Future Social and Economic Loss and Health Impacts Due to Extreme Weather Events and Sea-Level Rise

Prepared for

Rhode Island Department of Health

Prepared by

TETRA TECH

October 25, 2013

(This page intentionally left blank)

Contents

Tables

Figures

(This page intentionally left blank)

1 Executive Summary

The Rhode Island Department of Health is charged with identifying likely climate change effects on Rhode Island and how these effects could impact public health in the state. This report provides technical information in support of this goal. Specifically, this document focuses on future potential health impacts associated with flooding, hurricanes, and drought, including how sea-level rise exacerbates the losses from flood and hurricane events.

Information on potential changes in Rhode Island's climate was previously developed and assembled for *Safe***Water** *RI: Phase 2 Report*, *Assessment of Impacts* (Tetra Tech 2012). *Safe***Water** RI studied the impacts of climate change on drinking water utilities in the state and provided specific information for water utility managers to evaluate and plan for the future. To predict future climate conditions, *Safe***Water** RI used various Global Climate Models, which are computer simulations that use mathematical equations to predict future weather conditions based on historical weather data.

All the climate change models evaluated under *Safe***Water** RI are in agreement in predicting increases in temperature in Rhode Island. The climate models do not agree as to whether annual average rainfall will increase or decrease in the state over the coming years. The models do show, however, that there will be greater variation when precipitation events occur. An increase in heavy rain events could lead to episodic flooding along the state's river systems and coastline. On the other hand, longer periods between rain events could lead to severe droughts. Thus, the frequency of both droughts and flood events could be increased. As the climate changes, sea-level rise and increased storminess could affect the magnitudes of hurricanes. The *Safe***Water** RI hurricane surge model found that hurricane wind speeds and storm surge will likely increase in response to climate change.

Extreme weather events could directly cause death and injury, such as from drowning or physical injury, and could also result in significant indirect health impacts. Indirect health impacts could occur as a result of damage to infrastructure, population displacement, and disruption of jobs and services, which can lead to psychological and social effects and reduced access to health care services (Greenough, et al. 2001). Although the health effects of extreme weather events are difficult to quantify because indirect impacts often have delayed consequences and are poorly reported, this report explores the potential impacts on the health of Rhode Island citizens from extreme weather events. The cities of Newport and Providence were selected for in-depth modeling and analysis, as these cities have the largest populations in the state and larger tidal datasets were available for these two cities. Several key indicators of future flood and hurricane events were assessed for Newport and Providence, including:

- Exposure of vulnerable populations in future floodplains
- Population displacement
- Loss of local infrastructure (e.g., general building stock, residential building stock, health and social support facilities)
- Business interruption losses
- Debris

Modeled results of these indicators clearly show that climate change will increase the vulnerability of the populations in Newport and Providence. These general effects could be extrapolated to other coastal populations along Rhode Island.

This report also discusses the health implications of future drought events, although these impacts are not as well understood. Climate change is projected to increase the risk of both floods and droughts in Rhode Island. When drought conditions continue for long periods, research has shown that stress levels can climb and lead to anxiety and traumatic stress.

2 Sea-Level Rise Projections

Rising sea levels can impact human health in several different ways. It can (1) exacerbate flooding and storm surge, causing damage to wastewater treatment facilities, water facilities, and other utilities, leading to water contamination and power outages; (2) increase the salinity of estuaries and groundwater, degrading water quality; and (3) displace coastal populations, initiating mental health stresses.

Rising temperatures cause the global melting of glaciers and ice sheets, which, coupled with the thermal expansion of ocean volume as water temperatures increase, will affect coastal areas through sea-level rise. Higher sea levels mean that the same storm will flood farther inland than it does now, which will be particularly challenging for Rhode Island because the majority of the population lives along the coastline. To adequately assess the impacts of flooding and hurricanes on Rhode Island, sea-level rise projections were developed based on historical records.

The sea level along the coast of Rhode Island has been rising rapidly when compared to the world as a whole. This can be seen in the tide measurements collected by the two National Oceanic and Atmospheric Administration (NOAA) gauging stations shown in Figures 1 and 2. Although there are other stations in the state, these two were selected because of the length of time they have been in service. The Newport Station has been collecting data since 1930. It shows an average annual change of +2.58 millimeters (mm) per year for the period 1930 to present. However, reviewing recent trends (2006 to present), an annual change of +2.70 mm per year is observed (Figure 3). The Providence Station has been collecting data since 1938. It shows an average annual change of +1.95 mm per year (2006 to present). Reviewing the recent trends at this station, an annual change of +2.19 mm per year is observed (2006 to present; Figure 4).

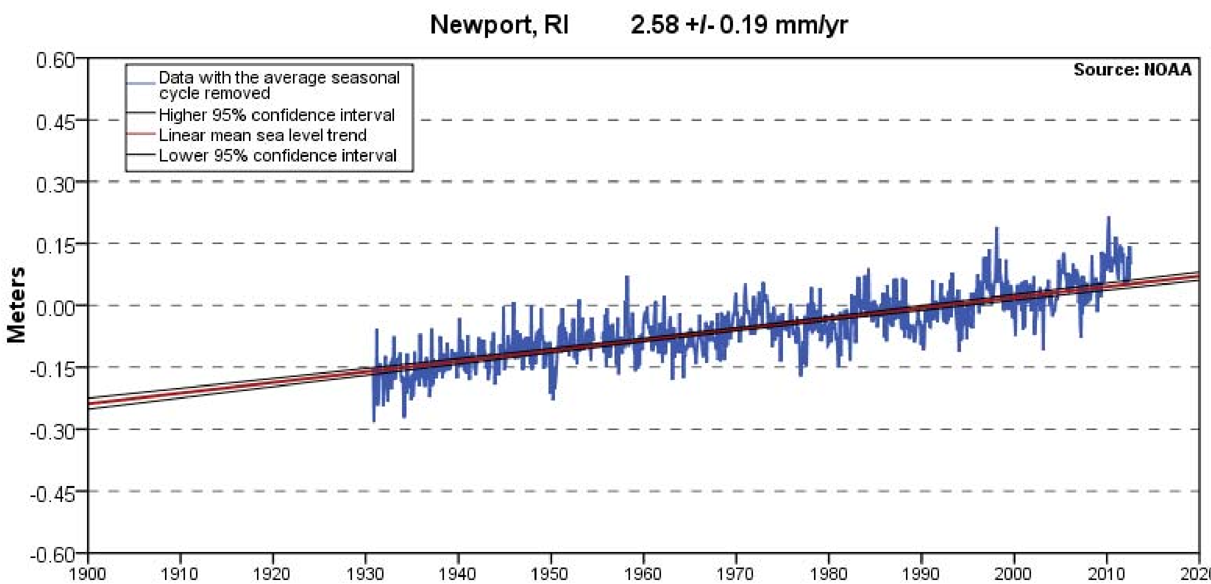

Figure 1. Observed Sea-Level Rise—Newport, Rhode Island, NOAA Gauging Station.

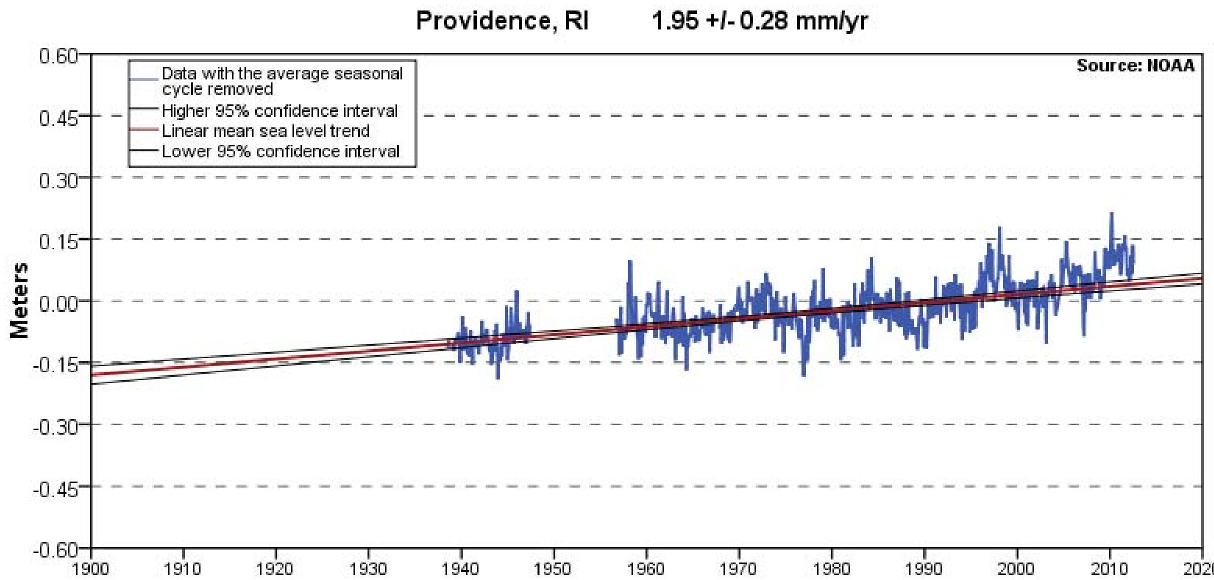

Figure 2. Observed Sea-Level Rise—Providence, Rhode Island, NOAA Gauging Station.

