RHODE ISLAND COASTLINE
COASTAL STORM RISK MANAGEMENT
Final Feasibility Study & Environmental Assessment

APPENDIX B: Coastal Engineering

JANUARY 2023

US Army Corps of Engineers®
New England District

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RHODE ISLAND COASTLINE
COASTAL STORM RISK MANAGEMENT

DRAFT FINAL FEASIBILITY REPORT
Appendix B: Coastal Engineering

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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.

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 comprises 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.

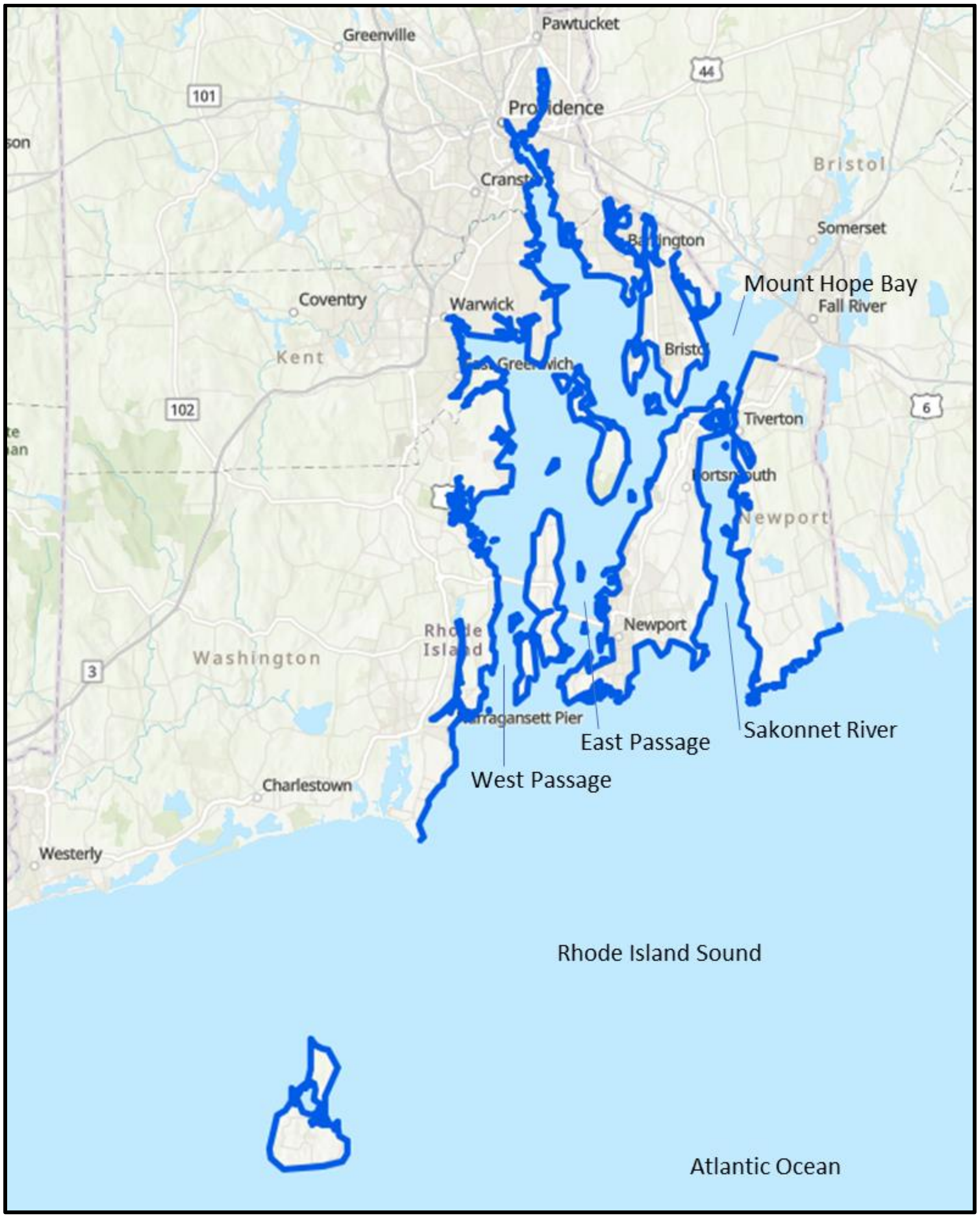


Figure B 2-1: Study location map

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 States. 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 National Oceanic and Atmospheric Administration (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 (EM 1110-2-6056). VDatum is a vertical datum transformation software tool that provides conversions between various tidal datums and MSL and MSL and NAVD88.

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.

