RHODE ISLAND COASTLINE
COASTAL STORM RISK MANAGEMENT
Draft Feasibility Study

APPENDIX B: Coastal Engineering

JANUARY 31, 2022

US Army Corps of Engineers®
New England District

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RHODE ISLAND COASTLINE
COASTAL STORM RISK MANAGEMENT

DRAFT FEASIBILITY REPORT
Appendix G: Real Estate Plan

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1. INTRODUCTION

This appendix presents the results of the Hydraulic, Hydrology and Coastal (HH&C) engineering evaluation and analysis for the Rhode Island Coastline (RI Coastline) Coastal Storm Risk Management (CSRM) Study. This report will discuss the existing information that was reviewed and how that information was used in the HH&C engineering evaluation and analysis to come up with the contribution of the elements to get to the TSP milestone and Draft Feasibility Report for the study.

2. STUDY AREA

The RI Coastline Study investigated the feasibility of various storm damage reduction measures along the Rhode Island coastline from Point Judith to the Massachusetts border including Narragansett Bay and Block Island. The RI Coastline study area is shown in **Figure B 2-1** and comprised approximately 457 miles of coastline including inlets, coastal lagoons, and islands. Within the study are the towns of Barrington, Bristol, and Warren in Bristol County; the city of Warwick and the town of East Greenwich in Kent County; the city of Newport and the towns of Jamestown, Little Compton, Middletown, Portsmouth, and Tiverton in Newport County; the cities of Cranston, East Providence, Pawtucket, and Providence in Providence County; and the towns of Narragansett, New Shoreham, North Kingstown, and South Kingstown in Washington County.

2.1. Narragansett Bay

Narragansett Bay is a bay and estuary on the north side of Rhode Island Sound. Covering 147 square miles, the Bay forms New England's largest estuary, which functions as an expansive natural harbor, and includes a small archipelago. While most of Narragansett Bay is located within Rhode Island, small parts of it extend into Massachusetts. The bay contains over forty islands, with the three largest being Aquidneck Island (containing Newport, Middletown, and Portsmouth), Conanicut Island (Jamestown) and Prudence Island. Bodies of water that are part of Narragansett Bay include the Sakonnet River, Mount Hope Bay, and the southern, tidal part of the Taunton River. The Bay opens on Rhode Island Sound, with Block Island (New Shoreham) located less than 20 miles southwest of its opening, and the Atlantic Ocean.

The bay is a ria estuary or drowned river valley which is composed of, from east to west, the Sakonnet River valley, the East Passage River Valley, and the West Passage river valley. The bathymetry varies greatly among the three passages, with the average depths of the East, West, and Sakonnet River passages being 121 feet, 33 feet, and 25 feet, respectively. The estuary system is vast compared to the present flow of the four small rivers that enter the Bay: in the northeast, the Taunton River and in the northwest, the Providence and Seekonk Rivers, along with the Pawtuxet River from the west.

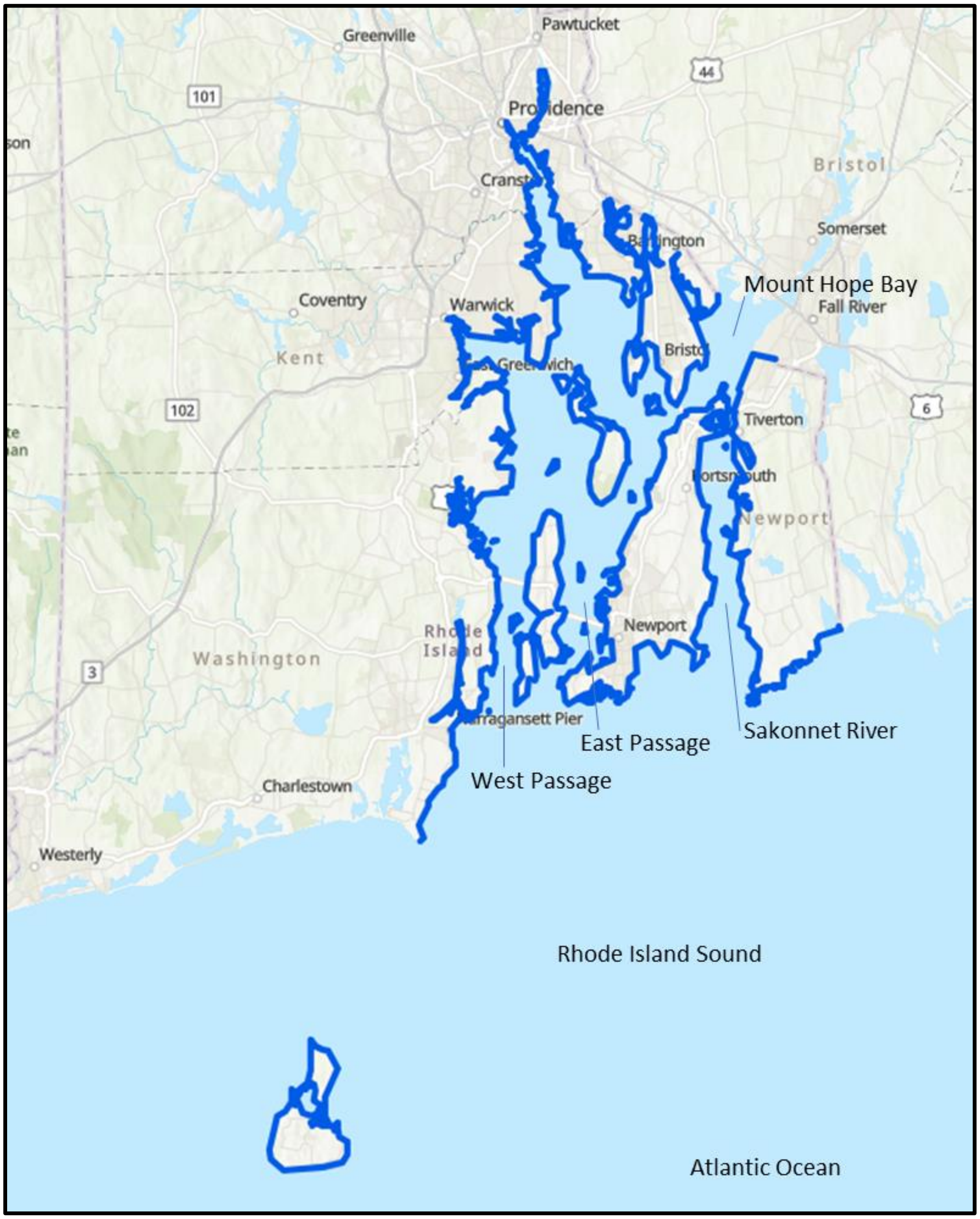

Figure B 2-1: Study location map

2.2. Geologic Setting and Shoreline Types

The present geologic framework of Narragansett Bay is heavily dependent on the bedrock geology and the configuration of glacial processes, landforms, and sediment type. Glacial deposits range from till to stratified deposits (gravel, sand and mud). Shoreline types mapped by Boothroyd and Al-Saud (1978), and summarized by Hehre (2007), comprise six main types within Narragansett Bay (**Table B 2-1**).

Within the study area, the density of development, types of infrastructure, and exposure to coastal flood hazards, including storm surge, waves, and erosion, vary considerably.

Table B 2-1: Geologic shoreline types in Narragansett Bay (modified from Boothroyd and Al-Saud (1978) and Hehre (2007), from RI Beach SAMP (2018))

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

3. VERTICAL DATUM

In accordance with ER 1110-2-8160 the RI Coastline Study is designed to North American Vertical Datum of 1988 (NAVD88), the current orthometric vertical reference datum within the National Spatial Reference System (NSRS) in the contiguous United Stated. The study area is subject to tidal influence and is directly referenced to National Water Level Observation Network (NWLON) tidal gages and coastal hydrodynamic tidal models established and maintained by the U.S. Department of Commerce (NOAA). The current NWLON National Tidal Datum Epoch (NTDE) is 1983-2001.

There are several active NWLON tidal gages within, and just adjacent to, the study area. Tidal conversions to NAVD88 at these tidal stations are presented in **Table B 3-1**. The locations of the NOAA tidal stations are shown in **Figure B 3-1**. The local NAVD88-MSL relationship at locations between gages is estimated using NOAA VDatum model of the project region (EM 1110-2-6056).

Table B 3-1: NOAA tidal gage datum relationships

Datum[1]	Providence	Conimicut Light	Fall River, MA	Quonset Point	Newport
	(feet)	(feet)	(feet)	(feet)	(feet)
Mean Higher High Water (MHHW)	2.37	2.20	2.34	1.87	1.81
Mean High Water (MHW)	2.12	1.95	2.10	1.62	1.57
NAVD88	0.00	0.00	0.00	0.00	0.00
Mean Sea Level (MSL)	-0.22	-0.28	-0.23	-0.37	-0.30
Mean Low Water (MLW)	-2.29	-2.23	-2.26	-2.08	-1.90
Mean Lower Low Water (MLLW)	-2.47	-2.39	-2.43	-2.24	-2.04
Great Diurnal Range (GT)[2]	4.84	4.58	4.78	4.10	3.85
Mean Range of Tide (MN)[3]	4.42	4.17	4.37	3.70	3.46

Notes: [1] Tidal datums based on 1983-2001 tidal epoch
[2] Great Diurnal Range (GT) = MHHW-MLLW
[3] Mean Tidal Range (MN) = MHW-MLW

Hydrodynamic modeling completed as part of the North Atlantic Coast Comprehensive Study (NACCS) and used in this study was performed in meters, MSL in the current NTDE. Water elevations have been converted to feet, NAVD88 using NOAA VDatum. VDatum is a vertical datum transformation software tool that provides conversions between various tidal datums and MSL and MSL and NAVD88.

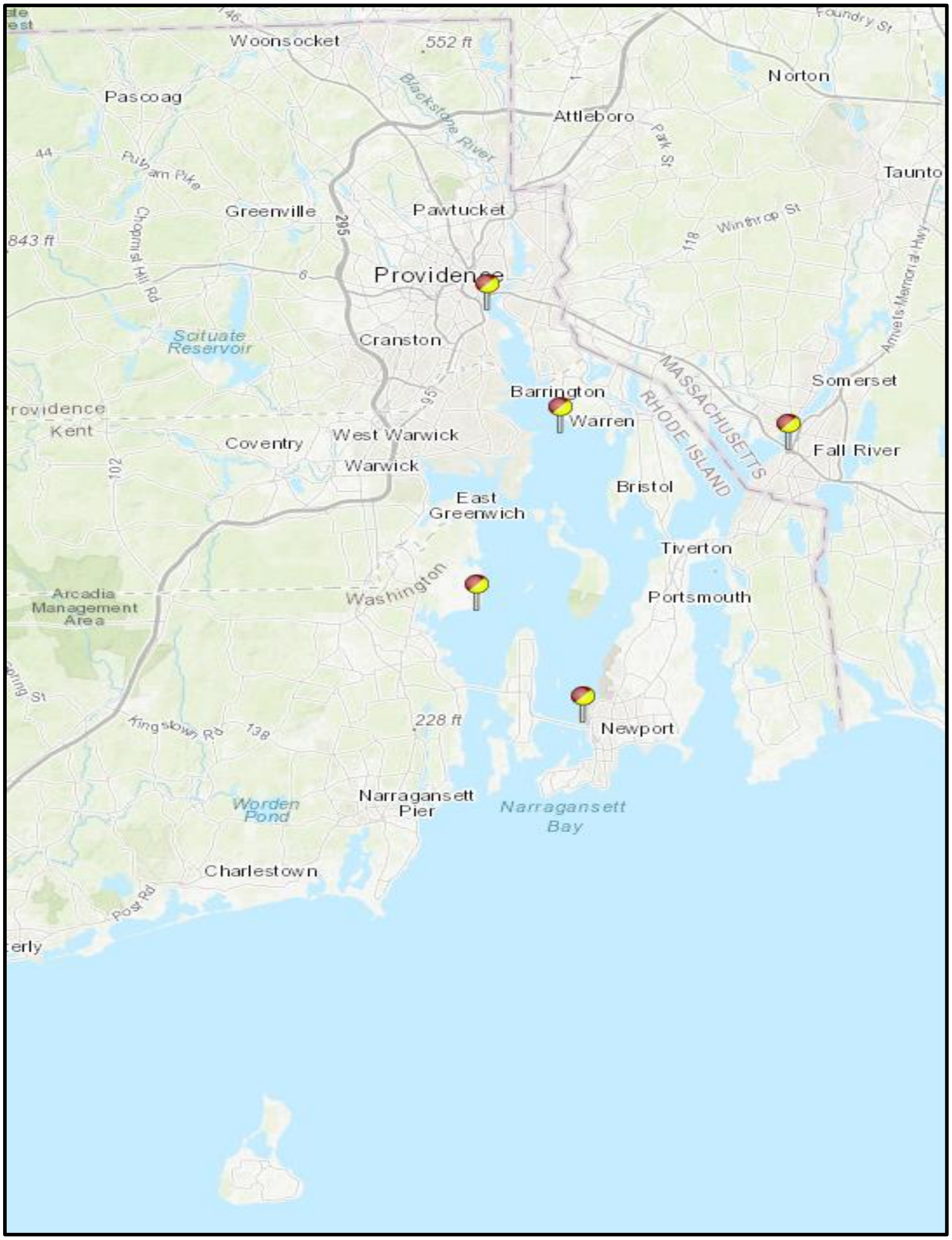

Figure B 3-1: NOAA tide gage locations

4. SEA LEVEL CHANGE

4.1. Background on Sea Level Change

Global sea level change (SLC) is often caused by the global change in the volume of water in the world's oceans in response to three climatological processes: 1) ocean mass change associated with long-term forcing of the ice ages ultimately caused by small variations in the orbit of the earth around the sun; 2) density changes from total salinity; and most recently, 3) changes in the heat content of the world's oceans, which recent literature suggests may be accelerating due to global warming. Global SLC can also be caused by basin changes through such processes as seafloor spreading. Thus, global sea level, also sometimes referred to as global mean sea level, is the average height of all the world's oceans.

Relative (local) SLC is the local change in sea level relative to the elevation of the land at a specific point on the coast. Relative SLC is a combination of both global and local SLC caused by changes in estuarine and shelf hydrodynamics, regional oceanographic circulation patters (often caused by changes in regional atmospheric patterns), hydrologic cycles (river flow), and local and/or regional vertical land motion (subsidence or uplift).

4.2. USACE Guidance

In accordance with ER 1100-2-8162, potential effects of relative sea level change (RSLC) were analyzed over a 50-year economic period of analysis and a 100-year planning horizon. USACE guidance states "the period of analysis shall be the time required for implementation of the lesser of: (1) the period of time over which any alternative plan would have significant beneficial or adverse effects, (2) a period not to exceed 50 years" (ER 1105-2-100). However, because infrastructure often stays in place well beyond the economic period of analysis, a 100-year adaptation planning horizon is used to address robustness and resilience in the time of service of the project that can extend past its original design life. Research by climate science experts predict continued or accelerated climate change for the 21st century and possibly beyond, which would cause a continued or accelerated rise in global mean sea level. ER 1100-2-8162 states that planning studies will formulate alternatives over a range of possible future rates of SLC and consider how sensitive and adaptable the alternatives are to SLC.

ER 1100-2-8162 requires planning studies and engineering designs to consider three future sea level change scenarios: low, intermediate, and high. The historic rate of SLC represents the low rate. The intermediate rate of SLC is estimated using the modified National Research Council (NRC) Curve I. The high rate of SLC is estimated using the modified NRC Curve III. The high rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007 to accommodate the potential rapid loss of ice from Antarctica and Greenland but is within the range of values published in peer-reviewed articles since that time.

4.3. Historical Sea Level Change

Historical RSLC for this study (2.77 mm/yr or 0.00909 ft/yr for the years 1930-2018) is based on NOAA tidal records at Newport, RI. An additional historical RSLC rate within the study area is available at Providence, RI (2.27 mm/yr or 0.00745 ft/yr for the years 1938-2018). The historical records with the relative sea level trends for both gages are shown in **Figure B 4-1** and **Figure B 4-2**.

The USACE Sea Level Tracker was also used to visualize historic SLC relative to the three USACE sea level change curves. The Sea Level Tracker presents several metrics for measuring sea level change: the monthly mean sea level (light blue), the 5-year moving average (orange), and the 19-year moving average (dark blue). **Figure B 4-3** and **Figure B 4-4** show historical RSLC at Newport for the gage's full record (1930-2021) and from 1983-2021, respectively. It is apparent that over long timescales (19 years) mean sea level is steadily increasing. However, over shorter time scales mean sea level may increase or decrease. The monthly mean sea level (light blue), for instance, goes up and down every year capturing the seasonal cycle in mean sea level. The 5-year moving average (orange) captures the interannual variation (2 or more years).

