CHAPTER 2

Trends and Status: Current and Future Impacts of Coastal Hazards in Rhode Island

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2.1 Overview

1. The purpose of this chapter is to provide a brief synopsis of the scientific basis underlying the Shoreline Change Special Area Management Plan. The Shoreline Change SAMP is focused on three sources of coastal hazard risk: **storm surge**, **coastal erosion**, and **sea level rise**. Whereas Rhode Island coastal communities have been grappling with these sources of risk for some time, our changing climate is exacerbating these sources of risk. This has driven the CRMC to develop the Shoreline Change SAMP in order to help coastal property owners and state and local decision-makers plan for changing future conditions. The science in this chapter provides a foundation for this document by characterizing trends in our changing climate and describing how those trends are influencing sources of coastal hazard risk.

2. This chapter is not intended to be an exhaustive discussion of the science of climate change, nor of all of the coastal and other hazards which may be influenced by climate change. These areas of science are complex and rapidly changing. Given this dynamism, CRMC chose to develop this chapter as a brief summary that is designed for ease of updating in the future as new data are available.

3. This chapter includes a brief summary of the most updated science available on these topics. It includes a brief, general discussion of the trends associated with climate change that are most relevant to changing conditions on Rhode Island's coast, as well as a summary of the physical effects associated with these trends, both globally and regionally. Discussion is narrowly focused on changing conditions on Rhode Island's coast and in particular on the three sources of coastal hazard risk, in order to retain a focus on the structures within the coastal zone that are under CRMC's jurisdiction and exposed to these sources of coastal hazard risk. The chapter concludes with discussion of future research needs related to these topics.

4. This chapter does not include detailed discussion about the exposure of Rhode Island's coastal communities and coastal resources to storm surge, coastal erosion and sea level rise. Please see Chapter 4 for a detailed discussion of Rhode Island's exposure.

5. CRMC recognizes that its policy and planning horizons will need to be regularly updated into the future as the science changes. CRMC's sea level rise policy is formulated to

address the dynamic nature of this science. 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. The latest "high" curve can be viewed using the U.S. Army Corps of Engineers (USACE) Sea Level Change Curve Calculator at http://www.corpsclimate.us/ccaceslcurves.cfm. This allows CRMC to always base policy decisions on the most recent SLR projections. 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.

6. Further, coastal conditions are rapidly changing. In late 2017, three hurricanes – Harvey, Irma, and Maria – hit U.S. coastal communities in rapid succession. These three hurricanes are now among the top five most expensive hurricanes in U.S. history (NOAA National Hurricane Center 2018; NOAA National Centers for Environmental Information 2018). Further, the intensity of these three storms is consistent with scientific predictions that climate change would result in the increasing intensification of storms (see e.g. Sneed 2017).

2.2 Trends

2.2.1 Sea Level Rise

2.2.1.1 Historic Sea Level Rise

1. Sea levels are rising, caused by rising sea temperatures, which causes thermal expansion, and rising air temperatures, which causes melting glaciers and ice sheets.

2. **Sea levels have risen**, both in Rhode Island and around the world. In Rhode Island, sea levels have risen over 10 inches (0.25 meters) since 1930, as measured at the Newport tide gauge. The historic rate of SLR at this gauge, measures from 1930 to 2017, is 0.11 inches (2.75 mm) a year. This is equivalent to a change of 0.90 feet (0.27 meters) in 100 years (NOAA n.d.; see also RI EC4 STAB 2017). Rhode Island's rate of SLR is slightly higher than global SLR statistics. Global mean SLR rose by 7.48 inches (0.19 meters) between 1901 and 2010, at an average rate of 0.07 inches (1.7 mm) a year (Intergovernmental Panel on Climate Change (IPCC) 2014). See Table 1 for a summary of these data.

3. **Sea level rise is accelerating**, both in Rhode Island and globally. In Rhode Island, the mean annual rate of SLR at Newport, is 0.16 inches (3.98 mm) a year over the 30-year period of 1986-2017 (31 years) as measured by the Permanent Service for Mean Sea Level (Permanent Service for Mean Sea Level n.d.) Again, Rhode Island's recent rate of SLR is slightly higher than the global average. The rate of global mean SLR, as measured by satellite altimetry, increased over the period from 1993 to 2017 (24 years) to a rate of 0.12 inches (3.1 mm) a year (University of Colorado CU Sea Level Research Group 2018). However, short-term datasets (less than 30 years) should be used with caution, because of inherently large regression errors and the anomalous sea level increase during 2009-2010 due to a slowdown in the Atlantic Meridonal Overturning Circulation (Goddard et al 2015). See Table 1 for a summary of these data.