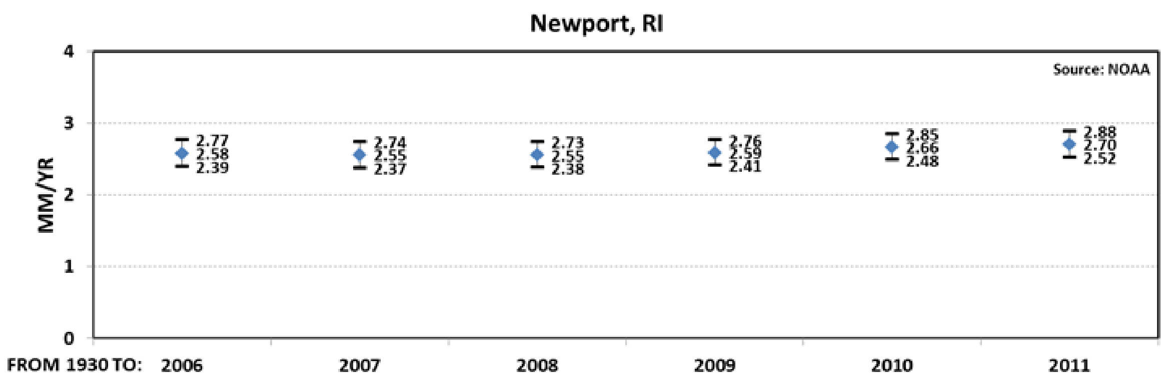

Figure 3. Recent Sea Level Trends—Newport, Rhode Island, NOAA Gauging Station.

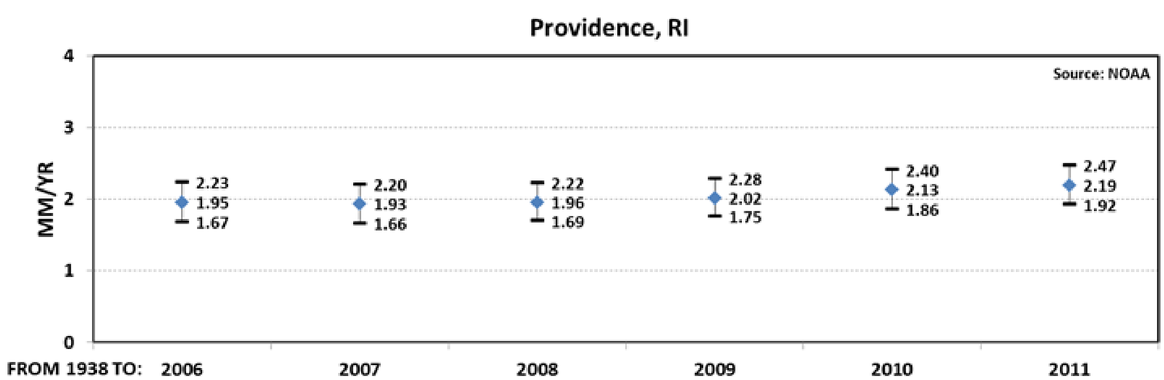

Figure 4. Recent Sea Level Trends—Providence, Rhode Island, NOAA Gauging Station.

For ***Safe***Water RI, historical trends in sea level rise were used to calculate low and high sea level rise scenarios for three time periods (2022, 2052, and 2084) (Figure 5). The data show an average sea level rise of approximately 2.92 feet in Newport and 2.80 feet in Providence by 2084.[1]

The Rhode Island Coastal Resources Management Program (CRMP) has begun to integrate a sea-level rise of 3 to 5 feet (Rubinoff et al. 2008) in its plans and policies. On the basis of the historical data and CRMP's projections, a 3-foot sea-level rise and a 5-foot sea-level rise were selected for analysis in this report.

The impacts from sea level rise will be gradual, providing the opportunity to relocate at-risk populations and infrastructure. While there will undoubtably be health impacts, such as mental stress and anxiety for those having to relocate due to sea level rise, this report focuses on the health impacts from extreme weather events. These events are episodic and are shocks to the system; thereby causing a greater toll on the population. The next sections detail how sea level rise will influence extreme weather events, and the resulting vulnerability to those events.

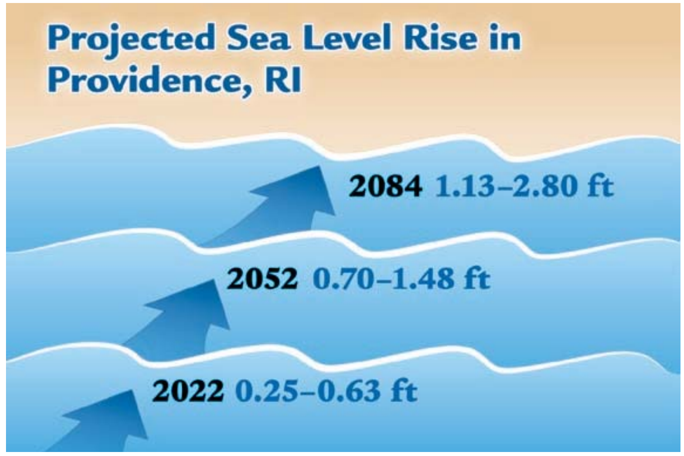

Figure 5. Projected Sea Level Rise in Providence, Rhode Island in 2022, 2052, and 2084.

[1] Further information on sea level rise calculations can be found in the *Phase 2 Report: Assessment of Impacts* (HEALTH 2012), which is available online: <http://www.health.ri.gov/materialbyothers/SafeWaterRIReport.pdf>.

3 Extreme Event—Floods

Flooding can greatly impact the mental health of affected populations. Physical and emotional strain has the potential to affect individuals over extended time periods, long after the initial flooding event. Because of the lengthy recovery period associated with flooding, there is a greater risk of secondary impacts such as economic stress associated with rebuilding businesses and industries. These secondary impacts arise as individuals try to recover their lives and livelihoods. To better understand the potential impacts following a flood, this report assessed key indicators of risk and projected infrastructure damage associated with extreme floods.

The *Rhode Island Hazard Mitigation Plan*, developed by the Department of Emergency Management (RIEMA 2008), ranked flooding as a priority hazard. It can be a result of extreme precipitation, storm surge, nor'easters, wind-driven waves, coastal erosion, and sea-level rise. These events can work alone or together to create flooding in Providence and Newport. As the climate changes, sea-level rise, increased precipitation, and increased storminess could affect the extent and depth of the coastal floodplains. These impacts will likely result in losses of life and property. To better understand the impacts, the future floodplain needs to be identified.

Overview of Vulnerability

Many sections of Newport and Providence are currently at risk of flooding; therefore, the population in those areas is considered vulnerable to both the direct and indirect health impacts of flood events. To assess how vulnerability might change under a changing climate, potential losses to key indicators were calculated in those cities for the 1 percent annual chance (100-year) mean return period (MRP) flood event (e.g. conditions under the current climate); the 1 percent (or base flood) event with 3 feet of sea-level rise; and the 1 percent event with 5 feet of sea-level rise. The flood hazard exposure and loss estimate analysis is presented below.

Data and Methodology

Current conditions and two future scenarios were examined to evaluate the municipalities' vulnerability to the flood hazard. The methodology used to delineate the future coastal floodplains involved a three-step process: (1) conduct an erosion assessment; (2) run a simplified Wave Height Analysis for Flood Insurance Studies (WHAFIS) model; and (3) run a Wave Runup Model following the procedures in the U.S. Army Corps of Engineers' *Coastal Engineering Manual* (USACE 2003). The Federal Emergency Management Agency's (FEMA) HAZUS-MH software was used to complete the last two steps, and the digital elevation model was eroded on the basis of historical erosion trends.

3.1 Future Flood Plain

Flooding presents immediate dangers to human life, such as drowning, physical trauma from debris, and electrocution from downed power lines. However, the total number of injuries and casualties resulting from typical flooding is generally limited based on advance weather forecasting, evacuations, and warnings. Therefore, injuries and deaths generally are not anticipated if proper warning and precautions are in place. Hazard mitigation efforts should help to avoid the most likely cause of injury, which results from persons trying to cross flooded roadways or channels during a flood.

All populations located in a dam or levee failure inundation zone are considered exposed and vulnerable. Figure 6 shows the Providence floodplain in a 1 percent annual chance flood event with a 3-foot sea-level rise. As shown, inundation occurs within all coastal regions near Providence Harbor, most of Downtown Providence, South Elmwood, and Washington Park neighborhoods, as well as sections of Federal Hill, Valley, and Olneyville neighborhoods. When a 1 percent annual flood event occurs with a base of 5-foot sea-level rise, the inundation stretches farther north along the Moshassuck River, west along the Woonasquatucket River.

Figure 7 shows the same data for the Newport floodplain. The impacts in this region are more extensive and affect large portions of southern and western Newport. Along the southern coast, the ocean will merge with Goose Neck Cove, Lily Pond, and Almy Pond. Over 50 percent of Coasters Harbor Island will be inundated, as well as the coastal regions of Newport and Coasters harbors.