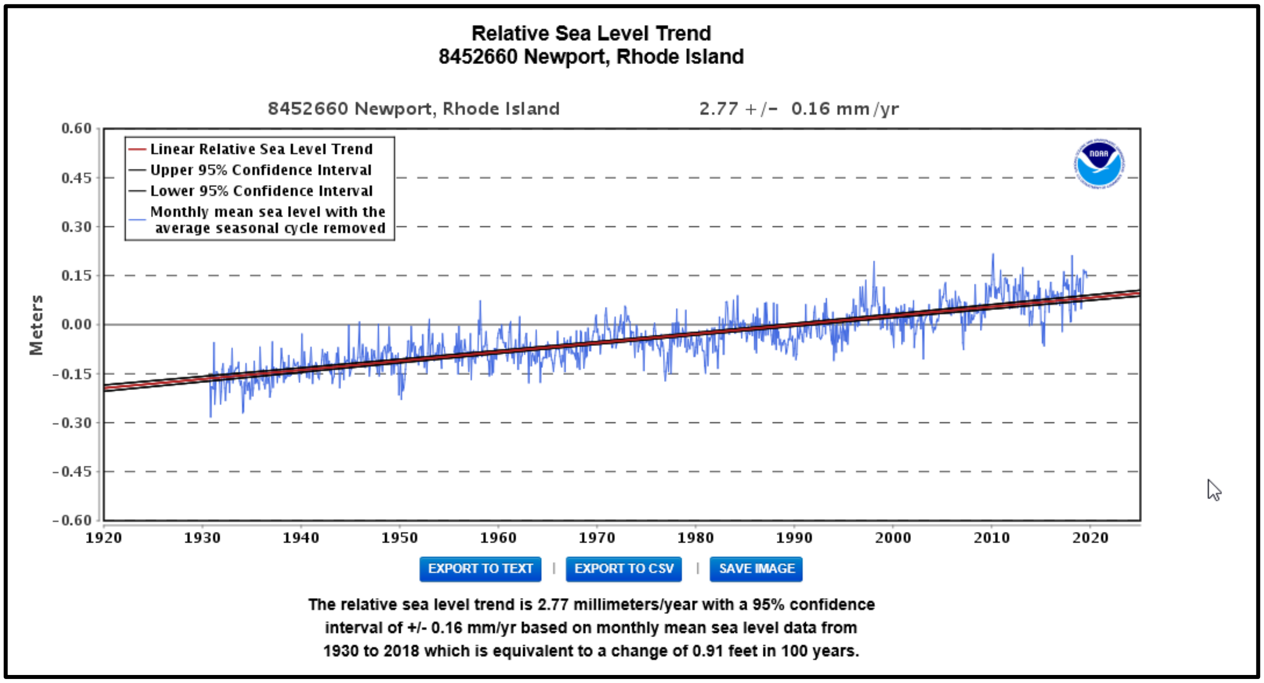

Figure B 4-1: Historical RSLC at Newport, RI NOAA tide gage

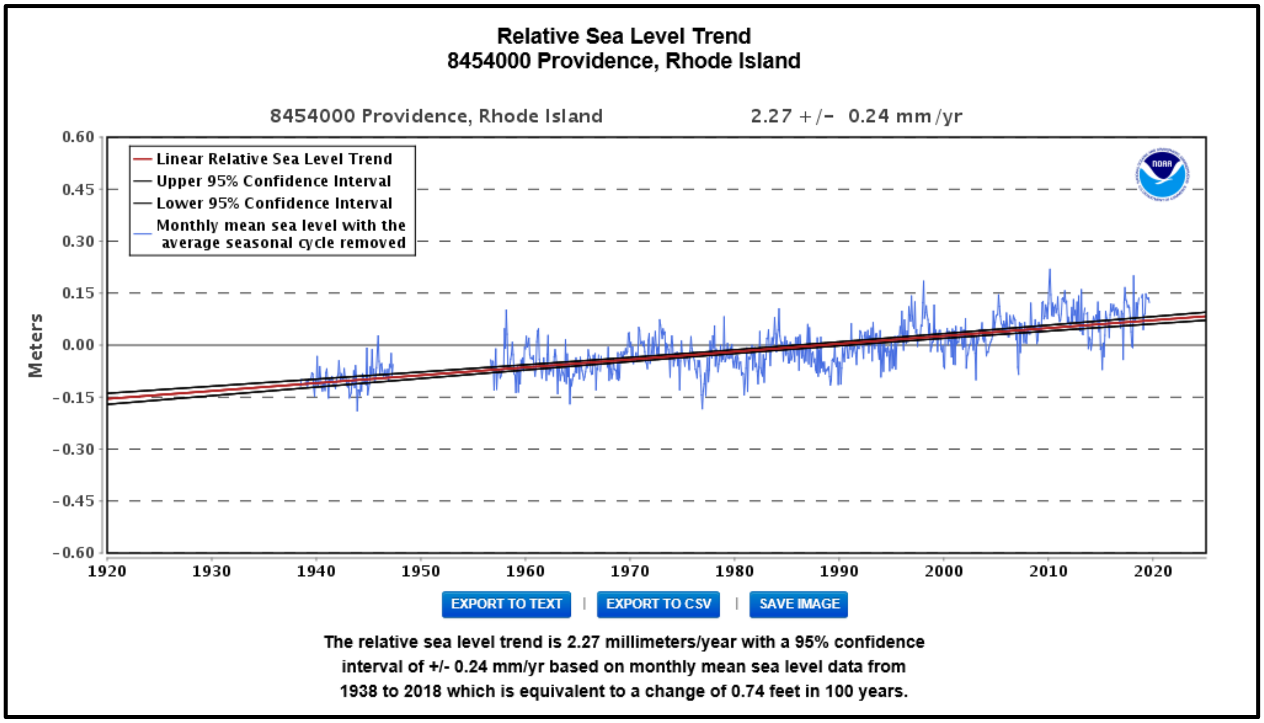

Figure B 4-2: Historical RSLC at Providence, RI NOAA tide gage

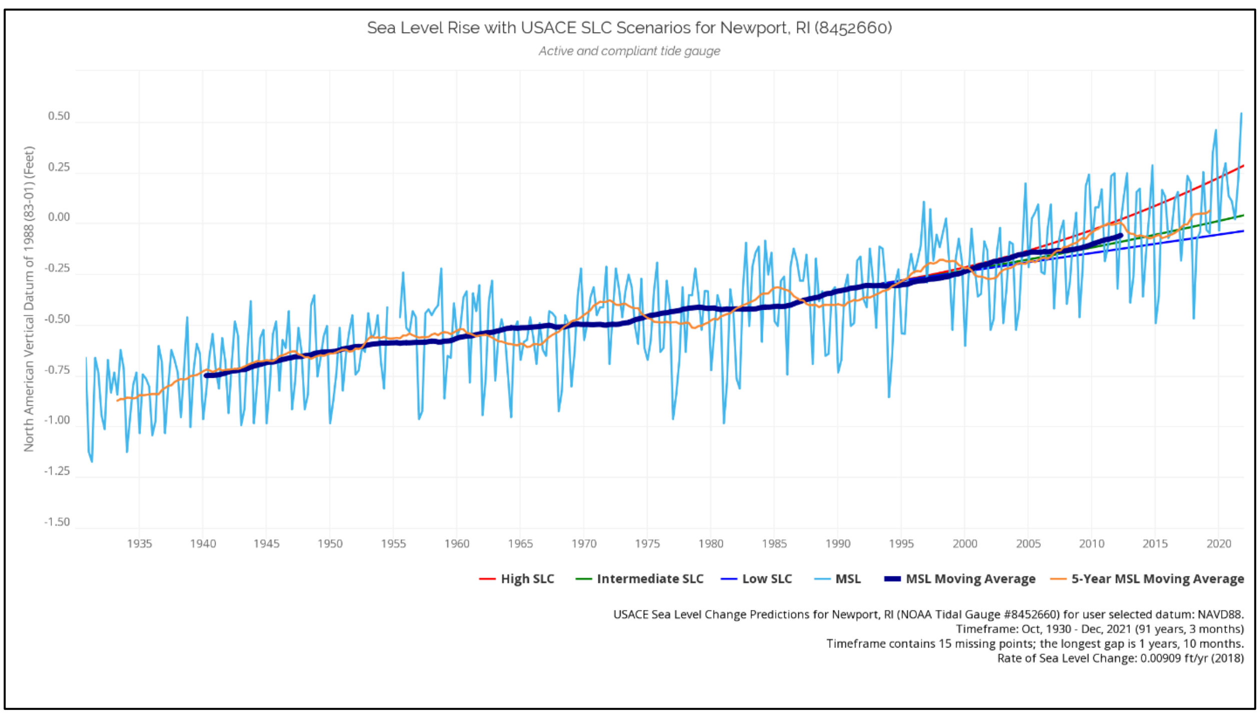

Figure B 4-3: Historical (1930-2021) RSLC at Newport, RI

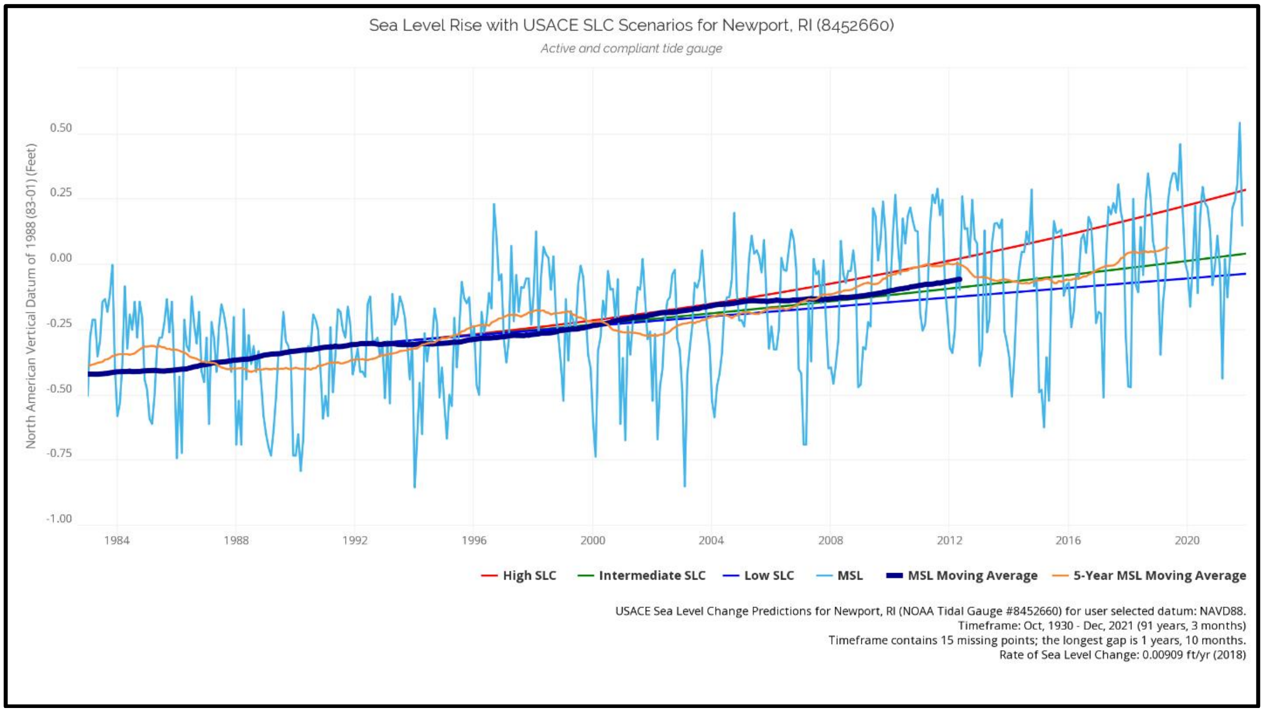

Figure B 4-4: Historical (1983-2021) RSLC at Newport, RI

4.4. USACE SLC Scenarios

USACE low, intermediate, and high SLC scenarios over the 100-year planning horizon at Newport, RI are presented in **Table B 4-1** and **Figure B 4-5**. Water level elevations at year 2030 are expected to be between 0.35 and 0.88 feet higher than the current NTDE. Water elevations at year 2080 are expected to be between 0.80 and 3.67 feet higher than the current NTDE.

Hydrodynamic modeling performed for the North Atlantic Coast Comprehensive Study (NACCS) and used in this study was completed in the current NTDE. Therefore, the modeled water levels represent MSL in 1992. Future water levels are determined by adding the SLC values in **Table B 4-1**. For example, a storm event with a peak water level of 10 feet NAVD88 based on the current NTDE (1983-2001), would be expected to produce a peak water level in the year 2080 of 10.80, 11.49 and 13.67 feet NAVD88 under the USACE low, intermediate, and high SLC scenarios, respectively.

Table B 4-1: USACE Sea Level Change Scenarios for Newport, RI

Newport, RI			
Year	**Low**	**Intermediate**	**High**
2030	0.35	0.47	0.88
2080	0.80	1.49	3.67
2130	1.25	2.95	8.31

All values are in feet relative to MSL, 1992

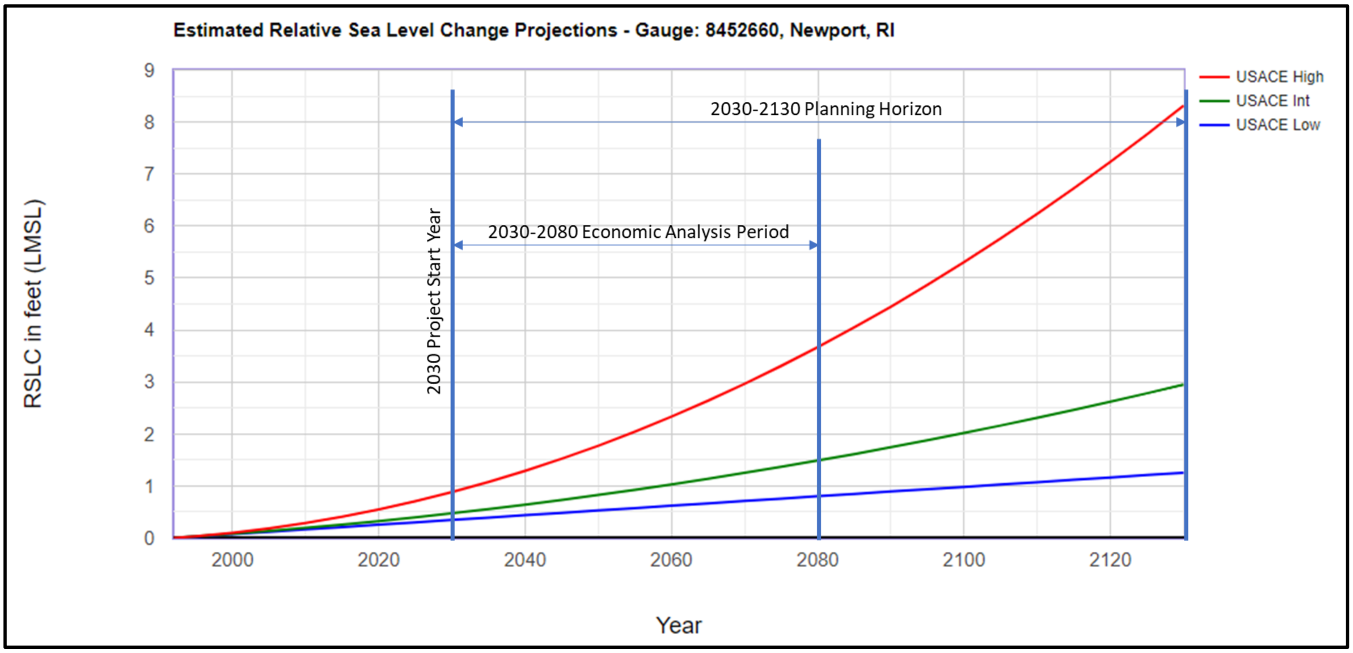

Figure B 4-5: USACE Sea Level Change Scenarios for Newport, RI

4.5. Rhode Island SLC Scenario

The Rhode Island Coastal Resources Management Council's (CRMC) sea level rise policy relies upon the high sea level change curve included in the most recent NOAA sea level rise data. CRMC developed the Rhode Island Shoreline Change Special Area Management Plan (SAMP, 2018) to tackle the need for comprehensive planning to address the impacts of storm surge, flooding, sea level change, and erosion. As detailed in the Shoreline Change SAMP, CRMC has adopted the NOAA (2017) high curve at the 83 percent confidence interval as the foundation of its sea level rise policy. From the year 2000, the NOAA high curve at the 83 percent confidence interval projects up to 9.6 feet of sea level rise in Rhode Island by 2100. CRMC has adopted the NOAA high curve and the 83 percent confidence interval, a worst-case scenario, for two reasons. First, NOAA (2017) recommended using the "worst-case" or "extreme" scenario to guide overall and long-term risk and adaptation. And second, CRMC views the use of worse-case scenarios as a way to hedge against the uncertainties inherent in projecting future sea level rise.

It is recognized that the NOAA 2017 high curve at the 83 percent confidence interval exceeds the USACE projections. The Rhode Island SLC scenario is discussed here for context but was not included in the feasibility study's alternative formulation and analysis process as this was not requested by the non-federal sponsor. However, regardless of the future scenario selected, coastal flooding is expected to increase as a result of sea level rise due to both nuisance (tidal) flooding and storm surge. Frequency and depth of coastal flooding are both expected to increase as sea level rise expands existing floodplains, causing flooding in places which have not previously experienced flooding, and resulting in deeper floodwaters in previously flooded areas.

5. EXISTING CONDITIONS

5.1. Astronomical Tide

Daily tidal fluctuations within the study area are semi-diurnal, with a full tidal period that averages 12 hours and 25 minutes; hence there are nearly two full tidal cycles per day. Tidal range generally increases from south to north within the study area and within Narragansett Bay. For instance, the mean tide range at Block Island and Newport is 2.85 and 3.46, respectively. At Providence, at the head of Narragansett Bay, the mean tide range is 4.42 feet.

The average seasonal cycle of mean sea level, shown in **Figure B 5-1**, is caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents and on average causes a 0.36-foot (0.11 m) difference in sea level from September (highest) to February (lowest).

Interannual (2 or more years) variations in sea level, shown in **Figure B 5-2**, are caused by irregular fluctuations in coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents (El Nino).

Seasonal and interannual variations in sea level can contribute to fluctuations in water levels within the study area.