Table 1. Historic sea level rise and annual SLR rates, Rhode Island and global average

	Historic sea level rise	**Annual rate of SLR**	**Annual rate – recent acceleration**
Rhode Island	10 in (0.25 m) *(1930 to 2017)*	0.11 in (2.75 mm)/yr *(1930 to 2017)*	0.16 inches (3.98 mm)/yr *(1986-2017)*
Global average	7.48 inches (0.19 m) *(1901 to 2010)*	0.07 inches (1.7 mm)/yr *(1901 to 2010)*	0.12 inches (3.1mm)/yr *(1993-2017)*

4. **Rhode Island is part of an accelerated sea level rise "hotspot."** The above statistics have shown that observed sea level rise in Rhode Island is higher than the global average. This is consistent with a regional trend along the entire North American Atlantic coast between the Canadian Maritimes and North Carolina. Sallenger et al. (2012) found that SLR in this Atlantic coast region was 3-4 times higher than the global average between 1950-1979 and 1980-2009, describing this region as a "hotspot".

2.2.1.2 Projected Sea Level Rise

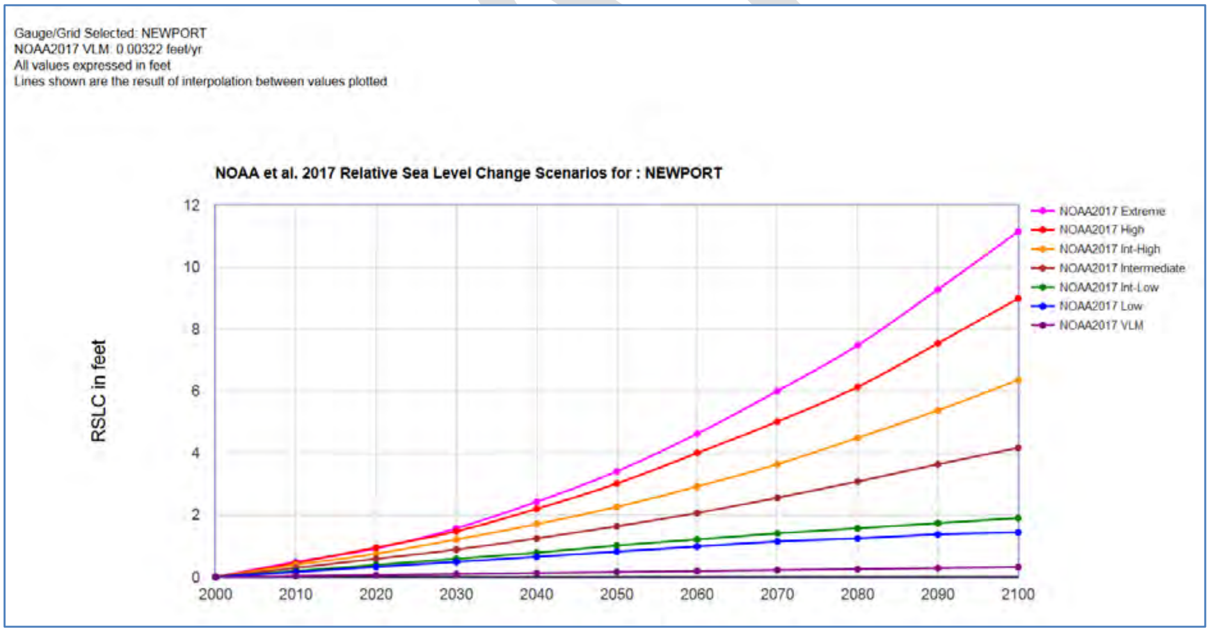
1. **Further sea level rise is projected for Rhode Island**. At the time of this writing, the National Oceanic and Atmospheric Administration (NOAA) **projects up to 9.6 feet of SLR in Rhode Island by 2100**. This projection is based on NOAA's 2017 analysis of SLR scenarios, and this particular statistic is based on the "high" curve and is estimated at the 83% confidence interval. 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. In the shorter term, the latest NOAA "high" curve projects 1.67 feet of SLR for 2030, 3.25 feet for 2050, and 6.69 feet for 2080, all at the 83% confidence level (NOAA 2017) (see Table 2 and Figure 1).

Table 2. Sea level rise projections for Rhode Island

	2030	**2050**	**2080**	**2100**
NOAA 2017 projections based on "high curve"	1.67 feet (83% CI)	3.25 feet (83% CI)	6.69 feet (83% CI)	9.6 feet (83% CI)

2. Importantly, NOAA also provides SLR projections at the 17% and 50% confidence intervals, but CRMC has adopted the NOAA high curve at the 83% confidence interval, which represent more extreme SLR scenarios, for two reasons. First, NOAA (2017) has recommended using the "worst-case" or "extreme" scenario to guide overall and long-term risk and adaptation planning. Second, CRMC views use of worse-case scenarios as a way to hedge against the uncertainties inherent in projecting future SLR.