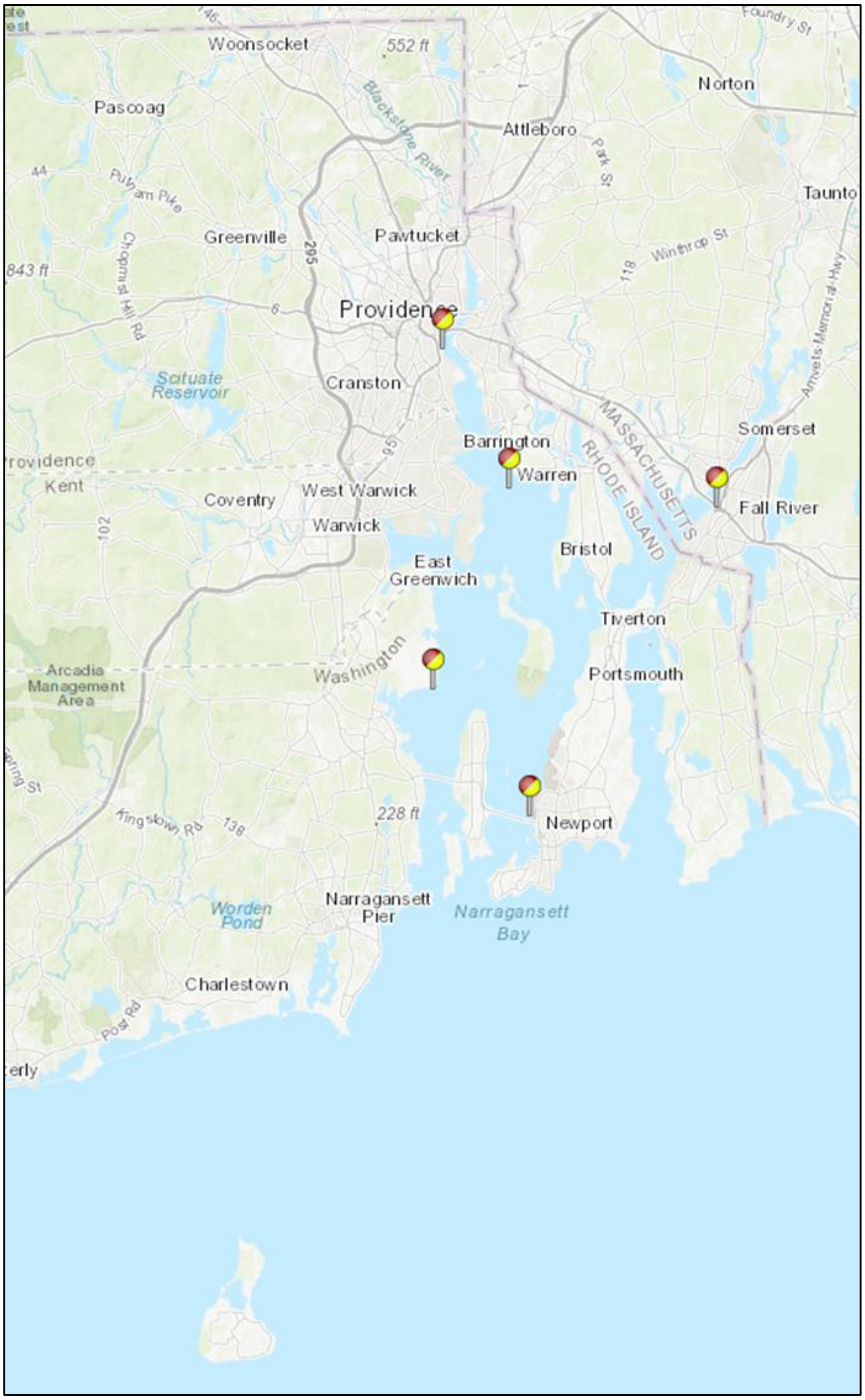


Figure B 3-1: NOAA tide gage locations

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 patterns (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

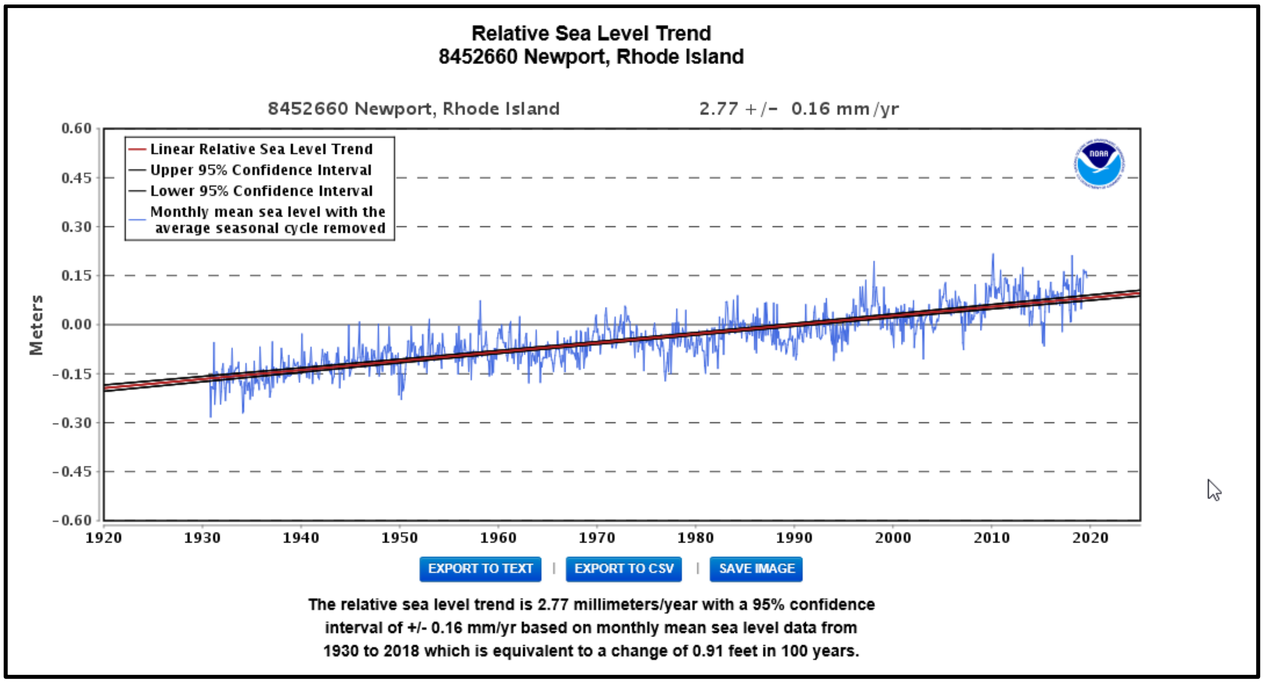
In accordance with ER 1100-2-8162, potential effects of relative sea level change (RSLC) were analyzed over a 50-year economic period of analysis and a 100-year planning horizon. USACE guidance states "the period of analysis shall be the time required for implementation of the lesser of: (1) the period 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 Intergovernmental Panel on Climate Change (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