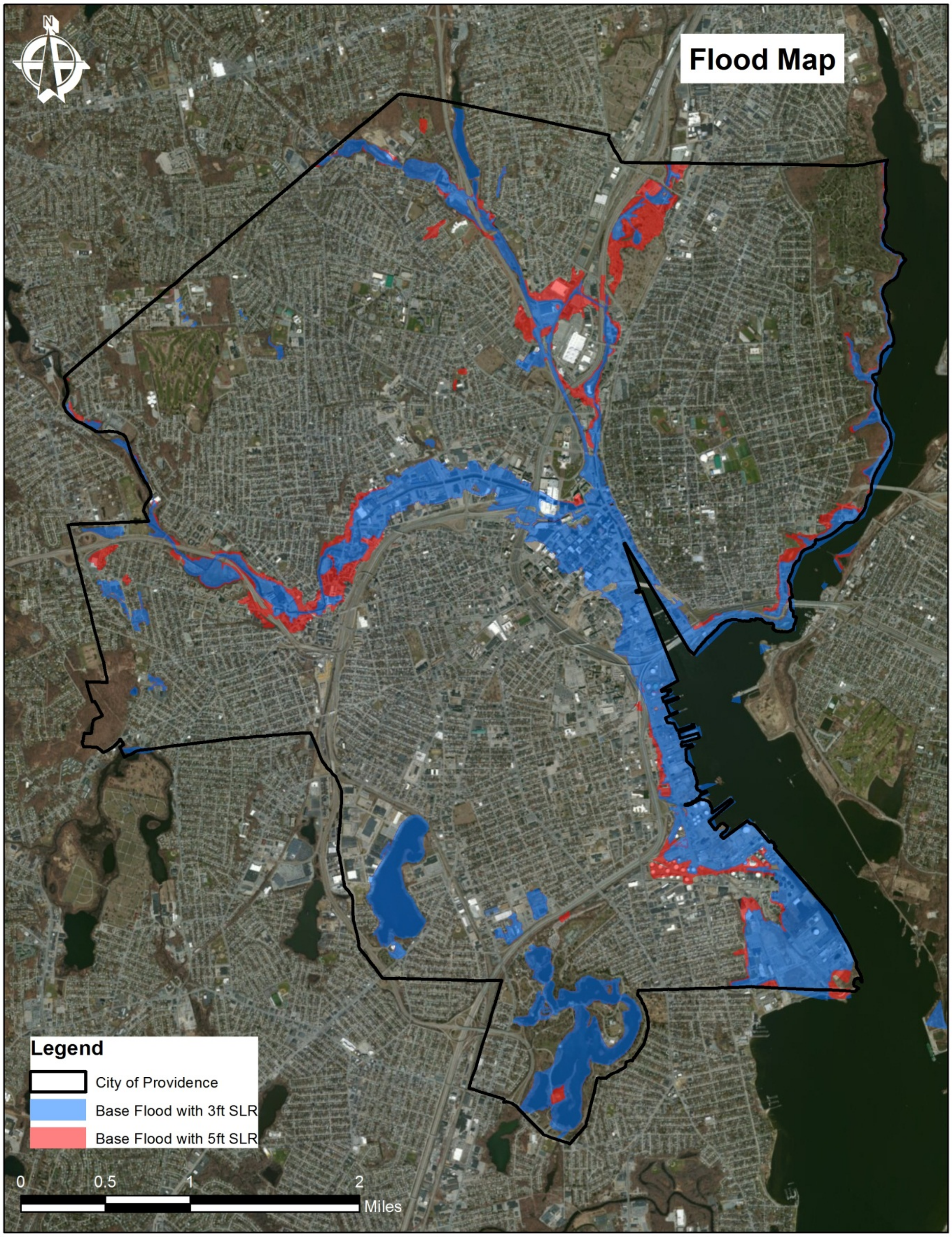

Figure 6. Providence Flood Map.

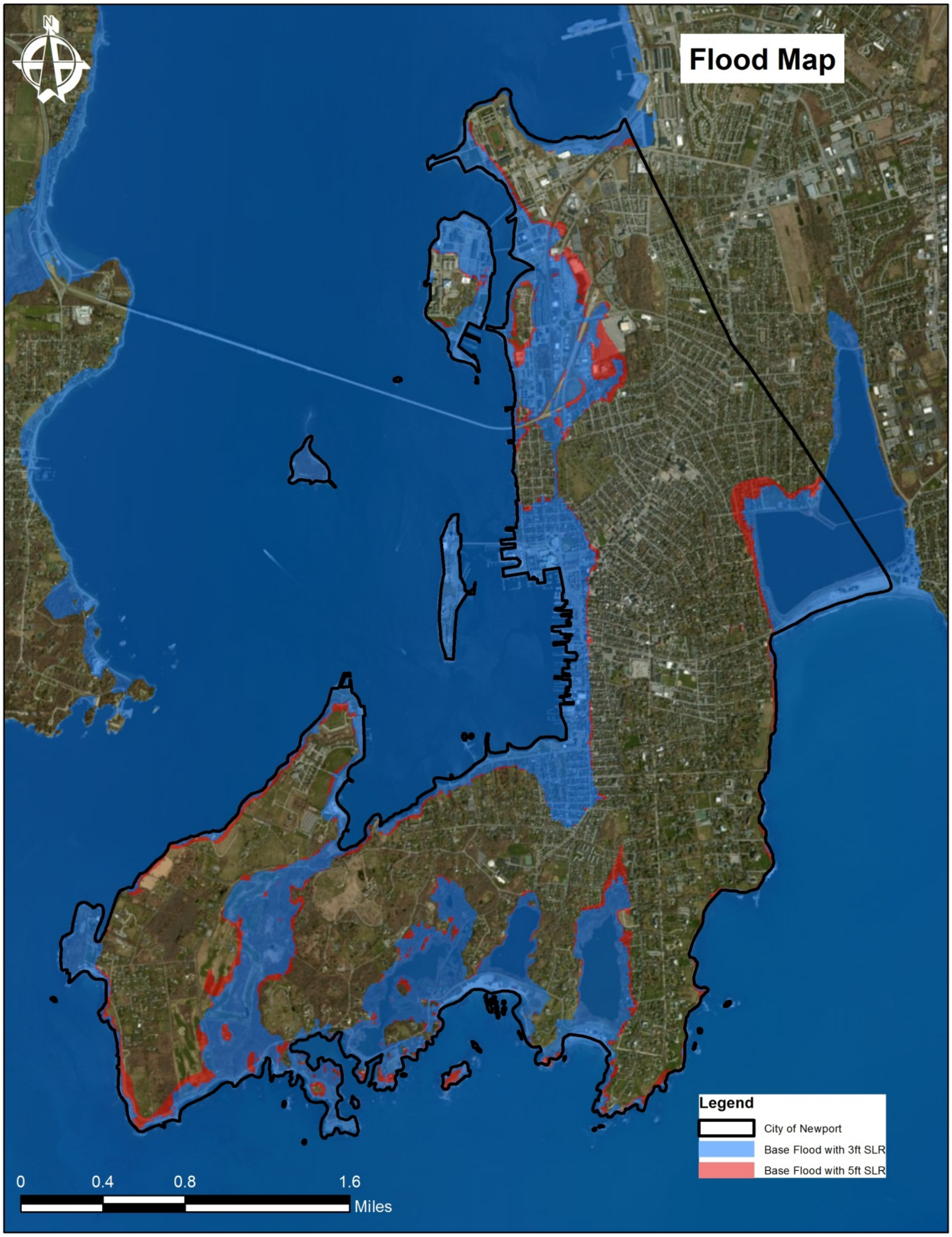

Figure 7. Newport Flood Map.

3.2 IMPACT ON LIFE, HEALTH, AND SAFETY

In addition to the direct health impacts from flood events, other flood-related impacts on life, health, and safety are less visible and occur within a longer time period. They include the proliferation of waterborne diseases, local waterway contamination, dangerous mold in homes, and psychological trauma. The economic impacts from a flood can range from direct property damage to decreased productivity of the local economy. Flooding can also affect the population's mental health.

In 2005 Ahern and others conducted a review of 28 hurricane studies and 20 flood studies in the United States to summarize the health impacts of flooding. They reported on the effects of flooding on common mental disorders, including anxiety and depression, post-traumatic stress disorder (PTSD), and suicide. Most of the studies exploring the effects of flooding on common mental disorders revealed significant increases in depression, anxiety and psychological distress among adults; relatively few studies examined the effects of flooding on children, but those that did revealed increases in aggression, bedwetting, and moderate to severe stress symptoms. The studies showed increases in PTSD following flooding, especially among children and elderly citizens.

No age groups are immune from the effects of flooding. It can cause bereavement, economic problems for families, behavioral problems in children, increased substance use and/or misuse, and increased domestic violence. It can also exacerbate or provoke people's existing mental health problems.