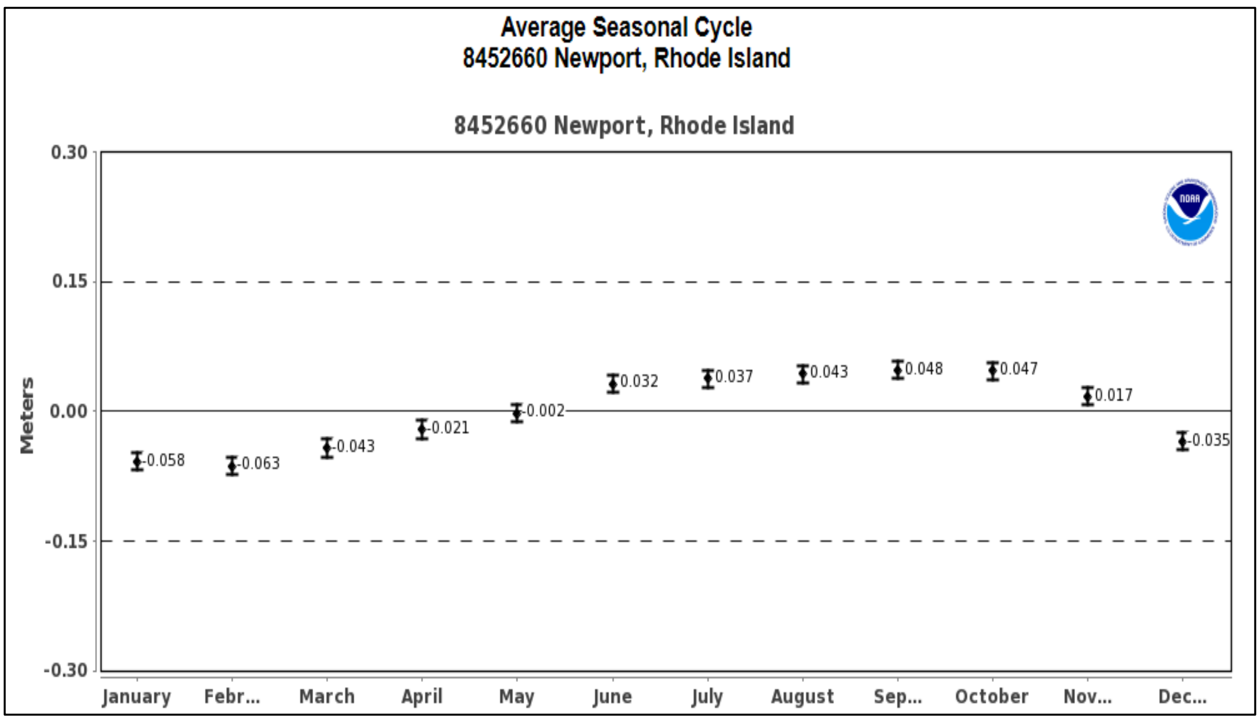

Figure B 5-1: Average seasonal cycle of mean sea level at Newport, RI

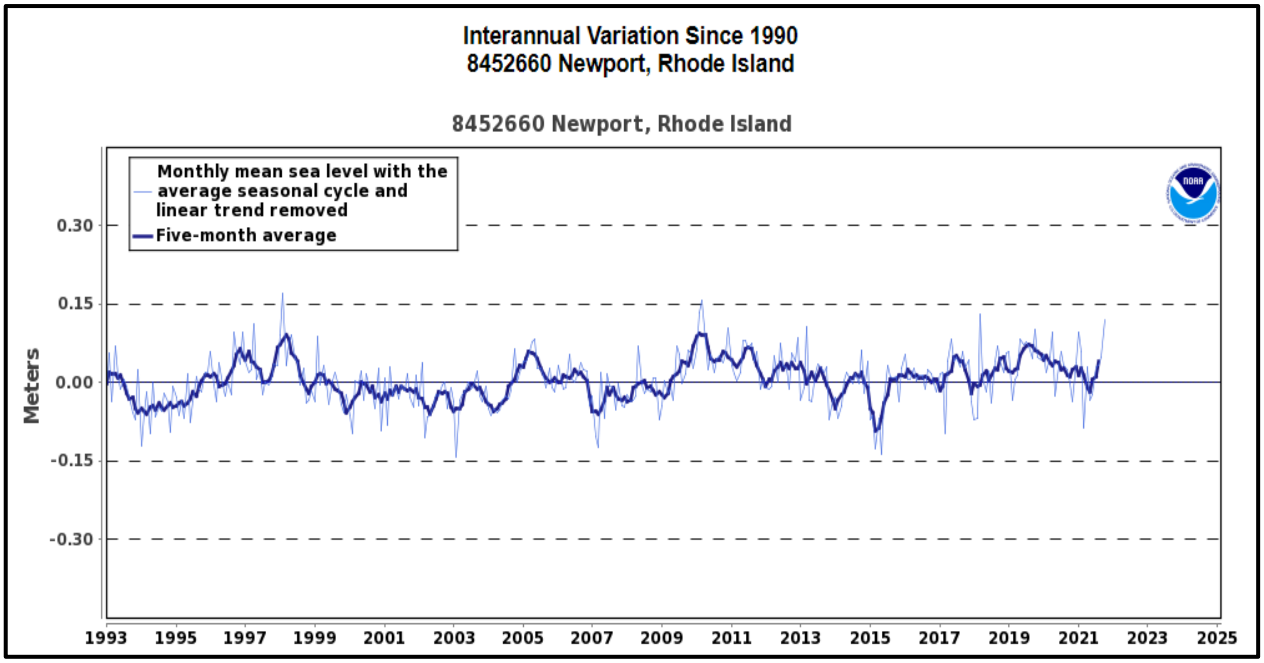

Figure B 5-2: Interannual variation in sea level at Newport, RI

5.2. Storm Surge

Storm surge is the increased water level above the predicted astronomical tide due to storm winds over the ocean and the resultant wind stress on the ocean surface. The principal factor that creates flood risk for the study area is storm surge generated by tropical and extratropical storms. The magnitude of the storm surge is calculated as the difference between the predicted astronomical tide elevation and the actual water surface elevation. Wind blowing over the ocean surface is capable of generating storm surge. However, the largest and most damaging storm surges develop as a result of either tropical cyclones (hurricanes and tropical storms) or extratropical cyclones ("nor'easters"). Although the meteorological origins of the two storm types differ, both can generate large, low-pressure atmospheric systems with intense wind fields that rotate counterclockwise (in the northern hemisphere). The relatively broad and shallow continental shelf along the east coast allows the generation of larger storm surges than are typically experienced on the U.S. Pacific coast where there is a narrower continental shelf. Analysis of storm surge levels within Rhode Island waters by Spaulding et al. (2015) showed that surge levels are approximately constant along the southern RI coastline and increase linearly with distance from the mouth to the head of the bay.

5.2.1. Historic Storms

The study area has experienced flooding from both tropical cyclones and extratropical cyclones. **Table B 5-1** displays the top ten historical storm tides at the Newport and Providence NOAA tidal stations. At both stations, tropical storms account for the highest historical water levels. However, extratropical storms also contribute significantly to the historical record. Note that the historical water levels have not been adjusted for sea level rise.

Table B 5-1: Top 10 recorded water levels at Newport and Providence

Newport, RI (since 1930)				Providence, RI (since 1938)			
Date	Name	Type	Feet NAVD88	Date	Name	Type	Feet NAVD88
21-Sep-38	Hurricane of 1938	T	11.27	21-Sep-38	Hurricane of 1938	T	15.04
31-Aug-54	Hurricane Carol	T	8.57	31-Aug-54	Hurricane Carol	T	13.93
29-Oct-12	Hurricane Sandy	T	6.13	14-Sep-44	1944 Great Atlantic Hurricane	T	8.24
19-Aug-91	Hurricane Bob	T	5.79	19-Aug-91	Hurricane Bob	T	7.61
14-Sep-44	1944 Great Atlantic Hurricane	T	5.77	9-Jan-78	Blizzard of 1978	ET	7.31
9-Jan-78	Blizzard of 1978	ET	5.15	29-Oct-12	Hurricane Sandy	T	6.89
31-Oct-91	1991 Perfect Storm	ET	5.08	12-Sep-60	Hurricane Donna	T	6.83
2-Dec-74	Unnamed	ET	5.02	30-Nov-63	Unnamed	ET	6.74
30-Nov-63	Unnamed	ET	4.97	27-Sep-85	Hurricane Gloria	T	6.68
10-Jan-97	Unnamed	ET	4.87	23-Jan-87	Unnamed	ET	6.65

Note: Type T denotes tropical storm event. Type ET denotes extratropical storm event.

5.2.2. National Weather Service Flood Stages

The National Weather Service (NWS) has established three coastal flood severity thresholds at the NOAA tidal stations within and in the vicinity of the study area: minor, moderate, and major flood stages. The definition of minor, moderate, and major flooding at each tidal station is provided in **Table B 5-2**.

Table B 5-2: National Weather Service flood stage definitions

Flood Categories (in feet, MLLW)	Providence	Conimicut Light	Fall River, MA	Quonset Point	Newport
Major Flood Stage	10.5	10.0	12.0	9.5	9.0
Moderate Flood Stage	9.0	8.5	9.5	7.5	7.5
Flood Stage	7.0	7.0	7.0	6.0	6.0
Action Stage	6.0	6.0	6.0	5.0	5.5
Flood Categories (in feet, NAVD88)	**Providence**	**Conimicut Light**	**Fall River, MA**	**Quonset Point**	**Newport**
Major Flood Stage	8.03	7.61	9.57	7.26	6.96
Moderate Flood Stage	6.53	6.11	7.07	5.26	5.46
Flood Stage	4.53	4.61	4.57	3.76	3.96
Action Stage	3.53	3.61	3.57	2.76	3.46

At each tidal station, NWS provides the following impacts which describe the present flood risk:

Newport:

- Flood Stage, Elevation 6.0 ft MLLW (3.96 ft NAVD88)—Minor coastal flooding occurs along the most vulnerable shoreline locales in Newport, Portsmouth and Middletown. This includes flooding at parking lots near beaches in Newport, and a portion of Hazard Road. Minor flooding also occurs on several streets in the Common Fence Point area.

- Elevation 6.5 ft MLLW (4.46 ft NAVD88)—Minor coastal flooding is expected in the lowest lying areas of Newport, Portsmouth and Middletown. A few immediate coastal roads briefly flood due to wave action. Minor coastal flooding occurs in the Common Fence Point area. A few parking lots adjacent to beaches are flooded in Newport.

- Elevation 7.0 ft MLLW (4.96 ft NAVD88)—Minor flooding can be expected across low lying areas of Newport, Middletown, and Portsmouth. Several immediate coastal roads will be impassable for a few hours around time of high tide. Minor beach erosion on the south side of Newport is possible.

- Major Flood Stage, Elevation 9.0 ft MLLW (6.96 ft NAVD88)—Widespread flooding is likely across coastal sections of Newport and Middletown. The combination of high tides and wave action may force evaluations of some lower lying areas. Alternate routes may be required as coastal roads become impassable.

Providence:

- Flood Stage, Elevation 7.0 ft MLLW (4.53 ft NAVD88)—Minor coastal flooding is expected in the lowest lying areas of Cranston and Warwick, from Sandy Point and Greenwich Bay northward. A few immediate coastal roads may briefly flood due to wave action.

- Elevation 8.0 ft MLLW (5.53 ft NAVD88)—Flooding of low-lying coastal areas can be expected over the West Bay from Wickford Cove north to areas in Providence that lie outside flood protection. Flooding will also impact portions of the Upper East Bay including Bristol, Barrington and communities along Mount Hope Bay northward through Somerset and Fall River. Some coastal roads will be impassable for a brief time nearest high tide.

- Moderate Flood Stage, Elevation 9.0 ft MLLW (6.53 ft NAVD88)—Significant coastal flooding is expected across Narragansett Bay and Mount Hope Bay. Some local evaluations may be required, and coastal roads will be flooded around the time of high tide. Marine interests should take necessary precautions to protect boats that are in port.

- Elevation 10 ft MLLW (7.53 ft NAVD88)—Flooding will be widespread across many Narragansett Bay communities and evacuations are likely for the period of a few hours around high tide. Flooding will impact Mount Hope Bay as well. Coastal roads will become impassable and alternate routes for travel will be required.

Conimicut Light:

- Flood Stage, Elevation 7.0 ft MLLW (4.61 ft NAVD88)—Minor coastal flooding is expected in the lowest lying areas of Warwick, Barrington, Bristol, and Warren. Low lying coastal roads flood around high tide. Floodwaters encroach on lowest lying homes and businesses.

- Elevation 8.0 ft MLLW (5.61 ft NAVD88)—Minor to moderate coastal flooding is expected within Warwick, Barrington, Bristol, and Warren. This includes low lying roads and some homes and businesses near shore. Heed the advice of local officials and evacuate if asked to do so.

- Elevation 9.0 ft MLLW (6.61 ft NAVD88)—Moderate to major flooding is expected in the vicinity of Warwick, Barrington, Bristol, and Warren. This includes but is not limited to the following. In Warwick, flooding occurs in and around Oakland Beach, Strand Ave, Goddard Memorial State Park, and Sandy Point. In Bristol, impacts occur in the vicinity of Bristol Harbor, Route 114, Colt State Park, and the East Bay Bike Path. In Barrington and Warren, flooding occurs along the Warren and Barrington Rivers, near Belchers Cove and the Kickemuit River.

- Major Flood Stage, Elevation 10 ft MLLW (7.61 ft NAVD88)—Major coastal flooding is expected in Warwick, Bristol, Barrington, and Warren. Numerous homes, businesses, and roadways near the coastline will be impacted by this event. In Warwick, flooding occurs in and around Oakland Beach, Strand Ave, Goddard Memorial State Park, and Sandy Point. In Bristol, impacts occur in the vicinity of Bristol Harbor, Route 114, and Colt State Park. In Barrington and Warren, flooding occurs along the Warren and Barrington Rivers, near Belchers Cove and the Kickemuit River.

Quonset Point:

- Flood Stage, Elevation 6.0 ft MLLW (3.76 ft NAVD88)—Minor coastal flooding occurs on vulnerable shore roads in North Kingstown.

- Elevation 7.0 ft MLLW (4.76 ft NAVD88)—Flooding of low-lying coastal areas can be expected in the vicinity of North Kingstown, East Greenwich, and Prudence Island. Some evacuations are possible. Some coastal roads will be impassable for a period of time nearest high tide.

- Elevation 8.0 ft MLLW (5.76 ft NAVD88)—In East Greenwich, flooding occurs to some marinas in Greenwich Cove. In North Kingstown, flooding occurs in lowest lying homes and businesses along Shore Acres and Quonset Point. Flooding occurs along Plum Beach and in nearshore buildings along Plum Point. Inundation of low-lying businesses and streets occurs near Wickford Harbor, Wickford Cove, and Duck Cove. On Prudence Island, flooding occurs along portions of Neck Farm Road.

- Elevation 9.0 ft MLLW (6.76 ft NAVD88)—Moderate to major coastal flooding is expected in North Kingstown, East Greenwich, and Prudence Island. In East Greenwich, flooding occurs to some marinas in Greenwich Cove. In North Kingstown, flooding occurs in low lying homes and businesses along Shore Acres and Quonset Point. Flooding occurs along Plum Beach and in nearshore building along Plum Point. Inundation of low-lying buildings and streets occurs near Wickford Harbor, Wickford Cove, and Duck Cove. On Prudence Island, flooding occurs on Neck Farm Road.

- Elevation 10 ft MLLW (7.76 ft NAVD88)—Major flooding is expected in the vicinity of North Kingstown, Prudence Island, and East Greenwich. Flooding of numerous homes, businesses and roadways are expected. Heed the advice of local officials and evacuate if asked to do so.

Fall River:

- Flood Stage, Elevation 7.0 ft MLLW (4.57 ft NAVD88)—Minor coastal flooding occurs around the time of high tide along the most vulnerable shore roadways in the vicinity of Tiverton, Fall River, Somerset, and Swansea. If heavy rainfall accompanies this event, significant poor drainage flooding could occur near shore.

- Elevation 8.0 ft MLLW (5.57 ft NAVD88)—Minor coastal flooding is expected on low lying roadways and some structures in the vicinity of Fall River, Somerset, Swansea, and Tiverton. Flooding begins to encroach on buildings on Delano’s Island in Tiverton. If heavy rainfall accompanies this event, significant poor drainage flooding could occur near shore.

- Elevation 9.0 ft MLLW (6.57 ft NAVD88)—Flooding occurs in Swansea, Fall River, Somerset, and Tiverton, including some area roadways, vulnerable residences and businesses in the region. In Tiverton, marinas and other buildings are flooded along portions of Riverside Drive. Flooding also occurs along homes on Delano’s Island within Nannaquaket Pond. A portion of Main Road becomes inundated. In Swansea, Route 6 becomes flooded and impassable. In Fall River, Battleship Cove is flooded.

- Elevation 10 ft MLLW (7.57 ft NAVD88)—Coastal flooding is expected in the greater vicinity of Fall River, Tiverton, Swansea and Somerset, including some nearshore roadways, residences and businesses. In Tiverton, marinas and other buildings are flooded along portions of Riverside Drive. Flooding also occurs along homes on Delano’s Island within Nannaquaket Pond. A portion of Main Road becomes inundated. In Swansea, Route 6 becomes flooded and impassable. In Fall River, Battleship Cove is flooded.

- Major Flood Stage, Elevation 12 ft MLLW (9.57 ft NAVD88)—Major coastal flooding is expected in the vicinity of Fall River, Somerset, Swansea, and

Tiverton. This includes shoreline roads and nearshore homes and businesses. Heed the advice of local officials and evacuate if asked to do so.

5.2.3. NACCS

The North Atlantic Coast Comprehensive Study (NACCS) was authorized under the Disaster Relief Appropriations Act, P. 113-2, in response to Superstorm Sandy. The Act provided the USACE up to $20 million to conduct a study with the goal to (1) reduce flood risk to vulnerable coastal populations, and (2) promote resilient coastal communities to ensure a sustainable and robust coastal landscape system, considering future sea level change and climate change scenarios.

As part of the NACCS, the U.S. Army Engineer Research and Development Center (ERDC) completed a coastal storm wave and water level modeling effort for the U.S. North Atlantic coast from Virginia to Maine. This modeling study provided nearshore wind, wave, and water level estimates and the associated marginal and joint probabilities critical for effective coastal storm risk management. This modeling effort involved the application of a suite of high-fidelity ADCIRC and STWAVE numerical models within the Coastal Storm Modeling System (CSTORM-MS) to 1050 synthetic tropical storms and 100 historical extratropical storms. Documentation of the numerical modeling effort is provided in Cialone et al. (2015) and documentation of the statistical evaluation is provided in Nadal-Caraballo et al. (2015). Products of the study are available for viewing and download on the Coastal Hazards System (CHS) website: https://chs.erdc.dren.mil/.

Based on data developed by the NACCS, significant tropical storm events impacted the Rhode Island coastline area at a frequency of approximately once every 5.75 years. These tropical storms occur between June and November with 74 percent of the storms occurring in the months of August and September.

Extratropical storms, on the other hand, are a more frequently occurring storm type that impacts the study area annually with significant events occurring at a rate of approximately one storm per year. Extratropical storms typically occur at the project area between early fall through the spring (October through May) with most occurring in the months of November through February.

Tropical storm events are typically fast-moving storms associated with elevated water levels and large waves whereas extratropical storms are slower moving with comparatively lower water level elevations and large wave conditions. Both storm types can produce erosion and morphology change, as well as coastal inundation, leading to economic losses to property within the study area.