Gauge/Grid Selected: NEWPORT
NOAA2017 VLM: 0.00322 feet/yr
All values expressed in feet
Lines shown are the result of interpolation between values plotted

Figure 1. Relative Sea Level Change Scenarios for Newport, RI (NOAA, 2017).

3. **Sea level rise projections have changed**. Importantly, scenarios developed for the Shoreline Change SAMP document, planning tools and analyses are based on 2012

NOAA SLR analyses which projected up to 6.6 feet of SLR in Rhode Island in 2100 under the high curve. In the shorter term, the NOAA 2012 SLR scenarios predicted 0.75 feet of SLR by 2030 0, 1.9 feet by 2050, and 4.39 feet by 2080 (NOAA 2012). **Scenarios in the Shoreline Change SAMP are based on these 2012 projections because these were the best available data at the time when Shoreline Change SAMP analyses and tools were undergoing development**. CRMC plans to update Shoreline Change SAMP tools and analyses with the newest SLR projections as time and resources allow.

4. **Sea level rise projections continue to change.** Just as observed sea level rise has accelerated in recent years (see discussion above), so has the development of new sea level rise projections. Over the course of the Shoreline Change SAMP development process (2011 to 2018), three different sets of sea level rise projections have been in use. Early Shoreline Change SAMP analyses and tools began with consideration of 3- 5 feet of SLR by 2100, which was determined by a team of scientific advisors to the CRMC, based on Rahmstorf 2007 and Rahmstorf et al. 2011, and was incorporated into CRMC policy (see RICRMP section 1.1.10). NOAA’s 2012 SLR scenarios offered new projections of up to 6.6 feet of SLR by 2100 under the high curve, and NOAA’s most recent 2017 SLR scenarios offered newer projections of up to 9.6 feet of SLR under the high curve and the 83% confidence interval. See Figure 2 for a comparison of 2012 and 2017 SLR projections. This rapid succession of SLR scenarios illustrates the rapidly changing nature of the science and the need for policymakers to be prepared to absorb and incorporate new data and science on these sources of coastal hazard risk.

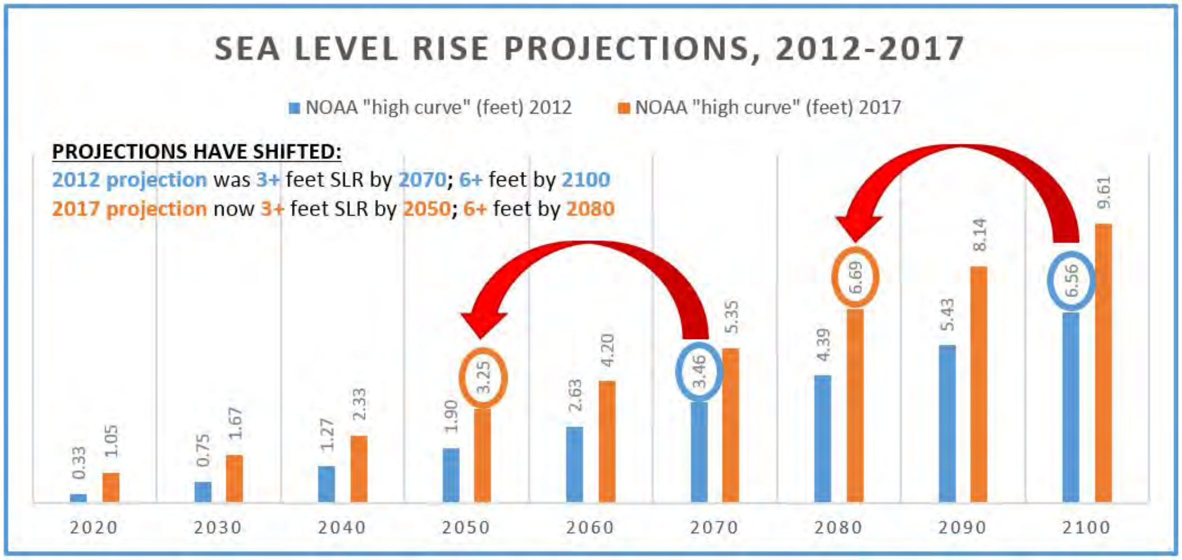


Figure 2. Comparison of NOAA 2012 and NOAA 2017 SLR projections (data sources: NOAA 2012; NOAA 2017)

5. **CRMC has adopted the NOAA high curve**. The CRMC has adopted the NOAA “high curve” at the 83% confidence interval as the foundation of its sea level rise policy as reflected in the Shoreline Change SAMP as well as the RICRMP. CRMC has adopted NOAA’s SLR scenarios as foundational to the Shoreline Change SAMP because NOAA, as the nation’s leading ocean and atmospheric science agency, has a wealth of experience and longstanding credibility in performing cutting-edge research using high-tech instrumentation to understand and predict changes in climate, weather, oceans, and coasts. CRMC has adopted the high curve and 83% confidence interval, a worse-case scenario, for two reasons. First, NOAA (2017) has recommended using the “worst-case” or “extreme” scenario to guide overall and long-term risk and adaptation planning. Second, CRMC views use of worse-case scenarios as a way to hedge against the uncertainties inherent in projecting future SLR.