The studies also show that the experiences of people who are distressed in the aftermath of disasters are not always easy to distinguish from the symptoms of common mental disorders. On the other hand, the research suggests that the incidence and prevalence of common mental disorders after flooding is substantially increased and that these disorders can persist long after the flooding has passed. Planning for and providing effective and timely public mental health and clinical responses is important and this report attempts to identify the number of people potentially affected. The impact of flooding on life, health, and safety is dependent upon several factors, including the severity of the event and whether adequate warning time is provided to residents. Exposure represents the population living in or near floodplain areas that could be affected should a flood event occur. In addition, exposure should not be limited to only those who reside in a defined hazard zone but should include everyone who could be affected by the effects of a hazard event (e.g., people who are at risk while traveling in flooded areas or people whose access to emergency services is compromised during an event). The degree of that impact will vary and is not easily measurable.

To estimate the current population exposed to the 1 percent annual chance flood event, HAZUS-MH was used to create floodplain boundaries for the current sea levels, for 3 feet of sea-level rise, and for 5 feet of sea-level rise (refer to Figures 6 and 7); then these boundaries were overlaid on the 2010 Census population data in a geographic information system, or GIS (U.S. Census 2011). All 2010 Census blocks with their centroid in the flood boundaries were used to calculate the estimated population exposed to this hazard. Table 1 lists the estimated population located within the 1 percent annual chance flood zone by municipality. Newport is considered highly vulnerable to the projected increase in flood hazard from climate change, with approximately 15 percent of its population located in the floodplain with a 5 foot sea level; while Providence's population has significantly less exposure, with 2.6 percent of the population located in the floodplain under the same conditions.

To better understand the vulnerability of the population to flooding, the projected impact to those considered *most vulnerable* was assessed. Of the population exposed (i.e., the population in the inundation area), the most vulnerable include:

1. The economically disadvantaged, because they might not have the resources to evacuate.
2. Persons over the age of 65, because they are more likely to seek or need medical attention, which might not be available because of isolation during a flood event, and they might have more difficulty evacuating.
3. Children, as they are dependent on their parents for evacuation, are more vulnerable to chemicals and organisms they are exposed to in their environment, and more susceptible to stress and anxiety than adults. For example, one year after Hurricane Katrina, exposed children were four times more likely than before the storm to be depressed or anxious and twice as likely to have behavioral problems (Abramson, et al. 2007).
4. Disabled populations, who often require special assistance and conditions for evacuation and temporary shelter.

Tables 2 - 5 describe the at-risk populations in the two municipalities. As illustrated in these tables, at-risk populations constitute a sizable share of population located in the future floodplains, with the elderly being the highest at-risk population in Newport (16.8 percent with a 5 foot sea level rise), and the economically disadvantaged making up the highest at-risk population in Providence (2.8 percent with a 5 foot sea level rise). Table 5 shows the disabled population, under current conditions (2010 Census) that are exposed to the flood hazard.

Table 1. Population Exposed to the 1 Percent Flood Hazard

Municipality	Total population (2010 Census)	1% annual chance event		1% event with 3 ft of SLR[1]		1% event with 5 ft of SLR	
		Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain
City of Newport	24,672	2,754	11.2%	3,415	13.8%	3,796	15.4%
City of Providence	182,911	4,321	2.4%	4,485	2.5%	4,776	2.6%
Total	207,583	7,075	3.4%	7,900	3.8%	8,572	4.1%

[1]SLR = sea-level rise.

Table 2. Population Over 65 Years Exposed to the Flood Hazard

Municipality	Elderly population (2010 Census)	1% annual chance event		1% event with 3 ft of SLR		1% event with 5 ft of SLR	
		Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain
City of Newport	3,510	446	12.7%	525	15.0%	590	16.8%
City of Providence	19,249	233	1.2%	249	1.3%	265	1.4%
Total	22,759	679	3.0%	774	3.4%	855	3.8%

Table 3. Economically Disadvantaged Population Vulnerable to the Flood Hazard

Municipality	Annual income $20K or less population (2010 Census)	1% annual chance event		1% event with 3 ft of SLR		1% event with 5 ft of SLR	
		Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain
City of Newport	2,967	248	8.4%	271	9.1%	331	11.2%
City of Providence	24,779	591	2.4%	628	2.5%	692	2.8%
Total	27,446	839	3.1%	899	3.3%	1,023	3.7%

Table 4. Population Under 18 Years Exposed to the Flood Hazard

Municipality	Child population (2010 Census)	1% annual chance event		1% event with 3 ft of SLR		1% event with 5 ft of SLR	
		Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain	Population in floodplain	Percent population in floodplain
City of Newport	4,595	532	11.6%	556	12.1%	636	13.8%
City of Providence	46,450	907	2.0%	921	2.0%	1052	2.3%
Total	51,045	1,439	2.8%	1,477	2.9%	1,688	3.3%

Table 5. Disabled Population Exposed to the Flood Hazard

		Sensory disability	Physical disability	Mental disability	Self- care
Newport	**Ages 5–15**	10	36	199	26
	Ages 16–64	276	832	753	170
	Ages 65+	504	906	264	196
	Total	**790**	**1,774**	**1,216**	**392**
Providence	**Ages 5–15**	254	449	1483	464
	Ages 16–64	2,498	6,975	6,825	2,411
	Ages 65+	2,542	5,005	1,951	1,823
	Total	**5,294**	**12,429**	**10,259**	**4,698**

HAZUS-MH was used to model the potential sheltering needs as a result of the 1 percent chance flood event, the event with 3 feet of sea-level rise, and the event with 5 feet of sea-level rise. The displaced population is defined as the population in the inundation area plus an evacuation buffer equal to the size of a Census Block. For the 1 percent flood event with 5 feet of sea-level rise, HAZUS-MH estimates 11,962 people will be displaced, representing approximately 5.8 percent of the two jurisdictions. Table 6 presents these statistics by municipality.

Table 6. Estimated Population Displaced or Seeking Short-term Shelter from the Flood Hazard

Municipality	Total population (2010 Census)	1% annual chance event		1% event with 3 ft of SLR		1% event with 5 ft of SLR	
		Displaced population	Shelter requirements	Displaced population	Shelter requirements	Displaced population	Shelter requirements
City of Newport	24,672	3,924	3,028	4,465	3,636	4,594	3,755
City of Providence	182,911	5,072	4,435	5,936	5,152	7,368	6,558
Total	207,583	8,996	7,463	10,401	8,788	11,962	10,313

3.3 Impact on General Building Stock

After the population vulnerable to the flood hazard was considered, the community's infrastructure was evaluated. As described in Section 3.2 people directly affected by a flood event are more likely to experience mental disorders such as anxiety, depression, and post-traumatic stress disorder (PTSD). To understand the potential magnitude of human health impacts, residential areas were evaluated separately. Exposure in the flood zone includes those buildings located in the flood zone. Potential damage is the modeled loss that could occur to the exposed inventory, including structural and content value.

To provide a general estimate of number of structures and structural/content replacement value exposure, the HAZUS-MH flood boundaries were overlaid on each municipality's building stock inventory (Means 2005). The structures within the boundaries were totaled for each municipality. Tables 7 through 12 display these values.

For the two municipalities, it is estimated there are 2,711 structures located in the 1 percent annual chance floodplain (12.9 percent of the structures in Newport and 3.4 percent of the structures in Providence) and 3,490 structures located in the base flood, as well as 5 feet of sea-level rise (17.6 percent of the structures in Newport and 4.1 percent of the structures in Providence). Of the buildings located in and exposed to these flood events, the majority are residential structures, as shown in the tables below.

There is approximately $1.45 billion of damages for the 1 percent annual chance flood in the two municipalities. For the base flood plus 5 feet, there is approximately $2.40 billion in modeled damages. This represents approximately 5.0 percent and 8.3 percent of the municipality's total general building stock replacement value inventory ($28.8 billion), respectively.

Table 7. Estimated General Building Stock Exposure and Loss to the Base Flood Event

Municipality	Total number of buildings	Total RCV[1] ($)	Base floodplain			
			# of bldgs	% of total	Total loss ($)	% of total
City of Newport	10,205	4,572M[2]	1,312	12.9	619M	13.5
City of Providence	41,746	24,202M	1,399	3.4	832M	3.4
Total	51,951	28,774M	2,711	5.2	1,451M	5.0

[1]RCV = replacement cost value.

[2]Million dollars.