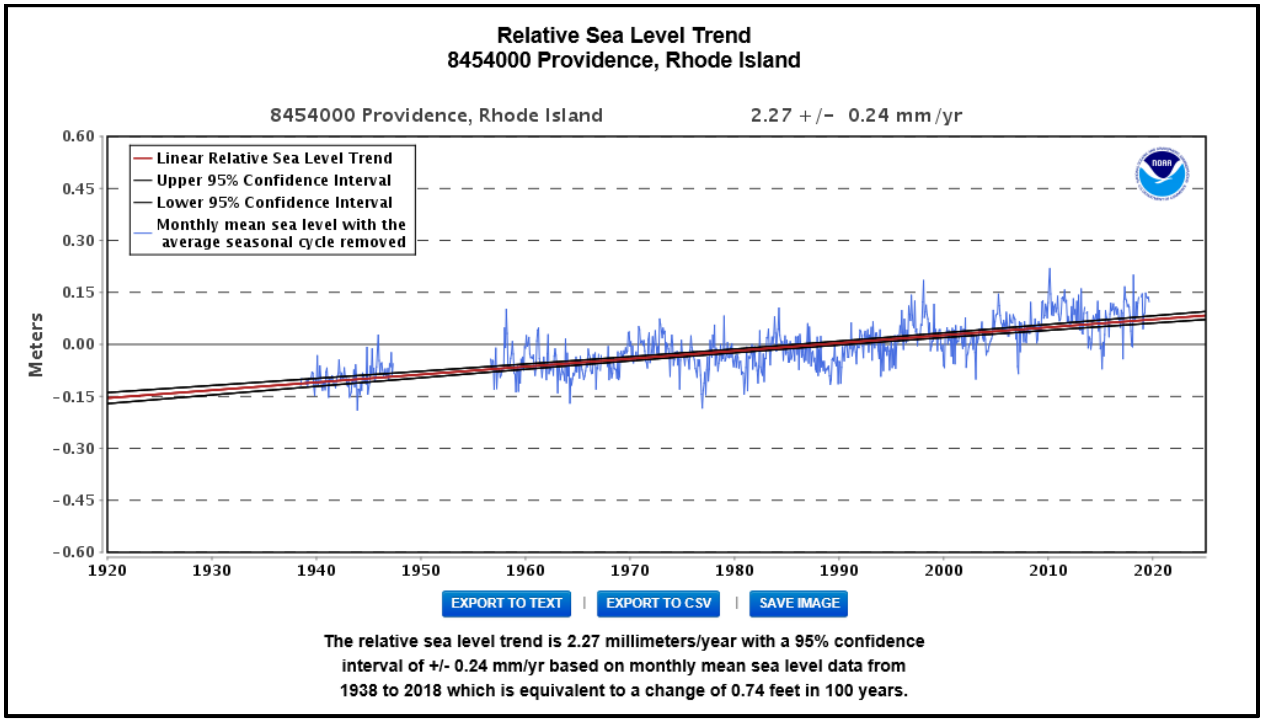
Historical RSLC for this study (2.77 mm/yr or 0.00909 ft/yr for the years 1930-2018) is based on NOAA tidal records at Newport, RI. An additional historical RSLC rate within the study area is available at Providence, RI (2.27 mm/yr or 0.00745 ft/yr for the years 1938-2018). However, the Newport tide gage was selected as a conservative assumption to represent the entirety of the study area. 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 sea level (orange), and the 19-year moving average sea level (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).



Note: The historical SLC rate has changed since the study began in 2018. However, the slight change in rate should not impact the outcome of study findings.

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



Note: The historical SLC rate has changed since the study began in 2018. However, the slight change in rate should not impact the outcome of study findings.

