (6.6 ft). To further complicate the situation, the time scale for passage of storms is several days for an extratropical storm, but only 6 to 10 hrs for a tropical storm, the latter being consistent with the semi-diurnal time scale. Alignment of peak storm surge with spring high tide results in the highest surge levels.

2. Elevation of storm surge can be measured using water level gauge records (i.e. the Newport gauge) and estimated from observations and photographs taken during and after storm events. The NACCS reported surge elevations during a 100-year storm event exceeding 3.6 m (12 feet) throughout the bay, and reaching 5.3 meters (17.5 feet) in the Providence River. A review of the extreme water elevations recorded by NOAA NOS at Newport and Providence show that the highest levels are attributed to tropical storms with 1938, 1944, Carol (1954) and Bob (1991) dominating. The 1938 Hurricane surge in Newport peaked at 2.9 m (9.5 ft) above MHHW (3.5 m (11.3 ft) relative to NAVD88)); and in Providence, 1938 Hurricane surges peaked at 3.9 m (12.8 ft) above MHHW (4.6 m (15.1 ft) relative to NAVD88)) (NOS, 2017b). During Hurricane Carol in 1954, storm surges in Newport peaked at 2.1 m (6.9 ft) above MHHW (2.62 m (8.6 ft) above NAVD88) (1954 data are not for Providence) (NOS 2017c). The largest extratropical storm of January and February 1978 ranks 4th in Providence and 6th in Newport out of the top ten events. Spaulding et al. (2015a, 2015b) have performed an analysis of the top ranked events, when data are available at both Newport and Providence, and show the surge levels scale with distance up the bay. Scaling values vary from a low of 1.1 to a high of 1.4, with an average of 1.3. The latter is comparable to the tidal amplification in the bay noted above. The scaling is strongly correlated to the strength, forward speed, radius of maximum winds, and track of the storm (Hashemi et al, 2016).

3. Spaulding et al. (2015a) have performed a detailed analysis of simulations performed by NOAA using their Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model for tropical storm events by strength (Category 1 to 4).[2] Category 5 is excluded since no storm of that strength has reached Rhode Island waters. The analysis shows that surge levels are approximately constant along the southern RI coastline and comparable to the level at Newport. Surge levels then increase linearly with distance up Narragansett Bay, with a scale factor of 1.4 when referenced to Newport. Spaulding et al. (2015b) also performed a detailed analysis of the predicted surge levels performed as part of the

[2] For further information see www.nhc.noaa.gov/surge/slosh.php.

Army Corp of Engineers, North Atlantic Coast Comprehensive Study (NACCS) for 1,050 synthetic tropical storms (Cialone et al, 2015). Simulations were performed for surge only and surge plus tide cases. The analysis once again shows that the surge levels are approximately constant along the southern RI coastline and increase linearly with distance from the mouth to the head of the bay. The surge levels for the 100-year return period surge scale linearly with distance up the bay, with the scale factor dependent on inclusion of the tides and whether the mean or upper 95% confidence value return value is used. STORMTOOLS flooding maps are based on the scaling factors from this analysis for the selected return periods of interest (e.g. 25, 50, and 100 yrs) using the Newport levels as the base. The scaling is based on the upper 95% confidence interval value, surge plus tide case to address uncertainty in the modeling and data analysis methods and to ensure the effects of tides are considered. The 100 yr water level at Providence for this case is 5.49 m (18.0 ft), compared to a value of 3.93 m (12.9 ft) at Newport (both NAVD88 referenced), giving a scale factor of 1.4 relative to Newport. As an alternative, the NACCS study provided return period analysis for water levels at selected save points (approximately 1,000) covering the RI area. Most of the save points are located immediately along the shoreline. These data are also available via STORMTOOLS and can be used to give very high resolution estimates of surge heights (with and without tide) over the entire range of return periods, including mean and upper and lower 95% confidence interval values.

4. When the elevation of the storm surge and wave runup exceeds the elevation of the coastal feature, water moves rapidly over low barrier spits and headlands in a process called overwash. Driven by the wind, waves and swash of the storm, overwash delivers sediment eroded from the beach, dunes, and front of the barrier onto the backbarrier flat and into the lagoon, or onto the low surfaces of headlands. The overwash process results in deposition of washover fans on the back of the barrier or top of the headland and the formation of storm-surge platforms in the lagoons. During overwash, temporary storm-surge channels are eroded through the barriers, providing a conduit for sediment and water into the lagoon. Shallow, temporary inlets, or surge channels formed along the Misquamicut Barrier during the 1938 Hurricane and Hurricane Carol (1954); deeper inlets also formed along Napatree, Quonchontaug and Winnapaug Barriers in the 1938 hurricane (Nichols and Martson, 1939) . These areas will likely be subject to similar breaches during future significant storm events.

5. The resulting storm-surge deposits form extensive storm-surge platforms within the coastal lagoons and raise the elevation of the back barrier flat, making the barriers more resilient to sea level rise and storm impacts. It has been known for some time (Godfrey and Godfrey, 1976; Leatherman, 1979), and more recently reinforced (Houser and

Hamilton, 2009; Timmons et al., 2010), that overwash and subsequent deposition of washover fans onto the backbarrier is critical for barriers to continue to migrate in response to storms and sea level rise. This geologic process, which can look catastrophic in the immediate aftermath of a storm, is vital to the evolution of the shoreline in response to future storms and sea level rise. While the response and fate of barriers to sea level rise is complicated and ultimately dependent on a number of factors (Moore et al., 2010), leaving these deposits in place following a storm allows for a better chance of the barriers to migrate in response to sea level rise and future storms (FitzGerald et al., 2008).

6. Coastal processes during storms remain difficult to quantify, however surge velocity can be estimated from photographs taken after the 1938 and 1954 hurricanes. Bedforms (small dunes), created by the flow of surge across the spit, and visible in post-storm photographs of Conimicut Point, have a crest-to-crest spacing of > 2 meters (6.6 feet) (Ashley, 1990). These bedforms require a flow velocity of close to 1 meter/second (3.3 feet/second), and represent a *minimum* velocity of storm surge. Calculated design flood velocities (velocities associated with base flooding) during 100-year events increase with increasing surge depth, and the upper limit of the design flood velocity for a water depth of 3.3 meters (10 feet) approaches 5 meters/second (17 feet/second) (FEMA, 2011).

Wave

1. Observations of waves in Rhode Island Sound and Block Island Sound have been very limited with no long term observation stations in the area. Wave observations were collected at three stations located along the immediately offshore of the southern RI coastal line (Misquamicut, Charlestown and Matunuck) from a recent study performed on behalf of the US Army Corps of Engineers (WHG, 2012). Measurements were made from approximately July 2010 to September 2011 and show significant wave heights were typically 1 m (3.3 ft) or less, with periods typically ranging from 5 to 11 sec, and directions generally from the southwest to southeast. The observations captured wave heights during the passage of Tropical Storm Irene, which made landfall 200 km (125 mi) west of Charlestown on August 28, 2011), which included a maximum significant wave height of 4.1 m (13.5 ft), with a peak period of 10 sec, at the Charlestown station. A maximum wave height exceeding 6 meters (19.7 feet) (WHG, 2012) was observed during that same storm at Acoustic Doppler Current Profiler sites in 9 meters (29.5 feet) of water in Block Island Sound.

2. The U.S. Army Corps of Engineers performed wind and wave hindcast in the Wave Information Study (WIS)[3] for selected locations off the coast from 1980 to 2014 . WIS provides time series of wave spectral parameters as well as some general statistical analysis. As an example, for the site closest to the coast and directly east of Block Island in a water depth of 33 m (108.3 ft) (# 63079), the annual mean significant wave heights is in average of the order of 1.0 m (3.3 ft), varying between 0.5 to 1.6 m and the annual mean peak period is 8 seconds,in average varying between 5 and 11 seconds. Waves are predominately from the south and south-southeast sectors. The 100-yr significant wave height at this station is estimated to be 9.7 m (30.8 ft) with a peak period of the order of 17 sec. During superstorm Sandy significant wave height at this location was hindcast to be 8.6 m (28.3 ft), with a peak period of 15 sec, from the southeast.

[3] For further information see http://wis.usace.army.mil/.

3. The U.S. Army Corps of Engineers, in the context of the North Atlantic Coast Comprensive Study (NACCS),[4] has performed simulations of synthetic tropical storms (1,050) and historical extratropical storms using state of art, coupled surge and wave models providing estimations of the wave characteristics at thousands of virtual stations or “save points” (Cialone et al 2015; Jensen et al. 2016). In addition the NACCS provided an extreme value statistical analysis of the simulated data at the save points. The data have been provided in the form of peak values for each event and in the terms of wave heights vs return periods. The data is provided at the same save points as the surge level data describe above. This data has been analyzed in depth and compared WIS data at selected locations by Spaulding et al. (2015b, 2017a, 2017b). The NACCS data generally show slightly higher wave heights and longer periods for the 100 yr return period than the WIS hindcast, consistent with the limited length of the WIS hindcast period. Access to the NACCS wave data is available via STORMTOOLS, providing contour maps of the 100-yr surge as well as wave heights vs return period curves for the save points The focus of the NACCS analysis is on wave heights associated with tropical storm events and not locally generated waves(Spaulding et al. 2015b, 2017a, 2017b). The wave pattern in RI coastal waters is quite complicated as a result of the complex bathymetry and associated refraction and diffraction in the vicinity of Block Island Sound. In particular, the shielding from the eastern end of Long Island Sound ,the shoal from Montauk to Block Island fronting the deeper Block Island Sound and the presence of Block Island strongly affect the tropical storms’wave pattern generally propagating from the South (Spaulding et al, 2017a). Additional information on these effects can be found in recent work performed as part of the Ocean SAMP (Asher et al, 2010; Grilli et al, 2010) with a particular focus on the area in the vicinity of the Block Island wind farm.

4. A review of the NACCS 100-yr return period significant wave height immediately offshore shows values of approximately 9 m (29.5 ft) at the entrance to Narragansett Bay decreasing to 7 m (23.0 ft) at Charlestown and finally to 6 m (19.7 ft) at Misquamicut. The wave period is about 20 sec and the direction typically from South to South East. 100-y significant wave height south of Block Island is typically 9 m (29.5 ft) or greater. The pattern of decreasing wave height with distance westward along the RI shoreline from the bay entrance is a result of the complex interaction of the wave field with the coastal topography and bathymetry. The interaction of these large waves as they break with shallowing water depths results in wave induced set up typically on the order of 0.5 to 1 m and a substantial reduction in wave heights (Spaulding et al, 2017a).

[4] For further information see http://www.nad.usace.army.mil/CompStudy/

5. Historically there have been no observations of the waves in Narragansett Bay. The bay is thought to have a relatively low wave energy environment given the shallow water. Wave modeling predict (Spaulding et al. 2017b) significant wave heights for the 100 yr event of the order of 9 m (29.5 ft) and 20 sec of peak- period at the bay mouth. These large waves decrease dramatically once entering the bay. Indeed the shallow water in the bay induces dissipation by friction for the longer waves as well as wave breaking limiting the wave energy propagating in bay. However, southerly wind conditions provide enough fetch to create local short-waves which can grow significantly in the upper part of the bay reaching up to 2 m (6.6 ft), although limited by whitecapping (breaking due to high curvature of short waves). A good example of significant wave action in the upper section of the bay is shown by the significant erosion observed at Oakland Beach on the northern shore of Greenwich Bay. The pattern in the bay is hence quite complex, with southern facing coastlines showing the largest wave heights. The model predicts waves that are consistent with observations of erosion on Oakland Beach and other exposed shorelines.

4.3.1.5 Shoreline Protection Structures

1. Where a shoreline type (see Table 1) has been modified by the construction of a shoreline protection structure that is viable and functional (that is, the structure either traps sediment or offers protection from direct wave action on a bluff or foredune), the shoreline is reclassified to reflect the shoreline protection structure (“hardened shorelines”). Great care was taken in Boothroyd and Al-Saud’s original study of shoreline protection structures in 1978 to ensure that the structure actually was viable. If not, the shoreline was classified based on the geologic habitat even though a structure may have been present. Shoreline protection structures (working) comprised 24.5 percent of the Bay shoreline in 1978 (Boothroyd and Al-Saud, 1978). A complete inventory of the type and condition of shoreline protection structures has not been undertaken statewide. However, shoreline change mapping in the Bay using 2003 orthophotography suggest that 30 percent may more closely represent actual length of these structures, as additional structures were likely constructed in areas where they are not prohibited (Boothroyd and Hehre, 2007). This points to the need for a new, systematic review of the state’s shoreline protection structures; see Section 4.8, Future Research Needs, for further discussion.

2. Shoreline protection structures may be revetments, bulkheads, seawalls, groins, breakwaters or jetties. See Section 300.7 of the RI Coastal Resources Management Plan (Redbook) (RI CRMC 1996, as amended) for a fuller discussion of structures. Other structures, such as piers, are not strictly protection structures but often have a

protection element such as a seawall incorporated in the facility. Structural installation ideas have evolved through time. Pre-1954 seawalls were often concrete, and newer walls constructed of wood, sheet pile or rip-rap have replaced or in some areas, have been placed in front of, the pre-1954 concrete walls. Based on CRMC's permitting history and experience, the design of most such structures (i.e. wall height, stone size, return period event for which wall is designed, and other construction features) is insufficient to protect against the intensifying storm conditions discussed in this document (see Chapter 2 for detailed discussion and references). Further,such structures are typically designed to protect adjacent land, not necessarily the residential and other structures constructed on that land.

Impact of shoreline protection structures

1. The construction of new structural shoreline protection facilities on all barriers classified as undeveloped, moderately developed and developed and along all Type 1 waters has been prohibited in Rhode Island for more than 30 years pursuant to Section 300.7 of the RI Coastal Resources Management Program. Only maintenance of existing structural shoreline protection facilities is permissible in these cases, and these facilities cannot be expanded beyond preexisting conditions. If a shoreline protection structure has been physically destroyed 50% or more by wind, storm surge, waves or other coastal processes, or must be demolished to be maintained or repaired, such an application is subject to current CRMC prohibitions and regulations. Construction of shore parallel shoreline protection structures (seawalls, revetments, bulkheads etc.) along eroding bluffs and dunes have negative impacts to beaches directly in front of the structure, as well as adjacent shorelines. There can be an immediate response (placement loss), or loss can occur over time (loss of fronting beach and impacts to adjacent shorelines due to sediment impoundment. Impoundment refers to the retention of sediment behind structures which otherwise would be available to replenish beaches when eroded from the bluff/dune). Placement loss represents a direct and instant loss of the beach when the construction of structures (i.e. revetments) extend onto the adjacent beach (Griggs, 2005; Pilkey and Wright, 1988). While vertical structures can impact some portions of the beach, sloping structures typically have a greater impact. Revetments are typically constructed at slopes of 1.5 or 2 to 1, so a revetment built on a 15-foot bluff face has a footprint of at least 30 feet at the base. This encroachment onto the adjacent beach may have minimal impact on wide beaches, however this impact can be significant on narrower, steeper (frequently gravelly) beaches (Griggs, 2005). Additional impacts occur in cases where one protected structure extends further seaward than adjacent structures. This disrupts longshore sediment transport, causing sediment accretion on the updrift side of the structure but erosion to the downdrift shoreline(USACE 2002).

2. Significant controversy remains regarding the acceleration of erosion (i.e. "active erosion" in the parlance of Pilkey and Wright, (1988)) in front of the shoreline protection structures (Dean, 1987; Griggs, 2005; Kraus, 1988; Kraus and McDougal, 1996; USACE, 2002). Less controversial is additional erosion immediately adjacent to the shoreline protection structures (known as edge effects or flanking) as well as the potential for additional impacts for structures down the sediment transport direction (USACE, 2002). The Coastal Engineering Manual (USACE 2002) provides a review of the potential impacts of shoreline protection structures (accelerated erosion, hindering post-storm recovery etc.). Largely based on Dean (1987), the manual concludes that many of the notions regarding the impact of structures on the frontal beach are not definitive and may require further research. This represents a change from the earlier USACE Shore Protection Manual (USACE, 1984), which noted that when constructed on eroding shorelines, erosional processes may be intensified.

3. Regardless of whether shoreline protection structures accelerate shoreline change in front OR simply makes the continuation of shoreline migration more noticeable, the fact remains that along an eroding coast, the position of the shoreline will continue to migrate. This results in a narrowing beach in front of the structure (Pilkey and Wright, 1988; USACE 2002). Once the shoreline reaches the structure, the beach in front will be lost. While this is sometimes referred to as "passive erosion" (Pilkey and Wright, 1988), it can simply be thought of as the continuation of the coastal processes on a migrating shoreline. Once the adjacent shorelines migrate landward of the shoreline protection structure, the protruding structure can change the local wave refraction patterns and interrupt longshore sediment transport along the coast, affecting downdrift shorelines (USACE, 2002).

4. Sediment impoundment behind armored bluffs (and dunes) is another impact of shoreline protection structures (Griggs, 2005; O'Connell, 2010). Armoring the coastal bluffs impounds sediment behind the structure that would otherwise have been eroded from the bluff, contributing sediment to the coastal system. The coastal bluffs (headlands) in Rhode Island are composed of a glacially deposited sediment ranging from sand and gravel along the stratified headlands to glacial till (a diamict composed of gravel, sand silt and clay) (Boothroyd et al., 2001; Kaye, 1960, Schafer, 1961, 1965). With an instantaneous berm volume of approximately 1,000,000 m^3 (approximately 1,100,000 yd^3) along the 30 km (18.6 mile) south shore, this represents a relatively sediment starved system (Boothroyd, 2002). Most of the sediment within the coastal system is derived from the erosion of the glacial bluffs, and transported by longshore currents to adjacent shorelines. Longshore transport of sediment eroded from the bluffs is the primary mechanism responsible for the formation of the barrier spits along the shoreline.