Table 8. Estimated Residential Exposure and Loss to the Base Flood Event

Municipality	Number of residential buildings	Total RCV ($)	Base floodplain			
			# of bldgs	% of total	Res. loss ($)	% of total
City of Newport	9,074	3,133M	1,074	11.8	326M	10.4
City of Providence	35,994	13,368M	587	1.6	61M	0.5
Total	45,068	16,501M	1,661	3.7	387M	2.4

Table 9. Estimated General Building Stock Exposure and Loss to Flood with 3-foot SLR

Municipality	Total number of buildings	Total RCV ($)	Base floodplain plus 3-foot SLR			
			# of bldgs	% of total	Total loss ($)	% of total
City of Newport	10,205	4,572M	1,487	14.6	822M	18.0
City of Providence	41,746	24,202M	1,550	3.7	1,156M	4.8
Total	51,951	28,774M	3,037	5.8	1,978M	6.9

Table 10. Estimated Residential Exposure and Loss to Flood with 3-foot SLR

Municipality	Number of residential buildings	Total RCV ($)	Base floodplain plus 3-foot SLR			
			# of bldgs	% of total	Res. loss ($)	% of total
City of Newport	9,074	3,133M	1,226	13.5	464M	14.8
City of Providence	35,994	13,368M	621	1.7	94M	0.7
Total	45,068	16,501	1,847	4.1	558	3.4

Table 11. Estimated General Building Stock Exposure and Loss to Flood with 5-foot SLR

Municipality	Total number of buildings	Total RCV ($)	Base floodplain plus 5-foot SLR			
			# of bldgs	% of total	Total loss ($)	% of total
City of Newport	10,205	4,572M	1,799	17.6	1,024M	22.4
City of Providence	41,746	24,202M	1,691	4.1	1,378M	5.7
Total	51,951	28,774M	3,490	6.7	2,402M	8.3

Table 12. Estimated Residential Exposure and Loss to Flood with 5-foot SLR

Municipality	Number of residential buildings	Total RCV ($)	Base floodplain plus 5-foot SLR			
			# of bldgs	% of total	Res. loss ($)	% of total
City of Newport	9,074	3,133M	1,499	16.5	584M	18.6
City of Providence	35,994	13,368M	698	1.9	123M	0.9
Total	45,068	16,501	2,197	4.9	707	4.3

Specific infrastructure impacts might also further exacerbate the health issues after a storm. Impacts on clinics, hospitals, hazardous material facilities (HAZMAT), chemical drug facilities, and water and wastewater utilities are shown in Table 13. Of particular concern are the numbers of impacted medical clinics, with 8 clinics projected to be impacted in Newport and up to 38 medical clinics in Providence with a 5 foot sea level. A significant number of these clinics (5 and 27 respectively) are currently located in the floodplain and thus already vulnerable to flooding. Loss of these medical clinics would decrease the ability of the municipalities to provide vital health and human services, and would be a particular concern when considering the needs of vulnerable populations during and after a flood event.

Newport has both water and wastewater facilities that are currently located in the floodplain, which is also of critical concern. Damage to the water facilities could mean the loss of potable water or interruption of service for the impacted area, while damage to wastewater facilities could contaminate flood waters as well as drinking water.

Impacts to HAZMAT and chemical or drug facilities is of concern as damage to these facilities could cause contamination of nearby air, water, and soil resources depending on the contaminant. There are 2 such facilities in Newport and 15 in Providence that are currently vulnerable to flood events.

Table 13. Potential Impacted Infrastructure

	Impacted infrastructure	Floodplain	3 ft	5 ft
Newport	Medical Clinics	5	6	8
	Hospitals	0	0	0
	HAZMAT Facilities	0	0	0
	Chemical/Drug Facilities	2	2	2
	Water Facilities	2	2	2
	Wastewater Facilities	1	2	2
Providence	Medical Clinics	27	29	38
	Hospitals	0	0	0
	HAZMAT Facilities	6	7	8
	Chemical/Drug Facilities	11	11	13
	Water Facilities	0	0	0
	Wastewater Facilities	0	0	0

3.4 Impact on the Economy

Economic losses from a flood event include but are not limited to general building stock damages, agricultural losses, business interruption, and impacts on tourism and the tax base. Damages to general building stock can be quantified using HAZUS-MH, as discussed above. Other economic components such as loss of facility use, functional downtime, and social economic factors are less measurable with a high degree of certainty. For the purposes of this analysis, general building stock damages are discussed further.

Flooding can cause extensive damage to public utilities and disruptions to service delivery. Loss of power and communications could occur, and drinking water and wastewater treatment facilities might be temporarily out of operation, all of which impact public health. Flooded streets and road blocks make it difficult for emergency vehicles to respond to calls for service. Floodwaters can wash out sections of roadways and bridges (Foster, no date).

Direct building losses are the estimated costs to repair or replace the damage caused to the building. The tables below show the potential damage estimated to the general building stock inventory associated with the base flood. These dollar-value losses to the municipality's total building inventory replacement value, in addition to damages to roadways and infrastructure, would greatly impact the local economy.

For the base flood event, HAZUS-MH estimates $11.0 million in business interruption losses. For the base flood plus 3 feet of sea-level rise, HAZUS-MH estimates $13.7 million in business interruption losses. For the base flood event plus 5 feet of sea-level rise, HAZUS-MH estimates $16.3 million in business interruption losses for the two municipalities, which includes loss of income, relocation costs, rental costs, and lost wages. Tables 14 through 16 provide details on the business interruption losses.

Following a flood event, the debris remaining can cause serious pollution problems and potentially harm public health. Such harm can be the result of released household hazardous waste and other chemical products, asbestos-containing materials, electrical transformers on downed power lines that might still contain polychlorinated biphenyls, and underground storage tanks. Floodwater and sand might be contaminated with human and animal waste; oil and gasoline residue; and farm chemicals such as fertilizers, pesticides, and herbicides. To estimate the amount of debris generated from a flood event, HAZUS-MH was used, and the result are presented in Tables 17 through 19. The model breaks down debris into three categories: (1) finishes (dry wall, insulation, etc.); (2) structural (wood, brick, etc.); and (3) foundations (concrete slab and block, rebar, etc.). This debris will be found in and near structures; most of it will be in residential and commercial areas, where a returning population come into contact with it.

Table 14. Business Interruption Losses for the Base Flood Event

Municipality	Relocation loss ($)	Income loss ($)	Rental loss ($)	Wage loss ($)	Total ($)
City of Newport	0.31M	1.15M	0.29M	1.54M	3.29M
City of Providence	0.77M	2.53M	0.57M	3.85M	7.72M
Total	1.08M	3.68M	0.86M	5.39M	11.01M

Table 15. Business Interruption Losses for a Flood with 3-foot SLR

Municipality	Relocation loss ($)	Income loss ($)	Rental loss ($)	Wage loss ($)	Total ($)
City of Newport	0.39M	1.23M	0.30M	1.74M	3.66M
City of Providence	1.00M	3.33M	0.74M	4.96M	10.03M
Total	1.39M	4.56M	1.04M	6.7M	13.69M

Table 16. Business Interruption Losses for a Flood with 5-foot SLR

Municipality	Relocation loss ($)	Income loss ($)	Rental loss ($)	Wage loss ($)	Total ($)
City of Newport	0.51M	1.56M	0.35M	2.14M	4.56M
City of Providence	1.17M	3.89M	0.86M	5.77M	11.69M
Total	1.68M	5.45M	1.21M	7.91M	16.25M

Table 17. Estimated Debris Generated from the 1 Percent Flood Event

Municipality	Base flood event			
	Total (tons)	Finish (tons)	Structure (tons)	Foundation (tons)
City of Newport	116,808	39,744	49,676	27,388
City of Providence	57,923	18,249	25,011	14,663

Table 18. Estimated Debris Generated from the 1 Percent Flood Event with 3-foot SLR

Municipality	Base flood plus 3-ft event			
	Total (tons)	Finish (tons)	Structure (tons)	Foundation (tons)
City of Newport	211,842	60,156	98,117	53,569
City of Providence	88,612	28,109	36,361	24,142

Table 19. Estimated Debris Generated from the 1 Percent Flood Event with 5-foot SLR

Municipality	Base flood plus 5-ft event			
	Total (tons)	Finish (tons)	Structure (tons)	Foundation (tons)
City of Newport	294,399	73,569	141,955	78,875
City of Providence	121,210	34,153	51,314	35,743

4 Extreme Event—Hurricanes

Hurricanes can impact human health in several different ways. First, they can cause damage directly to wastewater treatment facilities, water facilities, and other utilities, which would mean water contamination, no air-conditioning, and no heating. Second, they can destroy homes and businesses. Finally, as described in Section 3.2, people directly impacted by a hurricane event are more likely to experience mental disorders such as anxiety, depression, and PTSD.

NOAA defines hurricanes as non-frontal, low-pressure, synoptic-scale systems that develop over tropical or subtropical water and have definite organized circulations. As the climate changes, sea-level rise and increased storminess could affect the magnitude of hurricanes. Hurricane hazards include strong winds and storm surge, both of which are intensified because of climate change and warming oceans. Wind-related hazards rank as the number two priority hazard in the *Rhode Island Hazard Mitigation Plan* (RIEMA 2008), and many of Rhode Island's coastal communities are at risk to both wind and storm surge. To better understand the impacts, the future storm surge area and wind speeds need to be identified.

Overview of Vulnerability

The high winds and air speeds of a hurricane or any severe storm often result in power outages, disruptions to transportation corridors and equipment, loss of workplace access, significant property damage, injuries and loss of life, and the need to shelter and care for people affected by the events. A large amount of damage can be inflicted by trees, branches, and other objects that fall onto power lines, buildings, roads, vehicles, and, in some cases, people. The risk assessment for severe storms evaluates available data for a range of storms included in this hazard category. Secondary flooding associated with the torrential downpours during hurricanes/tropical storms is also a primary concern in the municipalities. Rhode Island has experienced flooding in association with hurricanes and tropical storms in the past.