6. **CRMC has adopted the U.S. Army Corps of Engineers Sea Level Change Curve Calculator**. The CRMC has also adopted the USACE’s sea level change curve calculator for use in identifying and plotting sea level change scenarios. This online calculator offers a simple way for decision-makers to view, for themselves, the

latest SLR scenarios and to view short, mid, and long-range SLR projections in both graph and table form. The CRMC has adopted this calculator because of ease of access and use, both for state and local decision-makers and individual coastal property owners. The calculator is online here: http://www.corpsclimate.us/ccaceslcurves.cfm.

2.2.2 Storm Intensity

1. **Hurricanes and tropical storms *may* be impacted by a changing climate.** The physics driving climate are complex, making it difficult to determine how a changing climate will affect hurricanes and other tropical storms (RI EC4 STAB 2016). Whereas rising sea surface temperatures associated with climate change could influence the frequency and strength of such storms, other effects, such as increasing upper troposphere temperature and vertical wind shear, are detrimental to storm development and intensification (see NOAA GFDL 2018 and the sources cited therein).

2. **The extent to which climate change has affected hurricanes and other tropical storms is unclear**. A recent research review by the NOAA Geophysical Fluid Dynamics Laboratory concluded that it is premature to conclude that climate change has had a detectable impact on Atlantic hurricanes and tropical storms. However, NOAA notes that changes may already be occurring but are undetectable due to observational limitations and other constraints (NOAA GFDL 2018).

3. **Climate change is expected to result in the intensification of hurricanes and tropical storms worldwide**. Research predicts a global increase in the intensity of such storms on average, by to 2 to 11% based on IPCC mid-range emission scenario projections (Knutson et al. 2010), as well as a poleward expansion in the latitude range at which storms reach their highest intensity (Kossin et al. 2014). This increase in intensity also includes higher rainfall rates (discussed below). This increase in very intense storms is expected to take place despite a likely decrease or small change in the number of tropical cyclones worldwide (see NOAA GFDL 2018 and the sources cited therein). Some experts have noted that the three massive storms that characterized the 2017 hurricane season – Harvey, Irma, and Maria – are consistent with this expected intensification (see e.g. Sneed 2017).

4. **Hurricanes and tropical storms are likely to increase in intensity in the Atlantic basin, including the U.S. East Coast**. Overall, based on a synthesis of current science, NOAA GFDL (2018) reported with medium confidence that hurricane and tropical storms will be more intense on average in the coming century (as indicated by higher peak wind speeds and lower central pressures). Bender et al. (2010) projected a significant increase in the frequency of very intense storms (Category 4 and 5), although this increase may not be seen until the latter half of the century. However, based on Knutson et al. (2013) and a review of other studies, NOAA scientists reported *low* confidence that there will be an increase in these very intense Category 4 and 5 hurricanes in the Atlantic basin (NOAA GFDL 2018). Further, a reduction in the number of tropical storms and hurricanes is predicted for the Atlantic basin (Knutson et al. 2008, 2013). This does not, however, change the projection that future storms may be more intense on average (although not reaching the high intensity of a Category 4 or 5 storm).

5. **The frequency and intensity of extra-tropical storms is expected to increase**. The IPCC AR5 (2014) predicts an increase in both the frequency and intensity of extra-tropical storms for the U.S. East Coast. However, less research has been conducted on extra-tropical storms in comparison to hurricanes and tropical storms.

2.2.3 Increasing Precipitation

1. **Hurricanes and tropical storms are expected to result in more rainfall**. This increase has been observed and is expected both globally (IPCC 2014) and for the Atlantic basin, including the U.S. east coast. Based on a synthesis of current science, NOAA GFDL reported with high confidence that Atlantic hurricanes and tropical storms in the coming century will have higher rainfall rates than present storms, particularly near the storm center (see NOAA GFDL 2018 and the sources cited therein). 2017’s Hurricane Harvey, which resulted in a record 51.9” (1318 mm) of rainfall at one station west of Houston, Texas (van Oldenborgh et al. 2017), is one recent example of this trend (see further discussion below).

2. **Heavy precipitation events are becoming more frequent and intense**. Whether a hurricane, tropical storm, or extra-tropical storm (e.g. a nor’easter), there has been a global increase in both the frequency and the intensity of heavy precipitation events (NCA 2017, IPCC 2014). This trend is consistent with physical responses to a warming climate, e.g. an increased amount of moisture in the atmosphere. This

trend has both been observed and is expected to continue. An important recent example is 2017's Hurricane Harvey, which resulted in record rainfall in Houston, Texas. Both van Oldenborgh et al. 2017) and Risser and Wehner (2017) found that the extreme precipitation and flooding associated with Harvey was likely enhanced climate change (see also Waldman 2017).