Some sediment may be brought onshore in a manner as observed along Fire Island, NY (Schwab et al., 2013), however the lack of an offshore bar system in Rhode Island suggests this is likely not a significant source of sediment. Little to no sediment is transported down the rivers to the coastal system in Rhode Island (Ji et al., 2002).

5. The amount of sediment impounded behind shoreline protection structures that is lost to the coastal system varies depending the height of bluff/dune being armored, alongshore extent of the structure and estimated shoreline change (erosion) rate of the bluff, combined with the proportion of sediment within the bluff that is compatible with the beach, (generally any sediment sand-sized and larger). As an example, a 30 meter (100 ft) wide structure installed on a sandy bluff that is 3 meters (10 feet) tall, with a historic shoreline change rate of 1.1 m/year (3.3 ft/year), represents a loss of $90m^3$/yr (120 yd^3/yr) to the coastal system. Without on-going (and permanent) beach replenishment, this loss of sediment will impact the beach in front of the structure as well as adjacent shorelines (Griggs, 2005).

6. Shoreline protection structures result in negative impacts including loss of lateral access; ecological impacts; and cumulative impacts. A significant negative outcome of these structures and the processes described above is the loss of lateral access along the shoreline in front of these structures. Beyond the physical alteration of the structure and loss of access, construction of hardened structures has deleterious ecological impacts on adjacent structures (Cooper et al., 2017; Dugan et al., 2008). The construction of these structures can have a significant cumulative impact, and it has been estimated that on Cape Cod, complete armoring of the bluffs would lead to a loss of fronting beaches within a century (Giese et al., 2015). Similar values have been reported from California, where modelling suggests 31-67% of southern California beaches could erode completely by 2100 with >2 m (6.6 ft) of sea level rise (Vitousek et al., 2017).

4.3.2 Coastal Wetlands

4.3.2.1 Overview

1. This section summarizes what is known to date about the exposure of Rhode Island's coastal wetlands to storm surge, coastal erosion and sea level rise. For CRMC's policies regarding coastal wetlands, see the RICRMP. For information on adaptation strategies regarding coastal wetlands, see Chapter 7 of the RI Shoreline Change SAMP.

2. Coastal wetlands include salt marshes as well as brackish or freshwater wetlands. This section focuses on salt and brackish marshes, i.e. those that are mostly vegetated, tidal, and saline. Coastal wetlands include areas of open waters within coastal wetlands,

wetlands directly associated with non-tidal coastal ponds, or wetlands located on a barrier beach or separated from tidal waters by a barrier beach. As of 2010, according to the National Wetlands Inventory there were 3,742 acres of coastal wetlands within the state of Rhode Island and 4,172 acres when including Connecticut and Massachusetts contiguous areas that are part of RI's coastal wetlands complex (see RI CRMC 2015).

3. Salt marshes are typically characterized by distinct high and low salt marsh zones. High salt marsh is the marsh area typically flooded by spring, moon or storm tides but not on a daily basis. Low salt marsh is the portion of a marsh that is flooded daily. Each zone is dominated by distinct types of vegetation with varying tolerances to salt water, which makes these areas particularly dependent on and sensitive to changes in frequency and duration of flooding.

4. Coastal wetlands are critically important because of the functions and values they provide to humans and the environment. These ecosystem services include providing habitat for finfish, shellfish, birds, mammals, and invertebrates, including species important to commercial and recreational fishermen, hunters, birders, and other outdoor enthusiasts (Kutcher 2017). Examples of species of commercial interest in Rhode Island include summer and winter flounder and blue crabs (Raposa and Roman 2001, Raposa 2003). Ecosystem services also include influencing water quality through the filtering, uptake and storage of sediment, nutrients and pollutants (Kutcher 2017). Additionally, coastal wetlands serve as important and effective long-term carbon sinks. Coastal wetlands are known to sequester substantial amounts of carbon, primarily in the organic underlying soils, aiding in climate change mitigation (Howard et al. 2017). Drake et al. (2015) estimate that the annual carbon sequestration rate for northeast tidal marshes is 74 – 127 grams of carbon per square meter per year.

5. Coastal wetlands provide habitat for finfish and shellfish species that are important to Rhode Island's commercial and recreational fishing industries. These industries are of great economic, social and cultural value to the state and the region. In 2015, NOAA reported that RI recreational fishing generated $332 million in sales, $141 million in income, $217 million in value added to the economy, and supported 3,554 jobs. In that same year RI commercial fishing – excluding imports - generated $100 million in sales, $44 million in income, $57 million in value added to the economy, and supported 2,107 jobs (NOAA 2015). The loss of nursery habitat for finfish and shellfish species important to commercial and recreational fisheries could result in impacts to these valuable industries and in particular to the fishing community of Point Judith, which supports these industries. For more detailed information on Rhode Island's recreational and

commercial fisheries please see CRMC's Rhode Island Ocean Special Area Management Plan (2010) at http://www.crmc.ri.gov/samp_ocean.html.

6. Ecosystem services provided by coastal wetlands also include flood protection for residential and commercial properties as well as erosion control for the natural and built environments. Coastal wetlands can enhance coastal resilience through wave attenuation and shoreline stabilization, protecting adjacent structures from these impacts (Shepard et al. 2011; Kutcher 2017). A 2008 study estimated that salt marshes provide $8,240 worth of protection, per hectare, from coastal storms each year, totaling $23.4 billion in coastal storm protection throughout the United States (Costanza et al. 2008).

7. Coastal wetlands in Rhode Island and elsewhere have suffered widespread degradation over time due to past and ongoing human-induced stressors. Human activities impacting coastal wetlands have included filling, mosquito ditching, impoundment, nutrient loading, and the influx of invasive plant and animal species as well as alterations to tidal hydrology (e.g. infrastructure that impedes tidal exchange) (see Kutcher 2017 and the sources cited therein). A 2005 study that analyzed historical maps estimated that Rhode Island lost approximately 1,831 hectares (4,524 acres), or 53%, of salt marshes over the previous 200 years (Bromberg and Bertness 2005).

4.3.2.2 The Effects of Sea Level Rise and Other Coastal Hazards on Coastal Wetlands

1. Salt marshes are unique in that the frequency and duration of tidal flooding play a significant role in controlling physical and biological processes, making marshes especially sensitive to changes in flooding (Roman et al. 1997, Mitsch and Gosselink 2000). Additionally, salt marshes are sustained through the accretion of sediment and the settling of organic matter, but in Rhode Island accelerating sea level rise is outpacing accretion (Raposa et al. 2015). As a result, salt marshes in Rhode Island and elsewhere are showing signs of erosion, ponding, drowning, and shifts in vegetation (Warren and Niering 1993, Donnelly and Bertness 2001, Raposa et al. 2016a, Watson et al. 2016).

2. Recently, evidence is mounting that accelerating sea level rise is having demonstrable impacts on coastal wetlands in Rhode Island and elsewhere, exacerbating the trend of marsh degradation and loss (Kutcher 2017). A nationwide study found that southern New England salt marshes are among the most vulnerable to sea level rise in the entire U.S. (Raposa et al. 2016b).

3. Coastal wetlands face many human-induced stressors, and sea level rise may work in a synergistic way with some of these stressors (and other natural factors such as herbivory) to further degrade marsh condition. For example, high nutrient inputs may decrease

below-ground marsh biomass, making marshes more susceptible to erosion and subsidence with increased flooding from sea level rise (Watson et al. 2014). Increased inundation periods may be related to increases in crab populations that graze on marsh plants and exacerbate erosion (Bertness et al. 2014).

4. In 2012 and 2013, a research team led by Save the Bay and the Narragansett Bay National Estuarine Research Reserve (Cole Ekberg et al. 2014) evaluated the potential impacts of sea level rise on Rhode Island salt marshes. The team chose 39 marsh units from 31 marshes throughout Rhode Island and the Massachusetts section of the Bay as study sites in order to capture the geographic range of marshes from north to south, east to west, and along the coastal ponds. The team used a three-tiered assessment comprising a GIS analysis of land use; a rapid field assessment; and in-depth biological, biogeochemical and physical studies at select sites. The assessment protocol and results from this first round of the Rhode Island Salt Marsh Assessment (RISMA) are presented in Cole Ekberg et al. 2014.

5. Subsequently, Cole Ekberg and other researchers (Cole Ekberg et al. 2017) built upon elements of the RISMA to assess the vulnerability of Rhode Island's coastal wetlands to sea level rise. Focusing on the same 31 marshes (see Figure 7), Cole Ekberg et al. used a variety of methods and tools to assess coastal wetland vulnerability to SLR: field measurements made as part of rapid condition assessments; field and remote sensing measurements of elevation; outputs of a VDatum model which estimated marsh platform height relative to mean high water (MHW); and outputs of a Sea Level Affecting Marshes Model (SLAMM; discussed below). The authors examined these metrics together with the goal of developing and testing an integrated vulnerability assessment tool that considered elevation capital, marsh vegetation, and sea level rise projections.

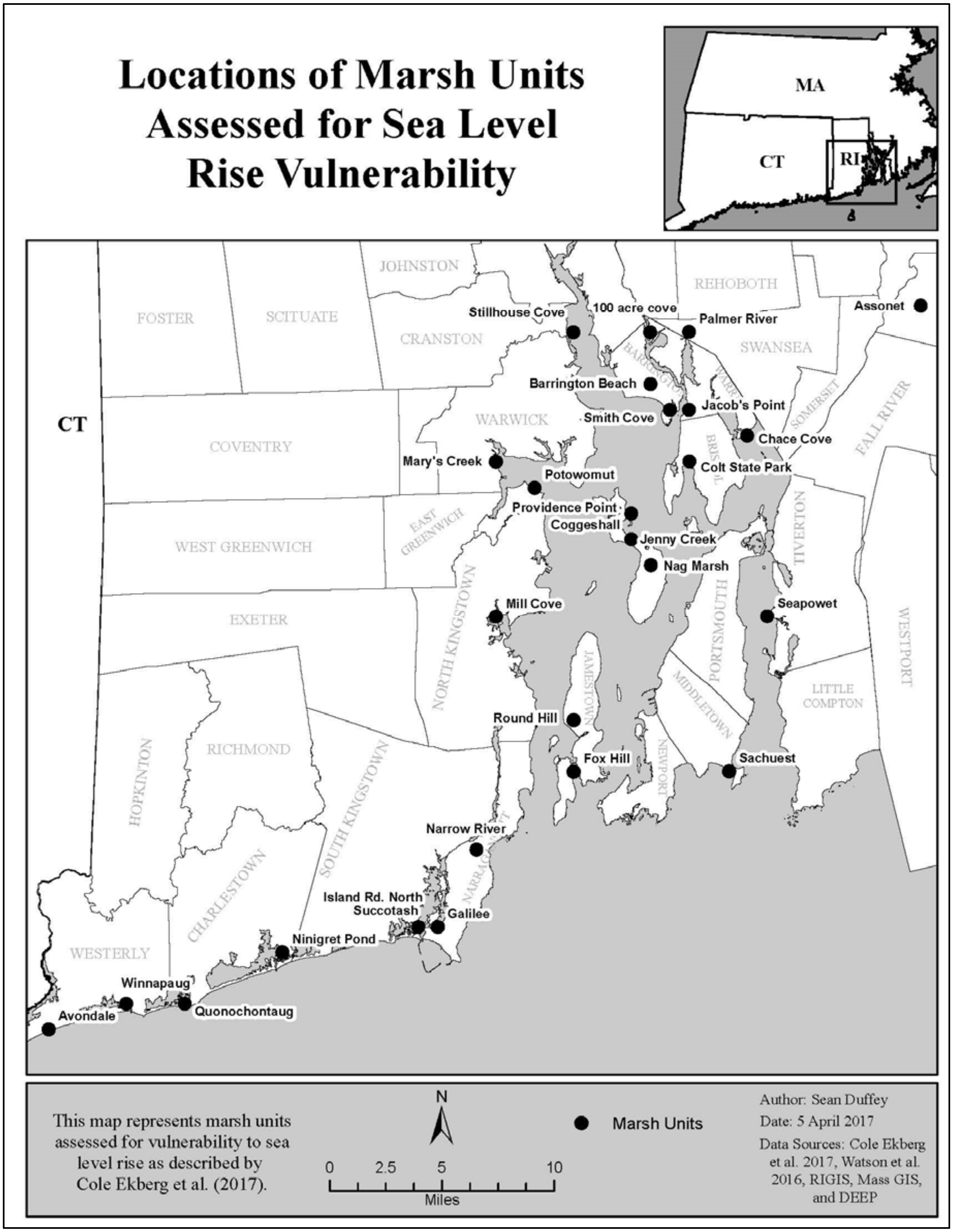

Figure 7. Location of marsh units assessed for sea level rise vulnerability (based on data used by Cole Ekberg et al. 2017).

6. Cole Ekberg et al. (2017) report vulnerability rankings for a subset of these marshes; these results are discussed below in sections 4.3.2.3 and 4.3.2.4. The authors also report findings on the best indicators to use to measure coastal wetland vulnerability to SLR. The authors found that elevation of the marsh above MHW was the single factor with the greatest impact on vulnerability, identifying it as a crucial component of measuring vulnerability to SLR moving forward. They also note that vegetation metrics explained the largest variability in marsh loss data, with high percentages of tall *Spartina alterniflora* and low marsh vegetation as indicators of high vulnerability (see Table 3 and Table 5 below). The authors further note a correlation between tidal range and marsh loss and SLR vulnerability, finding that marshes with a tidal range below 0.4 meters (1.3 feet) were particularly vulnerable.

7. Cole Ekberg et al.'s analysis revealed contrasting patterns of vulnerability between Rhode Island regions, with south coast marshes generally much more vulnerable to SLR, and marshes up Narragansett Bay much less vulnerable. For a summary of some site-specific results see discussion below in sections 4.3.2.3 and 4.3.2.4. For complete study methods and results see Cole Ekberg et al. (2017).

8. In 2015, the CRMC completed an analysis of the potential impacts of sea level rise on coastal wetlands. The analysis included modeling of potential coastal wetland loss as well as the landward migration potential of coastal wetlands located within Rhode Island's 21 coastal communities (RI CRMC 2015; hereafter "SLAMM study"). This analysis applied the Sea Level Affecting Marshes Model (SLAMM) and used 2011 state LiDAR elevation data and the 2010 National Wetland Inventory dataset to model SLR projections of 1, 3, and 5 feet (above 1990 levels). These models were used to both simulate short- and long-term impacts on coastal wetlands and to assess potential upland wetland migration pathways.

9. The SLAMM study revealed that Rhode Island is likely to face a substantial loss of coastal wetlands. Total statewide losses are expected to be 13% under the 1-foot SLR scenario, 52% under the 3-foot SLR scenario, and 87% under the 5-foot SLR scenario. Under the assumption that marshes would be able to migrate onto adjacent developed upland areas, the SLAMM study projects that there would be a net gain of new coastal wetlands statewide under all three of the SLR scenarios, although individual communities may experience an overall net loss of coastal wetlands under some scenarios. Importantly, much is not known about marsh migration processes and how substrate types and upland vegetation will affect migration extent and rates; this is currently an area of CRMC-funded research in Rhode Island and is an area recommended for future research (see Section 4.6). Under the assumption that marshes would be unable to migrate onto adjacent developed areas, lower net wetland acreage is projected, which illustrates how

upland development decisions will have great influence on the ability of coastal wetlands to migrate. For further information see RI CRMC (2015). Specific community results are included in sections 4.3.2.3 and 4.3.2.4 below.

10. Importantly the SLAMM study acknowledges several limitations of the SLAMM model and findings. Data used in the study to characterize wetland baseline conditions did not include information on some key indicators of wetland condition that reflect stress and degradation due to SLR. Additionally, the authors point out model limitations that may indicate that future new marsh development is overestimated, rate and extent of wetland loss are underestimated, and results regarding barrier systems contain a higher degree of uncertainty (RI CRMC 2015). Specifically, limitations associated with model inputs such as existing wetlands data, LiDAR elevation data, accretion rates, barrier system dynamics and recently updated sea level rise rates may mean that model results may overestimate future new marsh migration and underestimate the rate and extent of future wetland loss. This assumption is supported by recent observational data. Cole Ekberg et al. (2017) also point out that LiDAR elevations (which were used in the SLAMM) consistently overestimate marsh elevation. For these reasons, SLAMM study results should be used with caution and as a general planning tool only, especially when considering potential marsh migration.