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

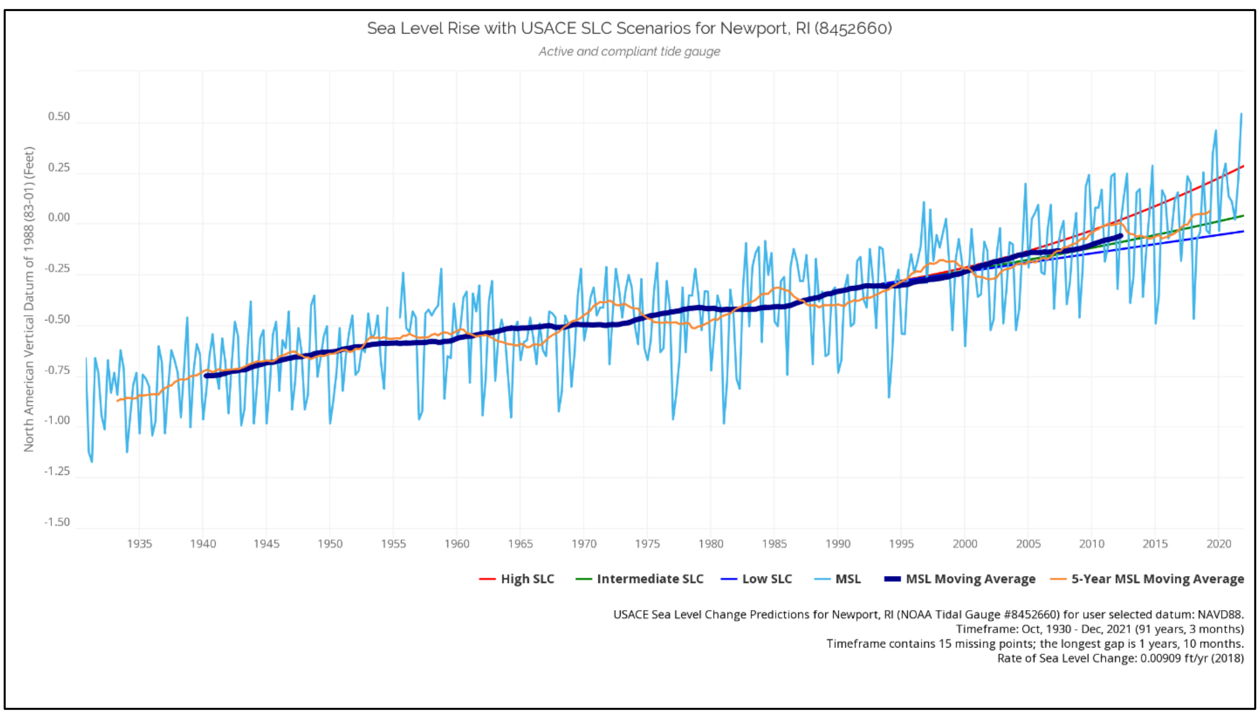


Figure B 4-3: Historical (1930-2021) RSLC at Newport, RI

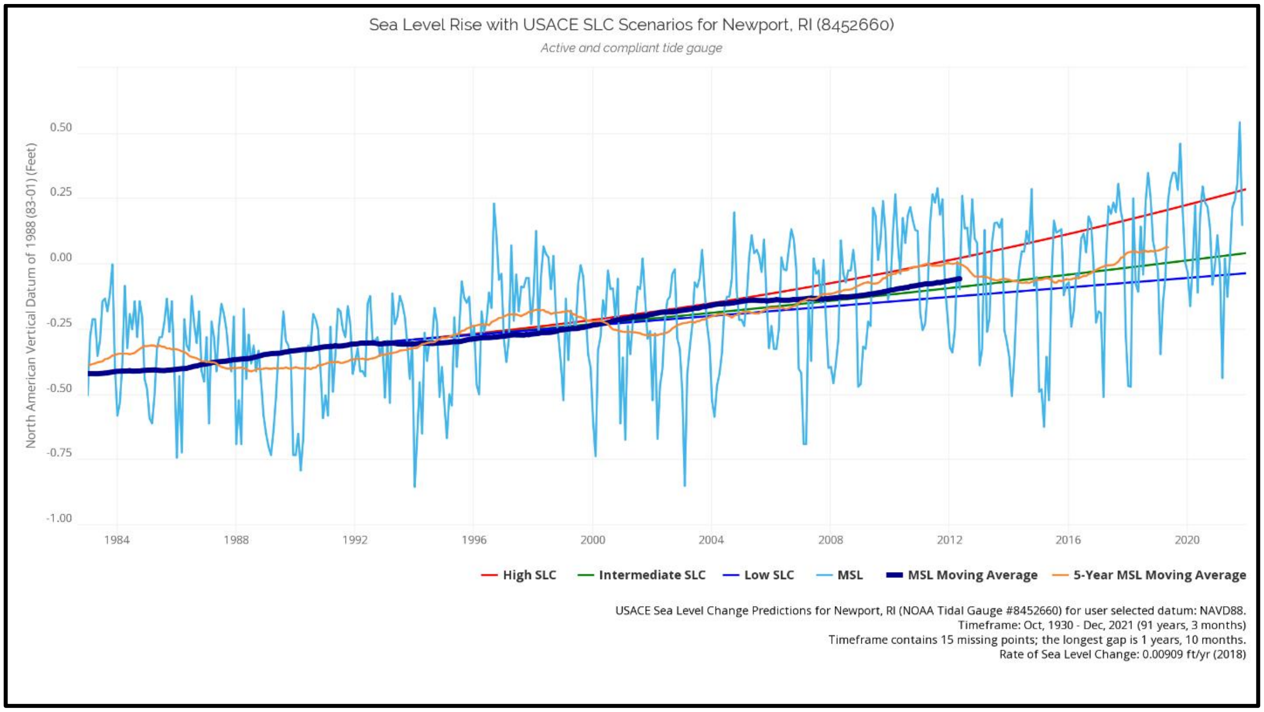


Figure B 4-4: Historical (1983-2021) RSLC at Newport, RI

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 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** via linear superposition. 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. This assumption to linearly superimpose sea level change was made considering the NACCS showed the nonlinear residuals for sea level change plus astronomic tides within the study area having combined biases of less than 0.1m (**Figure B 9-1**).

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

Note: The historical SLC rate has changed since the study began in 2018. However, the slight change in rate should not impact the outcome of study findings (1.51 ft vs 1.49 ft through 2080 under the intermediate scenario).

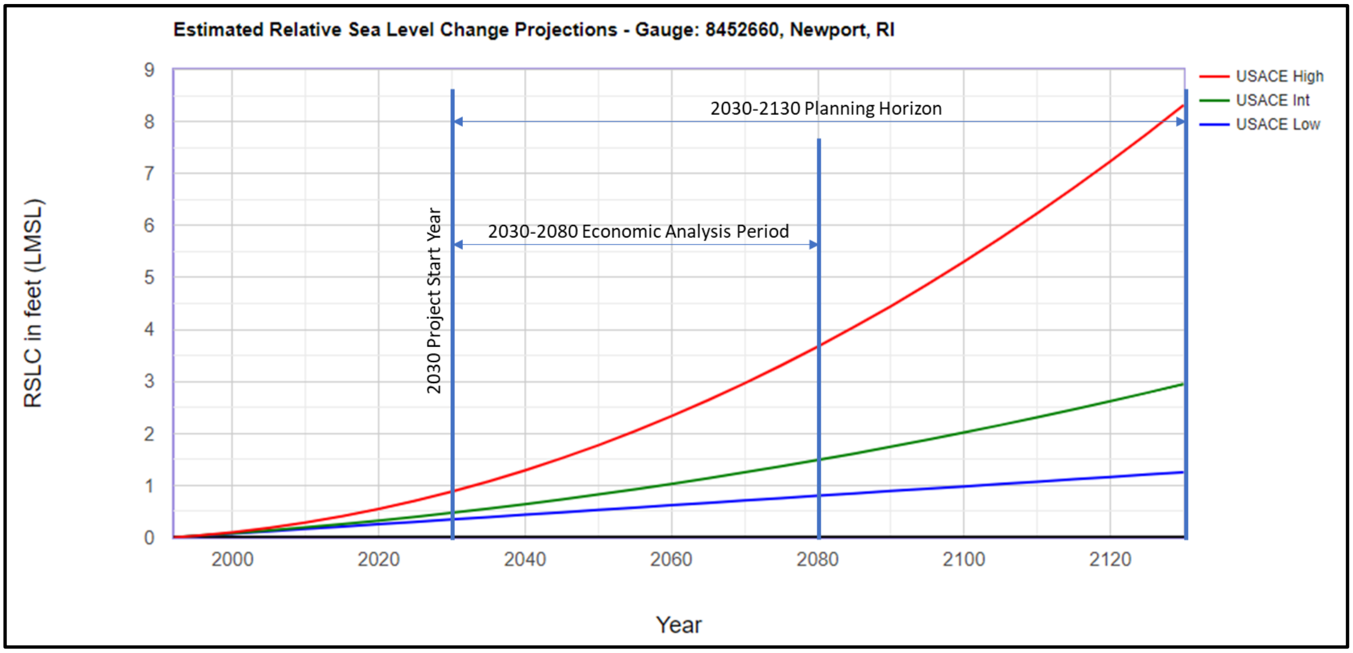


Figure B 4-5: USACE Sea Level Change Scenarios for Newport, RI

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 address 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. CLIMATE HYDROLOGY

A climate assessment for the RI Coastline study area was developed to address the requirements contained within ECB 2018-14, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects. The assessment is an evaluation of potential climate vulnerabilities facing the RI Coastline study area. The study area is located within the state of Rhode Island from Point Judith east to the Massachusetts border, including Narragansett Bay, and Block Island. While the primary focus of the study is coastal flooding, this assessment was performed to highlight existing and future challenges facing the study area due to past and future climatic changes in accordance with the guidance in Engineering Construction Bulletin (ECB) 2018-14, revised 10 Sep 2020.