3. Within the United States, this trend is most pronounced in the Northeast. For example, the NCA (2017) reports that between 1958 and 2016, this region has experienced a 55% increase in precipitation events that exceed the 99th percentile, and a 92% in the number of 2-day events exceeding the largest amount that is expected to occur over a 5-year period. Walsh et al. (2014) studied rainfall from 1901 to 2012 in New England and found that the intense rainfall events (heaviest 1% of all daily events) have increased 71% since 1958, although the 1960s were a particularly drought-prone time in the region. For further discussion and more sources please see RI EC4 STAB 2016.

2.3 Coastal Hazards Resulting from These Trends

2.3.1 Flooding

1. **Flooding is expected to increase as a result of sea level rise, increasing intensity of storms, and increased precipitation**. In the coastal environment, this includes both nuisance (tidal) flooding and storm surges, and other coastal flooding events. Inland, this includes riverine flooding. The U.S. Global Change Research Program indicates that both tidal and storm-related flooding are expected to increase in frequency and depth in the U.S. due to these drivers (NCA 2017). The IPCC (2014) found that "coastal systems and low-lying areas will increasingly experience submergence, flooding and erosion throughout the 21st century and beyond, due to sea level rise (*very high confidence*)." Further, the IPCC identified flooding and associated damages as a "key risk" for eastern North America due to its expected large magnitude, high probability or irreversibility of impacts, vulnerability or exposure of the region, and limited potential to reduce risk through adaptation or mitigation. Importantly, increased flooding means both an increase in the *areas* which are flooded as well as the *depth* of floodwaters. This is because sea level rise will expand existing floodplains, causing flooding in places which have not previously experienced flooding, and resulting in deeper floodwaters in previously-

flooded areas.

2. **Nuisance flooding** is also sometimes called tidal or high tide flooding, and increasingly occurs in coastal locations both locally and globally as a result of sea level rise, which in turn causes higher than normal high tides. Nuisance flooding may affect individual coastal properties as well as roads, parking lots, and other public or commercial infrastructure in low-lying areas. The U.S. Global Change Research Program (2017) reported that this type of flood event has increased 5 to 10-fold since the 1960s in several U.S. coastal cities, and that rates of increase are accelerating in over 25 cities on the U.S. Atlantic and Gulf coasts. They further reported that this type of flooding will continue increasing in depth, frequency and extent over the 21st century.

3. ***In Rhode Island***, nuisance flooding is already occurring in numerous low-lying locations around the state. STORMTOOLS can be used to view potential inundation in Rhode Island associated with nuisance flood events (1, 3, 5, and 10-year return period storms). Please see www.beachsamp.org.

4. **Storm surge** refers to the rise of water levels caused explicitly by a storm, and is measured as the height above the normal predicted tide. The combination of sea level rise and increased storm intensity causes storm surges characterized by higher water levels that may extend further inland, causing greater damage. The U.S. Global Change Research Program (2017) reported that this type of extreme flooding is expected to increase due to both sea level rise and increased storm intensity, and associated sea level rise with increased storm surge flooding at a very high confidence level. The IPCC (2014) found that increasing storm surges and other forms of coastal flooding have the potential to disrupt livelihoods and create severe health risks across various sectors.

5. Storm surges are often described with an associated return period, or recurrence interval, which is an estimate of the likelihood that the storm or flooding event will occur (for further discussion see Shoreline Change SAMP Chapter 4). This concept is also useful in illustrating how, over time, rising sea levels result in more damaging storm surges. Over time, as sea levels rise, water levels associated with what is thought of as today’s 100-year return period storm will increase, because a higher base sea level will increase the extent and depth of storm-related flooding. As a

result, the 100-year return period storm of the future could result in much more flood-related damage than the 100-year return period storm of today. Further, from the perspective of water levels, SLR will cause today's 100-year return period storm to become a more regularly-occurring storm. For example, a future 20-year return period storm on top of a 2-foot SLR will have the same water level and depth as today's 100-year return period storm. For further discussion, please see Shoreline Change SAMP Chapter 4.

6. ***In Rhode Island***, many coastal communities, including individual residential properties as well as commercial and industrial properties, are highly exposed to storm surges. For example, 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 + 100-year storm surge, inundating approximately 65 square miles of Rhode Island's existing coastline). STORMTOOLS and the Shoreline Change SAMP provides numerous tools and analyses to help coastal residents and decision-makers understand their exposure under different scenarios representing both storm surge and varying levels of sea level rise. Please see Chapter 3 for discussion of the storm surge scenarios used as planning scenarios in the Shoreline Change SAMP, and please see Chapter 4 for a detailed discussion of the exposure of Rhode Island's coastal communities under a range of storm surge scenarios. Please also see www.beachsamp.org to use STORMTOOLS to view other storm surge scenarios.