The entire inventory of both Providence and Newport is at risk of being damaged or lost due to the impacts of severe wind. Certain areas, infrastructure, and types of buildings are at greater risk than others because of proximity, orientation, and manner of construction. Potential losses associated with high-wind events were calculated for the municipalities for two hurricane events, a category 3 (125-mph winds) with 3 feet of sea-level rise and a category 4 (143-mph winds) with 5 feet of sea-level rise. The impacts on population, existing structures, and the economy are presented below, following a summary of the data and methodology used. These scenarios will help answer the questions above—who will be impacted, how many homes and businesses will be impacted and where, and whether resources are available to deal with these events.

Data and Methodology

After reviewing historical data, the HAZUS-MH methodology and model were used to analyze the severe storm hazard for the cities of Newport and Providence. Data used to assess this hazard include data available in the HAZUS-MH hurricane model and professional knowledge.

Hurricane scenarios were run for Providence and Newport, including a category 3 storm with 3 feet of sea-level rise and a category 4 storm with 5 feet of sea-level rise. The HAZUS-MH maximum peak wind speeds for the study area are associated with these hurricane events. The category 4 model assumed a full levee breach, further impacting Providence.

HAZUS-MH contains data on historical hurricane events and wind speeds. It also includes surface roughness and vegetation (tree coverage) maps for the area. Surface roughness and vegetation data support the modeling of wind force across various types of land surfaces. Hurricane and inventory data available in HAZUS-MH were used to evaluate potential losses from the two scenario events (severe wind impacts and surge).

Figure 8 and 9 show hurricane storm surge for Providence and Newport. Similar to the projected impacts of flooding, hurricane storm surge will likely inundate all coastal regions of Providence and Newport. The category 3 storm with 3 feet of sea-level rise will cause the southwestern peninsula of Newport to be cut off from the mainland. Furthermore, the category 4 storm with 5 feet of sea-level rise assessment has even greater impacts than the flooding assessment predicted for the 5-foot, 1 percent annual flooding event. With a category 4 storm, inundation will impact additional areas farther north and south.

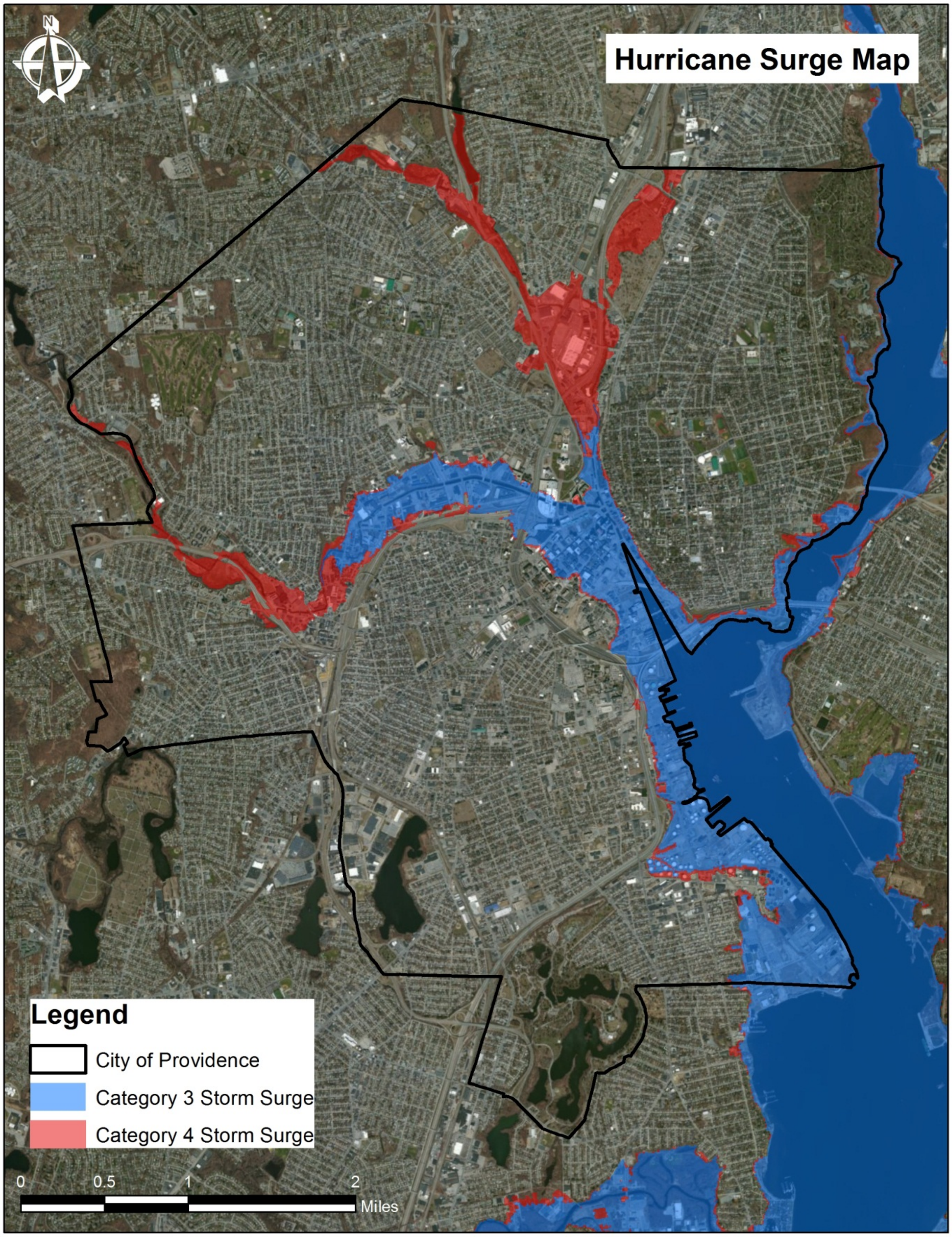

Figure 8. Providence Hurricane Surge.

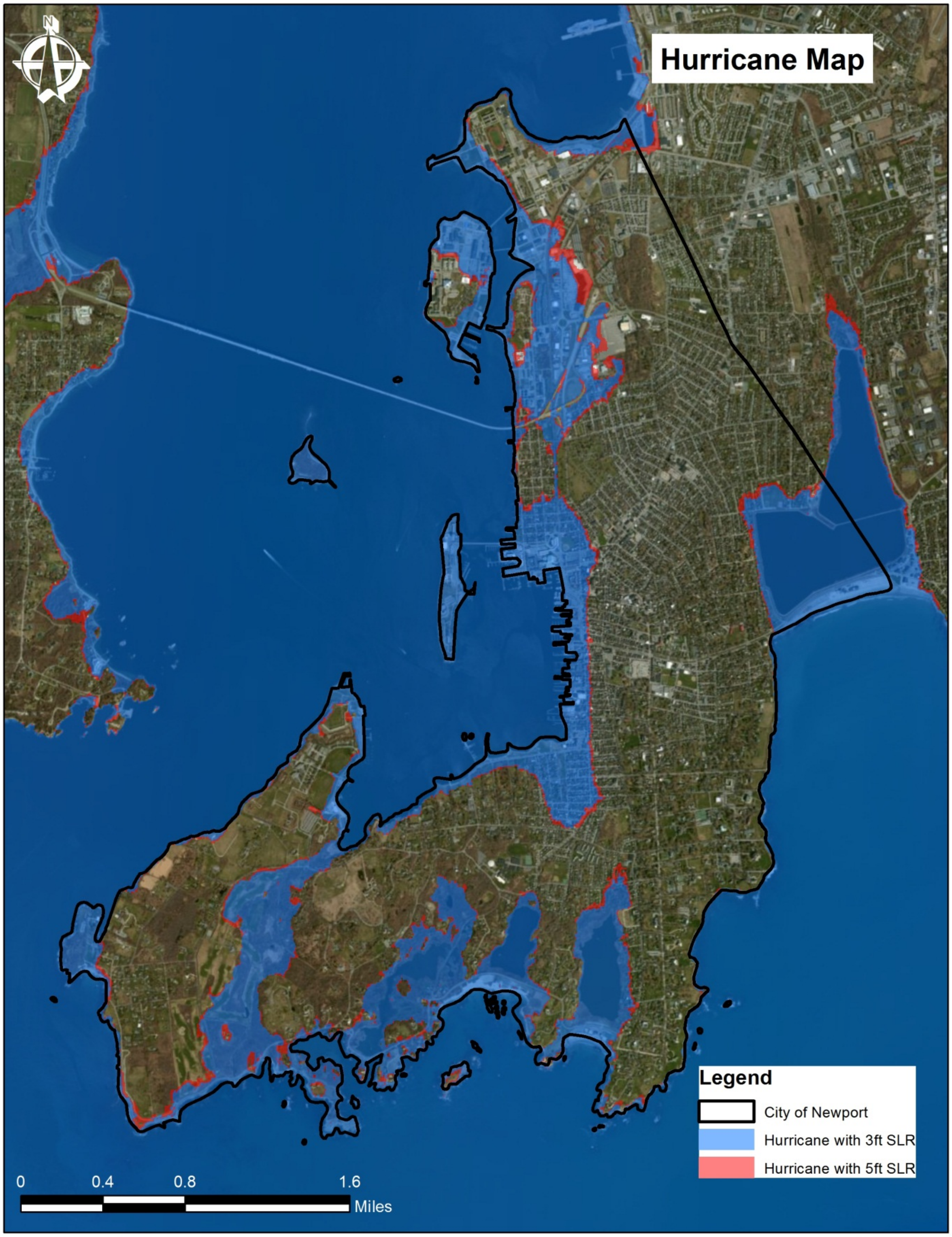

Figure 9. Newport Hurricane Surge.