5.1. Literature Review

The RI Coastline study area is largely situated within the Narragansett basin (HUC-8 watershed 01090004). Two exceptions, Block Island and the southern coast of Little Compton, are located within the Pawcatuck-Wood (HUC-8 watershed 01090005) and Cape Cod (HUC-8 watershed 01090002) basins, respectively (**Figure B 5-1**). These three basins, and the entire study area, are located within the Massachusetts-Rhode Island Coastal HUC-4 watershed. The Massachusetts-Rhode Island Coastal watershed itself is located entirely in Water Resource Region (i.e., HUC-2 watershed) number 01, the New England Region. Given the study's coastal storm risk management purpose, climate variables of greater concern include any increases in precipitation or increased streamflow which could exacerbate coastal flooding. Examples are extreme precipitation events such as intense rains during the hurricane season (e.g., Hurricane/Tropical Storm Irene in August 2011), which coincide with coastal flood events.

A January 2015 literature synthesis conducted by the USACE Institute for Water Resources (USACE 2015b) summarizes the available climate change literature for this region, covering both observed and projected changes. These include temperature, precipitation, and streamflow. Dupigny-Giroux, L.A. et al (2018) reviewed climate changes in progress in the United States in a report widely referred to as simply the fourth National Climate Assessment (NCA) or NCA4. The USACE literature synthesis and NCA4 are the two major sources of the information referenced in this literature review. The focus of these references is on summarizing trends identified within historical and observed temperature, precipitation, and streamflow records, as well as providing an indication of future hydrometeorology based on the outputs from Global and Regional Climate/Circulation Models (GCMs and RCMs). In this assessment, background on observed and projected temperature and precipitation is provided as context for the impact they have on observed and projected streamflow.

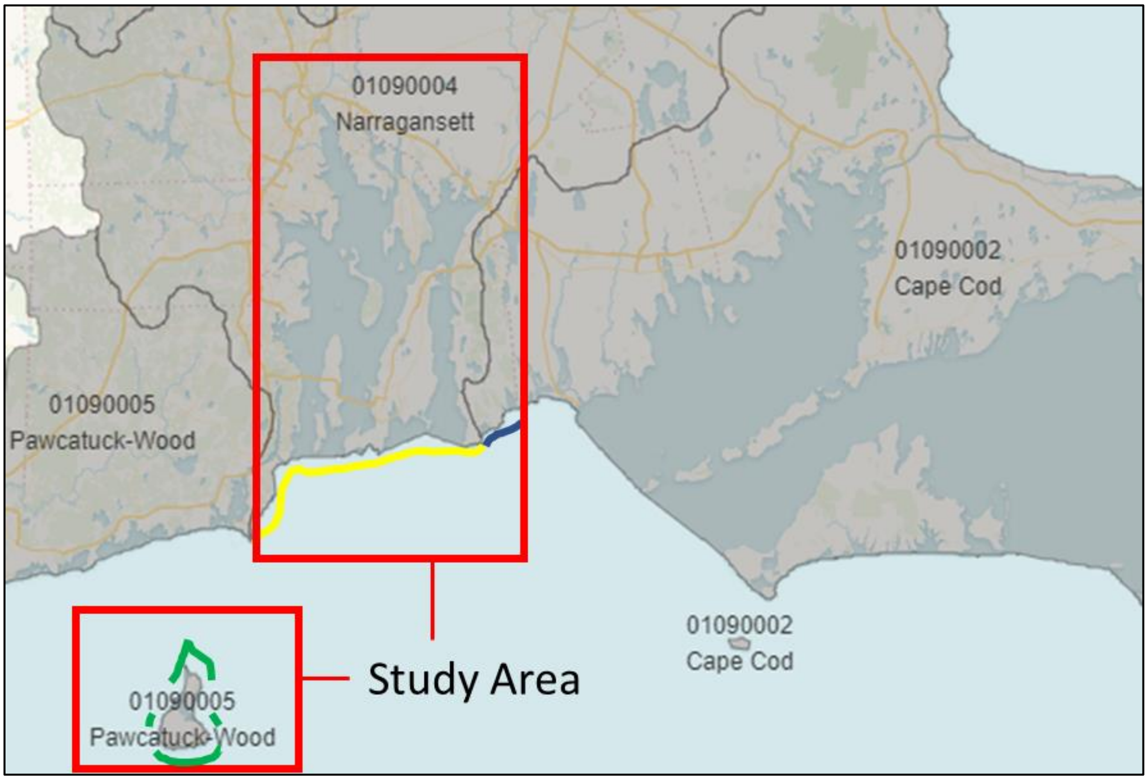


Figure B 5-1: RI Coastline study area relative to HUC-8 watersheds

Temperature: Observed changes in annual average temperature for the Northeast Region have increased by 1.43°F for the 1986-2016 period relative to the 1901-1960 period. Observed annual average maximum and annual average minimum temperature has increased by 1.16°F and 1.70°F in the Northeast region, respectively (Dupigny-Giroux, L.A. et al (2018)). Observed increases in temperature in the Northeast Region (New England, New York State, Pennsylvania, and New Jersey), including statistically significant increasing trends, have been reported in numerous studies (Hayhoe et al (2008); Burakowski et al 2008; the Northeast Climate Impacts Assessment (NCIA) (Frumhoff et al, 2007); Brown et al (2010); Huntington et al (2009)). These included increases in summer temperatures, an average increase of temperature of 1.5°C during the 20th Century, and a doubling of the number of days per year exceeding 32°C (90°F) since 1970.

More specifically, in New England, a general warming trend has been observed, with a rising trend of 0.8°C to 3.0°C per century, although two studies also detected a cooling trend for the months of December to February. Spring warming since 2001 appears to be occurring 0 to 4 days earlier than it did during the 1950's which indicates a potential change in seasonality. In a review of 361 station records over the period 1930 to 1996, only 4 stations had records of decreasing temperatures, and none of these results was statistically significant. These studies are included in Wang et al (2009); Westby et al (2013); Meehl et al (2012); Schwartz et al (2013); DeGaetano et al (2002); Horton et al (2014).

Trombulak and Wolfson (2004) reviewed temperature data at 36 locations in New England and New York State for 1903-2000, reporting an average increase of 3°C per century for the region, without reporting on significance. For the RI Coastline study area, the interpolated rate of temperature-change appeared to be 1°C to 2°C per century (See **Figure B 5-2**).