5.2.4. NACCS Water Levels

NACCS water levels were used directly as coastal forcing inputs to RI Coastline study. Through ERDC's CHS, NACCS water level and wave outputs are provided at save points throughout the study area as both annual exceedance probabilities and storm timeseries. **Figure B 5-3** depicts the 1-percent annual exceedance probability (AEP) water levels at the mean confidence level at the save points within the study area. The amplification in storm surge from south to north within Narragansett Bay is evident.

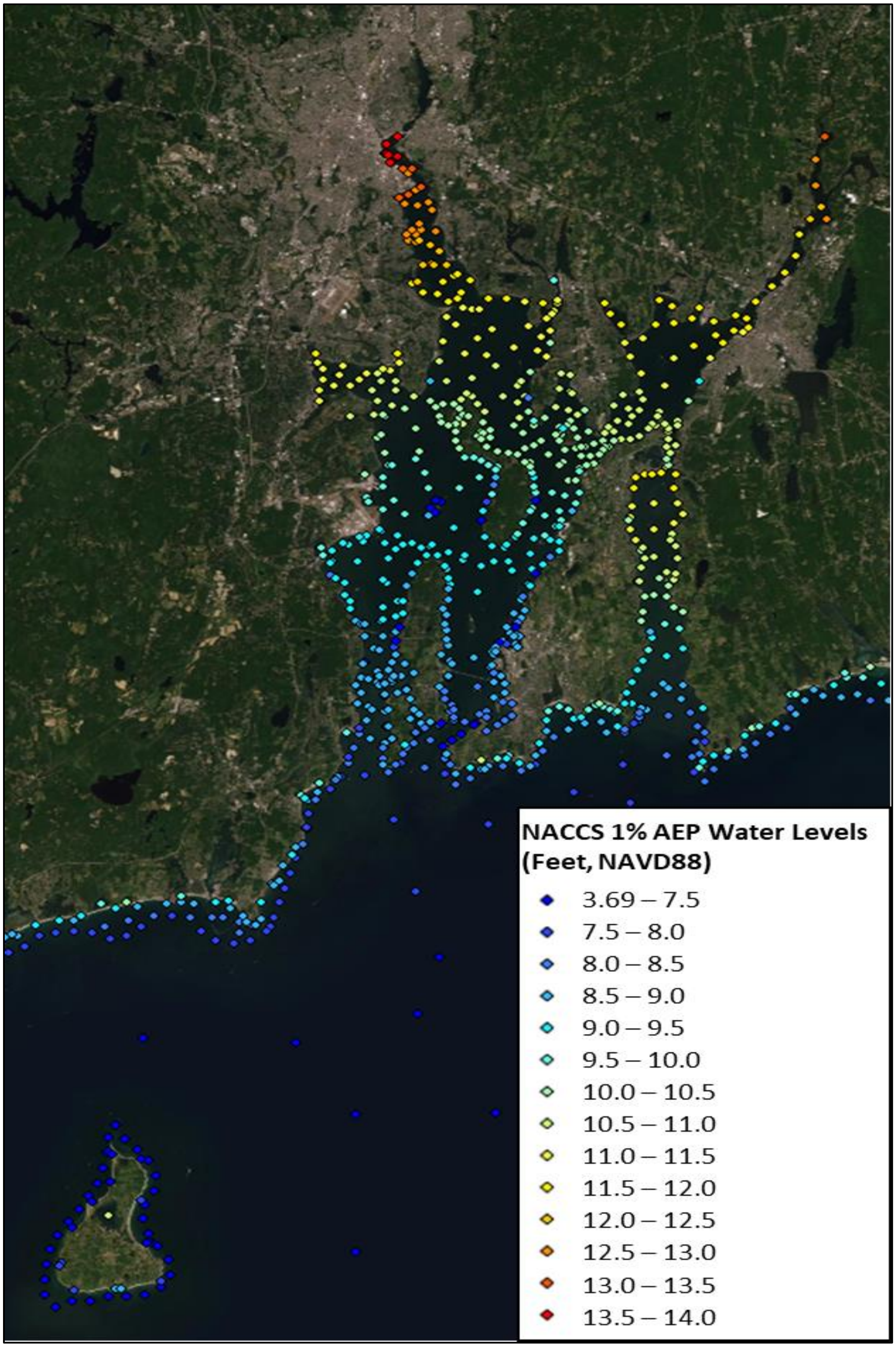

Figure B 5-3: NACCS 1-percent AEP water levels in feet, NAVD88

The study area was discretized into regions known as model areas for the Generation II Coastal Risk Model (G2CRM) economic modeling. This discretization was based on the NACCS 1-percent AEP water levels, study area topography, and flood sources. Within each model area, the 1-percent AEP water levels were within 1 foot of one another. A representative NACCS save point was selected for use in the G2CRM model to represent each model area. The 1-percent AEP water level at each representative save point was at the approximate midpoint of the 1-percent AEP water level range in each model area such that all 1-percent AEP water levels within a model area were within 0.5 feet of the 1-percent AEP water level at the representative save point. This approach balanced uncertainty in water level application within each model area without overly discretizing the study area appropriate for a planning feasibility study. The model areas and representative save points are shown in **Figure B 5-4**.

Mean and 90% confidence limit AEP water levels for the current NTDE are provided in **Table B 5-3** and **Table B 5-4**, respectively. While the G2CRM economic model uses timeseries water levels, the AEP water levels were used to define the study area and to formulate alternatives.

Figure B 5-4: Study area discretization and representative save points

Table B 5-3: NACCS mean AEP water levels by model area

MODEL AREA	NACCS ADCIRC SAVE POINT	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
Block Island	447	4.05	4.79	5.32	5.82	6.51	7.10	7.82	8.95
Bristol	8710	4.93	5.84	6.65	7.65	9.26	10.56	11.91	13.75
Cranston	180	5.21	6.32	7.42	8.85	10.96	12.59	14.27	16.44
Greenwich Bay	8561	5.04	6.10	7.02	8.11	9.84	11.31	12.85	14.85
Little Compton	1152	4.22	4.98	5.58	6.24	7.33	8.38	9.52	11.00
Mount Hope Bay	8662	5.06	6.04	6.96	8.19	10.07	11.49	12.92	14.86
Narragansett	203	4.34	5.19	5.87	6.59	7.65	8.64	9.80	11.35
Newport	10282	4.55	5.35	5.97	6.63	7.58	8.46	9.49	10.86
Providence	8603	5.37	6.56	7.77	9.39	11.75	13.56	15.42	17.78
Sakonnet Mid	10403	4.70	5.66	6.50	7.52	9.17	10.48	11.87	13.72
Sakonnet North	8730	6.34	7.36	8.46	9.94	11.95	13.39	14.86	16.86
Sakonnet South	8735	4.43	5.28	6.02	6.87	8.20	9.34	10.57	12.22
Warren	8626	5.00	6.00	6.96	8.20	10.05	11.52	13.03	14.98
Wickford	202	4.65	5.57	6.31	7.09	8.28	9.40	10.66	12.25

All values in feet, NAVD88, MSL 1992

Table B 5-4: NACCS 90% confidence limit AEP water levels by model area

MODEL AREA	NACCS ADCIRC SAVE POINT	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
Block Island	447	5.92	6.59	7.14	7.71	8.54	9.30	10.22	11.40
Bristol	8710	6.87	7.76	8.68	9.94	11.73	13.04	14.39	16.23
Cranston	180	7.16	8.25	9.54	11.23	13.45	15.09	16.77	18.94
Greenwich Bay	8561	6.96	8.00	9.06	10.41	12.33	13.82	15.36	17.36
Little Compton	1152	6.13	6.84	7.51	8.36	9.75	10.85	11.99	13.48
Mount Hope Bay	8662	7.01	7.96	9.03	10.54	12.56	13.98	15.42	17.35
Narragansett	203	6.24	7.03	7.80	8.68	9.95	11.06	12.27	13.82
Newport	10282	6.46	7.22	7.91	8.73	9.92	10.91	11.96	13.32
Providence	8603	7.31	8.49	9.92	11.82	14.26	16.08	17.94	20.30
Sakonnet Mid	10403	6.62	7.56	8.55	9.84	11.64	12.96	14.34	16.19
Sakonnet North	8730	6.77	7.78	8.92	10.47	12.50	13.93	15.41	17.41
Sakonnet South	8735	6.35	7.18	8.01	9.07	10.63	11.81	13.05	14.70
Warren	8626	6.95	7.93	9.04	10.53	12.52	14.01	15.51	17.47
Wickford	202	6.57	7.44	8.27	9.24	10.67	11.87	13.13	14.73

All values in feet, NAVD88, MSL 1992

5.3. Waves

The wave pattern in Rhode Island coastal waters is quite complicated due to the complex bathymetry and associated refraction and diffraction in the vicinity of Block Island Sound. Historically there have been no observations of waves in Rhode Island Sound and Narragansett Bay. The bay has a relatively low wave energy environment given the shallow water. Wave modeling predicts large waves at the mouth of the bay decrease dramatically upon entering the bay as the shallow water in the bay induces dissipation by friction for the longer waves as well as wave breaking limiting the wave energy propagating in the bay. However, southerly winds can provide enough fetch to create local short waves which can grow significantly in the upper part of the bay, although they too are limited by whitecapping. South facing coastlines are typically exposed to the largest wave heights.

Offshore, USACE maintains a wave buoy 25 miles southeast of Block Island (NDBC 44097) with records from 2009. USACE has also performed wind and wave hindcast in the Wave Information Study (WIS) for selected locations off the coast from 1980 to 2014. The nearest WIS site to the coast and directly east of Block Island is # 63079 in 33 m (108.3 ft) of water. The annual mean significant wave height at this point averages 1.0 m (3.3 ft), varying from 0.5 to 1.6 m, and the annual mean peak period averages 8 seconds, varying between 5 and 11 seconds. Waves predominantly approach from the south and south-southeast. The 1-percent AEP significant wave height at this station is estimated to be 9.7 m (30.8 ft) with a peak period of 17 seconds. During Superstorm Sandy, the significant wave height at this location was hindcast to be 8.6 m (28.3 ft) with a peak period of 15 seconds from the southeast.

The NACCS modeling effort also provided time series and extreme value statistical wave output at the same save points as the storm surge data described above. Compared to the WIS hindcast, the NACCS data generally show slightly higher wave heights and longer periods at the 1-percent AEP. Expected value AEP wave heights in feet at eight frequencies are provided in

Table B *5-5* at the representative save points by model area.

Table B 5-5: NACCS AEP wave heights in feet by model area

MODEL AREA	NACCS STWAVE SAVE POINT	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
Block Island	150	16.1	19.8	21.9	23.4	25.1	26.0	26.7	27.6
Bristol	1596	3.1	3.6	4.0	4.4	4.9	5.2	5.5	5.9
Cranston	81	2.9	3.4	3.7	3.9	4.3	4.5	4.9	5.4
Greenwich Bay	1449	3.0	3.6	3.9	4.2	4.5	4.8	5.1	5.7
Little Compton	611	17.4	21.5	23.0	24.0	25.1	26.0	26.8	27.7
Mount Hope Bay	1548	3.2	3.7	4.0	4.2	4.5	4.8	5.0	5.4
Narragansett	104	15.0	16.7	17.7	18.4	19.0	19.3	19.6	20.2
Newport	2485	2.7	3.0	3.3	3.5	3.9	4.1	4.4	4.8
Providence	1489	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.2
Sakonnet Mid	2606	3.6	4.4	4.9	5.4	6.0	6.4	6.8	7.2
Sakonnet North	1616	3.3	3.8	4.2	4.7	5.2	5.6	5.9	6.4
Sakonnet South	1621	9.5	11.9	13.6	14.9	16.6	17.6	18.4	19.5
Warren	1512	2.6	2.8	3.0	3.1	3.3	3.5	3.7	3.9
Wickford	103	4.0	4.7	5.1	5.3	5.6	5.7	5.9	6.3

6. G2CRM MODELING

The Generation II Coastal Risk Model (G2CRM) is a computer model that implements an object-oriented Probabilistic Life Cycle Analysis (PLCA) model using event-driven Monte Carlo Simulation. This allows for incorporation of time-dependent and stochastic event-dependent behaviors such as sea level change, tide, and structure raising and removal. The model is based on driving forces (storms) that affect a coastal region (study area). The study area is comprised of individual sub-areas of different types that may interact hydraulically and may be protected by coastal defense measures that serve to shield the areas and the assets they contain from storm damage (USACE, 2018b). To determine the damages for a specific event and time, G2CRM compares the total water level (sum of storm surge, tide, SLC, and potential wave inputs) to asset first floor elevations within Future Without Project (FWOP) or Protective System Element (PSE) elevations and then first floor elevations within the Future With Project (FWP) condition. G2CRM consists of multiple engineering inputs to accurately represent the study area which are described in the sections below. See the **Appendix C**, *Economic and Social Considerations* for more information regarding the development of the G2CRM economic inputs.

6.1. Digital Elevation Model

A Digital Elevation Model (DEM) consists of arrays of regularly spaced land surface elevation values referenced to a horizontal reference datum. The elevation data for the study area was derived from the 2016 USGS CoNED Topobathymetric Model which integrates disparate light detection and ranging (LiDAR) and bathymetric data sources into a common database aligned both vertically and horizontally to a common reference system. The cell size of the DEM is 1 meter. The vertical accuracy of the input topographic data varies due to multiple input sources for the model. Because the input elevation data were derived primarily from LiDAR, the vertical accuracy ranges from 15 to 20 centimeters (.5 to .6 feet) in root mean square error (RMSE).

6.2. Model Areas

Model areas (MAs) are areas that comprise the overall study area. The water level in the modeled area is used to determine consequences to the assets contained within the area (USACE, 2018b). The study area was divided into MAs based on similar storm surge values at the 1-percent annual exceedance probability and flood source. The DEM was used to determine separability of flood sources where inundation occurred from multiple sources. **Figure B 5-4**, displayed above, shows the location of the fifteen MAs.

6.3. Protective System Elements

A protective system element (PSE) is the infrastructure that defines the coastal boundary; be it a coastal defense system that protects the modeled areas from coastal flooding (levees, pumps, closure structures, etc.) or a locally developed coastal boundary comprised of bulkheads and/or hardened shoreline (USACE, 2018b). PSEs were applied in MAs where structural measures such as closure structures and floodwalls were considered in the FWP. Within the FWOP, the top elevation of the PSE was set equal to the lowest ground elevation along the PSE. Within the FWP, the top elevation of the PSE corresponded to the selected design elevation.

G2CRM contains two types of PSEs: bulkheads and flood barriers. The bulkhead PSE was used for structural measures such as levees and floodwalls. The flood barrier PSE was employed where surge barrier systems were evaluated. In addition to specifying a top elevation for each PSE, the flood barrier PSE also requires inputting a closure threshold to define the water level necessary to deploy the flood barrier. If the closure threshold is exceeded during a storm event, the barrier is closed and protects the assets in the interior up to the top elevation of the PSE. Anticipating sea level change, the closure threshold for surge barriers was set to 5 ft NAVD88. This value was based off a 2080 MHHW of 3.86 feet NAVD88 under the intermediate sea level change scenario plus a buffer of approximately 1 foot to ensure that the closure structures would not need to operate daily to protect against tidal flooding within the 50-year economic period of analysis.

6.4. Meteorological Driving Forces

Meteorological driving forces are location-specific storm hydrographs (surge and waves) which are generated externally from high fidelity storm surge and nearshore wave models such as ADCIRC and STWAVE (USACE, 2018b). Additionally, the number of storms per year and relative storm probability are incorporated into G2CRM and further described below.

6.4.1. Storm Hydrographs

Storm hydrographs from the NACCS coupled ADCIRC and STWAVE models were used to force the G2CRM model. ADCIRC is a two-dimensional hydrodynamic model that conducts short- and long-term simulations of tide and storm surge elevations and velocities in deep-ocean, continental shelves, coastal seas, and small-scale estuarine systems. ADCIRC uses the finite element method to solve the reformulated, depth-averaged shallow water equations. The model runs on a triangulated mesh with elevations derived from a seamless bathymetric/topographic DEM that includes both offshore and overland areas. The triangulated format of the mesh allows variation in the element size, so the study area can have a high concentration of nodes while fewer nodes (with higher element areas) can be placed farther away to make the mesh more efficient without compromising accuracy. STWAVE is a steady-state, finite difference, spectral model based on the wave action balance equation. Using the Coastal Storm Modeling System (CSTORM-MS), the ADCIRC and STWAVE models are two-way coupled.

For each MA, storms were sampled from the NACCS suite of 1050 synthetic tropical storms using a radius of 200 km about each model area save point. This storm sampling resulted in a range of 469 to 495 tropical storms per model area. In addition to the sampled tropical storms, the 100 historical extratropical storms from the NACCS were included in the storm suite for each MA, resulting in a total of 569 to 595 storms per model area. The number of storms sampled for each MA is provided in

Table B *6-1*.

Table B 6-1: G2CRM storm and tide station information by model area

MODEL AREA	NACCS STWAVE SAVE POINT	# of Storms Sampled (Tropical Storms (Total Including 100 Historical Extratropical Storms))	Tide Station (NOAA Station ID)
Block Island	150	495 (595)	Block Island, RI (8459338)
Block Island Great Salt Pond	150	495 (595)	Block Island, RI (8459338)
Bristol	1596	475 (575)	Bristol, Bristol Harbor, RI (8451929)
Cranston	81	474 (574)	Providence, RI (8454000)
Greenwich Bay	1449	469 (569)	East Greenwich, RI (8454578)
Little Compton	611	483 (583)	Sakonnet, RI (8450768)
Mount Hope Bay	1548	475 (575)	Fall River, MA (8447386)
Narragansett	104	484 (584)	Narragansett Pier, RI (8454658)
Newport	2485	478 (578)	Newport, RI (8452660)
Providence	1489	468 (568)	Providence, RI (8454000)
Sakonnet Mid	2606	488 (588)	TS1: Sakonnet, RI (8450768) TS2: Anthony Point, RI (8450948) TS1 Interpolation Factor: 0.66
Sakonnet North	1616	475 (575)	Anthony Point, RI (8450948)
Sakonnet South	1621	483 (583)	Sakonnet, RI (8450768)
Warwick	1512	476 (576)	Warren, Narragansett Bay, Rhode Island
Wickford	103	475 (575)	Wickford, Narragansett Bay, RI (8454538)

6.4.2. Wave Generation

G2CRM can represent wave hazards through several approaches. First, if wave model data is available through STWAVE, it can read in the wave information as is. Second, if wave data is not available, it can generate wave heights using a depth-limited wave assumption whereby the wave height will be 0.78 times the water depth. The third approach is to use the wave model data but apply depth-limitation if the STWAVE wave height exceeds the depth-limited wave height. This third approach was used throughout the study area, with STWAVE model output applied directly to all model areas with depth-limitation applied as applicable.