7. **Riverine flooding** refers to flooding that takes place throughout the watershed (i.e. inland) along the banks and in the floodplains of rivers and streams. Riverine flooding is expected to be exacerbated by increased storm intensity as well as increased precipitation. The IPCC (2017) identifies inland flooding in some urban regions as a "key risk" in North America which may result disrupt livelihood and result in severe health risks. Importantly, riverine flooding and coastal flooding due to sea level rise can have a coupling effect. Rising seas can set 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).

8. ***In Rhode Island***, increased precipitation has been observed and is expected to continue. Increased precipitation, in particular, is expected to increase stream flow

in the Northeastern U.S., contributing to increases in flooding risk due to increases in 3-day peak flows (Demara et al. 2015). Vallee and Giuliano (2014) reported a doubling of the frequency of flooding and an increase in the magnitude of flood events, many of which are riverine flooding events, such as in 2010, when the Pawtuxet River crested and caused extensive inland flooding following a series of heavy rain storms that took place over a 5-week period. A great deal of research is needed on projected riverine flooding in Rhode Island, specifically on the coupling effects within Rhode Island watersheds of storm surge and precipitation events, sea level rise and flooding events; please see Chapter 4 for further discussion.

9. Scientists' understanding of these sources of coastal hazard risk are rapidly evolving, and further research is needed on all of these topics. Please see section 2.4, Future Research Needs, for a discussion of some research needs identified by the Shoreline Change SAMP team.

10. Please see Chapter 4, "Rhode Island's Exposure to Coastal Hazards," for a detailed discussion of Rhode Island's exposure to all of these hazards. This includes a detailed discussion of the exposure of both the built and the natural environment to sea level rise and/or storm surge scenarios, as well as future scientific needs associated with these topics.

2.3.2 Coastal Erosion

1. **Coastal erosion is expected to increase due to the increase in storm intensity and associated flooding**. The IPCC (2017) found that coastal and low-lying areas have been experiencing increased erosion, and will continue to do so, due to sea level rise, in North America and throughout the world. Erosion has been noted to be of particular concern in the northeastern U.S. (Horton et al. 2014). In their study of climate change impacts in the Northeastern U.S., Horton et al. (2014) noted that increased rates of coastal erosion are likely to compromise aging coastal infrastructure, including transportation, communications, and energy infrastructure.

2. ***In Rhode Island***, coastal erosion is of particular concern because it is characterized by a storm-driven coastline. This is especially the case on Rhode Island's south shore, which has been found to be largely erosional (Boothroyd et al. 2016). Studies of shoreline change in Rhode Island have documented an average annualized rate

of shoreline change of 0.57 meters/year (1.9 feet/year), though these annualized rates should be used with caution because coastal erosion is not a gradual process, but rather the result of abrupt changes due to storms. Some of the highest rates of change occur along the Matunuck Headline, where the annualized rate of change exceeds 1.4 meters/year (4.7 feet/year), and total erosion since 1951 has approached 90 meters (300 feet) (Boothroyd et al. 2016). It is difficult to project future rates of shoreline change, but one Shoreline Change SAMP analysis 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 (Oakley et al. 2016). These results should be used with caution given the uncertainty associated with projecting future shoreline change.

3. Scientists' understanding of coastal erosion and other coastal processes is rapidly evolving, particularly with regard to how processes are changing due to changing climate trends and what may happen in the future. Please see Chapter 4 for a detailed discussion of what is known about coastal erosion in Rhode Island, and please see section 2.4 Future Research Needs, for a discussion of some research needs identified by the Shoreline Change SAMP team

2.3.3 Groundwater and Saltwater Intrusion

1. **Groundwater levels are expected to increase with rising sea levels, resulting in saltwater intrusion for any structures and systems below grade along the coast.** Research on coastal groundwater systems in Connecticut, New Hampshire, and Massachusetts has suggested that groundwater levels will not only rise with rising sea levels, but are expected to extend farther inland than surface water (Bjerklie et al. 2012, Knott et al. 2017, and Walter et al. 2016). Increases in coastal groundwater levels can: impact the ability of stormwater to infiltrate in coastal areas, increasing the risk of localized flooding and ponding (Bjerklie et al. 2012); pose an increased risk of groundwater seepage into basements of existing buildings and underground infrastructure (Bjerklie et al. 2012); impact the structural integrity and reduce the lifespan of built infrastructure (Walter et al. 2016, Knott et al. 2017); cause wetlands to expand and possibly form in areas they didn't exist before (Knott et al. 2017); and change the health of natural ecosystems (Knott et al. 2017).
2. ***In Rhode Island,*** many coastal properties rely on onsite wastewater treatment systems (OWTS, a.k.a., septic systems) for wastewater disposal, and private wells

for drinking water. Research at the University of Rhode Island suggests that as coastal groundwater is projected to rise, the soil volume that is designed around an OWTS to absorb and treat effluent will decrease, thereby potentially resulting in contaminant transport within the water table, and a threat to aquatic and ecosystem health (Cooper et al. 2016). Additionally, research on sea level rise and salt water intrusion in coastal aquifers and private drinking water well systems along Rhode Island's coast was funded and is underway in 2018. For more information, contact Dr. Soni Pradhanang at the University of Rhode Island's Department of Geosciences.