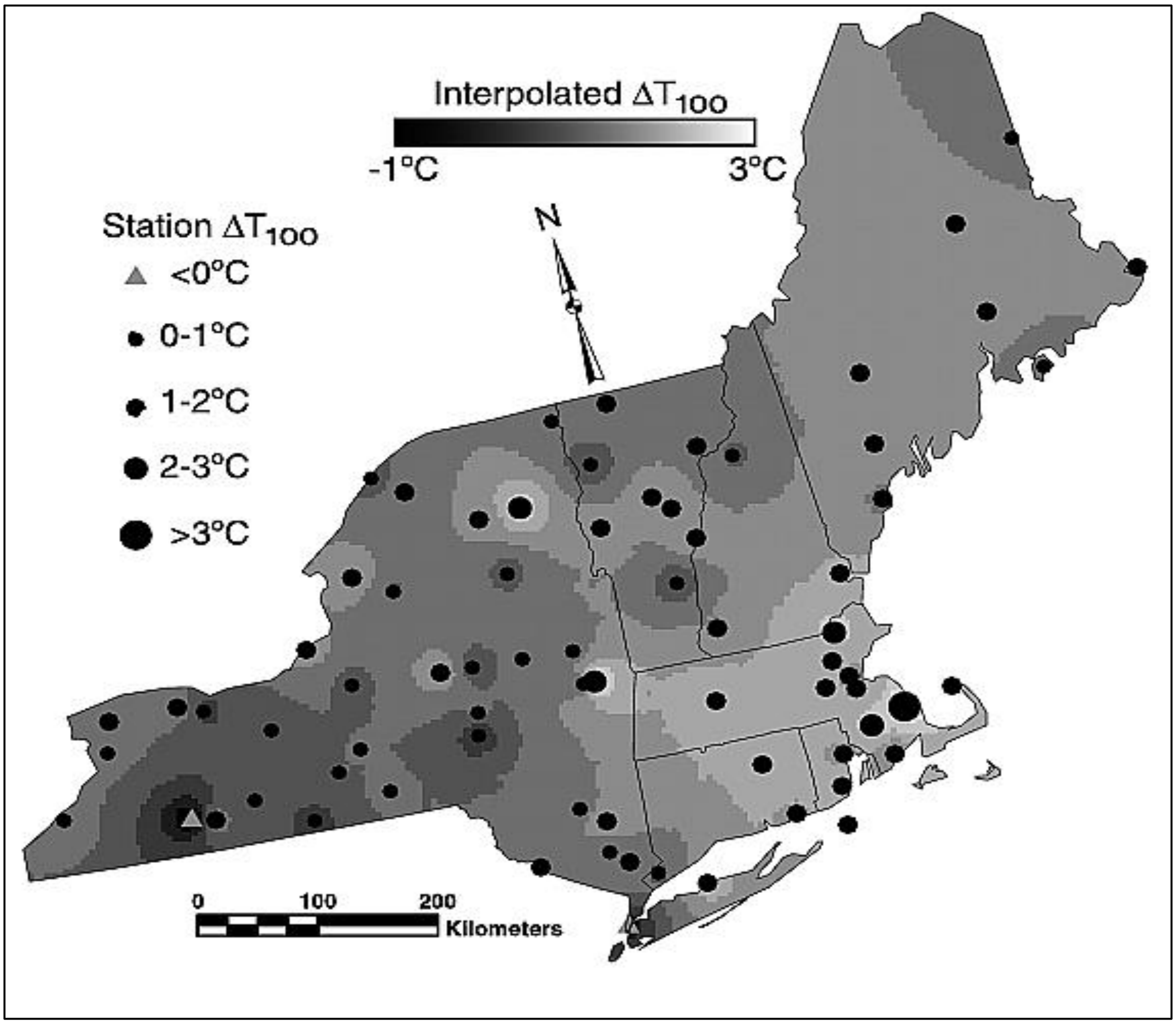


Figure B 5-2: Trombulak and Wolfson 2004 Review of Temperature Changes in the New England - New York Region

Temperature:

Projections: NCA4 (Dupigny-Giroux, L.A. et al (2018)) reviewed temperature changes and projections of temperature-change for 7 regions of the US. For the Northeast, they reported on average, minimum, and maximum temperatures and how these were expected to differ from "near-present" (1976-2005) conditions as projected by 32 climate models, under two sets of assumed inputs, during the 21st century. Time periods examined were for mid-century (2036-2065) or late-century (2071-2100). The average temperatures were expected to rise 4.0 to 5.1 °F by mid-century and by 5.3 to 9.1°F by late-century.

For temperature extremes, NCA4 reported results for the mid-century (2036-2065) as these were projected to have shifted from the 1976-2005 conditions. For the Northeast, the change in the warmest day of the year was expected to be 6.5 °F warmer; the change in the coldest day of the year was expected to be 9.5°F warmer. For 5-day periods, the 1-in-10 year coldest spell was expected to be 15.9°F warmer; the 1-in-10 year warmest spell was expected to be 12.9°F warmer.

For projections, global climate models, also known as General Circulation Models or GCMs, are used to simulate future weather conditions. Scherer and Diffenbaugh (2014) used varying assumptions about emissions to model conditions in the United States: their results for New England indicated increased summer and winter temperatures of 5.2°C (9.4°F) and 1.7°C (3.1°F) by 2090 compared to a 1980-2009 baseline period.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. Regarding temperatures in Rhode Island, NOAA reported as follows (Runkle et al 2022):

> *"Temperatures in Rhode Island have risen almost 4°F since the beginning of the 20th century. Under a higher emissions pathway, historically unprecedented warming is projected to continue through this century. Increased intensity of heat waves is also projected, while cold waves are projected to decrease in intensity."*

Figure B 5-3 provides a summary of the expected changes. Historically unprecedented warming is projected to continue (higher emission) through the 21st century. Less warming is expected under a lower emissions future (the coldest years being about 2°F warmer than the historical average; green shading) and more warming under a higher emissions future (the hottest years being about 10°F warmer than the hottest year in the historical record; red shading).