No adjustments were made to the STWAVE model output, with the exception of the Block Island Great Salt Pond MA. While the NACCS modeling has a save point in Great Salt Pond, output at this save point was questioned after review of the ADCIRC and STWAVE grids in the vicinity of Great Salt Pond revealed that the mesh resolution was not refined enough to capture the hydrodynamics within Great Salt Pond. Therefore, an open coast save point was selected to represent the storm surge within Great Salt Pond and a wave adjustment factor of 0.6 was applied to adjust the open coast wave height. This adjustment factor was based off review of the effective FEMA floodplain mapping and a fetch-limited wind wave growth analysis. The FEMA mapping showed VE flood zones along segments of the Great Salt Pond shoreline, indicating the potential for wave heights of at least 3 feet to occur during a 1-percent AEP event. Separately, the fetch-limited wave growth analysis estimated wave heights of approximately 3.5 feet could be generated by a wind speed of 80 miles per hour over a 1.4-mile fetch. The 3.5-foot wave height for the Pond was compared to output from G2CRM for the maximum wave height applied to the Block Island MA of 6.1 feet to obtain the wave adjustment factor of 0.6 used in the Block Island Great Salt Pond MA.

6.4.3. Storms Per Season

To determine the storm event generation, G2CRM first selects the tropical and extratropical events to occur through each season within the year. This study implemented two storm seasons within each year: June through November as the tropical storm season and October through May as the extratropical storm season. G2CRM then uses the Poisson distribution to randomly select the number of storms that occur within each season based on the predetermined average number of storms in a season input. The average number of storms per season was determined based on output from the NACCS. summarizes the season definitions and average number of storms per season.

6.4.4. Relative Storm Probability

After G2CRM selects the number of storms occurring in each season the model then chooses which storms will occur in each season by randomly selecting storms out of the available storm suite using bootstrap sampling with replacement (higher probability storms are chosen more often). Relative storm probabilities were taken from the NACCS storm recurrence rates.

6.4.5. Tide Stations

The nearest hydraulically similar tidal prediction station was applied to each model area. Two tidal prediction stations were selected for the Sakonnet Mid model area with a weighted interpolation applied. The tide station assignments by model area are shown in

Table B *6-1*.

6.4.6. Sea Level Change Rate and Curve

The study implemented a sea level change rate of 2.77 mm/year (0.00909 feet/year) based on the MSL trend at Newport, RI tidal station 8452660. G2CRM requires the selection of a SLC curve. The USACE low, intermediate, or high SLC curves can be calculated within the model or a custom SLC curve can be applied. The USACE intermediate scenario was selected for alternative formulation and evaluation prior to the Tentatively Selected Plan (TSP) milestone. Following the TSP, the PDT will run the low and high SLC curves within G2CRM to evaluate the TSP's performance under alternate SLC scenarios.

Table B 6-2: Storms per season

Season Description	Season Type	Average Storms per Season
Trop Season June	Tropical	0.00703856
Trop Season July	Tropical	0.00703856
Trop Season August	Tropical	0.04575064
Trop Season September	Tropical	0.08446272
Trop Season October	Tropical	0.02111568
Trop Season November	Tropical	0.01055784
Etrop Season October	Extratropical	0.146666667
Etrop Season November	Extratropical	0.213333333
Etrop Season December	Extratropical	0.293333333
Etrop Season January	Extratropical	0.226666667
Etrop Season February	Extratropical	0.2
Etrop Season March	Extratropical	0.16
Etrop Season April	Extratropical	0.08
Etrop Season May	Extratropical	0.013333333

6.4.7. Stage-Volume Input

G2CRM has an optional data import tool for stage-volume relationships, which is used to represent internal ponding within a model area. If a stage-volume relationship is not employed, G2CRM will instantaneously transmit the stage when it exceeds the input PSE top elevation into the model area. To more accurately represent the coastal flooding within a model area with a PSE in place, G2CRM has an option to use the weir equation to calculate a time-dependent volume transmitted into the model area until the storage capacity within the model area is filled, after which G2CRM transitions back to transmitting the stage unmediated into the model area. Stage-volume relationships were created using the DEM to determine the volume within each model area in relation to various stage elevations where structural measures such as storm surge barriers and floodwalls were considered. By establishing these stage-volume relationships, the coastal flooding within a model area protected by a PSE could be better represented.

7. STUDY MEASURES

The Future Without Project (FWOP) results indicate that coastal storm events, along with tides, will continue to cause socioeconomic impacts within the study area. These impacts are expected to increase in frequency due to sea level change. Therefore, measures were considered to reduce these impacts with a focus on the twelve problem areas identified in the initial scoping meetings held with the non-federal sponsor and the municipalities within the study area. Measures were evaluated considering scale, combinability of measures, and sound engineering design and practice. Structural, nonstructural, and natural and nature-based features (NNBF) measures were considered to reduce impacts from coastal flooding and wave attack. Reference the main report for additional detail on the various measures and screenings conducted prior to engineering analysis and design.

7.1. Levee

Levees are embankments constructed along a waterfront to prevent flooding in relatively large areas. They are typically constructed by compacting soil into a large berm that is wide at the base and tapers toward the top, forming a trapezoidal cross section. Grass or another non-woody vegetation is usually planted on the levee to add stability to the structure. If a levee is located in an area where it may be subject to erosive forces, it may be necessary to armor the levee slope with a more protective rock face. A typical levee is shown in **Figure B 7-1**. Levees may be constructed in urban areas or coastal areas; however, large tracts of real estate are usually required due to the levee width and required setbacks. The height and width usually limit access to the water for recreation and commercial activities, and like floodwalls, impact the viewshed of coastal properties. In some cases, levees have been incorporated into trail systems with a path on the crest. Structural measures, such as floodwalls, levees and dikes tend to trap rainfall runoff associated with storms on the landward side, creating a residual flooding risk. To reduce this residual risk, gravity outlets are installed along the length of the structure. In cases where significant runoff may be trapped behind the structure, ponding areas and pump stations are required. Depending on the density of development of a vulnerable area, levees and floodwalls are often constructed as a system whereby floodwalls are interspersed between levee segments as available property space dictates.

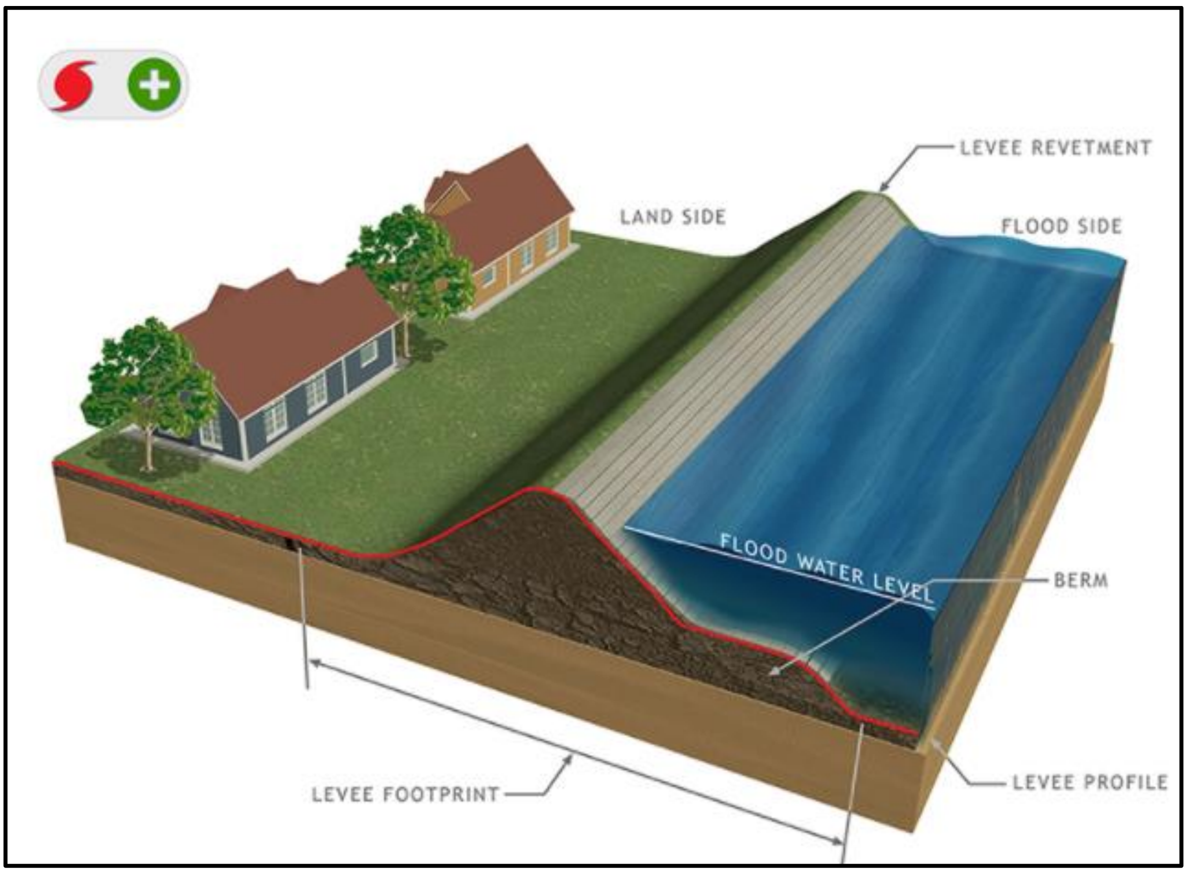

Figure B 7-1: Levee example image

7.2. Floodwall

Floodwalls are structures used to reduce risk in relatively small areas or areas with limited space for flood risk management against lower levels of flooding. Unlike wider, more stable levees, narrow floodwalls require significant reinforcement and anchoring construction to prevent collapse from hydrostatic pressure. The significant amounts of steel sheeting and/or reinforced concrete used in constructing a typical wall make the feature extremely heavy. Because construction in a flood prone area, such as near a river or estuary, may occur on soft organic soil, pile reinforcement may be required under the base of the wall. The combination of steel sheeting, reinforcement, concrete, and pile support make a floodwall a much more costly structural risk management measure than a similar length and height levee. A typical floodwall is depicted in **Figure B 7-2**. In addition to the cost of building such a structure, the real-world engineering considerations must be factored in and also the quality of life for the nearby residents. Floodwalls often block views, shade private property, separate communities, impact local hydrology, reduce wildlife mobility, etc.

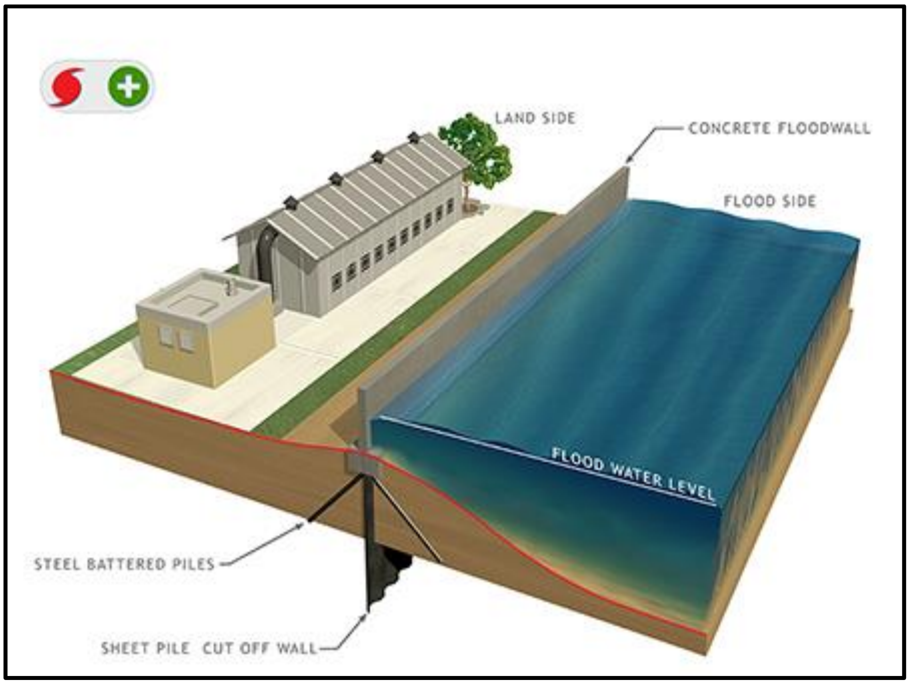

Figure B 7-2: Floodwall example image

7.3. Surge Barrier

Storm surge barriers reduce risk to estuaries against storm surge flooding and waves. In most cases the barrier consists of a series of movable gates that stay open under normal conditions to let the flow pass but are closed when storm surges are expected to exceed a certain level. Storm surge barriers are often chosen as a preferred alternative to close off estuaries and reduce the required length of perimeter flood risk management measures behind the barriers. Another important characteristic is that they are often (partly) opened during normal conditions to allow for navigation and saltwater exchange with the estuarine areas landward of the barrier. Nonetheless, storm surge barriers can have negative effects on the ecological system and on navigation. These types of structures have been used in the US and in numerous locations around the world. Gates can vary in size from controlling the flow into small tidal creeks to massive structures blocking flow into very large rivers, navigation channels, estuaries, etc. There are many types of gates that can be used, and selection is often based on cost, predicted surge elevations, navigation, bottom type, habitat considerations, etc. Within Rhode Island there is a hurricane surge barrier at Fox Point to reduce flood damage potential for the city of Providence (**Figure B 7-3**). Another example of a surge barrier, consisting of a dike and sector gates, is located nearby in New Bedford and Fairhaven, Massachusetts (**Figure B 7-4**).

Figure B 7-3: Fox Point hurricane barrier

Figure B 7-4: New Bedford hurricane barrier

7.4. Structure Elevation

As discussed in the main report, the primary recommendation of this study is to elevate structures in place (**Figure B 7-5**). Basically, the structures first floor living area is lifted to an elevation above the FEMA Base Flood Elevation (BFE) or 1-percent AEP flood elevation and placed on piles of some type. To elevate a structure, the existing structure is placed on a temporary wood or steel frame, lifted off the existing foundation or grade, and moved to the side. Piles are then driven into the ground, cut to a uniform elevation, and then the house is placed on top of those piles and secured. The minimum height required for structure elevation will consist of setting the first floor at the 1-percent AEP flood hazard elevation, plus 1 foot in accordance with Corps/NFIP (National Flood Insurance Program) standards, and another measure anticipating future sea level rise. Another key consideration when elevating a structure is to ensure that access to the home will not be affected by sea level change such that the house is cut off and inaccessible.

Figure B 7-5: Structure elevation example

7.5. Floodproofing

Dry floodproofing is a nonstructural technique that prevents the entry of flood waters into a structure. Dry floodproofing measures typically include the retrofit of an existing structure and can include measures such as continuous impermeable walls, sealing openings, backflow valves, flood shields and internal drainage systems. All measures require ongoing maintenance and human intervention to deploy during flood events. Typically, the retrofitting of existing exterior walls is only performed up to a 3-foot flood depth. Floodproofing was considered for non-residential structures and large multi-family structures not in a designated VE Zone and without a basement. For floodproofing, a 3-foot height was assumed for all measures.

7.6. Buyout/Acquisition

This nonstructural technique consists of buying the structure and the land. The structure is demolished, and the land is allowed to return to its natural state. Property owners would be relocated. Acquisition was considered for single family residences expected to be inundated at the 2080 MHHW plus 1.5 feet (approximately the highest annual tide (HAT)) under the intermediate SLC scenario or have access roads which would be cut off from utility access at this flood level.

7.7. Inland Hydrology Measures

Inland hydrology measures such as pump stations were considered where structural measures were proposed to mitigate for residual flooding due to entrapped rainfall runoff. Flap gates were also proposed for outfalls located along structural alignments to prevent backflow and flooding of the interior via the stormwater system.

8. ALTERNATIVES ANALYSIS

As described in the main report, the feasibility of specific structural alternatives was considered for localized areas within the study area whereas nonstructural measures were evaluated for their feasibility throughout the entire study area. Both structural and nonstructural measures were compared against the No Action Alternative.

Preliminary crest elevations for storm surge barriers are based on the 0.2% AEP with 50% assurance provided in the NACCS hazard curves for the year 2080 under intermediate SLC. Selection of the 0.2% AEP was based on the assumption that surge barriers with gates would be costly to construct and difficult to adapt. Therefore, higher crest elevations (lower AEPs) were initially selected for design of storm surge barriers. Preliminary crest elevations for other structural measures such as floodwalls and levees are based on the 1% AEP with 50% assurance provided in the NACCS hazard curves for the year 2080 under intermediate SLC. It is emphasized that there is no policy requirement that USACE projects be designed to the 1% AEP water level or any minimum performance standard. In subsequent phases of the RI Coastline Feasibility Study the performance of selected measures will be optimized to maximize NED benefits, which could result in higher or lower performance. For nonstructural elevations, the decision to design structures to the 1% AEP water level at this stage of the study is consistent with the parametric designs in NACCS and ECB 2013-33 that required all Sandy rebuilding projects receiving funds for construction under the Sandy supplemental (Public Law 113-2) be meet a flood risk reduction standard of one foot above the best available and most recent Base Flood Elevation.

8.1. No Action Alternative

The No Action Alternative or Future Without Project (FWOP) simulations were performed in G2CRM to estimate the expected future damages within the RI Coastline study area in the absence of a Federal CSRM project. The analysis involved 100 iterations of 58-year duration life cycles from the model start year (2021) through the 50-year period of analysis (2030-2079) for each of the model areas. Each simulation was run using the intermediate sea level change scenario for Newport, RI.