4.1 IMPACT ON LIFE, HEALTH, AND SAFETY

The impact of a severe storm on life, health, and safety is dependent upon several factors, including the severity of the event and whether adequate warning time was provided to residents. It is assumed that the entire municipality's population (U.S. Census 2010 population of 207,583 people) would be exposed to this storm hazard.

Residents can be displaced or require temporary to long-term sheltering. In addition, trees can be blown down into structures or become wind-borne debris striking structures or people; damaged building roofing or other damaged components can also be carried by high winds and lead to injury or loss of life. Socially vulnerable populations are most susceptible, based on a number of factors such as their physical and financial ability to react or respond during a hazard and the location and construction quality of their housing. HAZUS-MH estimates there will be 7,073 households displaced and 2,190 people that might require temporary shelter due to a category 3 event. For a category 4 event, HAZUS-MH estimates 33,837 households will be displaced and 10,569 might require short-term sheltering. Refer to Tables 20 and 21, which summarize the sheltering estimates for the 500-year MRP event by municipality.

Table 20. Sheltering Needs for the Category 3 Hurricane Event with 3-foot SLR

Municipality	Displaced households	Population requiring short-term shelter
City of Newport	932	217
City of Providence	6,141	1,973
Total	7,073	2,190

Table 21. Sheltering Needs for the Category 4 Hurricane Event with 5-foot SLR

Municipality	Displaced households	Population requiring short-term shelter
City of Newport	5,630	1,412
City of Providence	28,207	9,157
Total	33,837	10,569

4.2 IMPACT ON GENERAL BUILDING STOCK

After the population exposed to the severe storm hazard was considered, the general building stock replacement value inventory exposed to and damaged by the category 3 and 4 events were examined. Hurricane impacts from a severe storm are reported based on the hurricane runs in HAZUS-MH using the wind and surge models. Potential damage is the modeled loss that could occur to the exposed inventory, including damage to structural and content value based on the impacts associated with a hurricane.

It is assumed that both municipalities' general building stock is exposed to the severe storm hazard (greater than $28.7 billion). For the category 3 event, HAZUS-MH estimates $2.99 billion in losses for the two municipalities, as shown in Table 22. For the category 4 event, the modeled losses increase to $9.35 billion, as shown in Table 23. Residential buildings comprise the majority of the losses, but there is a significant amount of commercial loss.

Table 22. Total and Residential Loss for the Category 3 Hurricane Event with 3-foot SLR

Municipality	Total RCV ($)	Total loss ($)	% Loss	Residential loss ($)
City of Newport	4,572M	534M	11.7	397M
City of Providence	24,202M	2,453M	10.1	1,553M
Total	28,774M	2,987M	3.4	1,950M

Table 23. Total and Residential Loss for the Category 4 Hurricane Event with 5-foot SLR

Municipality	Total RCV ($)	Total loss ($)	% Loss	Residential loss ($)
City of Newport	4,572M	1,766M	28.1	1,284M
City of Providence	24,202M	7,584M	31.3	4,663M
Total	28,774M	9,350M	32.5	5,947M

Because of differences in building construction, residential structures are generally more susceptible to wind damage than commercial and industrial structures. Wood and masonry buildings in general, regardless of their occupancy class, tend to experience more damage than concrete or steel buildings. The damage counts include buildings damaged at all severity levels, from minor damage to total destruction. Total dollar damage reflects the overall impact on buildings at an aggregate level.

4.3 Impact on the Economy

Severe storms also impact the economy. Potential effects include loss of business function (e.g., tourism, recreation), damage to inventory, relocation costs, and wage loss and rental loss due to the repair/replacement of buildings. HAZUS-MH estimates the total economic loss associated with each storm scenario (direct building losses and business interruption losses). Direct building losses are the estimated costs to repair or replace the damage caused to the building. This is reported in the Impact on General Building Stock section discussed in Section 4.2. Business interruption losses are the losses associated with the inability to operate a business because of the wind damage sustained during the storm or the temporary living expenses of those displaced from their homes because of the event.

For the category 3 hurricane event, HAZUS-MH estimates $350 million in business interruption losses. For the category 4 hurricane event, HAZUS-MH estimates $1.41 billion in business interruption losses for the two municipalities, which includes loss of income, relocation costs, rental costs, and lost wages. Tables 24 and 25 provide details on the business interruption losses.

Table 24. Business Interruption Losses for a Category 3 Hurricane with 3-foot SLR

Municipality	Relocation loss ($)	Income loss ($)	Rental loss ($)	Wage loss ($)	Total ($)
City of Newport	35.5M	13.3M	22.9M	13.4M	85.1M
City of Providence	166.7M	40.9M	104.4M	57.0M	369.0M
Total	202.2M	54.2M	127.3M	70.4M	454.1M

Table 25. Business Interruption Losses for a Category 4 Hurricane with 5-foot SLR

Municipality	Relocation loss ($)	Income loss ($)	Rental loss ($)	Wage loss ($)	Total ($)
City of Newport	93.9M	52.4M	64.2M	54.5M	265M
City of Providence	414.9M	153.9M	268.0M	205.3M	1,042.1M
Total	508.8M	206.3M	332.2M	259.8M	1,307.1M

HAZUS-MH also estimates the amount of debris that could be produced as a result of the category 3 and 4 wind events. Table 26 shows the estimated amount of debris produced. Following a hurricane event, the remaining debris can cause serious pollution problems and potentially harm public health. Such harm can be the result of released household hazardous waste and other chemical products, asbestos-containing materials, electrical transformers on downed power lines that might still contain polychlorinated biphenyls, and underground storage tanks. Surge inundation areas might be contaminated with human and animal waste; oil and gasoline residue; and farm chemicals such as fertilizers, pesticides, and herbicides. Vegetative debris can block major transportation routes or become wildfire fuel if they are not removed. Because the estimated debris production does not include storm surge, this is likely a conservative estimate that might be higher if multiple impacts occur. According to the *HAZUS-MH Hurricane User Manual*:

> The Eligible Tree Debris columns provide estimates of the weight and volume of downed trees that would likely be collected and disposed [of] at public expense. As discussed in Chapter 12 of the HAZUS-MH Hurricane Model Technical Manual, the eligible tree debris estimates produced by the Hurricane Model tend to underestimate reported volumes of debris brought to landfills for a number of events that have occurred over the past several years. This indicates that that there may be other sources of vegetative and non-vegetative debris that are not currently being modeled in HAZUS. For landfill estimation purposes, it is recommended that the HAZUS debris volume estimate be treated as an approximate lower bound. Based on actual reported debris volumes, it is recommended that the HAZUS results be multiplied by three to obtain an approximate upper bound estimate. It is also important to note that the Hurricane Model assumes a bulking factor of 10 cubic yards per ton of tree debris. If the debris is chipped prior to transport or disposal, a bulking factor of 4 is recommended. Thus, for chipped debris, the eligible tree debris volume should be multiplied by 0.4.

Table 26. Hurricane Debris Estimates

Municipality	Brick and wood (tons)		Concrete and steel (tons)		Tree (tons)		Eligible tree volume (cubic yards)	
	Cat 3	Cat 4	Cat 3	Cat 4	Cat 3	Cat 4	Cat 3	Cat 4
City of Newport	49,195	144,661	303	1,387	10,302	17,799	102,933	178,006
City of Providence	237,221	620,495	900	4,548	10,160	16,188	101,611	161,900

5 Extreme Event—Droughts

With higher average temperatures, climate change will lead to increased climate variability and will increase the risk of both floods and droughts (Wetherald and Manabe 2002; IPCC 2007). Climate change can also intensify the impacts of a drought because of decreased precipitation and increased evapotranspiration reducing the surface water flows and ground water availability. These issues can be exacerbated by other stressors, such as an increased population and water demand. According to the U.S. Geological Survey, a drought is a lack or insufficiency of rain for an extended period that severely disturbs the hydrologic cycle in an area.[2] Droughts involve water shortages, crop damage, streamflow reduction, and depletion of ground water and soil moisture. They occur when evaporation and transpiration exceed precipitation for a considerable period. Rhode Island experiences extended periods of dry weather, typically during the summer months, despite getting more rain annually (39–54 inches) than the average for the United States (29.5 inches) (NWS 2012). The state has 1,498 miles of rivers, 20,917 acres of lakes and ponds, 22 major stratified drift aquifers, and usable quantities of ground water in almost all locations from bedrock aquifers.

Documentation and identification of the health impacts of droughts are quite difficult for a variety of reasons. Numerous indicators are used to identify and quantify the onset, length, and extent of a drought (National Drought Mitigation Center 2012). In addition, drought conditions commonly develop slowly and lack highly visible and structural impacts until they reach a critical stage (Stanke et al. 2013). The societal impacts of drought can also be slow to develop because they accumulate over time as conditions worsen.