4.3.2.3 South County and Block Island

1. Coastal wetlands found along Rhode Island's south shore include marshes located along the back-barriers and in small embayments that are less exposed to wave energy. The south coast back-barrier marshes have a restricted tidal range (Boothroyd et al. 1985; Lee and Olsen 1985) in comparison to the full tidal exposure of tidal riverine and fringing marshes. Many of these wetlands have been identified as highly exposed to the effects of sea level rise (although marshes are by definition located in lower-energy shoreline areas and are thus relatively less exposed compared to other shoreline types), and are vulnerable to being buried by sand from overwash events during coastal storms. Block Island salt marshes are relatively small in area, limited to mainly fringing marshes bordering the tidally connected ponds.
2. CRMC's 2015 SLAMM study projected the net change of coastal wetlands for each municipality under 1, 3 and 5-foot SLR scenarios. Separate projections were made under the assumption that wetlands could migrate upland where there is currently existing development such as impervious surfaces or structures ("unprotected development") and could *not* migrate upland where there is currently existing development ("protected development"). In undeveloped areas, the model assumed that marsh migration would occur if the appropriate elevation and flooding conditions were present. It did not take

into account current upland vegetation types, soil substrate types, variations in accretion rates or other factors that may impact marsh migration processes. See Table 2 for summary results. The entire town of Narragansett is included among south coast communities although much of its shoreline faces east toward Narragansett Bay or Rhode Island Sound. Importantly, although summary statewide data (discussed above) projected the state overall seeing net gains of coastal wetlands under all SLR scenarios, the south coast communities would be disproportionately negatively impacted, with Charlestown, Narragansett, South Kingstown and Westerly projected to see net coastal wetland losses under the 3- and 5-foot SLR scenarios, mainly due to losses of large back-barrier marsh complexes.

Table 2. Net change of coastal wetlands in acres by south coast municipality (adapted from RI CRMC 2015). The unprotected development scenario assumes that wetlands can migrate onto developed upland areas whereas the protected development scenario assumes that wetlands cannot migrate onto developed upland areas.*

		Net change (acres) of coastal wetlands: Unprotected development scenario			Net change (acres) of coastal wetlands: Protected development scenario		
Municipality	**Coastal wetlands (acres) in 2010**	**1 ft. SLR**	**3 ft. SLR**	**5 ft. SLR**	**1 ft. SLR**	**3 ft. SLR**	**5 ft. SLR**
Charlestown	340.1	7.0	-97.0	-41.7	12.0	-114.4	-113.8
Little Compton	159.9	34.2	20.2	67.0	30.7	9.7	46.8
Narragansett	396.6	82.3	-104.7	-92.5	67.2	-166.9	-212.0
New Shoreham	71.6	144.7	106.1	100.2	117.1	60.0	36.0
South Kingstown	311.1	43.1	-85.8	-40.8	43.8	-108.4	-86.9
Westerly	269.6	67.6	21.4	-1.1	60.3	-71.4	-139.6
Total	**1548.9**	**378.9**	**-139.8**	**-8.9**	**331.1**	**-391.4**	**-469.5**

** SLAMM results should be used with caution and as a general planning tool only. Limitations associated with model inputs such as existing wetlands data, LiDAR elevation data, accretion rates, barrier system dynamics and recently updated sea level rise rates may mean that model results may overestimate future new marsh migration and underestimate the rate and extent of future wetland loss.*

3. Cole Ekberg et al. (2017)'s analysis of the vulnerability of Rhode Island marshes to sea level rise resulted in a series of marsh assessment values for each site, rated according to relative vulnerability from red (most vulnerable to SLR) to green (least vulnerable to SLR). Table 3 includes values for elevation above MHW, mean *Spartina alterniflora* height, and percentage of low marsh vegetation; for complete marsh assessment values see Cole Ekberg et al. (2017). As discussed above, the authors found that elevation above MHW is the single factor with the greatest impact on vulnerability to SLR. Additionally, the authors found that the presence of tall *S. alterniflora* and high percentages of low marsh vegetation were indicative of high vulnerability to SLR.

Table 3. South coast marsh assessment values rated according to relative vulnerability. Values are outputs of marsh vulnerability assessment and are rated from red (most vulnerable to SLR) to green (least vulnerable to SLR). Adapted from Cole Ekberg et al. 2017

Marsh	Municipality	Elevation MHW	Mean S. alterniflora height	% low marsh veg.
Avondale	Westerly	-0.06	67	1.3
Galilee	Narragansett	0.23	51	0.5
Island Rd. North	South Kingstown	0.12	55	4.9
Ninigret Pond	Charlestown	-0.26	50	0.6
Quonochotaug	Charlestown	-0.09	58	2.5
Succotash	South Kingstown	-0.07	54	10.6
Winnapaug	Westerly	-0.16	42	4.1

4. Cole Ekberg et al. (2017) found that marsh attributes that are associated with vulnerability are common in the marshes along Rhode Island's southern coast. Marshes with these characteristics were identified at marsh units in Winnapaug pond (Westerly), Quonochontaug and Ninigret ponds (Charlestown), and Pt. Judith pond (South Kingstown/Narragansett) (see Table 3). Most prominently, these attributes included lower relative marsh elevations above MHW.

5. Together, study results indicate that salt marshes in Rhode Island's south shore region are expected to be disproportionately negatively affected by SLR when compared to other marshes in the state. Study results further indicate that elevation above MHW is a key indicator of marsh vulnerability to SLR, and that numerous south shore marshes have relatively low elevations.

4.3.2.4 Narragansett Bay

1. Coastal wetlands within Narragansett Bay are located throughout the estuary in small embayments off the bay, and in tidal rivers—areas that are less exposed to wave energy. Many coastal communities within the bay, particularly in urban areas like Providence and Quonset, have suffered significant wetland loss over time due in part to the historic practice of filling wetland areas. Many of the remaining coastal wetlands are narrow fringing marshes. These remaining wetlands provide important ecosystem services such as nutrient uptake and shoreline protection.

2. As discussed above, CRMC's 2015 SLAMM study projected the net change of coastal wetlands for each municipality under 1, 3 and 5-foot SLR scenarios. Projections were made under the assumption that wetlands could migrate upland where there is currently existing development such as impervious surfaces or structures ("unprotected development") and could *not* migrate upland where there is currently existing development ("protected development"). In undeveloped areas, the model assumed that marsh migration would occur if the appropriate elevation and flooding conditions were present. It did not take into account current upland vegetation types, soil substrate types, variations in accretion rates or other factors that may impact marsh migration processes. See Table 4 for summary results for Narragansett Bay, which project a net gain for coastal wetlands for every municipality under all scenarios through the process of marsh migration. However, as noted above, these results should be interpreted with caution as the SLAMM study reports that these results likely overestimate wetland gain.

Table 4. Net change of coastal wetlands in acres of Narragansett Bay municipalities (adapted from RI CRMC 2015). The unprotected development scenario assumes that wetlands can migrate onto developed upland areas whereas the protected development scenario assumes that wetlands cannot migrate onto developed upland areas.*

		Net change (acres) of coastal wetlands: Unprotected development scenario			Net change (acres) of coastal wetlands: Protected development scenario		
Municipality	**Coastal wetlands (acres) in 2010**	**1 ft. SLR**	**3 ft. SLR**	**5 ft. SLR**	**1 ft. SLR**	**3 ft. SLR**	**5 ft. SLR**
Barrington	365.1	206.9	418.7	395.6	130.8	253.4	80.4
Bristol	121.3	58.1	109.8	137.5	38.8	52.4	28.9
Cranston	2.9	5.9	20.3	76.7	0.2	11.9	43.0
East Greenwich	0.5	6.5	5.0	10.4	4.3	1.4	1.5
East Providence	80.3	84.6	130.7	174.1	51.1	74.9	62.6
Jamestown	121.7	77.0	17.8	21.7	66.8	2.1	-17.6
Middletown	49.4	48.0	18.7	3.5	32.6	12.2	-7.1
Newport	20.7	100.0	202.1	396.7	68.5	62.1	105.0
North Kingstown	180.3	223.0	336.2	719.9	176.0	174.9	214.8
Pawtucket	0	9.1	7.8	14.3	7.9	6.6	9.6
Portsmouth	434.9	220.9	156.5	145.0	182.4	75.7	-25.1
Providence	4.2	35.5	63.6	190.1	8.1	7.5	10.2
Tiverton	291.0	116.1	55.8	14.5	99.2	24.3	-40.0
Warren	280.4	120.8	299.1	268.6	80.1	186.3	84.7
Warwick	240.5	228.1	302.8	436.9	159.9	140.9	119.6
Total	**2193.2**	**1540.5**	**2144.9**	**3005.5**	**1106.7**	**1086.6**	**670.5**

** SLAMM results should be used with caution and as a general planning tool only. Limitations associated with model inputs such as existing wetlands data, LiDAR elevation data, accretion rates, barrier system dynamics and recently updated sea level rise rates may mean that model results may overestimate future new marsh migration and underestimate the rate and extent of future wetland loss.*

3. Cole Ekberg et al. (2017)'s analysis of the vulnerability of Rhode Island marshes to sea level rise resulted in a series of marsh assessment values for each site, rated according to relative vulnerability from red (most vulnerable to SLR) to green (least vulnerable to SLR). Assessment values for marsh sites in Narragansett Bay and its tributaries are included in Table 5 below. As with Table 3 above, values for elevation above MHW, mean *Spartina alterniflora* height, and percentage of low marsh vegetation are included here because of their importance in indicating vulnerability to SLR; for complete marsh assessment values see Cole Ekberg et al. (2017).

Table 5. Narragansett Bay and tributaries marsh assessment values rated according to relative vulnerability. Values outputs of marsh vulnerability assessment and are are rated from red (most vulnerable to SLR) to green (least vulnerable to SLR). Adapted from Cole Ekberg et al. 2017.

Marsh	Municipality	Elevation MHW	Mean S. alterniflora height	% low marsh veg.
100 acre cove	Barrington	0.02	61	3.8
Assonet	Assonet, MA	0.18	84	7.7
Barrington Beach	Barrington	0.16	38	0.5
Chace Cove	Warren	0.07	68	12.7
Coggeshall	Portsmouth	0.08	49	11.8
Colt State Park	Bristol	0.14	51	2.2
Fox Hill	Jamestown	-0.02	37	1.9
Jacob's Point	Warren	0.13	54	0.6
Jenny Creek	Portsmouth	0	43	2.2
Mary's Creek	Warwick	-0.01	71	21
Mill Cove	North Kingstown	0.07	78	8
Nag Marsh	Portsmouth	0.13	63	7.9
Narrow River	Narragansett	-0.06	30	0.4
Palmer River	Swansea MA	-0.01	47	0.7
Potowomut	East Greenwich	0.02	68	29.1
Providence Point	Portsmouth	0.09	60	4.4
Round Hill	Jamestown	0.07	35	4.2
Sachuest	Middletown	0.11	75	1.8
Seapowet	Tiverton	0.16	45	1.5
Smith Cove	Barrington	0.14	102	5.7
Stillhouse Cove	Cranston	-0.03	96	30.4

4. Cole Ekberg et al. (2017) found contrasting patterns of vulnerability between regions. While the most notable differences are between Narragansett Bay and the Rhode Island south coast (discussed above; see also Table 3), contrasting patterns of vulnerability were also evident within Narragansett Bay and its tributaries. For example, some sites closer to the mouth of the Bay (e.g. Fox Hill in Jamestown and the Narrow River in Narragansett) may be more vulnerable to SLR than those up the Bay, while in other cases marshes up the Bay and its tributaries (e.g. Stillhouse Cove in Providence and Mary's Creek in Warwick) exhibit relatively high vulnerability. See also Figure 8.

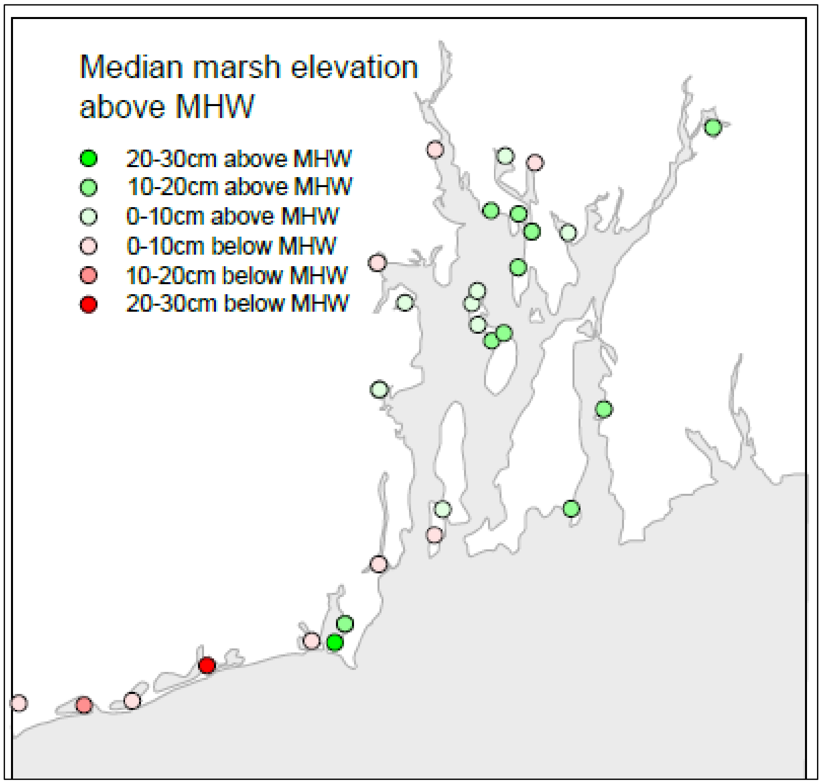

Figure 8. Median marsh elevation above MHW as an indication of marsh vulnerability to SLR (Source: Cole Ekberg et al. 2017)

5. In sum, study results indicate that Narragansett Bay marshes may be generally less vulnerable to the effects of SLR than south shore marshes, though there is considerable variability between bay locations.

4.3.3 Other Coastal Habitats

1. Other habitats of particular concern include low-lying coastal uplands and freshwater wetlands adjacent to coastal wetlands. Many of these freshwater wetland areas have been identified through modeling to be areas of future potential marsh migration. For example, the SLAMM study projected freshwater wetland losses of 204 acres with a 1-foot SLR, 635 acres with a 3-foot SLR, and 1060 acres with a 5-foot SLR statewide. Almost one half of the total freshwater wetland loss statewide is projected in just five towns: Barrington, Charlestown, South Kingstown, Warren and Westerly (RI CRMC 2015).

2. These areas may also include rare or threatened species, such as those found in sea level fens, that are at risk of being lost with future increases in sea level. Sea level fens are an emergent wetland community found at the interface at the upper end of tidal marshes where there is an upland freshwater source such as groundwater seepage. Sea level fens have a distinct species assemblage; in Rhode Island they are often dominated by the

grasses twig-rush (*Cladium*), bulrush (*Scirpus*) and spike-rush (*Elocharis*). There are only two sea level fens in Rhode Island, making them unique and rare in the state (RI CRMC 2015).

4.4 Effects of Erosion on Rhode Island's Coast

4.4.1 Historic Shoreline Change

1. Rhode Island's shoreline has experienced erosion over time, resulting in patterns of shoreline change that can be observed over the decadal time scale. These patterns vary by location depending on physical characteristics of the shoreline itself and the physical processes (e.g. wind, waves) to which the shoreline is exposed. Studies of shoreline change in Rhode Island and elsewhere indicate that shoreline change is not a consistently incremental process but rather is driven by storm events such as hurricanes or nor'easters which can cause significant shoreline change within short periods of time.

2. An assessment of historic shoreline change for portions of the Rhode Island coast was performed in support of the Shoreline Change SAMP. This section includes a brief summary of this analysis. For a complete set of shoreline change maps see Boothroyd et al. (2016) or http://www.crmc.ri.gov/maps/maps_shorechange.html. For a technical report summarizing methods and results see Oakley, Hollis and Boothroyd (2016).

3. Boothroyd et al. (2016) updated existing shoreline change maps for portions of the Rhode Island coast. Their mapping focused on the southern shoreline of Washington County, from Napatree Point to Point Judith (excluding Block Island), as well as the east facing shoreline of Narragansett and North Kingstown, from Point Judith to the Potowomut River, facing Rhode Island Sound and Narragansett Bay (see Figure 9). Shoreline change maps show the position of the shoreline at a given time based on measurements from georeferenced aerial and digital orthophotographs.

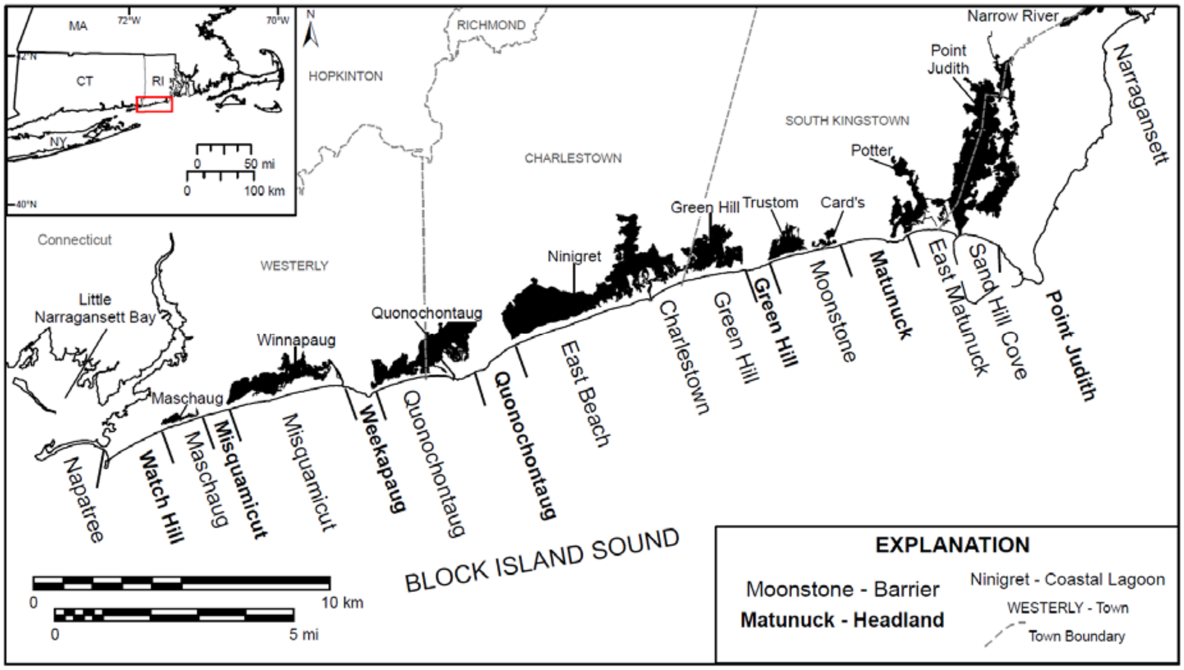

Figure 9. Barriers and headlands of the Rhode Island South Shore with headlands labeled in bold font. Modified from Boothroyd et al. 1998.