3. Scientists' understanding of these sources of coastal hazard risk are rapidly evolving, and further research is needed on all of these topics. Please see section 2.4, Future Research Needs, for a discussion of some research needs identified by the Shoreline Change SAMP team.

2.4 Future Research Needs

2.4.1 Flooding

1. Under the STORMTOOLS effort, flooding maps have been generated for once in 25, 50, 100, and 200-year return period storms, with sea level rise (SLR) ranging from 2 to 10-feet. Maps have also been prepared for 2, 3, 5 and 10-year return period nuisance flooding events to assist in emergency response. In addition, maps of inundation from sea level rise from 2- to 10-feet have also been prepared. Through the Coastal Environmental Risk Index (CERI) initiative that set out to assess the risk and damage to structures, STORMTOOLS design elevation maps (SDEs) (including the effects of SLR), which explicitly include surge, coastal erosion, and wave conditions and central to the CRMC permitting process, have been completed for Warwick, Barrington, Bristol, Warren, and Charlestown. Generation of SDE maps for the other coastal communities in the state is currently in progress. The SDE maps are comparable to the FEMA Base Flood Elevation (BFE) maps, with the important exception that they include SLR effects and address a number of technical weaknesses with the FEMA Flood Insurance Rate Maps (FIRMs). Flooding maps for the Pawtuxet River watershed have also been prepared by application of high resolution hydrologic models to the system, with a focus on flood control and management. The riverine flooding maps vs selected return periods are currently

available via the STORMTOOLS web site.

2. Continue to bring in new data and modeling that builds on flood risk tools that have been completed or in progress, the following are recommended:

   a) ***Enhancement in wave and associated damage modeling in CERI.*** Theory and field studies show that dynamic wave setup and run-up can extend the inundation zone well beyond that inundated by the storm surge alone. This extended inundation zone is defined as the *swash* zone and is characterized by periodic extreme water elevation (periods on the order of 10 to 100 seconds) with associated high velocities and force. Run-up can significantly increase the coastal hazard and the risk in coastal areas characterized by steep slopes or vertical walls (e.g. Dean and Bender 2005) (selected locations along the southern RI coastline). The method currently employed to model wave dynamics for the SDEs and as input to CERI, uses a phase average model (e.g. STWAVE) that unfortunately does not resolve time dependent processes such as wave diffraction, reflection, and run-up in the swash zone. Phase resolving models (time dependent models of individual wave events) that would address this problem are currently available but the high computational cost has, to date, precluded their routine use in practical applications. Li et al. (2018) have demonstrated the importance of using a phase resolving model to fully represent the damage due to wave run-up and overtopping. URI is part of the team developing a phase-resolving model, FUNWAVE (Shi et al. 2012) and has developed extensive experience in the use of the model (e.g. Shelby et al. 2016; Grilli et al. 2016). With access to high performance computational systems, this proposed effort would apply phase resolving models to predict wave dynamics in exposed southern RI coastal communities and result in improvements in both SDE maps and CERI damage estimates.

      CERI currently uses damage curves for both inundation and waves developed as part of the Army Corp of Engineers North Atlantic Comprehensive Coastal Study (NACCS) based on field surveys performed after hurricane Sandy impacted the NY-NJ area. The uncertainty in the estimates of wave damages, parameterized in terms of upper, mean, and lower values, are quite large. With more detailed modeling of wave dynamics available from FUNWAVE it will be possible to substantially improve damage estimates, including the proximity of other structures, using methodologies based on impulse forces on structures.

b) ***Modeling of riverine flooding in remaining RI watersheds.*** It is proposed to apply the existing hydrologic model suite to the remaining watersheds in the state (Blackstone, Ten Mile/Seekonk, Woonasquatucket, Moshasscuck, Warren, Hunt, Taunton, Narrow, and Pawcatuck) to predict flooding in response to changing climate conditions (rainfall rates, sea level rise). This will complete flooding (inland) maps for all riverine systems in the state. It will also allow improvement in flooding estimates where riverine and coastal systems meet. All mapping products will be available via the STORMTOOLS web site.

2.4.2 Coastal Erosion

1. There is a significant need to fund the ongoing and expanded study of shoreline change in Rhode Island. Shoreline change monitoring has been a longstanding practice in Rhode Island but is currently running on diminishing funds and/or volunteer efforts which are insufficient given the importance of this issue. Efforts beyond 2018 to expand these efforts and to continue measuring conditions within Block Island Sound remain unfunded. These previous and ongoing efforts, and the funding status of each, are detailed below.