Drought conditions, over which individuals have no control, can be a source of worry and concern. When these conditions continue for long periods, stress levels can climb and lead to anxiety and traumatic stress. A number of studies, mainly from Australia, have documented the impacts of drought on mental health (Carnie et al. 2011; Staniford et al. 2009). The results indicate that prolonged drought has negative impacts on the mental health of the populations studied. Studies examining the effects of drought on children found that they worry about family (Carnie et al. 2011; Dean 2007) and experience feelings of loss (Dean 2007, 2010).

Another health impact related to drought events relates to quality of drinking water. The low flow can cause higher concentration in chemicals, nutrients, and solid particulates and lower dissolved oxygen. The high temperatures result in greater evaporation, drying up water bodies, plants, and soils; this can impact a wide array of ecosystem functions and harm natural wildlife. With decreased discharge and water levels, dilution capacity is reduced and secondary impacts on freshwater systems develop, causing decreased water quality.

Drought is the fourth priority hazard in the state's *Hazard Mitigation Plan* (RIEMA 2008). According to the plan, drought has a 5 percent probability of occurring in any given year on the basis of the limited data available. Table 27 shows some of the major historical droughts that have affected the state. For each drought, the National Weather Service notes that the precipitation during the preceding fall and winter months was *below normal* to *much below normal* (90 and 75 percent less than typical levels) before the spring. The 1965–1967 drought lasted for three summers. Although short-term droughts, such as the one experienced in 1999, might not pose a significant threat for the state's public water systems, no water system is immune to periods of long-term drought (RIEMA 2008).

[2] As defined online at http://ks.water.usgs.gov/waterwatch/drought/definition.html.

Table 27. Historical Drought

Date	Area impacted	Impacts
1930–1931	State	Streamflow 70% of normal
1941–1945	State (Very severe in Pawtuxet and Blackstone Rivers)	Streamflow 70% of normal
1949–1950	State	Streamflow 70% of normal
1963–1967	State	Water restriction, well replacements
1980–1981	State (Very severe in eastern part of State)	Serious crop damage
1987–1988	Southern part of state	Crop damage ($25 million)

Source: NWS 2008.
Note: M = million.

Droughts are usually accompanied by high sustained temperatures, and maintaining personnel health during such a heat crisis is critical. It is important to note that many heat-related illnesses are commonly exacerbated by the impacts of drought conditions. In Rhode Island there have been 19 heat-related deaths during 1999–2013 (for both underlying and contributing causes). Nine were female and ten were male. Generally, drought-related economic, health, and social losses in Rhode Island have been minimal. The likelihood of future heat events is described in the accompanying report, *Future Heat-Related Illness Risk in Rhode Island: Evidence from Climate Models*.

6 Conclusions

The preliminary analyses presented in this report suggest that over the coming decades Rhode Island residents are likely to face increased risks from climate-related physical hazards, including floods, hurricanes, and droughts. Higher sea levels mean that the same storm will flood farther inland than it does now, which will be particularly challenging for Rhode Island because the majority of the population lives along the coastline.

Flooding can greatly impact the mental health of affected populations. Given the lengthy recovery period associated with flooding, there is a greater risk of secondary stressors such as the economic stress associated with rebuilding. These secondary stressors arise as individuals try to recover their lives and rebuild their homes and community. To better understand the potential impacts following a flood, this report assessed the potential building damage associated with extreme floods. For Providence and Newport, it is estimated that approximately $1.45 billion of damages will occur with a 1 percent annual chance flood. For the base flood plus 5 feet, there is approximately $2.40 billion in modeled damages. This represents approximately 5.0 percent and 8.3 percent of the municipality's total general building stock replacement value inventory ($28.8 billion), respectively.

Hurricanes can impact human health in several different ways. They can cause damage directly to various utilities; destroy homes and businesses; and potentially lead to mental illnesses, such as anxiety, depression, and PTSD, in affected communities. The hurricane surge projections show that storms will greatly impact the coastal and inland communities in both Providence and Newport. In terms of hurricane damage for a Category 3 event with 3 feet of sea-level rise, HAZUS-MH estimates $2.99 billion in losses for the both Providence and Newport. For the Category 4 event with 5 feet of sea-level rise, the modeled losses are 9.35 billion. Residential buildings account for the majority of the losses, but there is a significant amount of commercial loss as well.

In addition to the costs of physical damage, there will most certainly be costs associated with caring for people impacted by the storm. The public health costs of flooding and hurricane damage range from direct hospital care for residents with gastrointestinal symptoms to stress and other mental health problems. Although these long-term costs can be difficult to track, past incidents have shown that the public health challenges arising in the wake of a storm strain our already-taxed healthcare systems. The costs of mental health services aimed at helping flood and hurricane victims should be considered in future assessments.

Drought conditions, over which people have no control, can be a source of worry and concern. When these conditions continue over time, stress levels can climb and lead to anxiety and traumatic stress. Similar to the impacts of flooding and hurricane events, drought conditions can greatly affect the mental health of a region. Fortunately, historic drought-related economic and social losses in Rhode Island have been minimal, and future projections are difficult to make because of the divergence of precipitation models. Droughts are usually accompanied by high sustained temperatures, and maintaining personnel health during such a heat crisis is critical. It is important to note that many heat-related illnesses are commonly exacerbated by the impacts of drought conditions.

It is important to note that the results of this report provide only preliminary estimates of future trends and the possible range of outcomes that might require adaptation. Rhode Island must continue to monitor climate changes to further understand immediate and future impacts. The impacts discussed in this report will require that Rhode Island develop adaptation strategies geared toward protecting its citizens' health into the future.

7 References

Abramson, D., R. Garfield, and I. Redlener. 2007. The recovery divide: Poverty and the widening gap among Mississippi children and families affected by Hurricane Katrina. New York: Columbia University, Mailman School of Public Health. Available online at: http://www.ncdp.mailman.columbia.edu/files/recovery_divide.pdf.

Ahern, M., R.S. Kovats, P. Wilkinson, R. Few, and F. Matthies. 2005. Global health impacts of floods: Epidemiologic evidence. *Epidemiologic Reviews*, 27:36–46.

Carnie, T.L., H. Berry, S. Blinkhorn, and C. Hart. 2011. In their own words: Young people's mental health in drought-affected rural and remote NSW. *Australian Journal of Rural Health*, 19: 244–248.

Dean, J., and H. Stain. 2007. The impact of drought on the emotional well-being of children and adolescents in rural and remote new South Wales. *Journal of Rural Health*, 23(4): 356–364.

Dean, J., and H. Stain. 2010. Mental health impact for adolescents living with prolonged drought. *Australian Journal of Rural Health*, 18:32–37.

Foster, S.A. No date. Natural Hazards and Their Impacts on Agricultural and Urban Development in the Barren River Area. The Kentucky Climate Center.

Greenough, G. et al. 2001. The potential impacts of climate variability and change on health impacts of extreme weather events in the United States. *Environmental Health Perspectives* 109.

Means. 2005. *Means Square Foot Costs*. Kingston, MA: R. S. Means Company, Inc.

National Drought Mitigation Center (NDMC). 2012. Types of drought. Available online at: http://www.drought.unl.edu/DroughtBasics/TypesofDrought.aspx.

NWS (National Weather Service). 2012. Rhode Island Annual Precipitation. Accessed online, 2013.

RIEMA (Rhode Island Emergency Management Agency). 2008. *Rhode Island Hazard Mitigation Plan*. Providence, RI: Rhode Island Emergency Management Agency.

Rubinoff, P., N. Vinhateiro, and C. Piecuch. 2008. *Summary of Coastal Program Initiatives that address Sea Level Rise as a Result of Global Climate Change*. Kingston, RI: University of Rhode Island, Rhode Island Sea Grant/Coastal Resources Center.

Staniford, A., M. Dollard, and B. Guerin. 2009. Stress and help-seeking for drought-stricken citrus growers in the Riverland of South Australia. *Australian Journal of Rural Health*, 17:147–154.

Stanke, C., M. Kerac, C. Prudhomme, J. Medlock, and V. Murray. 2013. Health effects of drought: A systematic review of the evidence. *PLOS Currents Disasters* (2013, Jun 5), edition 1. doi: 10.1371/currents.dis.7a2cee9e980f91ad7697b570bcc4b004.

Tetra Tech. 2012. *Safe***Water** RI: Phase 2 Report, Assessment of Impacts. Prepared for Rhode Island Department of Health, Office of Drinking Water Quality, by Tetra Tech, Inc., Fairfax, VA.

USACE (U.S. Army Corps of Engineers). 2003. *Coastal Engineering Manual*. Washington, DC: U.S. Army Corps of Engineers. Available online at: http://chl.erdc.usace.army.mil/cem.

United States Census Bureau. 2011. *United States Census 2010*. Washington, DC: United States Census Bureau, Population Division.

Wetherald, R.T., and S. Manabe. 2002. Simulation of hydrologic changes associated with global warming. *Journal of Geophysical Research*, 107(D19), 4379, doi:10.1029/ 2001JD001195.