4. Shoreline change between 1939 and 2014 was mapped using the position of the last high tide swash, which is the limit of wave run-up on the beach and is used as a proxy for the position of mean high water (MHW). Transects were run at 50 meter intervals along the shoreline using the Digital Shoreline Analysis System 4.0 (DSAS) to measure these positions. Shoreline change rates and statistics for each transect were calculated using the shoreline change envelope (SCE) method which takes the absolute value of the total distance between the most landward and seaward shoreline positions. The annualized rate of change was calculated using this information in addition to the years of the most landward and seaward shoreline positions and the difference in time (years) between these two shoreline positions. An alternative measure, end-point rate (EPR), was used to calculate the annualized rate of change along marsh shorelines and in developed areas where fill and shoreline protection structures create complications for interpreting shoreline change. For further information on data sources, measurements and methods see Oakley, Hollis and Boothroyd (2016).

5. Oakley, Hollis and Boothroyd (2016) report that the Rhode Island coast is largely erosional: 95% of transects measured in the study area showed varying rates of shoreline retreat. The authors attributed this "systematic retreat" to storms and, to a lesser degree, sea level rise. While this study identified some areas of net accretion, or accumulation of sediment (e.g. at the north end of Scarborough Beach), the authors note

that most such areas are the result of interventions such as filling or the construction of shoreline protection structures (e.g. Quonochontaug Headland and Quonset Point).

6. Maps produced by Boothroyd et al. (2016) illustrate that the Rhode Island south shore (from Napatree Point to Point Judith) experienced higher amounts of erosion than the east-facing shoreline from Point Judith to the Potowomut River. Shoreline change ranged over the south shore from near zero to a total retreat of 90 meters (295 feet) along areas of the Matunuck Headland between 1951 and 2014.

7. Oakley, Hollis and Boothroyd (2016) calculated average annualized rates of shoreline change by shoreline type (e.g. glacial stratified, barrier/beach). The authors report that shoreline areas with the highest (most negative) shoreline change were those backed by glacial stratified bluffs with an average annualized loss of 0.75 meters (2.46 feet) per year. This statistic was influenced by the particularly high rate of erosion in an area of Matunuck from Cards Point to the east end of the South Kingstown Town Beach, where total shoreline change exceeded 90 meters (295 feet) between 1951 and 2014. Barriers averaged an annualized rate of loss of 0.57 meters (1.87 feet) per year, with rates of retreat greater than 1 meter (3.28 feet) per year found in portions of the Quonochontaug and Moonstone barriers. These statistics illustrate the finding that the Rhode Island south shore has experienced higher amounts of erosion than other parts of the state. Additionally, this area in particular experienced a great deal of overwash and migrated via washover fan deposition.

8. Oakley, Hollis and Boothroyd (2016) found that erosion rates were generally lower along the coast from Point Judith to the Potowomut River, and attribute this difference in part to the prevalence of bedrock and lower number of barriers in comparison to the south shore. They also found that the mixed energy environment inside Narragansett Bay (in comparison to the wave-dominate south shore environment), plus the larger number of shoreline protection structures inside the Bay, influence these lower erosion rates as they limit natural shoreline migration.

4.4.2 Projected Shoreline Change

1. Oakley, Hollis, Patrolia, Rinaldi and Boothroyd (2016) conducted an analysis of projected shoreline change, out to 2100, for the Rhode Island south shore. The projection of future shoreline change is a complex and sometimes controversial practice and findings should be interpreted with caution. The authors built upon previous studies of projected shoreline change including Anderson et al. (2015) and Moore et al. (2007). For a complete discussion of methods, see the study technical report at www.beachsamp.org. For maps depicting results, see the Hollis at-risk report discussed below.

2. Oakley et al.'s analysis employed a qualitative modeling approach and examined shoreline change projections for an "exponential high scenario" for 2100 based on a shoreline change rate that increases at an exponential rate of 2.5 times the historical trend by 2065. This rate was further extrapolated to increase exponentially to 2100.[5] Assuming an initial rate of 1 meter (3.28 feet) of shoreline change per year, this would produce a total change of 89 meters (292 feet) by 2065 and 216 meters (708 feet) by 2100. Oakley et al. produced 90 large-format maps depicting shoreline change for all of Rhode Island's south shore communities. Sample results are highlighted in section 4.6.2 below; see www.beachsamp.org to view maps for all communities.

3. Oakley et al.'s analysis also considered the policy implications of these projections by projecting future setbacks for coastal development based on CRMC's existing coastal policy. The projected shoreline change analysis assumed that the coastal feature (e.g. dune or bluff), as defined in the RICRMP, would migrate as well, maintaining a constant distance from the location of the shoreline. The projected future location of coastal features was used with some of CRMC's existing coastal construction setback requirements (30x the annual erosion rate for residential structures and 60x for commercial) to project future setback requirements, thus illustrating the potential effect of projected shoreline change on coastal development. Sample results are highlighted in section 4.3.3 below; see www.beachsamp.org to view maps for all communities.

4.5 Built Environment

1. Rhode Island's built environment is exposed in multiple ways to coastal hazards associated with climate change. Exposure refers to a community's assets, including people, property, infrastructure, and the natural environment, subject to a hazard's damaging impacts. The coastal hazards considered in this document include storm surge, coastal erosion and sea level rise. This section summarizes what is known to date about the exposure of Rhode Island's coastal residential, commercial, and industrial structures; public infrastructure; transportation infrastructure; ports and maritime infrastructure; public access and recreation facilities; and historic and archaeological assets.

[5] This results in a shoreline change rate 4.8 times the current rate by 2100.

4.5.1 CRMC Exposure Assessment

1. The exposure assessment presented below is a summary of a CRMC-led analysis of the impacts of sea level rise and storm surge on structures in all 21 Rhode Island coastal municipalities (Leporacci et al. 2016). CRMC's analysis used STORMTOOLS flood inundation data layers and Rhode Island's E-911 site database, which includes every known building or structure in the state, and analyzed future flooding risk to these structures through several sea level rise and storm surge scenarios. [6] Throughout this assessment, Prudence Island is listed separately, because this is how it is treated in the E-911 database, although it is part of the town of Portsmouth. The results illustrate future flood risk under SLR scenarios up to and including 7 feet, which are based upon the "high" sea level change curve included in NOAA's 2012 SLR analysis (NOAA 2012). These were the most up-to-date SLR data as of 2016 when this study was performed. Assessment findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise. For further information on study methods and results see Leporacci et al. 2016 or www.beachsamp.org/STORMTOOLS/e911/. In 2017, NOAA issued an updated SLR analysis which projected up to 9.6 feet of SLR under the high curve and up to 11.7 feet of SLR under the "extreme" curve, at the 83% confidence interval, for Rhode Island (NOAA 2017a).

2. Seven sea level rise (SLR) and storm surge scenarios were selected from the range of scenarios analyzed by Leporacci et al. (2016) for inclusion in this chapter. These scenarios are all based on the NOAA high SLR curve included in NOAA's 2012 analysis (NOAA 2012), which was the most current analysis as of December 2016. The first three scenarios address SLR, considering 3, 5, and 7-foot projections. The last four scenarios address storm surges. One addresses a 100-foot storm surge with no projected SLR scenario, which is the current standard in floodplain mapping. This can be considered a present day scenario. The last three scenarios consider a 100-foot storm surge combined with the 3, 5, and 7-foot SLR scenarios, which represent different points in the future (see Table 6).

[6] This geospatial data analysis was conducted using STORMTOOLS and used 2015 inundation surfaces based on LiDar/Digital Elevation Models as well as the state of Rhode Island's 2011 E911 database for categories of structures (i.e., commercial, residential, industrial, public service, utility).

3. The SLR scenarios considered here represent different points in the future, with the higher SLR projections representing projected conditions in the latter part of the 21st-century. The Shoreline Change SAMP identifies the 3-foot SLR + 100-year storm surge scenario as the "**Mid-century Planning Scenario**" because it represents projected conditions in 2065. CRMC recommends that property owners use this scenario to assess their risk between now and mid-century. The Shoreline Change SAMP identifies the 7-foot SLR + 100-year storm surge scenario as the "**Long-range Planning Scenario**" because it represents projected conditions in 2100. CRMC recommends that decision-makers use this scenario to inform long-term infrastructure planning and capital investment decisions (see Table 6).

Table 6. SLR and storm surge scenarios addressed in CRMC Statewide Assessment

Scenario	Explanation
Sea Level Rise (SLR) *based on the NOAA high SLR curve as of December 2016 (see NOAA 2012)*	
3-foot SLR	Equivalent of projected SLR in 2065.
5-foot SLR	Equivalent of projected SLR in 2085.
7-foot SLR	Equivalent of projected SLR in 2100.
Storm Surge + SLR *based on STORMTOOLS inundation mapping and the NOAA high SLR curve as of December 2016 (see NOAA 2012)*	
100-year storm surge	Current standard for floodplain mapping; excludes any SLR.
3-foot SLR + 100-year storm surge **("Mid-century Planning Scenario")**	Equivalent of projected SLR in 2065 combined with a 100-year storm surge. ***Recommended for use by property owners to assess their risk between now and mid-century.***
5-foot SLR + 100-year storm surge	Equivalent of projected SLR in 2085 combined with a 100-year storm surge.
7-foot SLR + 100-year storm surge **("Long-range Planning Scenario")**	Equivalent of projected SLR in 2100 combined with a 100-year storm surge. ***Recommended for use by state and municipal decision makers to inform long-term infrastructure planning and capital investment decisions.***

4. When considering these scenarios, it is important to note that STORMTOOLS surge elevations are based on a modeled 100-year storm surge event that occurs at every point along the shoreline, due to the point that there is no one event that produces 100-year storm surge water levels at all points of interest. Depending on a storm's track, not every storm will have this kind of impact on Rhode Island. For example, Superstorm Sandy in 2012 was a 25-year event in Westerly and an even smaller storm event in Newport. For further information on STORMTOOLS see Chapter 3.

5. The Long-range Planning Scenario, based on a 7-foot SLR + 100-year storm surge and representing projected conditions in 2100, is used as a reference point for much of the discussion in this section (see Figure 10 for a map depicting conditions during this scenario).

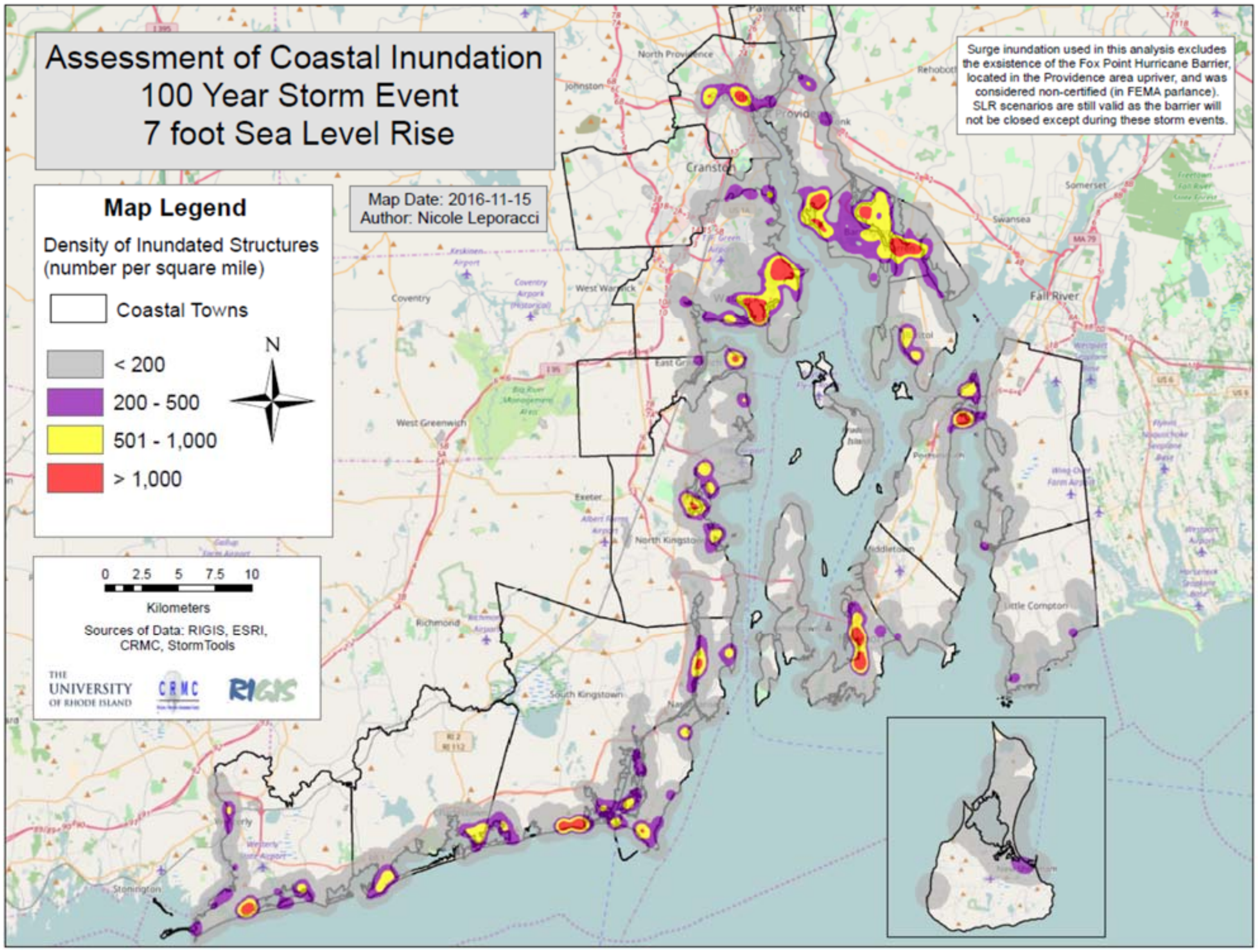

Figure 10. Long-range Planning Scenario (7-foot SLR + 100-year storm surge, representing projected conditions in 2100). This figure shows the density of inundated structures based on the number of structures by square mile, with red indicating the highest density of inundated structures and grey indicating the lowest. For example, red areas contain a density of greater than 1,000 inundated structures per square mile, and are the most exposed areas under this scenario.

4.5.1.1 Exposed Residential Structures

1. Leporacci et al. (2016) assessed residential structures in Rhode Island's 21 coastal communities. Residential structures evaluated in this assessment include single and multi-family homes, seasonal homes, mobile homes, camps, and other residential structures. This section presents some summary data from this assessment. See www.beachsamp.org/STORMTOOLS/e911/ for complete lists of exposed structures in all 21 coastal communities and by municipality under all planning scenarios considered in this assessment.

2. Leporacci et al. (2016) found that there is a total of 27,431 residential structures in the 21 coastal communities that are exposed to the combined effects of SLR and storm surge under the Long-range Planning Scenario. This represents 11.5% of the total such structures in these communities. See Table 7. This table illustrates that the exposure of individual municipalities varies widely under this scenario, ranging from Barrington, where 64% (3,930) residential structures are exposed, to Pawtucket, where only 1 residential structure (less than 1% of those in the town) is exposed. Importantly, findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.

Table 7. Exposed residential structures by municipality under Long-range Planning Scenario (7-foot SLR + 100-year storm surge; projected conditions in 2100)

Community	No. structures exposed	No. total structures in municipality	% of total structures in municipality	% of exposed structures in 21 coastal communities
Barrington	3930	6100	64.43%	14.33%
Block Island	101	1451	6.96%	0.37%
Bristol	922	7171	12.86%	3.36%
Charlestown	1384	5121	27.03%	5.05%
Cranston	302	26477	1.14%	1.10%
East Greenwich	68	4574	1.49%	0.25%
East Providence	1596	15712	10.16%	5.82%
Jamestown	210	2794	7.52%	0.77%
Little Compton	282	2389	11.80%	1.03%
Middletown	57	6353	0.90%	0.21%
Narragansett	2343	8794	26.64%	8.54%
Newport	1406	8313	16.91%	5.13%
North Kingstown	1869	10233	18.26%	6.81%
Pawtucket	1	20695	0.00%	0.00%
Portsmouth	1294	7284	17.76%	4.72%
Providence*	311	40841	0.76%	1.13%
Prudence Island (Portsmouth)	97	441	22.0%	3.54%
South Kingstown	2046	11857	17.26%	7.46%
Tiverton	349	6596	5.29%	1.27%
Warren	1703	3808	44.72%	6.21%
Warwick	5422	30498	17.78%	19.77%
Westerly	1738	10747	16.17%	6.34%
Sum	**27431**	**238249**	**11.51%**	**100.00%**

**Findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.*

3. The exposure of residential structures in individual municipalities varies by scenario. Table 8 and Table 9 list the top five most vulnerable communities based on the number of exposed residential structures under each of the seven scenarios considered here. These tables also present the sum of total exposed structures in those municipalities, and the percentage this sum represents of the total exposed residential structures within RI's 21 coastal communities based on the Long-range Planning Scenario (27,431 structures).