Model areas that were not considered for structural measures were set up as unprotected model areas. Where structural measures were considered, model areas were set up as upland model areas with the PSE elevation set to the existing ground elevation along the proposed structural alignment in the FWOP. The damages assigned to each model area were estimated in G2CRM using economic and engineering inputs to generate expected present value (PV) damages for each asset throughout the period of analysis. The possible occurrences of each economic and engineering variable were derived using Monte Carlo simulation and a total of 100 iterations were executed by the model. The expected PV damages was calculated as the average of PV damages across all iterations. The calculation and reporting of damages are summarized in the **Appendix C**, *Economic and Social Considerations*.

Mean and 90% confidence limit AEP water levels for the year 2080 under intermediate SLC are provided in **Table B 8-1** and **Table B 8-2**, respectively. While the G2CRM

Table B 8-1: 2080 NACCS mean AEP water levels by model area

MODEL AREA	NACCS ADCIRC SAVE POINT	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
Block Island	447	5.54	6.28	6.81	7.31	8.00	8.59	9.31	10.44
Bristol	8710	6.42	7.33	8.14	9.14	10.75	12.05	13.40	15.24
Cranston	180	6.70	7.81	8.91	10.34	12.45	14.08	15.76	17.93
Greenwich Bay	8561	6.53	7.59	8.51	9.60	11.33	12.80	14.34	16.34
Little Compton	1152	5.71	6.47	7.07	7.73	8.82	9.87	11.01	12.49
Mount Hope Bay	8662	6.55	7.53	8.45	9.68	11.56	12.98	14.41	16.35
Narragansett	203	5.83	6.68	7.36	8.08	9.14	10.13	11.29	12.84
Newport	10282	6.04	6.84	7.46	8.12	9.07	9.95	10.98	12.35
Providence	8603	6.86	8.05	9.26	10.88	13.24	15.05	16.91	19.27
Sakonnet Mid	10403	6.19	7.15	7.99	9.01	10.66	11.97	13.36	15.21
Sakonnet North	8730	7.83	8.85	9.95	11.43	13.44	14.88	16.35	18.35
Sakonnet South	8735	5.92	6.77	7.51	8.36	9.69	10.83	12.06	13.71
Warren	8626	6.49	7.49	8.45	9.69	11.54	13.01	14.52	16.47
Wickford	202	6.14	7.06	7.80	8.58	9.77	10.89	12.15	13.74

All values in feet, NAVD88 for 2080 Intermediate SLC scenario

Table B 8-2: 2080 NACCS 90% confidence limit AEP water levels by model area

MODEL AREA	NACCS ADCIRC SAVE POINT	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP
Block Island	447	7.41	8.08	8.63	9.20	10.03	10.79	11.71	12.89
Bristol	8710	8.36	9.25	10.17	11.43	13.22	14.53	15.88	17.72
Cranston	180	8.65	9.74	11.03	12.72	14.94	16.58	18.26	20.43
Greenwich Bay	8561	8.45	9.49	10.55	11.90	13.82	15.31	16.85	18.85
Little Compton	1152	7.62	8.33	9.00	9.85	11.24	12.34	13.48	14.97
Mount Hope Bay	8662	8.50	9.45	10.52	12.03	14.05	15.47	16.91	18.84
Narragansett	203	7.73	8.52	9.29	10.17	11.44	12.55	13.76	15.31
Newport	10282	7.95	8.71	9.40	10.22	11.41	12.40	13.45	14.81
Providence	8603	8.80	9.98	11.41	13.31	15.75	17.57	19.43	21.79
Sakonnet Mid	10403	8.11	9.05	10.04	11.33	13.13	14.45	15.83	17.68
Sakonnet North	8730	8.26	9.27	10.41	11.96	13.99	15.42	16.90	18.90
Sakonnet South	8735	7.84	8.67	9.50	10.56	12.12	13.30	14.54	16.19
Warren	8626	8.44	9.42	10.53	12.02	14.01	15.50	17.00	18.96
Wickford	202	8.06	8.93	9.76	10.73	12.16	13.36	14.62	16.22

All values in feet, NAVD88 for 2080 Intermediate SLC scenario economic model uses timeseries water levels, the AEP water levels were used to define the study area and to formulate alternatives.

Figure B 8-1 through **Figure B 8-6** show areas inundated by the 2080 1-percent AEP water level under the intermediate SLC scenario. The figures are presented starting with the west end of the study area at Point Judith and continue clockwise around the bay to the east end at the Massachusetts border, followed by Block Island.

Beginning in Narragansett in **Figure B 8-1**, the floodplain from Point Judith to Narragansett Pier is generally narrow as elevations increase quickly moving inland from the shoreline. However, inundation north of Narragansett Pier occurs across Narragansett Town Beach and along the Narrow River and Pettaquamscutt Cove. Parts of the Bonnet Shores neighborhood facing Narragansett Bay and through Wesquage Pond are also subject to inundation.

In Jamestown, the 2080 1-percent AEP inundation under the intermediate SLC scenario will cut off access to parts of the southern end of the island at Beavertail Road where it passes Mackeral Cove Beach and along Fort Getty Road. North Road is also inundated where it crosses Great Creek. Route 138 is narrowly outside of this floodplain but could be vulnerable under a higher SLC scenario or beyond the year 2080. Flooding of structures is generally limited to the first row of structures from the coast.

Downtown Newport is highly vulnerable to flooding with the 2080 1-percent AEP inundation under the intermediate SLC scenario extending inland to Thames Street, inundating the historic Point neighborhood north until Poplar Street, and the Fifth Ward neighborhood along Wellington Avenue south to Eastnor Road. Goat Island, Naval Station Newport, and the interchange where Admiral Kalbfus Road meets JT Connell Highway north of the Claiborne Pell Newport Bridge are also vulnerable to inundation and densely developed. Inundation shown along the south coast of Newport in **Figure B 8-1** is largely limited to coastal ponds and existing marshlands.

North Kingstown (**Figure B 8-2**) is vulnerable to inundation along much of its shoreline including neighborhoods along Wild Goose Point, Lone Tree Point, Poplar Point, and, especially, Wickford Cove. Quonset State Airport and industrial areas at the Port of Davisville at Quonset are also vulnerable to future inundation.

In East Greenwich, inundation primarily occurs along Water Street and affects several marinas and restaurants.

Warwick contains several areas which are vulnerable to flooding under existing and future conditions including the neighborhoods of Potowomut, Apponaug, Oakland Beach, Warwick Cove, and Conimicut. Although much of Warwick Neck is elevated outside of the inundation area, access to Warwick Neck could be limited during a future 1-percent AEP event.

In Cranston (**Figure B 8-3**), the Pawtuxet Village area is most vulnerable. The 2080 1-percent AEP inundation under the intermediate SLC scenario will cut off Pawtuxet Neck from the mainland. There is also potential for storm surge to propagate up the Pawtuxet River, inundating areas in both Warwick to the south and Cranston to the north.

The Fields Point and Port of Providence (ProvPort) areas of Providence are most vulnerable to inundation under existing and future conditions. Inundation is not shown propagating into Downtown Providence as it was assumed that the Fox Point hurricane barrier would remain in place and continue to reduce flood risk along the Providence River throughout the period of analysis. Along the Seekonk River, Gano Street and the Richmond Square area are also inundated.

East Providence is most vulnerable along Waterfront Drive and Bullock Cove.

Figure B 8-3 shows that Barrington is highly vulnerable to flooding. Particular areas of concern include the Latham Park neighborhood near Bullock Cove, Annawomscutt, Rumstick Neck, and the shorelines along the Warren River and the Barrington and Palmer Rivers. Route 114 (Wampanoag Trail/County Road) is an important transportation corridor that is low-lying.

Warren (**Figure B 8-4**) is vulnerable to inundation in present and future conditions. The most vulnerable area is along Belchers Cove, followed by Water Street and along the Kickemuit River.

In Bristol, future inundation will cut off Popasquash Neck from the mainland and flood the downtown area along Thames Street and Silver Creek where Route 114 is again vulnerable.

In Portsmouth, the most vulnerable area is the low-lying Island Park area which floods first through Island Park Cove, but also from the Sakonnet River across Park Avenue. Other areas of concern include Common Fence Point and Little Harbor/Melville area. Tiverton is subject to flooding along Riverside Drive through the Stone Bridge area, along Nanaquaket Pond and along Seapowet Cove. Fogland Beach will be overwashed.with most of Fogland Point underwater.

In Little Compton (**Figure B 8-5**), structures along Almy Brook and in the Sakonnet area are most vulnerable. Flooding along the south coast is primarily limited to salt ponds and marshes.

The Aquidneck Avenue area adjacent to Easton Beach is the most vulnerable developed area of Middletown. The Sachuest area is also vulnerable to inundation but is sparsely developed, containing beach and marsh resource areas.

At Block Island (**Figure B 8-6**), coastal flooding occurs through Great Salt Pond and also over Corn Neck Road on the Island's east side, with the most vulnerable structures along Ocean Avenue and Corn Neck Road. Inundation of Corn Neck Road would also cut off access to much of the north side of the island.

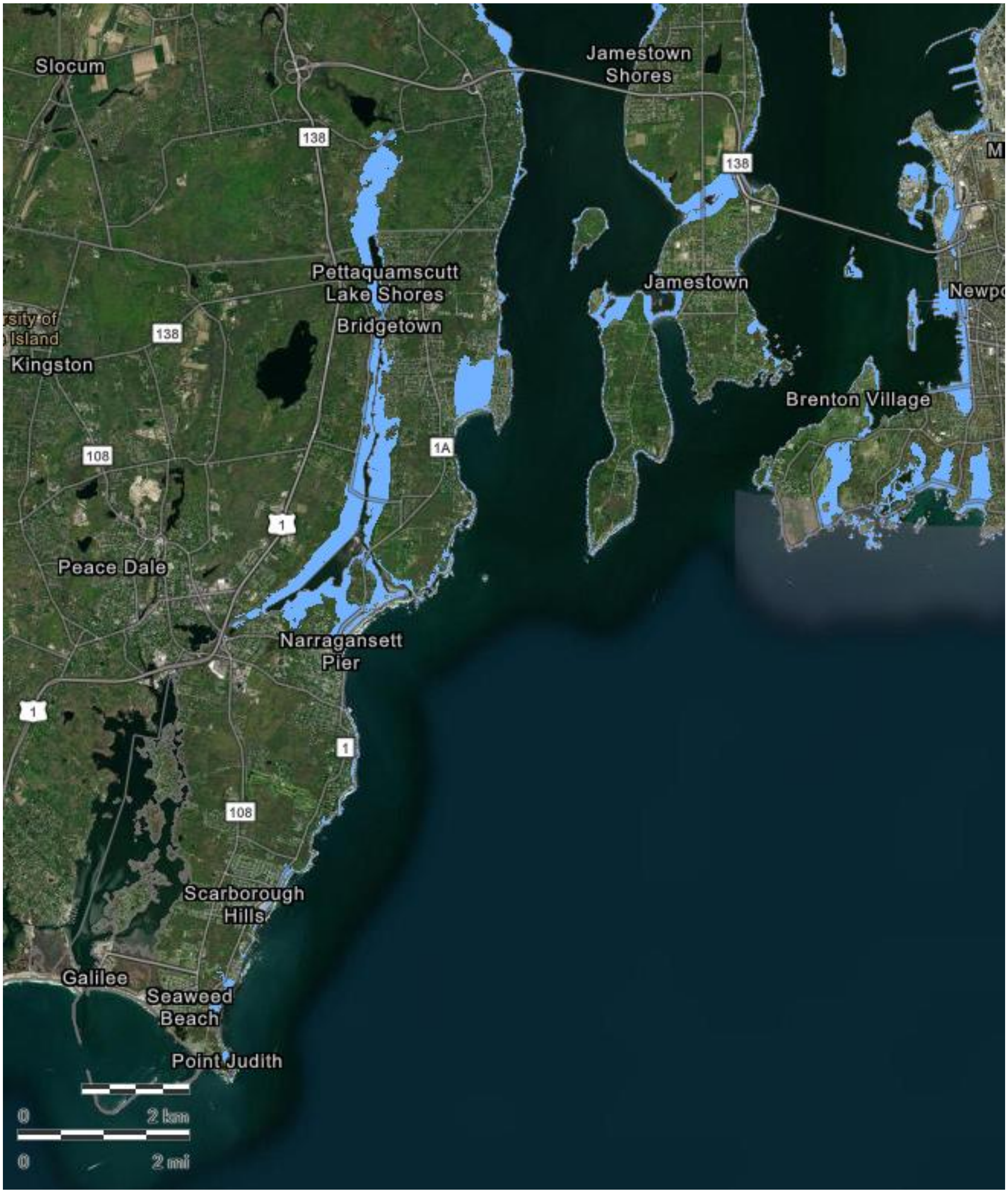

Figure B 8-1: 2080 1-percent AEP inundation under intermediate SLC—Narragansett, South Kingstown, North Kingstown, Jamestown, Newport

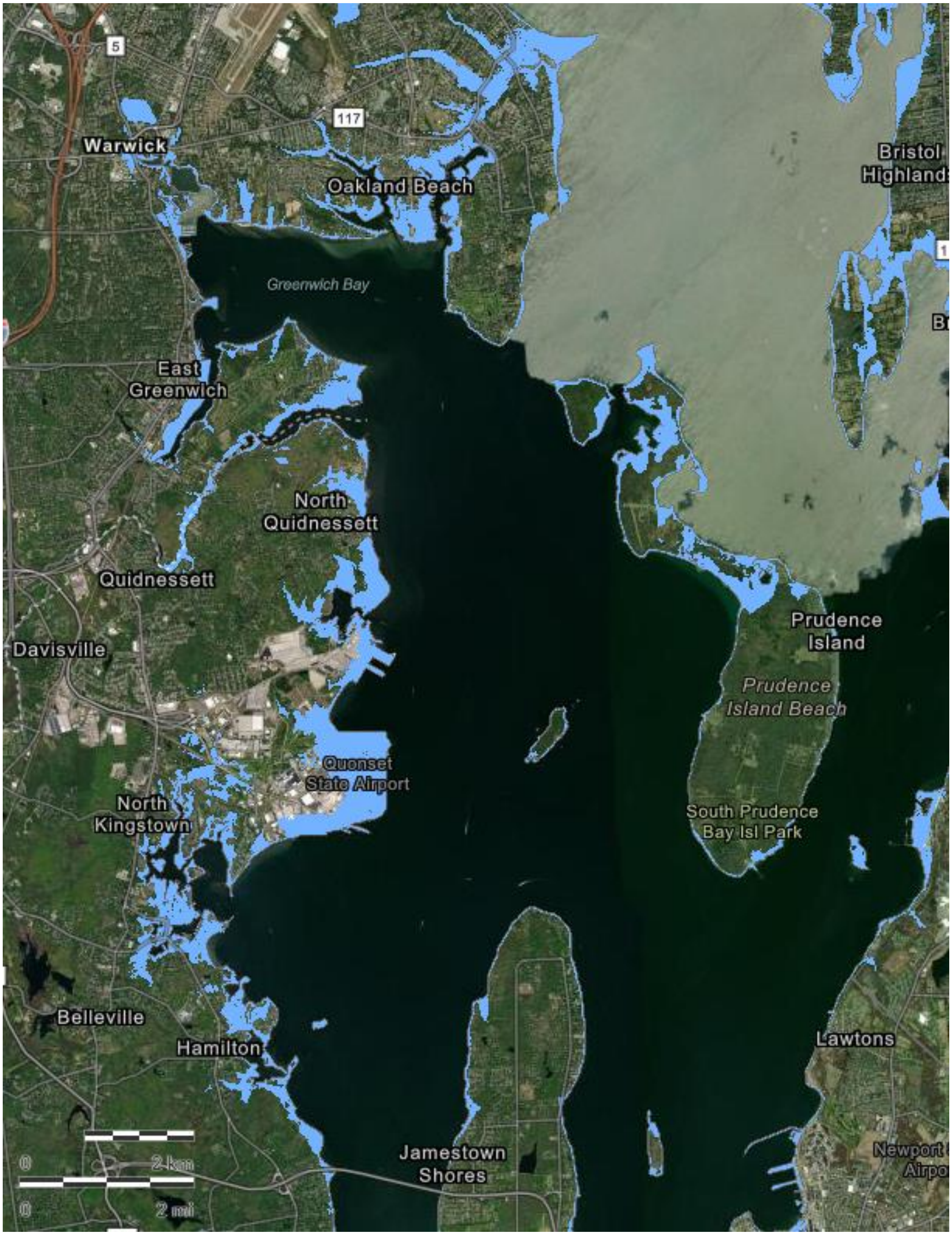

Figure B 8-2: 2080 1-percent AEP inundation under intermediate SLC—North Kingstown, East Greenwich, Warwick, Jamestown, Portsmouth (Prudence Island)