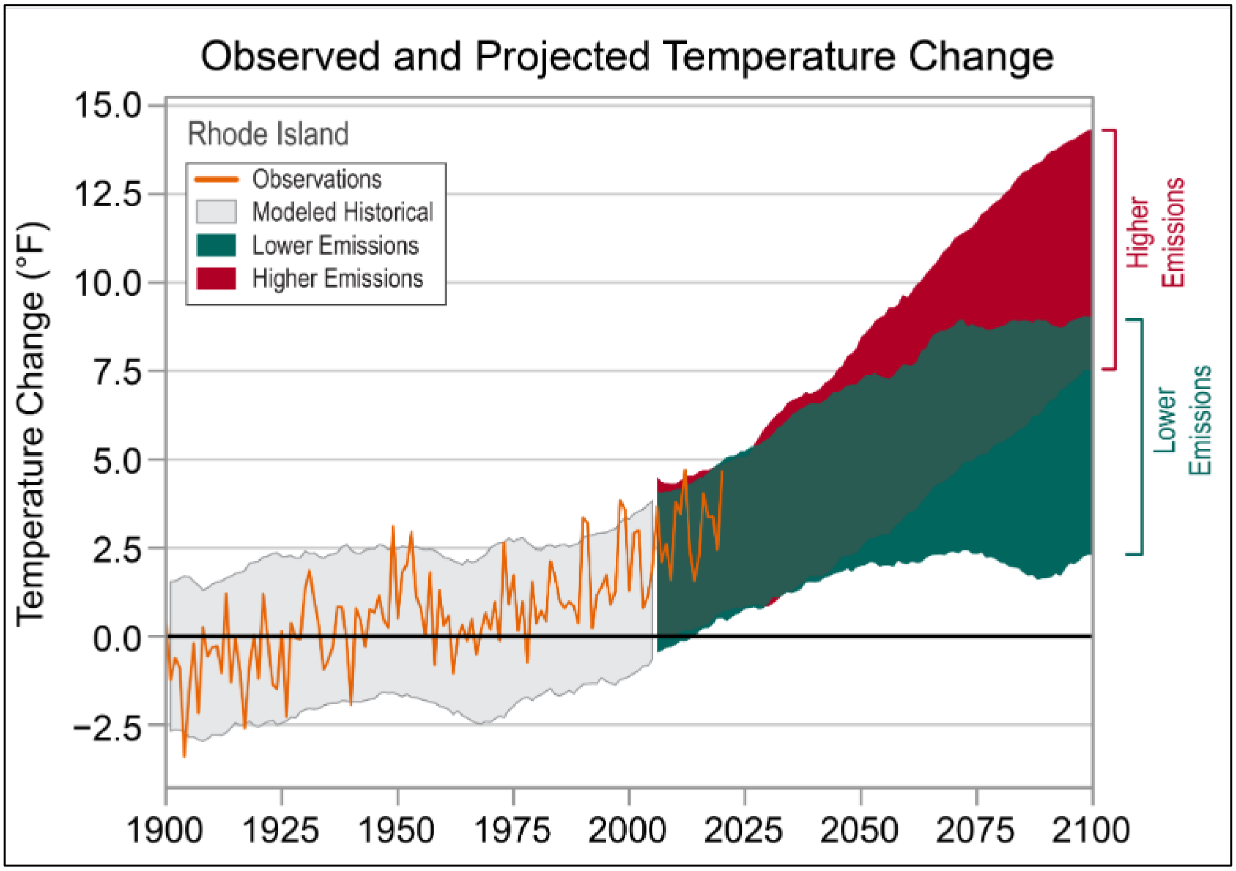


Figure B 5-3: Observed and Projected Temperature Change in Rhode Island
(Source: NOAA State Climate Summary 150-RI)

Precipitation: **Observations**

NCA4 (Dupigny-Giroux et al, (2018)) summarized changes that were observed over a period of 115 years from 1901 to 2016, for a grid of latitudes and longitudes that covered the contiguous United States. Maximum daily precipitation was reviewed for this grid, and it was noted that the 20-year-return-level precipitation had increased in each of the four seasons for the Northeast Region. The total increase in inches for winter was 0.08 inches; for spring 0.25 inches; for summer 0.16 inches; and for fall 0.23 inches.

The same database was reviewed to demonstrate that the size of a 5-day maximum daily precipitation had increased over 1901 to 2016 by 27% in the Northeast, and it was noted that the frequency of exceedances of the 5-year 2-day precipitation (as it had been at the start of the observation period) had increased by 74%, in the Northeast during this period; when the shorter, more recent period 1958 to 2016, was reviewed, the percentage increased from 74% to 92%. The 99th percentile annual 1-day precipitation had increased by 55% for the Northeast for the period 1958 to 2016.

Observations of summertime weather indicated that although extratropical cyclones seemed to be becoming less frequent since 1979 (by 35%), the associated intensity appeared to be increasing.

In its Volume II, NCA4 noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100. Although annual minimum streamflows had increased over the previous century, it was expected that late-summer warming might lead to decreases in the minimum streamflows in the late summer and early fall by the middle of the 21st century.

NCA4 also noted that larger cities in the Northeast are deliberately planning to mitigate impacts of more frequent flooding, and named Providence, RI among these cities. Providence is located at the head of Narragansett Bay in the northern portion of the RI Coastline study area.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. With respect to precipitation in Rhode Island, NOAA reported as follows (Runkle et al 2022):

> *"Annual precipitation in Rhode Island has increased since 1895. Extreme precipitation has increased since 1950, with the highest number of extreme events occurring during the 2005-2014 interval. Continued increases in frequency and intensity of extreme precipitation events are projected."*

Similar to NCA4, NOAA also reported that during the 20th century, precipitation had increased in Rhode Island. Annual precipitation had been above the long-term average for several decades, while summer precipitation has varied. The annual number of extreme precipitation events (number of days with greater than 2 inches) had shown an increasing trend overall, but the number of events was below average in the most recent 6-year period (2015-2020). The 5-year period from 2005 to 2009 was the period with both the greatest annual precipitation and highest number of extreme events (**Figure B 5-4**).