Table 8. Top five municipalities with exposed residential structures under sea level rise scenarios

	3-foot SLR			5-foot SLR			7-foot SLR		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	South Kingstown	130	1.1%	Westerly	360	3.3%	Westerly	600	5.6%
2	Westerly	98	0.9%	South Kingstown	320	2.7%	South Kingstown	546	4.6%
3	Narragansett	91	1.0%	Newport	225	2.7%	Warwick	499	1.6%
4	Charlestown	38	0.7%	Narragansett	203	2.3%	Narragansett	477	5.4%
5	Tiverton	25	0.4%	Warren	180	4.7%	Newport	438	5.3%
Sum		**382**			**1288**			**2560**	
% of exposed structures*		**1.4%**			**4.7%**			**9.3%**	

**in 21 coastal communities based on long-term planning scenario*

Table 9. Top five municipalities with exposed residential structures under storm surge and sea level rise scenarios

	100-year surge			3-foot SLR + 100-year surge			5-foot SLR + 100-year surge			7-foot SLR + 100-year surge		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	Warwick	2636	8.6%	Warwick	3895	12.8%	Warwick	4624	15.2%	Warwick	5422	17.8%
2	Barrington	2619	42.9%	Barrington	3413	56.0%	Barrington	3686	60.4%	Barrington	3930	64.4%
3	South Kingstown	1139	9.6%	South Kingstown	1636	13.8%	Narra-gansett	1997	22.7%	Narra-gansett	2343	26.6%
4	Warren	1090	28.6%	Narra-gansett	1576	17.9%	South Kingstown	1851	15.6%	South Kingstown	2046	17.3%
5	Westerly	1043	9.7%	Warren	1404	36.9%	North Kingstown	1578	15.4%	North Kingstown	1869	18.3%
Sum		**8527**			**11924**			**13736**			**15610**	
% of exposed structures*		**31.1%**			**43.5%**			**50.1%**			**56.9%**	

****total structures in 21 coastal communities based on long-term planning scenario***

4. Table 8 reveals that Narragansett, South Kingstown and Westerly are among the most exposed municipalities in the 21 coastal communities, with regard to exposure of residential structures, based on all three SLR scenarios. South Kingstown and Westerly are the top two most exposed municipalities under all three SLR scenarios.

5. Table 9 reveals that Barrington, South Kingstown, and Warwick are among the most exposed municipalities in the 21 coastal communities, with regard to exposure of residential structures, based on all four storm surge scenarios. Warwick is ranked first, and Barrington second, as the most exposed municipalities under all scenarios. This table also indicates that under the 5-foot and 7-foot SLR + 100-year storm surge scenarios, over 50% of the state's most exposed residential structures are located in just five communities: Barrington, Narragansett, North Kingstown, South Kingstown, and Warwick.

6. Evaluated together, these tables revealed that South Kingstown is among the most exposed municipalities in the 21 coastal communities, with regard to exposed residential structures, under all seven scenarios.

7. While this discussion only emphasizes a subset of Rhode Island coastal municipalities, it is important to note that there are exposed residential structures in all of Rhode Island's coastal communities. For further information see Leporacci et al. (2016) or www.beachsamp.org/STORMTOOLS/e911/.

4.5.1.2 Exposed Commercial Structures

1. Leporacci et al. (2016) also evaluated the exposure of commercial structures in all 21 coastal municipalities. Commercial structures in this assessment include all lodging, farm, and other commercial structures as described in the E911 database. This section presents some summary data from this assessment. See www.beachsamp.org/STORMTOOLS/e911/ for complete lists of exposed structures in all of the coastal communities and by municipality under all planning scenarios considered in this assessment.

2. Table 10 reveals that there is a total of 3,082 commercial structures in the 21 coastal communities that are exposed under the Long-range Planning Scenario (7-foot SLR + 100-year storm surge). This represents 18.9% of all such structures in the 21 coastal communities. This analysis also reveals that exposed commercial structures vary considerably by municipality, from 993 in Providence (23.2% of all such structures in the city) to just 5 in Pawtucket (less than 1% of all such structures in the city). As stated above, findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment

assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.

3. While Providence has the greatest number of exposed commercial structures included in this analysis, Barrington has the greatest percentage of its commercial structures exposed under this scenario with 70.8% (109 exposed structures). As stated above, findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge.

Table 10. Exposed commercial structures by municipality under Long-range Planning Scenario (7-foot SLR + 100-year storm surge; projected conditions in 2100)

Municipality	No. structures exposed	Total no. structures in municipality	% of total municipality structures	% of structures exposed in 21 coastal communities
Barrington	109	154	70.78%	3.54%
Block Island	84	155	54.19%	2.73%
Bristol	78	438	17.81%	2.53%
Charlestown	17	156	10.90%	0.55%
Cranston	57	1761	3.24%	1.85%
East Greenwich	8	306	2.61%	0.26%
East Providence	167	1246	13.40%	5.42%
Jamestown	20	91	21.98%	0.65%
Little Compton	11	64	17.19%	0.36%
Middletown	31	435	7.13%	1.01%
Narragansett	93	239	38.91%	3.02%
Newport	471	915	51.48%	15.28%
North Kingstown	138	603	22.89%	4.48%
Pawtucket	5	1318	0.38%	0.16%
Portsmouth	56	281	19.93%	1.82%
Providence*	993	4282	23.19%	32.22%
Prudence Island (Portsmouth)	1	2	50.0%	0.03%
South Kingstown	69	511	13.50%	2.24%
Tiverton	51	334	15.27%	1.65%
Warren	184	328	56.10%	5.97%
Warwick	200	1987	10.07%	6.49%
Westerly	239	678	35.25%	7.75%
Sum	**3082**	**16284**	**18.92%**	**100.00%**

**Findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.*

4. The exposure of commercial structures in individual municipalities varies by scenario, although there is somewhat less variation with regard to affected municipalities when compared to residential exposure. Table 11 and Table 12 list the top five most vulnerable communities based on the number of exposed commercial structures under each of the seven scenarios considered here. These tables also present the sum of total exposed structures in those municipalities, and the percentage this sum represents of the total exposed commercial structures in the 21 coastal communities (3,082) based on the Long-range Planning Scenario.

Table 11. Top five municipalities with exposed commercial structures under sea level rise scenarios

	3-foot SLR			5-foot SLR			7-foot SLR		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	Newport	23	2.5%	Newport	102	11.1%	Providence	196	4.6%
2	Westerly	23	3.4%	Westerly	62	9.1%	Newport	195	21.3%
3	Providence	19	0.4%	Providence	48	1.1%	Westerly	121	17.8%
4	Narragansett	13	5.4%	North Kingstown	42	7.0%	North Kingstown	65	10.8%
5	North Kingstown	9	1.5%	Narragansett	28	11.7%	Warren	48	14.6%
Sum		**87**			**282**			**625**	
% of exposed structures*		**2.82%**			**9.15%**			**20.28%**	

**total structures in 21 coastal communities based on long-term planning scenario*

Table 12. Top five municipalities with exposed commercial structures under both storm surge and sea level rise scenarios

	100-year surge			3-foot SLR + 100-year surge			5-foot SLR + 100-year surge			7-foot SLR + 100-year surge		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	Providence	767	17.9%	Providence	878	20.5%	Providence	919	21.5%	Providence	993	23.2%
2	Newport	346	37.8%	Newport	439	48.0%	Newport	460	50.3%	Newport	471	51.5%
3	Westerly	194	28.6%	Westerly	216	31.9%	Westerly	229	33.8%	Westerly	239	35.3%
4	Warren	123	37.5%	Warren	155	47.3%	Warren	174	53.0%	Warwick	200	10.1%
5	Warwick	109	5.5%	Warwick	143	7.2%	Warwick	170	8.6%	Warren	184	56.1%
Sum		**1539**			**1831**			**1952**			**2087**	
% of exposed structures *		**49.9%**			**59.4%**			**63.3%**			**67.7%**	

**total structures in 21 coastal communities based on long-term planning scenario*

5. Table 11 reveals that Newport, North Kingstown, Providence, and Westerly are among the top five most exposed municipalities, with regard to commercial structures, under all three SLR scenarios. Narragansett is included in this number under the 3- and 5-foot SLR scenarios, but is surpassed by Warren under the 7-foot SLR scenario.

6. Table 12 reveals that Newport, Providence, Warren, Warwick and Westerly are the top five most exposed municipalities with regard to commercial structures under all four storm surge scenarios. A comparison of these four scenarios reveals that while the number of commercial structures increases as SLR increases, the ranking of these five municipalities changes very little. Providence, Newport, and Westerly remain the first, second, and third most exposed municipalities, respectively, under all four scenarios. Warren remains the fourth most exposed municipality with regard to commercial structures in all but the final Long-range Planning Scenario.

7. Table 12 also reveals that, under all three of the combined SLR and storm surge scenarios, over 50% of the exposed commercial structures in the 21 coastal communities are concentrated in just these top five municipalities: Newport, Providence, Warren, Warwick and Westerly. Under the Long-range Planning Scenario, over two-thirds (67.72%) of the state's exposed commercial structures are located in these five municipalities.

8. Examined together, these two tables reveal that Newport, Providence and Westerly are the top three most exposed municipalities in the 21 coastal communities, with regard to commercial structures, under all four SLR and storm surge scenarios.

4.5.1.3 Exposed Public Service Structures

1. Leporacci et al. (2016) also evaluated the exposure of public service structures in the 21 coastal municipalities. Public service structures, as defined and included in the E-911 database, include emergency service facilities such as police and fire department structures and ambulance houses; healthcare facilities; and government, educational and public gathering structures. This section presents some summary data from this assessment. See www.beachsamp.org/STORMTOOLS/e911/ for complete lists of exposed structures in the 21 coastal communities and by municipality under all planning scenarios considered in this assessment. Importantly, this analysis did not address the relative importance of each individual public service structure to its coastal community, and therefore may underrepresent the community's exposure. For example, the exposure of just one public service structure could mean that a community is very highly exposed if that one structure is its only police or fire station.

2. Table 13 lists exposed public service structures by municipality under the Long-range Planning Scenario of 7-foot SLR + a 100-year storm surge. Leporacci et al. (2016) found that there are 566 public service structures that are exposed under this scenario. This represents 13.8% of all such structures in the 21 coastal communities. There is a wide range of exposed structures between municipalities, from Newport at 110 public service structures (representing 32% of such structures in Newport) to Little Compton at 1 public service structure (4% of such structures in the town). Although some municipalities have small numbers of exposed public service structures, those may represent a high percentage of such structures in that municipality. For example, Tiverton has 2 exposed structures which represent 55% of all public service structures in the municipality.

Table 13. Exposed public service structures by municipality under the Long-range Planning Scenario (7-foot SLR + 100-year storm surge; projected conditions in 2100)

Municipality	No. structures Exposed	No. total structures in municipality	% of total municipality structures	% of structures exposed in 21 coastal communities
Barrington	33	74	44.59%	5.83%
Block Island	12	28	42.86%	2.12%
Bristol	14	110	12.73%	2.47%
Charlestown	7	68	10.29%	1.24%
Cranston	11	310	3.55%	1.94%
East Greenwich	4	116	3.45%	0.71%
East Providence	14	145	9.66%	2.47%
Jamestown	8	43	18.60%	1.41%
Little Compton	1	24	4.17%	0.18%
Middletown	15	258	5.81%	2.65%
Narragansett	44	148	29.73%	7.77%
Newport	110	346	31.79%	19.43%
North Kingstown	60	165	36.36%	10.60%
Pawtucket	3	241	1.24%	0.53%
Portsmouth	7	87	8.05%	1.24%
Providence*	108	1104	9.78%	19.08%
Prudence Island (Portsmouth)	1	9	11.11%	0.18%
South Kingstown	9	256	3.52%	1.59%
Tiverton	2	44	4.55%	0.35%
Warren	38	69	55.07%	6.71%
Warwick	46	326	14.11%	8.13%
Westerly	19	139	13.67%	3.36%
Sum	**566**	**4110**	**13.77%**	**100.00%**

**Findings about Providence are valid with regard to the impacts of sea level rise but may overestimate damage due to storm surge. This is because this assessment assumed that the Fox Point Hurricane Barrier is not present. The barrier was originally designed to address storm surge, based on conditions at the time, but not sea level rise.*

3. As with residential and commercial structures, the exposure of each municipality's public service structures varies by scenario. Table 14 and Table 15 show the top five municipalities with the largest number of exposed public service structures under each of the seven scenarios.

Table 14. Top five municipalities with exposed public service structures under SLR scenarios

	3-foot SLR			5-foot SLR			7-foot SLR		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	Narragansett	2	1.4%	Newport	14	4.0%	Newport	22	6.4%
2	Block Island	1**	3.6%	Narragansett	6	4.1%	North Kingstown	12	7.3%
3	Bristol	1**	0.9%	Warren	6	8.7%	Narragansett	11	7.4%
4	East Providence	1**	0.7%	Westerly	4	2.9%	Providence	7**	0.6%
5	North Kingstown	1**	0.6%	Bristol	4	3.6%	Warren	7**	10.1%
	Prudence Is. (Portsmouth)	*1***	*11.1%*				*Westerly*	*7***	*5.0%*
	Warwick	*1***	*0.3%*						
Sum		**6**			**34**			**59**	
% of exposed structures*		**1.1%**			**6.0%**			**10.4%**	

**Total structures in the 21 coastal communities based on long-term planning scenario. **Six municipalities have one exposed public service structure under the 3-foot scenario, and three have seven exposed structures under the 7-foot scenario. All are listed here although in each case only the top five are included in the 'top five' sum and percentage.*

Table 15. Top five municipalities with exposed public service structures under storm surge and SLR scenarios

	100-year surge			3-foot SLR + 100-year surge			5-foot SLR + 100-year surge			7-foot SLR + 100-year surge		
	Muni.	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*	*Muni.*	*No. structures*	*% structures in muni.*
1	Providence	69	6.3%	Providence	93	8.4%	Newport	103	29.8%	Newport	110	31.8%
2	Newport	60	17.3%	Newport	87	25.1%	Providence	96	8.7%	Providence	108	9.8%
3	North Kingstown	43	26.1%	North Kingstown	46	27.9%	North Kingstown	52	31.5%	North Kingstown	60	36.4%
4	Narra-gansett	37	25.0%	Narra-gansett	40	27.0%	Narra-gansett	44	29.7%	Warwick	46	14.1%
5	Barrington	20	27.0%	Warwick	30	9.2%	Warwick	39	12.0%	Narra-gansett	44	29.7%
Sum		**229**			**296**			**334**			**368**	
% of exposed structures*		**40.5%**			**52.3%**			**59.0%**			**65.0%**	

**total structures in 21 coastal communities based on long-term planning scenario*

4. Table 14 reveals that Narragansett is among the top three municipalities with the most exposed public service structures under all three SLR scenarios. Other than Narragansett, there is a fair amount of vulnerability in the municipalities listed among the top five most exposed with regard to public service structures. In several cases there are ties for inclusion among the top five (e.g. Providence, Warren and Westerly all have seven public service structures exposed under the 7-foot SLR scenario).

5. There is some consistency among the storm surge scenarios. Table 15 reveals that Providence, Newport and North Kingstown are the top three most exposed communities with regard to public service structures across all four storm surge scenarios. Narragansett is also included among the top five most exposed communities in all four of these scenarios, and Warwick is included in three of the four scenarios.

6. Importantly, with only a 100-year storm surge and no sea level rise (i.e. current conditions), the top five municipalities of Providence, Newport, North Kingstown, Narragansett and Barrington included 40% of all exposed public service structures in the 21 coastal communities. Additionally, for all three of the scenarios combining SLR and storm surge, over 50% of the exposed public service structures in the 21 coastal communities are concentrated in just five municipalities. Under the Long-range Planning Scenario, the top five municipalities of Newport, Providence, North Kingstown, Warwick and Narragansett included 65% of the all exposed public service structures in the 21 coastal communities.

4.5.2 Other State Assessments

1. This section provides insight into what is known to date about the exposure of other aspects of Rhode Island’s built environment. This includes the demographics of potentially exposed populations; critical infrastructure; wastewater treatment facilities; drinking water utilities; transportation; ports and maritime infrastructure; public access and recreation assets; and historic and archaeological assets. In many cases the information included here summarizes studies completed by other state agencies or organizations, and/or addresses infrastructure, facilities or assets that are not managed by the CRMC. In all cases the reader is referred to the relevant agency or organization for further information.

2. Because the following state assessments each considered different sea level rise and/or storm surge scenarios, each study is preceded with a statement in bold highlighting the relevant scenarios.

4.5.2.1 Demographics

1. ***The following study considered SEA LEVEL RISE (1, 3, 5, and 7-foot scenarios).***

2. The Rhode Island Statewide Planning Program (RI SPP) conducted a "Socioeconomics of Sea Level Rise Project" which assessed population and characteristics of people living within the 1, 3, 5, and 7-foot STORMTOOLS sea level rise inundation zones in Rhode Island's coastal communities (RI SPP 2016a). Although this study used STORMTOOLS, it only considered sea level rise scenarios, not the additional inundation that would be caused by storm surges. This study utilized the statewide E911 dataset in addition to the 2010 U.S. census. For the complete study see http://www.planning.ri.gov/geodeminfo/data/socio-slr.php.