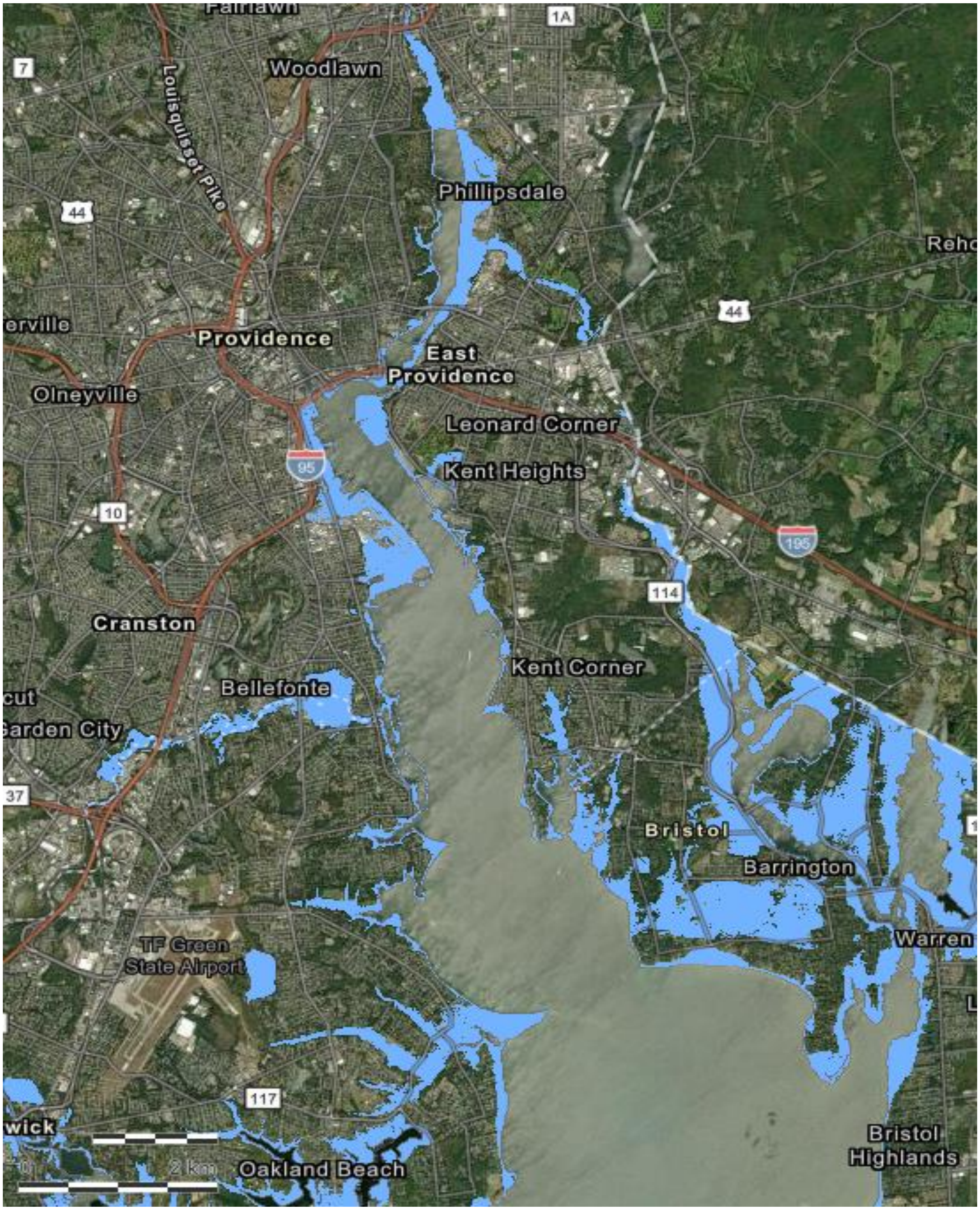

Figure B 8-3: 2080 1-percent AEP inundation under intermediate SLC—Warwick, Cranston, Providence, Pawtucket, East Providence, Barrington, Warren

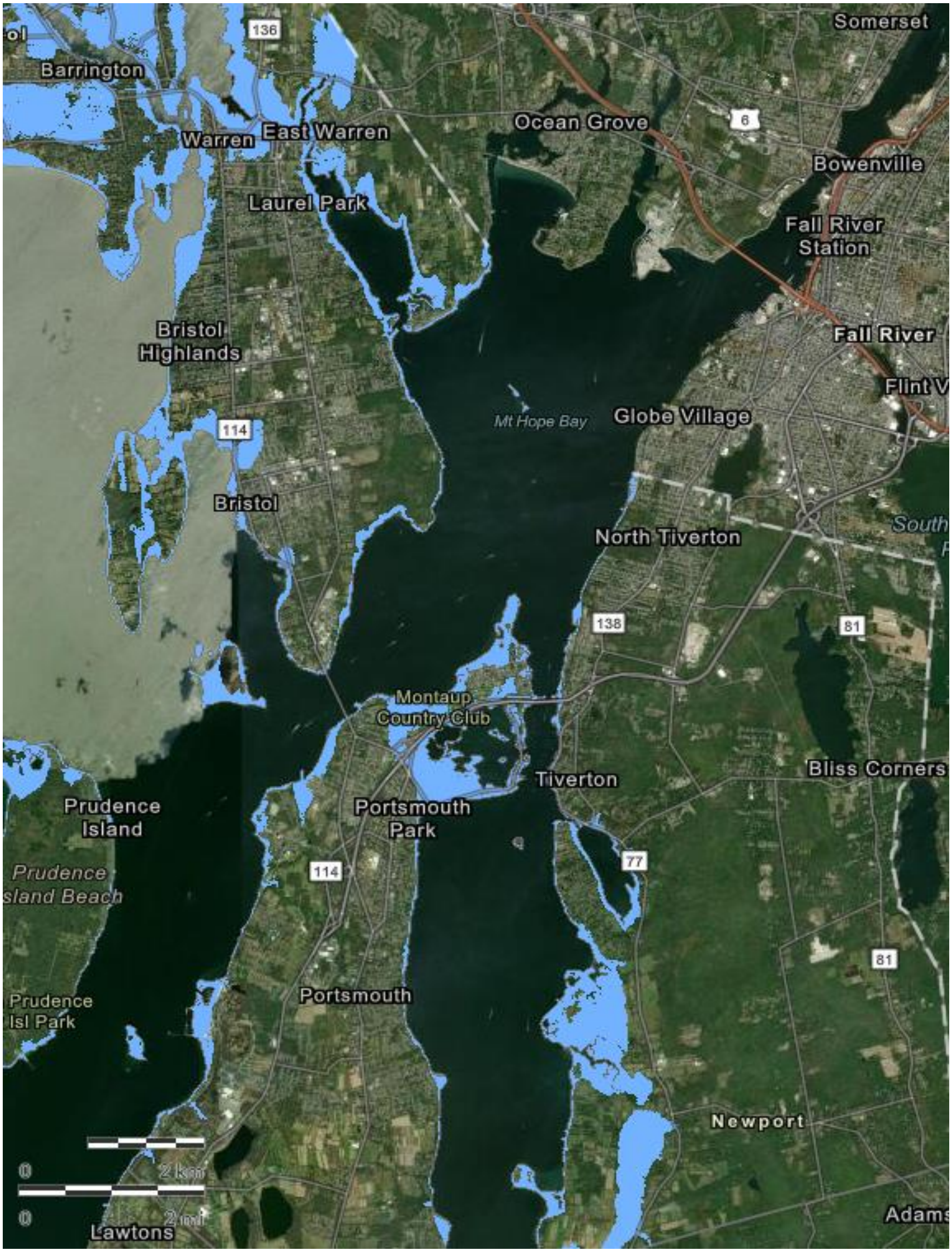

Figure B 8-4: 2080 1-percent AEP inundation under intermediate SLC—Warren, Bristol, Portsmouth, Tiverton

Figure B 8-5: 2080 1-percent AEP inundation under intermediate SLC—Tiverton, Little Compton, Middletown, Newport

Figure B 8-6: 2080 1-percent AEP inundation under intermediate SLC—Block Island

8.2. Warren-Barrington Surge Barrier

8.2.1. Alignment and Geometry

Two structural alignments were evaluated to reduce coastal flood risk within the Barrington and Warren areas. The primary feature of both alignments was a surge barrier crossing either the Warren River (lower alignment shown in red in **Figure B 8-7**) or the Barrington and Palmer Rivers (upper alignment shown in yellow in **Figure B 8-7)**. The design elevation selected for both alignments was the 0.2-percent AEP NACCS water level for the year 2080 under the intermediate SLC scenario. The upper barrier alignment would cross the Barrington and Palmer Rivers along the existing location of the East Bay Bike Path, with floodwall sections over land to tie into high ground. The lower barrier alignment would consist of a dike and sector gates in water, similar to the New Bedford hurricane barrier, and floodwalls over land to tie into high ground. The sector gate opening was proposed to be 150 feet, consistent with the width of the marked navigation channel and able to accommodate the passage of the specialty vessels such as the Grand Mariner which are made at Blount Boats, located just upstream (http://blountboats.com/boat-builders/specialty-vessels/), according to EM 1110-2-1613, *Hydraulic Design of Deep-Draft Navigation Projects*. Reference the **Appendix D**, *Engineering and Design* for additional detail on the surge barrier system alignments and design.

8.2.2. G2CRM Representation

Within G2CRM, both alignments were represented using the flood barrier PSE, with a stage-volume relationship for the interior area. The top elevation of the PSE was set to the 0.2-percent AEP water elevation for the year 2080 assuming intermediate SLC, 16.5 feet NAVD88. In addition to specifying a top elevation for each PSE, the flood barrier PSE also requires inputting a closure threshold to define the water level necessary to deploy the flood barrier. If the closure threshold is exceeded during a storm event, the barrier is closed and protects the assets in the interior up to the top elevation of the PSE. Anticipating sea level change, the closure threshold for surge barriers was set to 5 ft NAVD88. This value was based off a 2080 MHHW of 3.86 feet NAVD88 under the intermediate sea level change scenario plus a buffer of approximately 1 foot to ensure that the closure structures would not need to operate daily to protect against tidal flooding within the 50-year economic period of analysis.

8.2.3. Interior Drainage

EM 1110-2-1413 Hydrologic Analysis of Interior Areas references that if flooding within the interior area increases beyond what has occurred naturally, a relief system, such as pumps, should be recommended to mitigate for any increases in water level within the interior area. For the feasibility level analysis, the line-of-protection was the two closure system alignments at elevation 16.5 feet NAVD88, which excludes coastal flood waters originating from the exterior, but does not alleviate flooding that may subsequently occur from interior runoff. An interior drainage assessment was performed to ensure that for each project alternative, appropriate interior drainage components were identified to handle residual flooding due to the proposed project features. The interior area was defined as the interior watershed behind the line-of-protection, shown **Figure B 8-8**.

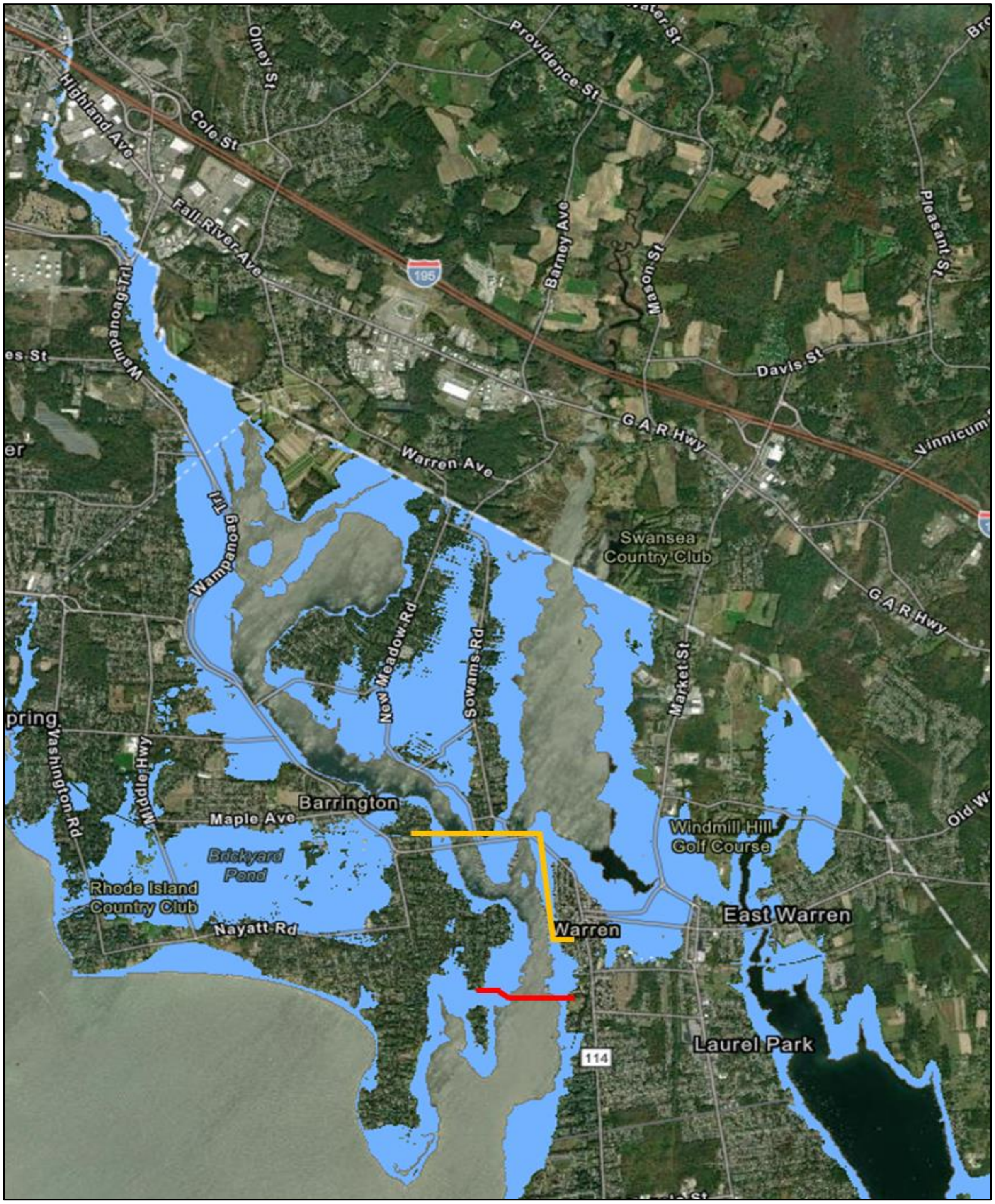

Figure B 8-7: Warren-Barrington surge barrier alignments

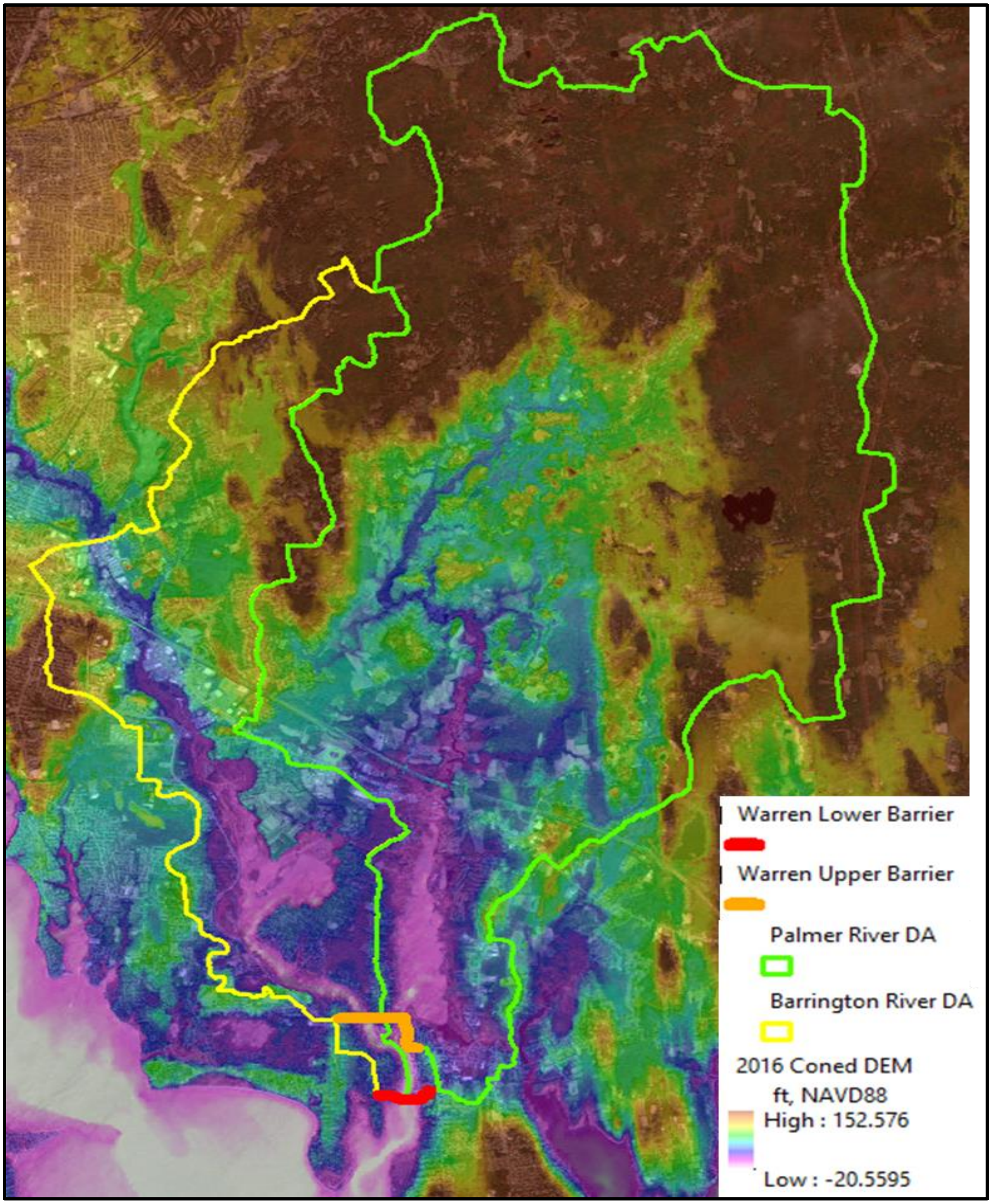

Figure B 8-8: Warren-Barrington surge barrier watersheds

The Barrington River drainage area (16 square miles) is outlined in yellow while the Palmer River drainage area (52 square miles) is outlined in green. Flows were estimated by scaling the 1-percent peak discharges at the farthest downstream cross sections in the effective FEMA Flood Insurance Studies. For the Barrington River, a peak flow of 900 cfs was based off the peak discharge of 535 cfs at the Runnins River cross section at School Street (drainage area of 9.6 square miles). For the Palmer River, a peak flow of 3300 cfs was based off the peak discharge of 2930 cfs at Palmer River Location 1 in Rehoboth (drainage area of 46.5 square miles). For the upper barrier alignment, it was assumed that two pump stations would be needed to separately pump flows from the Barrington and Palmer Rivers. As the lower barrier alignment is located downstream of the confluence of both rivers and it seemed unlikely that both rivers would peak at the same time, the pump sizing for the lower barrier alignment was reduced 10 percent. Therefore, a single pump station with 3750 cfs was recommended.