2. Rhode Island has had long-term monitoring of the shoreline using beach profiles/transects for >50 years. This represents a wealth of data at the short-term (event scale (storms + recovery)) and long-term (annual – decadal) scale along the Rhode Island south shore (RISS). The Graduate School of Oceanography has maintained seven profiles along the RISS for several decades. The GSO beach survey was established in the early 1960s and expanded to the current scope by the late 1970s. Currently, these profiles are run by the King Lab at URI-GSO, funded by a graduate assistantship and the King Lab.

3. Jon Boothroyd (now deceased), URI Geosciences Professor and RI State Geologist measured various profiles along the RISS, with the primary profile located on the Charlestown Barrier (CHA-EZ) measured near weekly since 1977. Two of Jon's profiles (CHA-EZ and SK-TB (south Kingstown Town Beach) continue to be measured by Scott Rasmussen, URI-EDC, funded by RICRMC. Additional profiles are measure by Bryan Oakley (Eastern Connecticut State University (ECSU)): Napatree Point (5 profiles) (2013-present) measured quarterly and post-storm; and Misquamicut State Beach (five profiles) also measured quarterly and post-storm. These profiles

began in 2014 in response to beach replenishment. An additional 8 profiles initiated by Oakley are measured on Block Island (monthly 2013-2017; quarterly 2018-present) but citizen scientists who send the data to ECSU for interpretation and archiving. These profiles have contributed greatly to the understanding of the RISS, published in numerous theses, papers, conference presentations and have helped to inform RICRMC policy greatly over the last 30 years.

4. Recent acquisition and a successful proof of concept for terrestrial laser scanning (TLS), a method of measuring elevations from a mobile platform (boat), coupled with swath bathymetric mapping shows that this technology could become a significant component of a robust coastal monitoring program. Boat-based TLS coupled with swath bathymetric mapping can be rapidly mobilized, providing a coast-wide assessment of the shoreline shortly after a storm event, in addition to periodic seasonal monitoring surveys.

5. Significant challenges remain for keeping these efforts funded in the long-term. Profiles measured by the URI-EDC remain funded by the RICRMC but are not a permanent line item in their budget. URI-GSO profiles depend on a research assistantship for a graduate student from the university, as well as in-kind support (equipment, vehicles, personnel) from the King Lab. ECSU profiles on Block Island and Misquamicut had some initial funding from the RIBRWCT, however these remain volunteer efforts by Oakley, citizen scientists and ECSU students. Napatree profiles are supported by the Watch Hill Conservancy. No current funding has been identified to incorporate TLS into the current coastal monitoring efforts.

6. While the current and historic coastal monitoring provides insight along the beaches of the RISS, significant data gaps exist in the offshore environment. Understanding the response of the shoreface (area from the beach extending offshore) at similar time scales as the beach profiles (event to decadal scale) remains a significant data gap along the RISS. The shoreface represents potentially a significant source and sink of sediment for the shoreline, and a lack of observations limits understanding of the complex relationships between the shoreface characteristics (sediment type, morphology) and coastal processes.

7. There is a DOI-NFWF funded project underway to deploy four ADCP wave/tide sensors along the RISS and four water level monitoring stations within the coastal

ponds, and will be maintained through 2018. This will provide similar data products to Woods Hole Group (2012). This represents important information on the real conditions during a storm. Coupled with coastal monitoring, the resulting parameterization of environmental data offers opportunities to use detailed observations to calibrate and expand the recent modeling efforts along the RISS

8. Geologic habitats mapped on the shoreface numerous times in part over the last 3 decades (Morang, JCB, Oakley, King) including recent mapping in 2015/2016 (DOI-NFWF funded). This provides baseline information on the extent and distribution of geologic habitats on the upper shoreface, as well as thickness and volume of sand on the uppermost shoreface.

2.4.3 Groundwater and Saltwater Intrusion

1. Future research is needed on the effects that sea level rise will have on groundwater dynamics and saltwater intrusion impacts within coastal areas. Research specific to the Rhode Island coastline that is modeled after current research on coastal groundwater systems in Connecticut, New Hampshire, and Massachusetts (as discussed in Section 2.3.3), is needed to determine:
    a. the inland extent of impacts from groundwater levels increasing with rising sea levels;
    b. the ability of stormwater to infiltrate in coastal areas, and impacts caused by related flooding and ponding;
    c. impacts of groundwater seepage into basements of existing buildings and underground infrastructure;
    d. impacts to the structural integrity and lifespan of built infrastructure;
    e. expansion of wetland areas in the coastal zone;
    f. changes to the overall health of coastal and inland freshwater ecosystems; and
    g. contaminant transport within coastal groundwater systems.

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