3. This study found that all but one of Rhode Island's 21 coastal communities – Pawtucket - have residential units in at least one of the SLR inundation zones. The average household size in the coastal communities ranges from 1.96-2.5. Residential units included in inundation zones include single- and multi-family homes as well as mobile home residential units. Not all of these housing units are occupied year round; this study found that approximately 70-73% of the units located within these four SLR inundation zones are occupied on a full-time basis (as a primary residence).

4. Analysis of residential units and occupation estimates within the 21 coastal communities revealed that an estimated 6,945 individuals live in an estimated 3,321 occupied housing units within the 7-foot SLR scenario. See Table 16 below.

Table 16. Occupied residential units and population estimates, 21 RI coastal communities (adapted from RI SPP 2016a)

SLR Inundation Zone	Residential Units	Occupied Unit Calculation (total units x occupied housing unit rate)	Population Calculation *(occupied units x 21 coastal community average household size)*
1-foot SLR	9 single-family, 1 multi-family, 1 mobile	8 *(70% occupancy rate per housing unit)*	20
3-foot SLR	300 single-family, 18 multi-family, 15 mobile	246 *(70% occupancy rate per housing unit)*	481
5-foot SLR	1646 single-family, 203 multi-family, 42 mobile	1487 *(71% occupancy rate per housing unit)*	2975
7-foot SLR	3642 single-family, 430 multi-family, 47 mobile	3321 *(73% occupancy rate per housing unit)*	6945

4.5.2.2 Critical Infrastructure

1. ***The following analysis considered STORM SURGE.***

2. Rhode Island's coastal communities include critical infrastructure of importance to the safety, security and economy of both Rhode Island and the nation. "Critical infrastructure" is a term used by the U.S. Department of Homeland Security (DHS) to describe sectors whose physical or virtual assets, systems, and networks are so vital to the United States that their damage or destruction would have a major impact on public safety, security, and the economy (DHS 2017). DHS defines 16 critical infrastructure sectors: chemical, commercial facilities, communications, critical manufacturing, dams, defense industrial base, emergency services, energy, financial services, food and agriculture, government facilities, healthcare and public health, information technology, nuclear, transportation systems, and waste. The "public service structures" described above as part of CRMC's exposure assessment includes many of these same sectors. The Rhode Island Emergency Management Agency (RIEMA) oversees an Infrastructure Protection Program whose purpose is to enhance critical infrastructure protection statewide as part of its hazard mitigation program. For further information see www.riema.ri.gov.

3. RIEMA's 2014 Hazard Mitigation Plan Update (RIEMA 2014) included a vulnerability assessment of Rhode Island's critical infrastructure to hurricanes and tropical storms, using DHS critical infrastructure data as well as Rhode Island "critical facilities" and "state-owned facilities" data. To conduct this assessment, RIEMA used inundation data provided by the U.S. Army Corps of Engineers (USACE) which were derived by overlaying storm surge water elevations from the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model results on ground elevations from FEMA LiDAR data. This analysis did not include sea level rise and other changing future conditions. RIEMA's assessment also identified the number of critical infrastructure facilities located within FEMA Special Flood Hazard Areas. For further information see the 2014 Hazard Mitigation Plan Update at www.riema.ri.gov.

4.5.2.3 Wastewater Treatment Facilities

1. ***The following study considered STORM SURGE and SEA LEVEL RISE (1, 2, 3, and 5-foot scenarios).***
2. The state of Rhode Island has 19 wastewater treatment facilities (WWTF). 15 of these facilities are located in coastal municipalities and therefore potentially exposed to coastal storms, sea level rise and coastal erosion. These facilities are regulated by the RI Department of Environmental Management (DEM) Office of Water Resources.
3. In March 2017 the RI DEM Office of Water Resources released the results of a RI DEM *Wastewater Infrastructure Vulnerability Study* (RI DEM 2017). This study evaluated both historic and projected impacts from coastal storms and other natural hazards and recommended adaptation strategies for potentially impacted facilities. This included use of STORMTOOLS inundation models that projected 1, 2, 3, and 5-foot SLR scenarios plus a 100-year storm surge. For further information on this study or the findings discussed below please contact the DEM Office of Water Resources.
4. This study found that six coastal WWTFs are at risk of being "predominantly inundated" through coastal flooding and four coastal WWTFs are at risk of being "partially inundated." Those facilities at risk of being predominantly inundated are: Bucklin Point (East Providence), East Greenwich, East Providence, Fields Point, Quonset Point, and Warren. Facilities at risk of being partially inundated are: Bristol, Cranston, Newport, and Westerly.
5. This study also found that while five coastal WWTFs are not at risk of being inundated, coastal hazards could still create other problems at those facilities, such as facility access or within facility collection systems. Those facilities are: Jamestown, Narragansett, New Shoreham, South Kingstown, and Warwick.

4.5.2.4 Drinking Water Utilities

1. ***The following study considered SEA LEVEL RISE (2.8, 2.92 and 5 ft. scenarios) and FLOODING.***

2. The state of Rhode Island's drinking water utilities include freshwater wells and reservoirs as well as pretreatment and treatment facilities, interconnections, pump stations, and pipelines which are owned and/or managed by a mix of municipal, regional and other public utilities. Many of these utilities are located in or serve Rhode Island's coastal municipalities and are thus potentially vulnerable to the impacts of coastal storms, sea level rise and coastal erosion. The RI Department of Health (DOH) is charged with ensuring the safety of Rhode Island's public water supplies. This includes planning for and implementing measures to ensure water security.

3. In 2013 the RI DOH Office of Drinking Water Quality released the results of the SafeWater RI initiative (RI DOH 2013) which sought to plan for the future of Rhode Island's drinking water supply in the face of threats associated with climate change. This assessment involved surveys and interviews with drinking water utilities; an assessment of the impacts of changing environmental conditions on these facilities; and the identification of management strategies and site-specific recommendations to address these impacts. Climate change indicators considered in this analysis included air temperature, precipitation, watershed hydrology, and sea level rise.

4. The SafeWater RI initiative considered conservative sea level rise scenarios as well as a hurricane storm surge model which considered coastal erosion and tidal movements. This assessment was based on a projected 2.8-foot sea level rise in Providence and a 2.92-foot sea level rise in Newport, but also considered a 5-foot "worst-case scenario," by 2084. Findings based on these scenarios were released in the 2013 final report *SafeWater RI: Ensuring Safe Water for Rhode Island's Future*. For further information see http://www.health.ri.gov/publications/reports/2013EnsuringSafeWaterForRhodeIslandsFuture.pdf.

5. It is notable that even with these conservative sea level rise projections, the SafeWater RI analysis considered the risk of hurricanes to the state's drinking water utilities and found that by 2084, 20 utilities may be impacted by sea level rise and 11 by coastal flooding.

4.5.2.5 Transportation Infrastructure

1. ***The following study considered SEA LEVEL RISE (1, 3, and 5-foot scenarios).***

2. The state of Rhode Island relies on a network of surface, marine, and air transportation assets throughout the state which include roads, rail, bike paths, ports and harbors, airports, bus routes, intermodal hubs, and bridges. Much of this infrastructure is located in coastal areas and is thus potentially vulnerable to the effects of coastal storms, sea level rise and coastal erosion. Much of this infrastructure is owned and/or managed by the RI Department of Transportation (RI DOT), which designs, maintains and constructs the state's surface transportation system.

3. In 2015 the Rhode Island Statewide Planning Program (RI SPP) completed a "Vulnerability of Transportation Assets to Sea Level Rise" study (RI SPP 2015) which assessed the vulnerability of state-owned or managed transportation assets to sea level rise, considering 1-foot, 3-foot and 5-foot sea level rise scenarios. This analysis did not include storm surge scenarios. This analysis involved conducting an exposure assessment and developing a simple vulnerability index to provide insight into the relative vulnerability of transportation assets. It was followed in late 2016 with a second study which focused on municipal transportation assets (see RI SPP 2016b). Some study results of the 2015 state analysis are highlighted below. For further details on this study including methods and full results please see http://www.planning.ri.gov/geodeminfo/data/slr.php.

4. **Roads**: SPP's analysis examined the exposure of roads throughout the state, and found that 2.3 miles of roadway are expected to flood at high tide under a 1-foot SLR; 28 miles under a 3-foot SLR; and up to 85 miles under a 5-foot SLR. SPP further determined that while miles of road will be affected by SLR, roughly 70% of these are local roads which do not qualify for federal transportation funding. SPP's vulnerability assessment found that, of all roads under state jurisdiction which will be impacted by a 5-foot SLR, the most vulnerable road segments are located in Barrington, Warren, Tiverton, Bristol, New Shoreham, and North Kingstown. For Barrington and Warren, this includes three road segments each. Importantly, all ten of these road segments are expected to experience daily high tide flooding even under the lower SLR scenarios. Additionally, nine out of these ten segments are currently designated as hurricane evacuation routes.[7]

5. **Railways**: SPP's analysis addressed the impacts of SLR on railways in Rhode Island and found that an area of railway at Quonset, and two areas of the Newport Secondary Track (the dinner train), are projected to flood under a 5-foot SLR, while additional areas of the Newport Secondary Track are projected to flood under both 3- and 5-foot SLR scenarios. Importantly, as this assessment was focused on state facilities, this did not fully consider Amtrak railways which are expected to experience SLR impacts.

6. **Rhode Island Public Transit Authority (RIPTA):** SPP's analysis also addressed RIPTA infrastructure, including bus stops and roadways, and found that in total (under all SLR scenarios), 16 routes are expected to experience flooding, and 52 bus stops are located within projected inundation zones. SPP's vulnerability index identified Bus 60 (the Providence/Newport route) as the single most vulnerable route statewide given flooding risk when combined with ridership and trip frequency.

7. **Bridges**: SPP examined the exposure and vulnerability of Rhode Island's bridges, which are of concern regarding SLR both because of bridge height itself (measured by freeboard) and bridge accessibility from the roadway. SPP identified 77 bridges of concern because of either freeboard heights or accessibility. Their vulnerability index identified the Barrington Bridge and the Warren Bridge, both of which carry RI-103/114 over the Barrington River in Barrington, as the top two most vulnerable bridges in the state under the 5-foot SLR scenario. The Barrington Bridge was built in 2009.

[7] Although SPP's analysis focused on which roads may be inundated through surface water flooding, it is important to note that changes in groundwater levels associated with sea level rise could also intersect with road infrastructure, reducing their service life (see Knott et al. 2017).

8. **Bicycle infrastructure**: SPP's analysis also included off-road paths and on-street lanes and routes. SPP identified the East Bay Bike Path as the most exposed bicycle infrastructure, projecting inundation at several places along this path under both the 3- and 5-foot SLR scenarios. They also identified several on-street bike routes as vulnerable to SLR. SPP's vulnerability index identified East Providence and Bristol segments of the East Bay Bike Path as the top two most vulnerable places in the state.

9. **Passenger intermodal hubs**: SPP's analysis also assessed the exposure and vulnerability of bus, rail, air, and ferry transportation facilities. This analysis indicated that seven intermodal hubs – all of which are ferry terminals – are expected to be inundated by SLR. The Galilee Block Island Ferry terminal was listed as the most vulnerable such hub statewide, followed by the Block Island Ferry terminal located in New Shoreham. The Galilee facility will be inundated under the 3-foot SLR scenario, while the New Shoreham facility will be inundated under the 5-foot SLR scenario. Both facilities provide critical lifeline ferry service for New Shoreham's year-round residents, who do not have a surface transportation alternative to reach the mainland.

10. **Maritime infrastructure**: SPP's analysis also addressed the exposure and vulnerability of "oceanfront ports and harbors." SPP did not conduct a full vulnerability assessment of these facilities. Instead, this study provided general insight into the impacts of SLR on such facilities by calculating the acreage of individual commercial/industrial port facilities and of commercial/industrial port areas within each municipality that is expected to be inundated through the different SLR scenarios. Based on this, SPP found that commercial/industrial port areas' exposure to SLR will be particularly significant in North Kingstown, Providence, East Providence, and Narragansett. They also found that individual facilities at Quonset, in Providence and East Providence, and Point Judith are expected to experience significant SLR impacts. As discussed above, Point Judith supports much of Rhode Island's commercial and recreational fisheries; see section 4.3.2.1 for further discussion.

4.5.2.6 Public Access and Recreation Assets

1. Rhode Island's 21 coastal communities include numerous shoreline public access points and recreational assets that together provide Rhode Island residents and visitors with opportunities to participate in a wide range of active and passive recreational activities. These activities may include swimming, fishing, boating, surfing, hiking, viewing of wildlife, historic sites, or scenic areas, and others. Sites and assets that provide these opportunities may include publicly-owned and managed beaches, parks, boat ramps, fishing piers and campgrounds. State-owned and managed facilities are overseen by the Rhode Island Department of Environmental Management (DEM) Office of Parks and

Recreation; for further information see http://www.riparks.com/. Public access sites and assets may also include designated public rights-of-way (ROW), established in some cases over private land, which provide access to coastal waters. The CRMC oversees the designation of public rights-of-way; for further information see http://www.crmc.ri.gov/publicaccess.html.

2. Many coastal recreation and public access sites and facilities are by definition exposed to the impacts of storm surge, coastal erosion and sea level rise due to their location in low-lying waterfront areas. To date, no systematic study has been conducted of the exposure of recreational assets to storm surge, coastal erosion and sea level rise (see Section 4.8). Generally, sites and facilities located in at-risk areas are of particular concern; see Section 4.6.1 below.

3. According to the RI CRMC, a public ROW to the shore is a piece of land over which the public has right to pass in order to access Rhode Island's tidal waters. CRMC reports in its 2016 ROW progress report (RI CRMC 2016) that there are currently 222 rights of way designations in the state. Table 17 lists the number of ROWs in each municipality. The top three municipalities with the most ROWs are Warwick, Bristol and Newport, which together have 40% of the entire state's ROWs; it is important to note that the Shoreline Change SAMP's at-risk area analysis (see Section 4.6.1) identified Bristol as one of the most at-risk areas for sea level rise and storm surge.

Table 17. Public shoreline rights-of-way listed by municipality (RI CRMC 2016)

Municipality	Number of shoreline public ROWs
Barrington	2
Bristol	30
Charlestown	2
Cranston	3
East Greenwich	6
East Providence	13
Jamestown	14
Little Compton	3
Middletown	10
Narragansett	13
New Shoreham	7
Newport	23
North Kingstown	3
Pawtucket	1
Portsmouth	17
Providence	3
South Kingstown	4
Tiverton	7

Warren	9
Warwick	41
Westerly	11

4.5.2.7 Historic and Archaeological Assets

1. Rhode Island's coastal communities contain numerous historic and archaeological assets which are of cultural, historic, social and economic importance to these communities as well as to other Rhode Island residents and visitors. The Rhode Island Historic Preservation and Heritage Commission (RI HPHC) is the state agency which oversees historic preservation and heritage throughout the state. RI HPHC maintains a State Register of Historic Places and facilitates the National Register for Historic Places, a federal program, throughout the state; see http://www.preservation.ri.gov/ for further information.

2. In 2015 the RI HPHC commissioned a study (Youngken Associates 2015) that evaluated the potential impacts of flood-related regulations to historic properties in Rhode Island's 21 coastal communities. This study did not evaluate the potential effects of sea level rise or other changing future conditions, and emphasized FEMA's National Flood Insurance Program, flood resiliency programs targeted at historic structures, and other topics only marginally related to the Shoreline Change SAMP.

3. This study found that there are 1,971 National Register-listed or eligible assets located in FEMA mapped "coastal and estuarine flood zones" in these 21 coastal communities. Numbers of assets per community range from 548 in Newport to just 4 in Middletown. The top five communities, by number of assets in flood zones, are Newport (548), North Kingstown (294), Warren (223), Bristol (194), and Westerly (178). In other words, 72.9% of the state's historic assets located in current flood zones are located in just these five municipalities. This study also found that the assessed value of Newport's exposed historical assets alone was over $432 million (Youngken Associates 2015).

4. Youngken Associates (2015) acknowledge that their study is a conservative estimate of flood-related impacts because it does not consider sea level rise or other changing future conditions. The authors provide a series of detailed recommendations for historic property owners and community officials; see summary report for further information.

4.6 Synthesis: Exposure of Rhode Island's Coastal Region to Storm Surge, Coastal Erosion and Sea Level Rise

4.6.1 At-Risk Areas

1. Areas of the Rhode Island coast that are at risk of the impacts of storm surge, coastal erosion and sea level rise were analyzed by Oakley, Hollis, and colleagues (Oakley, Hollis, Boothroyd, Freedman, Boyd and Fugate 2016; Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016; hereafter "Oakley and Hollis at-risk area studies"). "At-risk areas" were defined as those where "existing state, municipal or private infrastructure and/or public access are susceptible to erosion, shoreline migration, and/or inundation from sea level rise or storm surge." These studies were intended as initial, broad-brush analyses of the exposure of coastal areas and as coarse initial risk identification tools to be followed up with more detailed analyses at the municipal or individual site scale. The research reflected in these reports was developed prior to the development of STORMTOOLS, the development of the 7-foot SLR scenario, and other tools that are central to the Shoreline Change SAMP. As such, these study results are best used in conjunction with other more recent data and tools referenced in this document. Select results are presented below. Oakley and Hollis's reports include methods as well as detailed findings for each individual municipality; please see the full reports at www.beachsamp.org.