8.3. Middlebridge Surge Barrier

8.3.1. Alignment and Geometry

A surge barrier across the Narrow River at Middlebridge Road in South Kingstown and Narragansett was designed to prevent surge from propagating up the Narrow River and flooding the low-lying residential neighborhoods to the north (**Figure B 8-9**). A flood protection system for the area would consist of a floodwall to either side of the Narrow River bridge and integrate a stop log structure underneath the existing bridge. The existing bridge was built to withstand the 1-percent AEP storm water elevation levels. Therefore, the proposed surge barrier system was designed for the same event with a target elevation of 10.13 feet NAVD88. The existing clearance beneath the bridge only permits small recreational vessels such as kayaks as the water depth is minimal (approx. 2 to 3 feet). A structure would be built into the existing bridge and contain slots to install stop logs during storm events. The width of opening would be approximately 30 feet in order to maintain marine traffic. The west wingwall would utilize an existing cleared pathway along the shoulder of Middlebridge Road in South Kingstown and the east wingwall would be constructed along the shoulder of Middlebridge Road in Narragansett.

8.3.2. G2CRM Representation

The Middlebridge surge barrier was represented in G2CRM using a flood barrier PSE with a stage-volume relationship for the interior area. The top elevation of the PSE was set to the 1-percent AEP water elevation for the year 2080 assuming intermediate SLC, 10.1 feet NAVD88. In addition to specifying a top elevation for each PSE, the flood barrier PSE also requires inputting a closure threshold to define the water level necessary to deploy the flood barrier. If the closure threshold is exceeded during a storm event, the barrier is closed and protects the assets in the interior up to the top elevation of the PSE. Anticipating sea level change, the closure threshold for surge barriers was set to 5 ft NAVD88. This value was based off a 2080 MHHW of 3.86 feet NAVD88 under the intermediate sea level change scenario plus a buffer of approximately 1 foot to ensure that the closure structures would not need to operate daily to protect against tidal flooding within the 50-year economic period of analysis.

8.3.3. Interior Drainage

The interior area at Middlebridge was defined as the interior watershed behind the surge barrier, shown **Figure B 8-9**. The drainage area, outlined in yellow, is 10.2

square miles. Flows at Middlebridge were estimated by scaling the 1-percent peak discharge at the nearest cross section in the effective FEMA Flood Insurance Study. For Middlebridge, a peak flow of 825 cfs was estimated from the peak discharge of 405 cfs given for the Mattatuxet River confluence with the Pettaquamscutt.

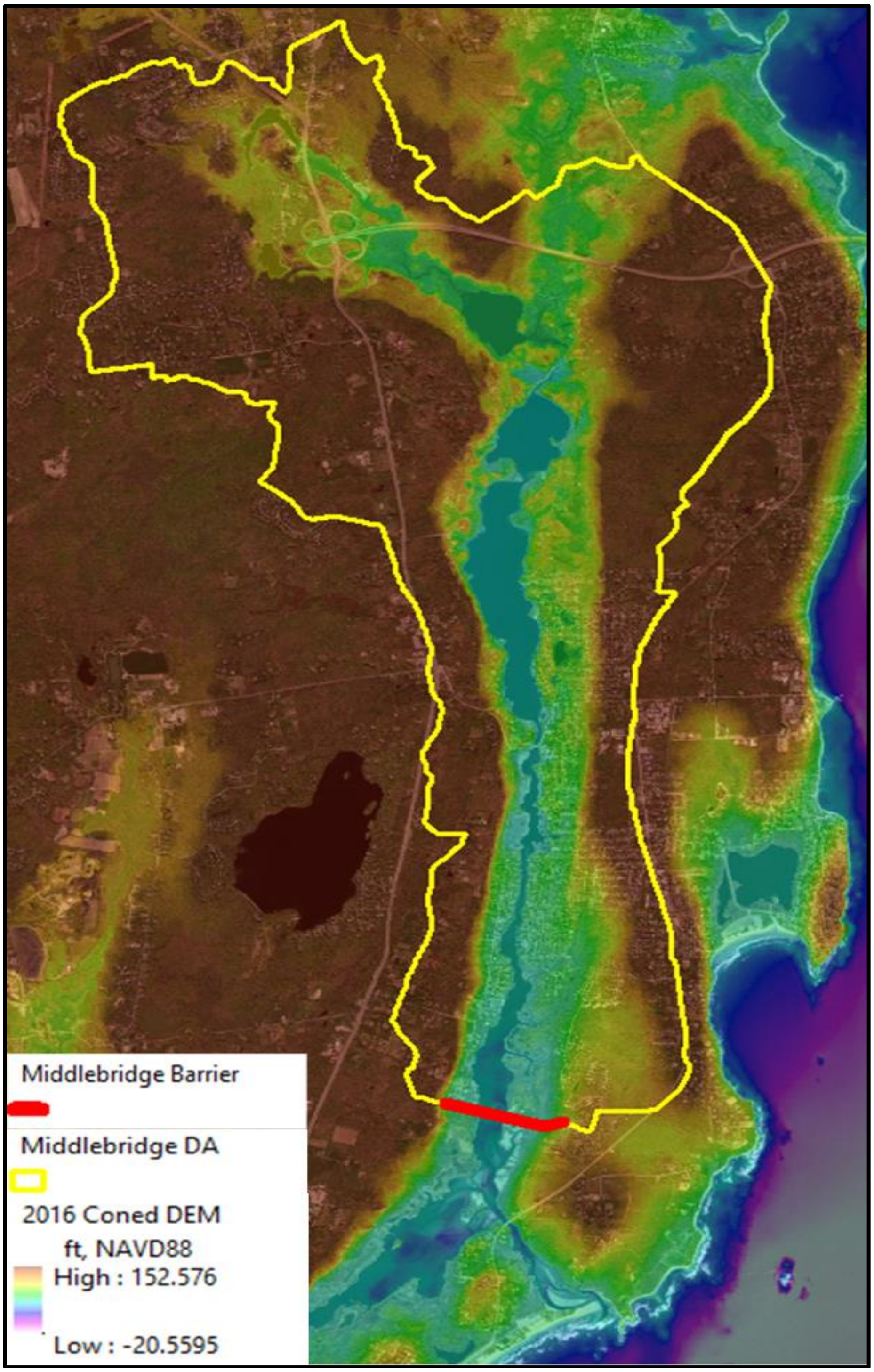

Figure B 8-9: Middlebridge surge barrier watershed

8.4. Wellington Floodwall and Levee System

8.4.1. Alignment and Geometry

A floodwall and levee system along Wellington Avenue between Thames Street and Columbus Avenue was investigated to reduce flood risk within the area south of Wellington Avenue known as the Fifth Ward (**Figure B 8-10**). Kings Park, which is a public recreational area and includes ball fields, two beaches, and public meeting areas borders Wellington Avenue to the north along Newport Harbor. A structural measure for the area would consist of a concrete floodwall and earthen levee system located along the westbound side of Wellington Avenue, with a vehicle barrier required to cross from the north side of Wellington Avenue to the high ground along Columbus Avenue. The design elevation for the floodwall and levee system was the 1-percent AEP water level for the year 2080 under the intermediate SLC scenario. The elevation does not include a wave runup height which would incorporate the effects of waves.

Figure B 8-10: Wellington floodwall and levee alignment with area of risk reduction

8.4.2. G2CRM Representation

The Wellington Avenue floodwall and levee system represented in G2CRM using a floodwall PSE with a stage-volume relationship for the interior area. The top elevation of the PSE was set to the 1-percent AEP water elevation for the year 2080 assuming intermediate SLC, 10. feet NAVD88.

8.4.3. Interior Drainage

The interior area at Wellington was defined as the interior watershed behind the floodwall and levee system, shown in **Figure B 8-11**. The drainage area, outlined in yellow, is 241 acres. For the preliminary hydrologic assessment, interior drainage calculations at Wellington were made using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) software. HEC-HMS was used to estimate runoff volumes and flow hydrographs within the upland watershed for use in the feasibility level design of interior drainage needs prior to the TSP.

The Loss Method, selected within HEC-HMS, for the sub-basin determines the infiltration calculations used for that sub-basin. The Soil Conservation Services (SCS) Curve Number Loss was selected as the Loss Method for the HEC-HMS model set-up because of its relative ease of use as well as land use and soil property data were available for the watershed. The Soil Conservation Services curve number method implements the curve number methodology for incremental losses. The SCS curve number method was used to estimate the amount of runoff potential from the rainfall event based on the relationship between soil type, land use and hydrologic soil conditions. This method is applicable for single storm event modeling.

The curve number was derived using 2011 State of Rhode Island Land Use and Land Cover and USDA NRCS web soil survey data for the watershed.

The Transform Method determines the runoff calculations performed for the sub-basin. The Transform method selected to represent the runoff within the watershed was the SCS Unit Hydrograph methodology, which requires a time of concentration and storage coefficient to be identified. The time of concentration is defined as the time it takes water to travel from the hydraulically furthermost point in the watershed to the outlet.

There are several formulas available to estimate the time of concentration. A common formula is the TR-55 Methodology (USDA, 1986). It uses parameters for three different flow characteristics for sheet flow, shallow concentrated flow, and channel flow to compute the time of concentration. Parameters such as the flow length, slope, and Manning's roughness coefficient are used to determine the adequate time. The parameters that could be estimated from the terrain data were computed in ArcMap. These parameters were used in the computation of the time of concentration, with no adjustment due to the lack of calibration data. However, the resulting hydrograph was reviewed using engineering judgement to ensure that the time appeared reasonable to describe the hydrologic conditions present.

For the meteorological input, point precipitation data was obtained from NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 10 Version 3.0: Northeastern States. The 100-year average recurrence interval, 24-hour storm event was selected for design of interior flood features.

HEC-HMS computed a peak discharge of 478 cfs. Therefore, a pump station of 480 cfs was suggested to keep up with the peak flow of the 100-year, 24-hour rainfall event. The flows are high because it is a small, rather dense watershed with a low lag time.

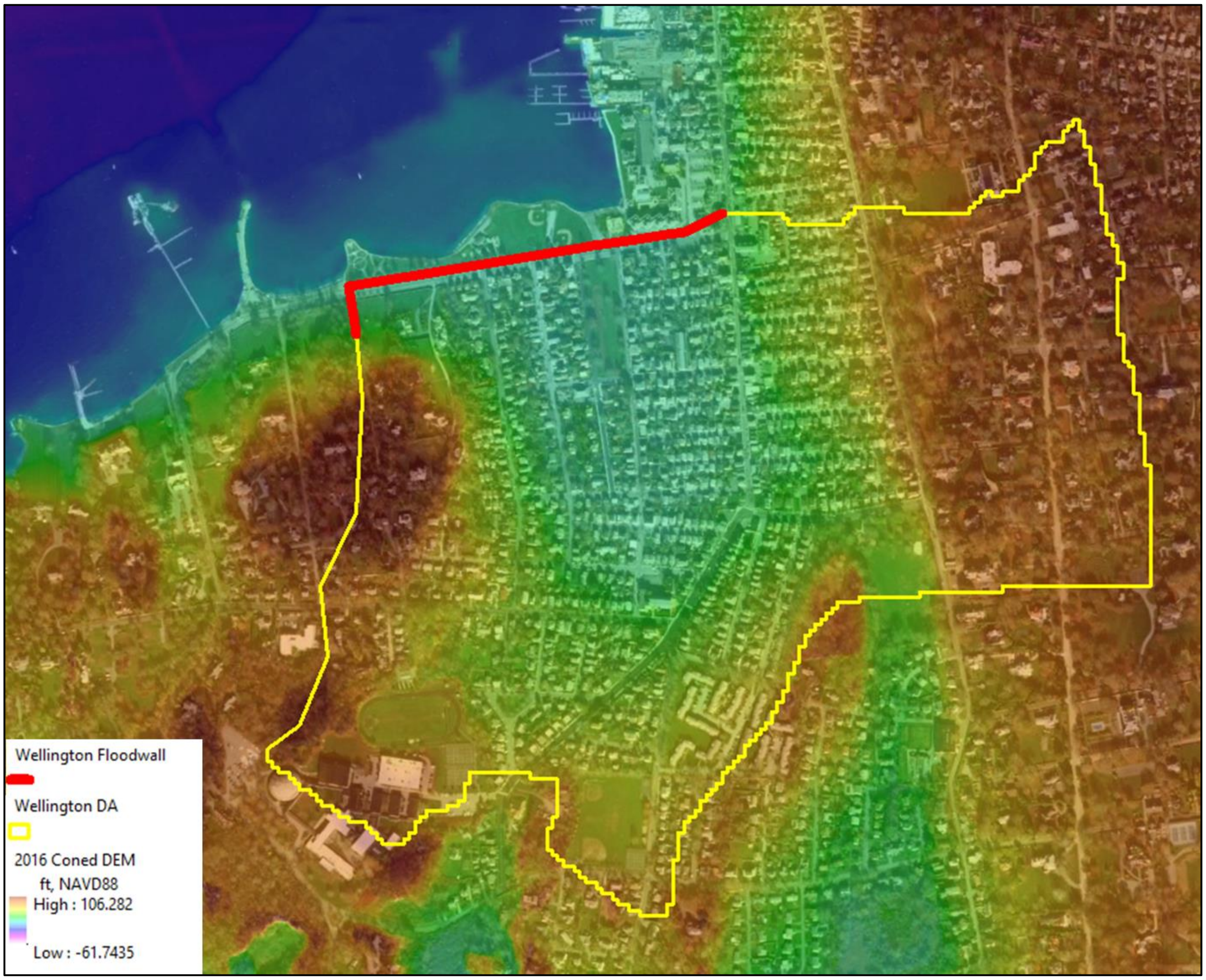

Figure B 8-11: Wellington Avenue floodwall watershed

8.5. Nonstructural Alternative

Elevation was considered for single family residences. The elevation design height was determined separately for each structure based on the 1% AEP NACCS water level + wave contribution + 1 ft + sea level change (intermediate through 2080). From the G2CRM User's Manual (USACE, 2018b) and per FEMA guidance, the wave contribution was computed as 0.705* (the smaller of the 1% wave height or 0.78* water depth).

9. TENTATIVELY SELECTED PLAN

The Tentatively Selected Plan (TSP) for coastal storm risk management in the Rhode Island Coastline CSRM Project is the nonstructural plan which includes 533 total structures – 323 residential recommended for elevation and 210 non-residential recommended for floodproofing.

9.1. Performance

ER 1105-2-101 requires risk assessment for coastal storm risk management studies. At this stage, the risk assessment provides additional information about project performance that is not provided by the National Economic Development (NED) economic results. When discussing project performance, the following terms are often used:

Annual Exceedance Probability (AEP) – The probability that a certain threshold may be exceeded at a location in any given year, considering the full range of possible values, and if appropriate, the incorporation of project performance. The AEP is expressed as a percentage. An event having a one in 100 chance of occurring in any single year would be described as the one percent AEP event.

Assurance –The probability that a target stage will not be exceeded during the occurrence of a flood of a specified exceedance probability considering the full range of uncertainties. The term selected to replace “conditional non-exceedance probability” (CNP).

Long-Term Exceedance Probability (LTEP) –The probability of capacity exceedance during a specific period. For example, 30-year exceedance probability refers to the probability of one or more exceedances of the capacity of a measure during a 30-year period; formerly long-term risk. This account for the repeated annual exposure to flood risk over time.

At this stage, the design elevation for the nonstructural plan was the 1% AEP NACCS water level + wave contribution + 1 ft + sea level change (intermediate scenario through 2080). Project performance is evaluated by determining the AEP, LTEP, and assurance associated with the flood hazard exceeding this design elevation. It is assumed that when these water elevations are reached the elevated structures will begin to experience damages.

Project performance (AEP, LTEP, and assurance) in the year 2080 assuming RSLC has followed the USACE intermediate SLC scenario is presented in **Table B 9-1**. Since the nonstructural plan has been designed to the 1% AEP in 2080, the mean AEP is equal to 1% and the LTEPs are all the same. The 90% assurance AEPs vary based on differences in uncertainty in the NACCS water level estimations across the study area.

Table B 9-1: Project Performance: AEP, LTEP, Assurance at Year 2080 (USACE Int. SLC)

Model Area	AEP		LTEP		
	Mean	90% Assurance	10-yr Period	30-yr Period	50-yr Period
Block Island	1%	10.4%	9.6%	26.0%	39.5%
Bristol	1%	3.5%	9.6%	26.0%	39.5%
Cranston	1%	2.8%	9.6%	26.0%	39.5%
Greenwich Bay	1%	3.1%	9.6%	26.0%	39.5%
Little Compton	1%	4.9%	9.6%	26.0%	39.5%
Mount Hope Bay	1%	3.2%	9.6%	26.0%	39.5%
Narragansett	1%	5.2%	9.6%	26.0%	39.5%
Newport	1%	6.4%	9.6%	26.0%	39.5%
Providence	1%	2.6%	9.6%	26.0%	39.5%
Sakonnet Mid	1%	3.5%	9.6%	26.0%	39.5%
Sakonnet North	1%	1.3%	9.6%	26.0%	39.5%
Sakonnet South	1%	4.1%	9.6%	26.0%	39.5%
Warren	1%	3.1%	9.6%	26.0%	39.5%
Wickford	1%	4.4%	9.6%	26.0%	39.5%

Project performance will be further refined as the tentatively selected plan is optimized, and project performance across all 3 USACE SLC scenarios will be reported in the final report.

9.2. Reliability and Life Safety

Nonstructural plans such as the TSP generally provide exceptional reliability, require little active intervention, and consist of independent failure points, unlike structural plans such as floodwalls and closure structures. Failure of a single structure within the tentatively selected plan will not lead to failure of the entire system. In addition, people located inside elevated structures will be able to evacuate vertically inside the structure or to the roof to greater elevations, potentially reducing life loss. However, when considering life safety, evacuation should be considered ahead of a significant storm event. The National Weather Service typically gives several days of storm warning and forecasts allowing the appropriate local, state, and federal governmental agencies to set evacuation requirements. Due to the relatively narrow floodplains with high ground only a short distance away and fairly robust road system within the study area, evacuation is very viable. Life safety is further discussed in the **Appendix C**, *Economic and Social Considerations*.

10. SUMMARY AND CONCLUSIONS

The Water Management Section's coastal assessment reviewed available water level and wave data and recommended water levels to be used for the formulation and design of plan alternatives. After discretizing the study area into representative model areas, G2CRM was used to estimate the inundation damages for project alternatives within the study area. Storm hydrographs from the NACCS were used as the driving forces within G2CRM. Water levels provided to the structural and geotechnical engineering disciplines were extracted from the NACCS and adjusted for anticipated changes due to sea level rise. Interior drainage analyses were performed for structural alternatives to inform pump sizing. Finally, the design elevation height for the nonstructural analysis was provided to economics for incorporation into G2CRM.

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