4.6.2 Storm surge, coastal erosion and sea level rise in RI

1. The analyses of historic shoreline change, at-risk areas, and projected shoreline change discussed in this chapter together provide insight into how areas of Rhode Island's coast may be impacted by the combined effects of storm surge, coastal erosion and sea level rise. This section provides examples of some of the ways in which a subset of communities on the south shore and in Narragansett Bay may be impacted based on the above-mentioned studies. Importantly, communities discussed in this section were also identified as highly exposed in Leporacci et al. (2016), discussed earlier in this chapter. This section is not exhaustive and the inclusion of only these communities does not mean that only these communities are at risk, nor that other communities are free from risk. Decision-makers and property owners are strongly encouraged to review findings related to their individual municipality in the reports and collections of online maps described above.

4.6.2.1 Matunuck Headland

1. The combined results of these studies indicates that the Matunuck Headland area is one of the most at risk in the state to the combined effects of storm surge, sea level rise and coastal erosion. Evaluation of historic shoreline change revealed a very high rate of erosion along a stretch of Matunuck from Cards Pond to the east end of South Kingstown Town Beach. Individual transects in this area exceed a loss of 1.4 meters/year (1.6 feet/yr), and total shoreline change in this area exceeded 90 meters (295.2 ft) between 1951 and 2014 (see Figure 11) (Boothroyd et al. 2016). Oakley et al. (2016) reported that high erosion rates in this area are most likely due to a combination of bluff composition (easily erodible glacial stratified deposits) and bluff elevation (impacted by many storms), as well as wave refraction and focusing around the adjacent gravel terraces.

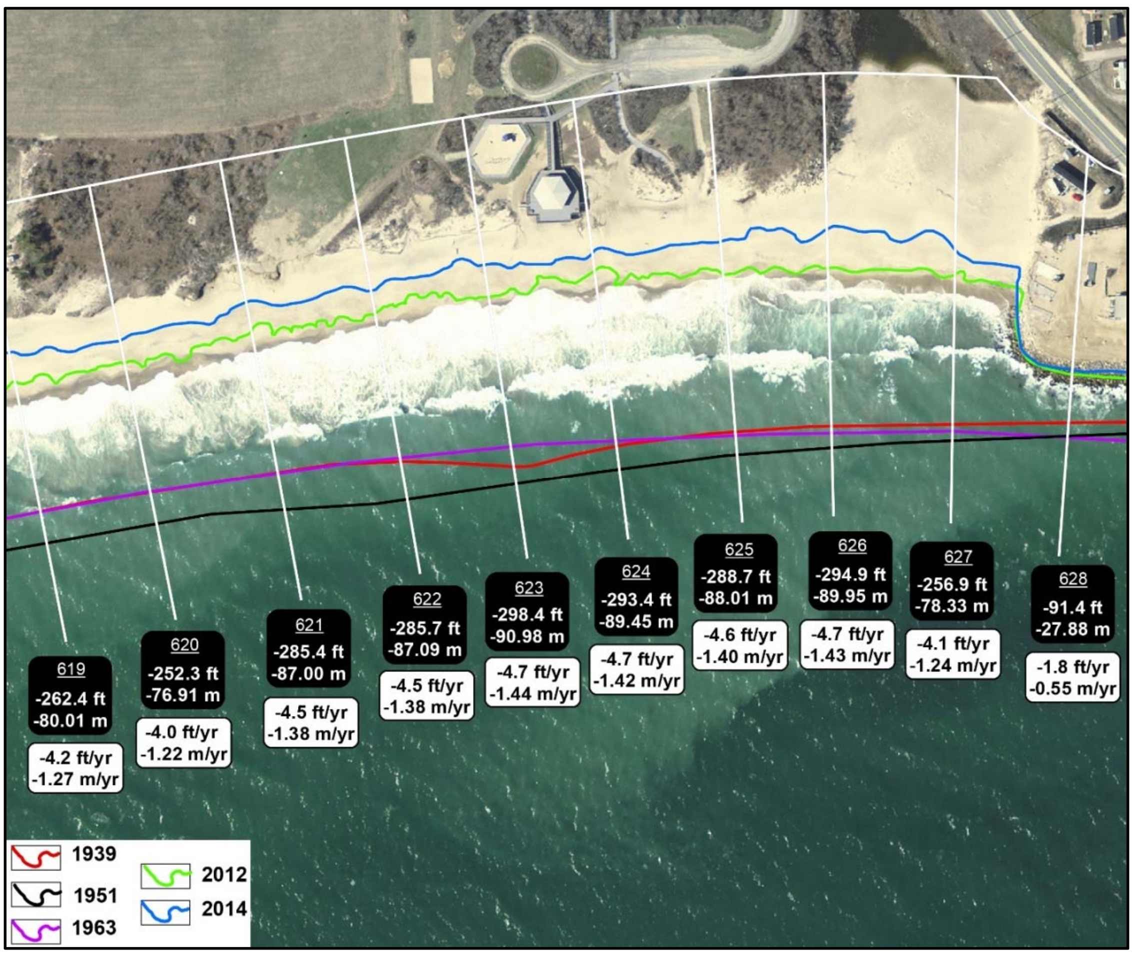

Figure 11. Portion of the Matunuck Headland Shoreline Change Map (Boothroyd et al. 2016).

2. The Hollis at-risk study, which considered these historic rates of shoreline change in addition to storm surge, SLR, and projected shoreline change, identified two areas of the Matunuck headland area at risk: the segment containing Roy Carpenter's Beach and South Kingstown Town Beach, and the commercial/residential neighborhood east of South Kingstown Town Beach. The following information is derived from this study; for further information please see Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016.

3. Roy Carpenter's Beach includes a high-density area of small cottages which were damaged in 2012 during Superstorm Sandy. This area exhibited a very high rate of erosion between 1939 and 2014 of 62 to 73 meters (206 to 240 feet). This area, particularly the seaward rows of cottage, will continue to be impacted by erosion and storm surge. As discussed above, the South Kingstown Town Beach area has exhibited very high erosion rates, exceeding 90 meters (295.2 ft). Beach profiling conducted by the Rhode Island Geological Survey found 29 meters (96 feet) of bluff migration since 1996, indicating that this area has been extremely erosional over the last 20 years. Infrastructure at risk includes the town beach pavilion, which was relocated landward after Sandy, and a revetment at the east end of the beach which encompasses a trailer park and Matunuck Beach Road. The commercial/residential area east of South Kingstown Town Beach is also at risk from continued erosion. Matunuck Beach Road, which runs parallel to the shoreline, provides the only road access to and evacuation route for over 200 homes and businesses east of South Kingstown Town Beach. Historic shoreline change in this area has been higher in the western section than the eastern.

4. Projected shoreline change reveals what the authors call "an incredible extent of land at risk to erosion in both sections of the headland" for these areas – the low-lying cottages on Roy Carpenter's beach; South Kingstown Town Beach; the mobile home park east of the beach; and Matunuck Beach Road. Homes to the east of these areas will be either directly impacted through erosion or indirectly impacted through lack of road access. See Figure 12 which also shows projected future CRMC setback requirements based on the projected future location of the coastal feature (see Section 4.4.2 above for further discussion).

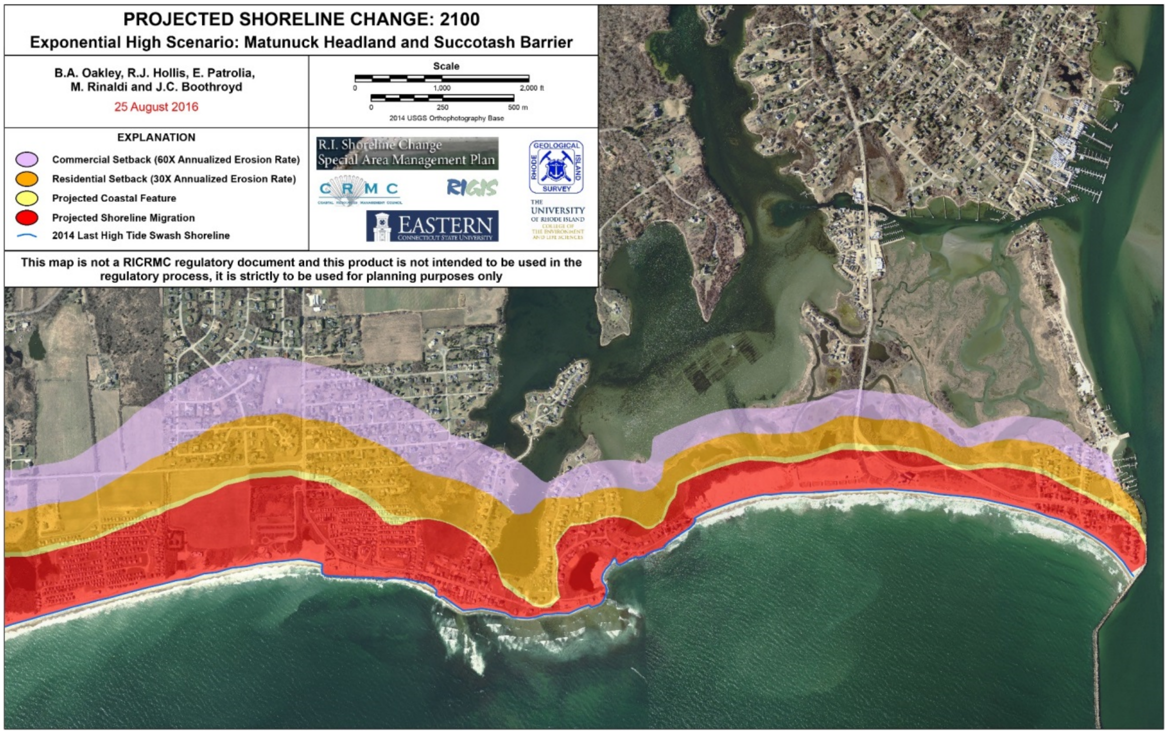

Figure 12. Projected shoreline position, controlling coastal feature, residential and commercial setbacks of Matunuck headland for the year 2100, where historical shoreline change between 1939 and 2014 was exponentially accelerated to the year 2100 (Source: Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016).

5. Sea level rise and storm surges will affect these as well as other areas. A five-foot SLR will inundate areas seaward of Theater by the Sea including the Browning Cottages, Roy Carpenters beach cottages, and Cards Pond Road. Importantly, flooding will also affect non-oceanfront areas such as Potter's Pond, raising water levels within the pond that will in turn affect adjacent homes and roads. See Figure 13. For further information see Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016.

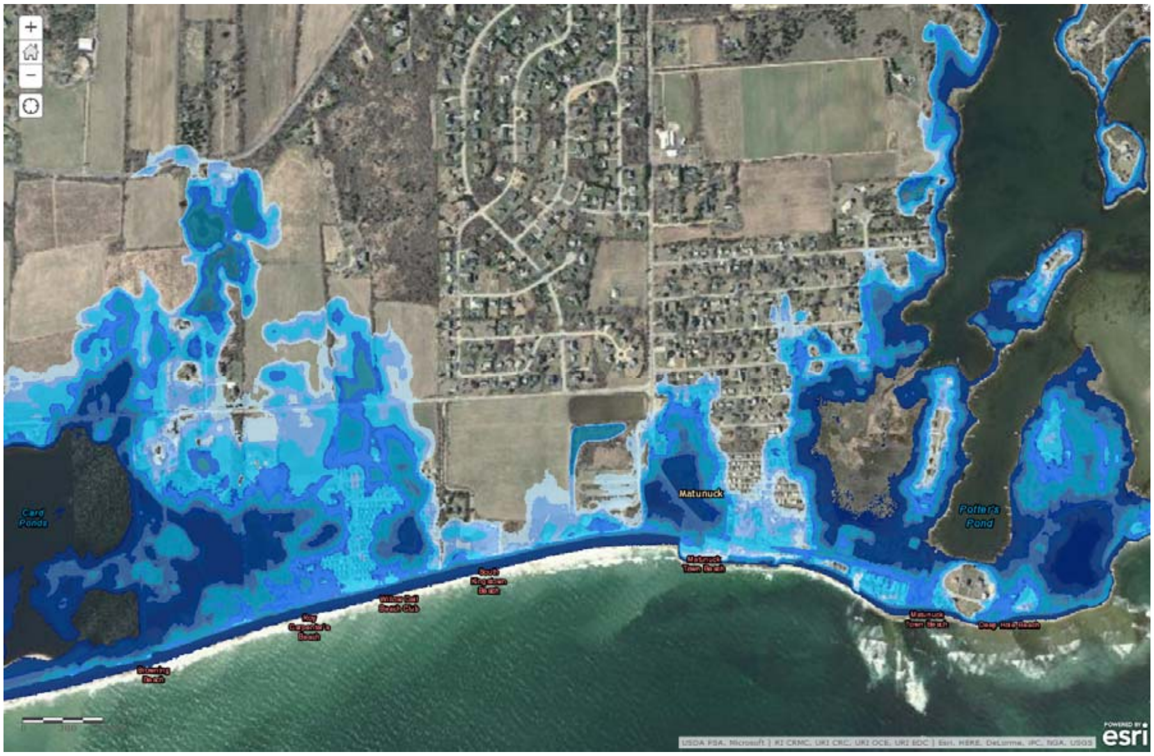

Figure 13. Five-foot SLR plus a 100-year storm surge affecting Matunuck Headland and adjacent areas. The blue-shaded areas indicate the extent of inundation; darker shades of blue indicate deeper waters. (Source: Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016).

4.6.2.2 Misquamicut

1. The combined results of these studies indicate that Misquamicut is another notable area at risk of the combined effects of storm surge, coastal erosion and SLR. Additionally, Misquamicut has greater exposure because of the higher density of development in this area compared to Matunuck. For analytical purposes, Misquamicut is treated as two separate areas: the Misquamicut Headland (west of Misquamicut State Beach) and the Misquamicut Barrier (including the beach and areas east). The barrier comprises three areas: the Misquamicut State Beach; the commercial area along Atlantic Avenue to the east; and the residential area along Atlantic Avenue to the east of the commercial area. For figures illustrating Misquamicut's at-risk areas, see the Hollis at-risk area report at www.beachsamp.org.

2. Historic shoreline change analysis revealed that the Misquamicut Headland area's shoreline change rate from 1939 to 2014 ranged from 12 to 28 meters (40 to 93 feet) of retreat (Boothroyd et al. 2016). Historic shoreline changes along the barrier are seemingly low with 16 meters (56 feet) at Misquamicut State Beach, between 13 and 25 meters (45 and 83 feet) along the Atlantic Avenue commercial district, and between 10 and 39 meters (33 and 130 feet) along the Atlantic Avenue residential district

(Boothroyd et al. 2016). It is important to note that semi-permanent inlets formed along the barrier during both the 1938 Hurricane and Hurricane Carol in 1954. Based on this history and the low elevation of this area, it is expected that the barrier will breach again during future storms. This is consistent with other studies which have shown that inlet formation is likely at the lowest and narrowest portions of barriers, which may coincide with the location of former inlets (Sallenger 2000; Stockdon et al. 2007; Stockdon et al. 2009).

3. Based on these data, it would seem that the Misquamicut Barrier is not subject to significant erosion risk compared to other areas along the south shore, but this is not the case. The Oakley et al. at-risk area reports notes that there have been multiple federal and private local investments in beach replenishment projects and other interventions designed to maintain the barrier for tourism and other purposes.

4. The Hollis et al. at-risk area report reported projected shoreline change analysis for Misquamicut, which reveals significant at-risk areas. By 2100, it is expected that all structures seaward of Atlantic Avenue in the Headland area will be at risk of erosion. Similarly, along the barrier, all structures seaward of Atlantic Avenue will be at risk of erosion, as will be portions of Atlantic Avenue itself, the shore parallel road. Additionally, some of the properties north of Atlantic Avenue would protrude out onto the beach; such structures can cause shore parallel access issues or be at extreme risk of storm damages.

5. The Hollis et al. at-risk area study reported that inundation due to a 5-foot SLR in addition to a 100-year storm surge will have extensive impacts on Misquamicut. Residential areas on the low-lying southern part of the Headland will be impacted by SLR. Storm surge penetrated more than 300 meters (984.2 feet) inland during Superstorm Sandy, and even further inland during the 1938 Hurricane and Hurricane Carol in 1954; this is considered a useful approximation for inundation associated with a 5-foot SLR. A 5-foot SLR coupled with a 100-year storm surge is expected to result in inundation extending 500 meters – 1 km (0.3 – 0.62 miles) inland. On the barrier, a 5-foot SLR coupled with a 100-year storm surge is projected to inundate the entire barrier, including the beach and all commercial and residential properties. Access roads off the barrier would be completely flooded, and historic storms in the area suggest the possibility that the barrier could breach, effectively cutting it in half. During storms with sufficient surge, the barrier migrates as sediment is transported landward via overwash and deposited as washover fans. However, it is important to note that during smaller storms the barrier may not be inundated nor migrate through the process of overwash, but rather could be narrowed via frontal erosion.

6. Hollis et al.'s report points out the presence of numerous discontinuous revetments along both the Misquamicut headland and barrier. Additionally, anthropogenic dikes are located in several places including seaward of the Misquamicut Beach pavilion and parking lot. Most of the revetments were damaged, and many of the dikes failed, during Superstorm Sandy in 2012. Projected shoreline change for this area indicates that, over time, all but the largest such structures in this area will likely fail. For further information see Hollis, Oakley, Rasmussen, Boothroyd, Freedman and Fugate 2016.

4.6.2.3 Barrington, Warren and Bristol

1. Inside Narragansett Bay, the municipalities of Barrington, Warren and Bristol together represent an area that is expected to be highly impacted by storm surge, coastal erosion and SLR. These three municipalities are grouped together as one region for this summary discussion. Unlike the south shore, Oakley et al.'s at-risk study for Narragansett Bay focused on historic shoreline change, not projected shoreline change, and identified areas where 50 feet or more of shoreline change had been observed; see below for results for each municipality. The following information is summarized from Oakley et al.'s at-risk study; please see Oakley, Hollis, Boothroyd, Freedman, Boyd and Fugate 2016 for more information.

2. Historic shoreline change analysis for the Barrington, Warren and Bristol region revealed some at-risk areas. Some portions of Barrington Beach experienced up to 60 meters (197 feet) of landward shoreline migration between 1939 and 2003, and structures at the eastern end of Barrington Beach will be at risk from future shoreline migration. In Warren, small sections of the marsh shoreline along the Palmer River and Belcher Cove, as well as the head of the Kickemuit River and a small barrier spit at the mouth of the river, exceeded 50 feet of shoreline change from 1939 to 2003, thus meeting the study's 'at risk' threshold.

3. SLR and storm surge are the primary threats to Barrington due to its low-lying nature. In Barrington, many low-lying areas are already inundated during spring tides. SLR will cause more extensive flooding, even at less than the 5-foot SLR scenario. For example, along the Warren River, even a 1-foot SLR impacts access roads, and a 3-foot SLR isolates properties along these roads. A 2-foot SLR will partially inundate the Barrington Yacht Club on Tyler Point, and at a 5-foot SLR, Tyler Point will be largely flooded. SLR alone will inundate some properties and isolate others by flooding access roads such as County Road (Rte. 103), one of the main access roads for the town. A 100-year storm surge on top of a 5-foot SLR will inundate significant portions of Barrington. This will result in isolation of large portions of the town due to the Providence River merging with the Barrington River via Massachuck Creek and another small creek. Many of these

same areas are expected to flood even during a 25-year “nuisance” storm event. Properties in multiple neighborhoods will be inundated, and others will be isolated due to flooding of access and evacuation routes. Major roads including Rt. 114/103 (Wampanoag Trail and County Road) will be flooded at multiple points. Almost all of New Meadow Neck, which has dense residential development, is projected to be inundated by surge.

4. SLR and storm surge represent significant threats to Warren. The Oakley et al. at-risk study reports that a 1-foot SLR will “begin to alter the configuration of the commercial district” along the Warren waterfront, whereas a 3-foot SLR will bring about “dramatic changes to the waterfront.” A 5-foot SLR will further inundate these same areas. The Warren Reservoir, which is part of the Bristol County Water Supply, may be inundated by as little as a 2-foot SLR. A 100-year storm surge on top of a 5-foot SLR will inundate significant portions of downtown Warren, and inundation across Main Street will isolate portions of downtown, affecting access and evacuation routes. The Kickemuit River and Belcher Cove will become connected under this flood inundation scenario, limiting access between downtown and east Warren, and the bridge to Warren from Barrington (Rte 103/114) will be inundated, further limiting access and evacuation.

5. Bristol is also at risk from the threats of sea level rise and storm surge, especially the waterfront commercial district and low-lying areas adjacent to several creeks and ponds. Oakley et al. report that a 1-foot SLR will begin to “alter the configuration of the commercial district along the waterfront” and that a 5-foot SLR will cause “dramatic changes to the waterfront.” A 5-foot SLR will also limit access to portions of the town and inundate several properties. A 100-year storm surge on top of a 5-foot SLR will have significant impacts on downtown Bristol, particularly the commercial district along Thames Street and residential areas along Hope Street. Projected inundations will limit access and evacuation from Poppasquash Point because Bristol Harbor will become connected to the Providence River via Mill Gut. Projected inundations will also affect Roger Williams University facilities including its southernmost dorm.

4.7 Synergistic Effects of Storm Surge, Coastal Erosion and Sea Level Rise

1. Storm surge, coastal erosion and sea level rise are coastal hazards that interact with each other and with other hazards (e.g. wind), resulting in synergistic effects. A synergistic effect is caused when the interaction between two or more structures or

processes results in effects that are greater than the sum of each individual effect. Whereas many tools and studies have been developed to date to examine these coastal hazards, both by the CRMC and other agencies and organizations, many such tools only consider one coastal hazard at a time, not addressing the interactions between hazards. This means that many tools and analyses may underestimate the collective impacts of these hazards. Synergistic effects may result in greater exposure of Rhode Island's built and natural environment than any one of these processes and are thus critical considerations for long-term planning.

2. Some of these synergistic effects have been considered by Rhode Island studies and tools referenced in this chapter, whereas others require further research and analysis to understand how they affect the exposure of the Rhode Island coast. Importantly, this means that in many cases exposure assessments discussed in this chapter may underestimate the potential impact of a specific hazard to Rhode Island.

3. One example of a synergistic effect that may mean increased exposure along the Rhode Island coast is the way in which sea level rise will increase the return period of stormsJ (Lin et al. 2012). The concept of a storm return period assumes that the probability of a storm's occurrence will not change over time, but this does not account for sea level rise and other effects of climate change. Over time, as sea levels rise, a relatively low-probability storm event such as the 100-year storm will increase in probability because higher base water levels will increase the extent and depth of storm-related flooding. For example, Figure 14 illustrates how a 2-foot SLR reduces a 100-year storm event to a 20-year storm event (Spaulding, pers. comm.).

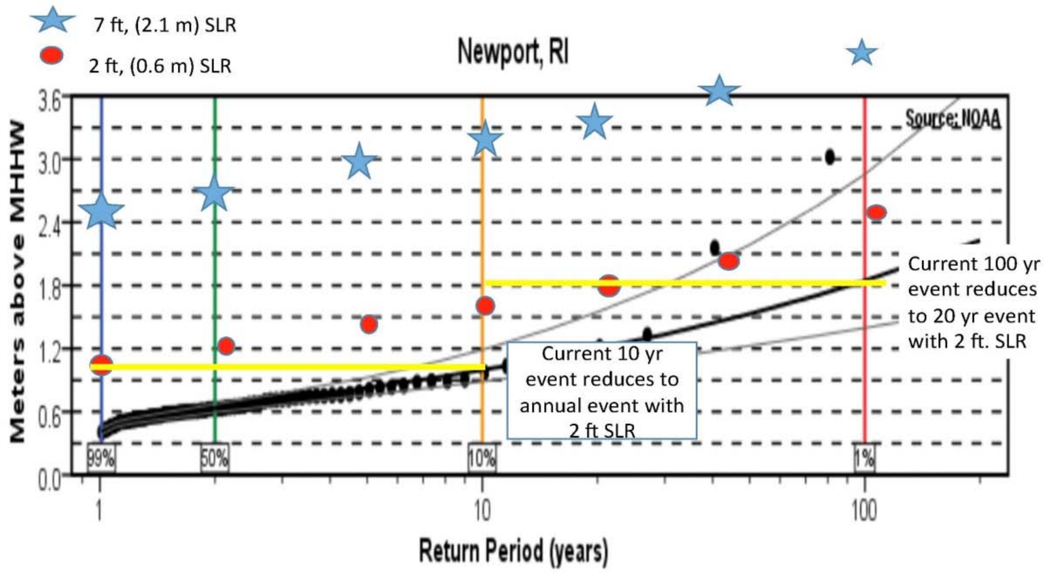

Figure 14. The effect of sea level rise on storm return periods (Spaulding, pers. comm.).

4. There are numerous other synergistic effects which may lead to increased exposure the Rhode Island coast. For example, storm surges on top of projected sea level rise will exacerbate existing storm-driven coastal erosion processes, accelerating future erosion. This is illustrated by the projected shoreline change maps included in Oakley, Hollis, Patrolia, Rinaldi and Boothroyd (2016). Storm surges on top of projected sea level rise will also increase the frequency of a given surge elevation occurring (i.e. a 100 year storm becomes a once in a decade storm) (Tebaldi et al., 2012; Grilli et al. 2017). Because rising seas raise the base water level, this could result in greater damage to coastal structures due to elevated storm surges and wave action. Additionally, synergistic effects will result from the interaction between rising seas and freshwater systems. These include setting a new flood stage in riverine systems, thus increasing flood risk in inland areas adjacent to rivers (Garcia and Loáiciga 2014; Hashemi et al. 2017), and causing a rise in the groundwater table, reducing groundwater separation distance to on-site wastewater treatment systems (Cooper et al. 2016). These are just a few of many synergistic effects which may increase the exposure of coastal Rhode Island's built and natural environment.

5. The synergistic effects of coastal hazards underscore the importance of long-term planning and adaptation. See Chapter 7 for adaptation strategies which can be used to reduce Rhode Islanders' exposure to these effects.

4.8 Ongoing and Future Research and Analysis

4.8.1 Overview

1. This chapter summarized much of the best available data and information on the exposure of Rhode Island's coast to the impacts of storm surge, sea level rise and coastal erosion. However, understanding of Rhode Island's exposure is rapidly changing, and research is under way in Rhode Island and elsewhere that may improve our understanding of Rhode Island's exposure. Additionally, other research questions and needs have arisen through the Shoreline Change SAMP development process that merit investigation. This section summarizes ongoing research projects with which CRMC is familiar, and describes future research needs which CRMC identifies as high priorities.

4.8.2 Ongoing Research

1. A team led by University of Rhode Island emeritus professor Dr. Malcolm Spaulding and other URI and CRMC colleagues is developing STORMTOOLS: Coastal Environmental Risk Index (CERI), a web-based GIS mapping tool. CERI uses state of the art modeling tools to predict storm surge and wave, combined with shoreline change maps (erosion), and damage functions, and applies these to Rhode Island's E-911 database of structures to perform exposure analyses for individual structures. CERI has been applied to two Rhode Island communities, Charlestown (representing a typical coastal barrier system directly exposed to ocean waves andhigh erosion rates), and Warwick (located within Narragansett Bay, with more limited wave exposure, lower erosion rates, and higher residential housing density. The CERI team is currently investigating the expansion of CERI to other communities and how best to help state and local decision-makers apply CERI to inform planning and policy decisions. For further information please see http://www.beachsamp.org/STORMTOOLS/STORMTOOLS-coastal-environmental-risk-index-ceri/.

2. University of Rhode Island professor Austin Becker is leading a U.S. Army Corps of Engineers (USACE)-funded study comparing the vulnerability of medium and high-use seaports in the North Atlantic. This study is piloting a climate vulnerability indexing method and will contribute to better understanding of climate vulnerability across North Atlantic ports. This vulnerability index includes SLR and storm surge. This study includes the port of Providence, and is expected to be completed by July 2019. For more information please see http://web.uri.edu/abecker/risk-indices/.

3. A team at the University of Rhode Island has partnered with the Coastal Resilience Center of Excellence at the University of North Carolina at Chapel Hill on a coastal resilience project funded by the U.S. Department of Homeland Security. URI's part of this project comprises three studies. The first, led by Dr. Chris Kincaid and Dr. Isaac Ginis, uses coastal prediction models to develop and apply the hypothetical scenario of Rhode Island's worst-case scenario storm, "Hurricane Rhody," in order to better understand the local effects of such a storm. The second, led by Dr. James Opaluch, tests the effectiveness of various incentives and policies with the goal of overcoming barriers to community actions that can reduce storm vulnerability. The third, led by Dr. James Prochaska, involves applying an established model of behavior change to coastal residents and tailoring interventions to encourage residents to choose mitigation options. For more information on this project please contact Pam Rubinoff at the URI Coastal Resources Center (rubi@crc.uri.edu).

4. A multi-agency assessment team led by the Narragansett Bay National Estuarine Research Reserve (NERR) has applied the Climate Change Vulnerability Assessment Tool for Coastal Habitats (CCVATCH) to fourteen different marshes within Rhode Island. A final report is forthcoming highlighting key findings including specific climate and climate/non-climate stressor interactions that were identified as primary drivers of potential future habitat condition change. For further information please visit www.ccvatch.com or contact Robin Weber at the Narragansett Bay NERR (robin@nbnerr.org).

4.8.3 Future Research Needs

4.8.3.1 The Built Environment

1. **New sea level rise projections**: Future research is needed to address new sea level rise data released by NOAA in early 2017, which project up to 9.6 feet of SLR under the "high" curve and up to 11.7 feet under the "extreme" curve, at the 83% confidence interval, for Rhode Island (see NOAA 2017a). Research should build new STORMTOOLS inundation layers that consider these new data and should examine the extent to which these new inundation layers change Rhode Island's exposure to storm surge and sea level rise. Additionally, all Shoreline Change SAMP and other studies included in this document should be updated to include these new SLR projections.

2. **Hurricane barrier**: Future research is needed on the Fox Point Hurricane Protection Barrier within the context of the broader Narragansett Bay system. This research should apply new knowledge of sea level rise and storm surge projections for Narragansett Bay to the hurricane barrier and examine the extent to which this structure will need to be

modified or any other changes should be made to accommodate these projected changes within the system. Any such analysis should be coordinated with others who are working on this or related issues, including but not limited to the Providence Office of Sustainability and the URI team working on the hypothetical "Hurricane Rhody" scenario (see section 4.8.2 above). If significant modifications are found to be necessary, then examining how best to deal with both storm surge and sea level rise at the facility might be warranted.

3. **Property values**: Future research is needed to determine the assessed value of properties that might be impacted by storm surge, coastal erosion and sea level rise. This research should also consider the property taxes associated with these properties and the potential impact of losses to municipal budgets. Last, research should address the broader economic impacts of damage to these properties.

4. **Recreational sites and infrastructure**: Future research is needed on the exposure of recreational sites and infrastructure to storm surge, coastal erosion and sea level rise. Recreational sites and infrastructure to be researched should include designated public rights of way (ROWs) which may be impacted by these hazards. This research could build upon existing Shoreline Change SAMP tools, such as STORMTOOLS, but should also consider the social, economic and cultural attributes of Rhode Island's shoreline recreational assets.

5. **Ports and working waterfronts**: Future research is needed on the exposure of Rhode Island's ports and working waterfronts to storm surge, coastal erosion and sea level rise. Ports and working waterfront facilities have unique vulnerabilities insofar as they must be located on the waterfront and allow access to waters of sufficient depth for commercial vessels. Analysis of these facilities could build upon existing Shoreline Change SAMP tools, such as STORMTOOLS, but should also consider the unique siting needs of these facilities as well as their economic importance to Rhode Island and to the nation.

6. **Existing shoreline protection structures**: Future research is needed to inventory and assess existing shoreline protection structures. Such an inventory has not been conducted, and the latest review of such structures took place in 2007 and only involved estimating structure length based on 2003 orthophotography. Current estimates of the length of the Rhode Island coast that is protected through such structures are only approximations. Such an assessment should examine the elevation and present condition of the structures.

7. **Railways**: Further research is needed on the exposure and vulnerability of Amtrak railways and infrastructure in Rhode Island to sea level rise. The RI Statewide Planning Program's 2015 state transportation infrastructure assessment referenced above focused on state infrastructure and did not fully assess Amtrak railways, which provides important services to Rhode Island and the region and which is expected to be vulnerable to SLR.

4.8.3.2 The Natural Environment

1. **Riverine systems**: Future research is needed on the effects that sea level rise and storm surge may have on Rhode Island's riverine systems, including but not limited to the Pawtuxet River, which has been modeled by the URI Department of Ocean Engineering (Hashemi et al. 2017).[8] There are multiple areas of research need regarding the Pawtuxet and other RI watersheds, which could inform the development of an operational flood forecasting system for these systems. First, research is needed on the coupling effect of storm surge and a precipitation event in the watershed. Second, research is needed on the coupling effect of new sea level rise scenarios with a flooding event in the watershed, considering both coastal and freshwater precipitation events. Third, research should consider scenarios in which a storm results in both storm surges and significant precipitation, potentially causing storm surge and inland flooding at the same time. Finally, research is needed on the problem of storm debris creating choke points on rivers, affecting river drainage and flooding.

2. **Groundwater**: Future research is needed on the effects that sea level rise will have on groundwater. Research should address two problems. The first is the problem of saltwater intrusion into drinking water supplies, which could have cascading effects through the state's water supply system. The second is the problem of sea level rise decreasing the separation distance between septic fields and groundwater, thus decreasing the effectiveness of the field in eliminating pathogens. Recent research examining how soil-based onsite wastewater treatment systems are affected by climate change in coastal regions can be found in Cooper et al. (2016).

[8] A team led by Dr. Reza Hashemi with the URI Department of Ocean Engineering has developed a spatially distributed hydrological/hydraulic modeling system for the Pawxuet watershed and river. The team simulated the March 2010 flood and developed a series of other scenarios, including multiple flood scenarios (see http://edc.maps.arcgis.com/home/webmap/viewer.html?webmap=d025e9fc58ae440a88b5ce590ddfa4cd). For further information please see Hashemi et al. 2017.

3. **Salt marshes**: Future research is needed on salt marsh migration, including how landward migration reacts to natural migration impediments, such as common coastal vegetation communities. Such research will be important for determining the marsh migration potential of adjacent lands and to help prioritize conservation of appropriate parcels as well as the effectiveness and cost of migration management practices. For further information on this and other salt marsh research needs, please see the Rhode Island Coastal Wetland Restoration Strategy (Kutcher 2017).

4. **SLAMM**: A Sea Level Affecting Marshes Model (SLAMM) analysis should be performed again, incorporating new assumptions including new sea level rise scenarios. The SLAMM analysis discussed in this chapter included only 1, 3 and 5-foot scenarios. Future analyses should include the 7-foot scenario used in this document as well as the new 9.6-11.7-foot scenarios introduced in early 2017 by NOAA (NOAA 2017a).

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