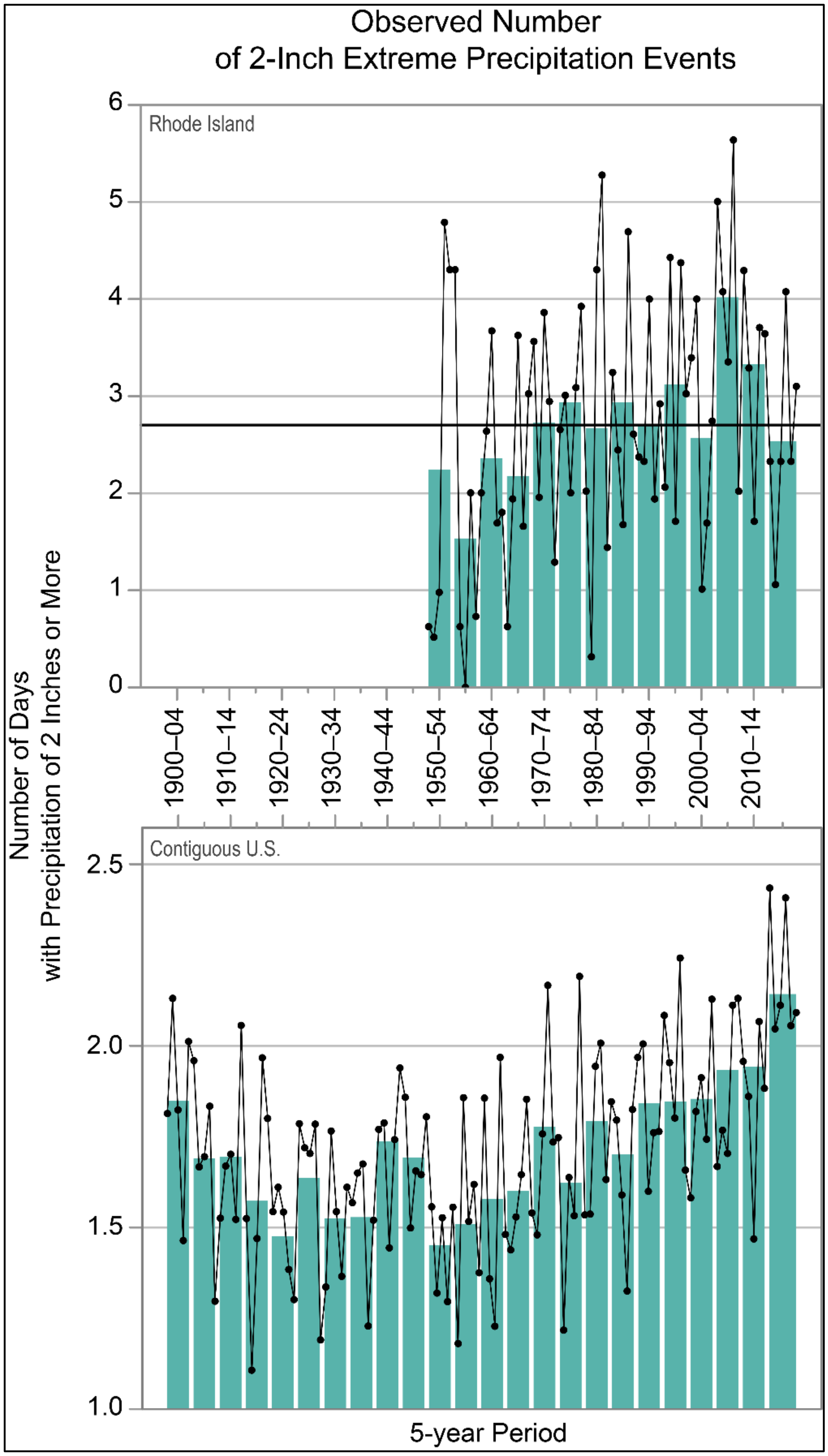


Figure B 5-4: Observed Number of Extreme Precipitation Events in Rhode Island (Source: NOAA State Climate Summary 150-RI)

Precipitation: Projections

NCA4 (Dupigny-Giroux et al, (2018)) reviewed modeling results that indicated increases in precipitation in the New England region of about 10% in all four seasons. They reference Janssen et al. (2016), in a review of modeling results, and summarized the following: extreme heavy precipitation was expected to manifest in a tripling of the frequency of storms previously designated "5-year return period storms" throughout the US, with the greatest increases being in the Northeast. The projected size of a "20-year" storm was projected to increase by 10 to 13% by mid-21st-century, and by 14 to 22% by late-21st century, for the New England region. Trends associated with hurricanes were less clear from the modeling.

Hayhoe et al (2007) and Hayhoe et al (2008) reviewed seasonal data to develop trends in New England. Rawlins et al (2012) reviewed seasonal data since 1971 and developed supporting seasonal trend data, for a wider northeastern US region (included New York, New Jersey, Philadelphia). Ahmed et al (2013) reviewed New England data from 1976-1995 for their own climate-based projection models.

Thibeault and Seth (2014) assumed a high greenhouse gas emissions scenario to develop projections for the Northeast Region, some of which had statistically significant increases of 1.5 mm/day. Liu et al (2013) projected increases in winter and fall precipitation over the period 1971-2055, largely offset by slight increases in the severity of droughts. Rawlins et al (2012) reviewed data since 1971 to develop projections of increases in precipitation through 2070 in New England of 12% in winter; 10% in spring; -2% (less rainy) in summer; and 3% in autumn.

For the RI Coastline study area, the ranges were 8 to 10% in winter, 6 to 8% in spring; not designated in summer; and 2 to 6% in autumn. These results can be inferred from review of **Figure B 5-5**.

The changes in projected seasonal total precipitation noted in the previous paragraph suggest a potential shift in flood seasonality. Winter and spring precipitation have important implications for flood risk management as increases in precipitation during this time of year may exacerbate flooding within the RI Coastline study area.

Thibeault and Seth (2014) reported seasonal findings and projections in support of seasonal findings and projections by Hayhoe et al (2007) and Hayhoe et al (2008) for the New England area, who reported projections through 2099. ***The Hayhoe et al (2008) results included an estimate of a 5-mm (0.2 inch) per day increase in precipitation, with more intense storms (10 to 15%) occurring more often (12 to 13% more per year), and the wettest annual 5-day period expected to contain 20% more volume by the end of the 21st century***. Ahmed et al (2013) created two climate model ensembles, using data from 1976-1995 and projecting to 2065: the average number of rain-days exceeding 10 mm (0.4 inch) increased by 0 to 4 days per year by 2065 under both scenarios, although the frequency and intensity of big storms were less clear (depended on the location). Huntington et al (2009) noted that an increase of up to 10% in annual precipitation was expected by the end of the 21st century, although there was limited agreement between models; the projected increase in winter precipitation, however, was a common theme, as summarized in NCA4 (Volume II) from NOAA (Dupigny-Giroux et al, 2018), who noted recent increases in rainfall intensity throughout the Northeast, with expected increases in monthly precipitation of about 1 inch during the months December through April by 2100.

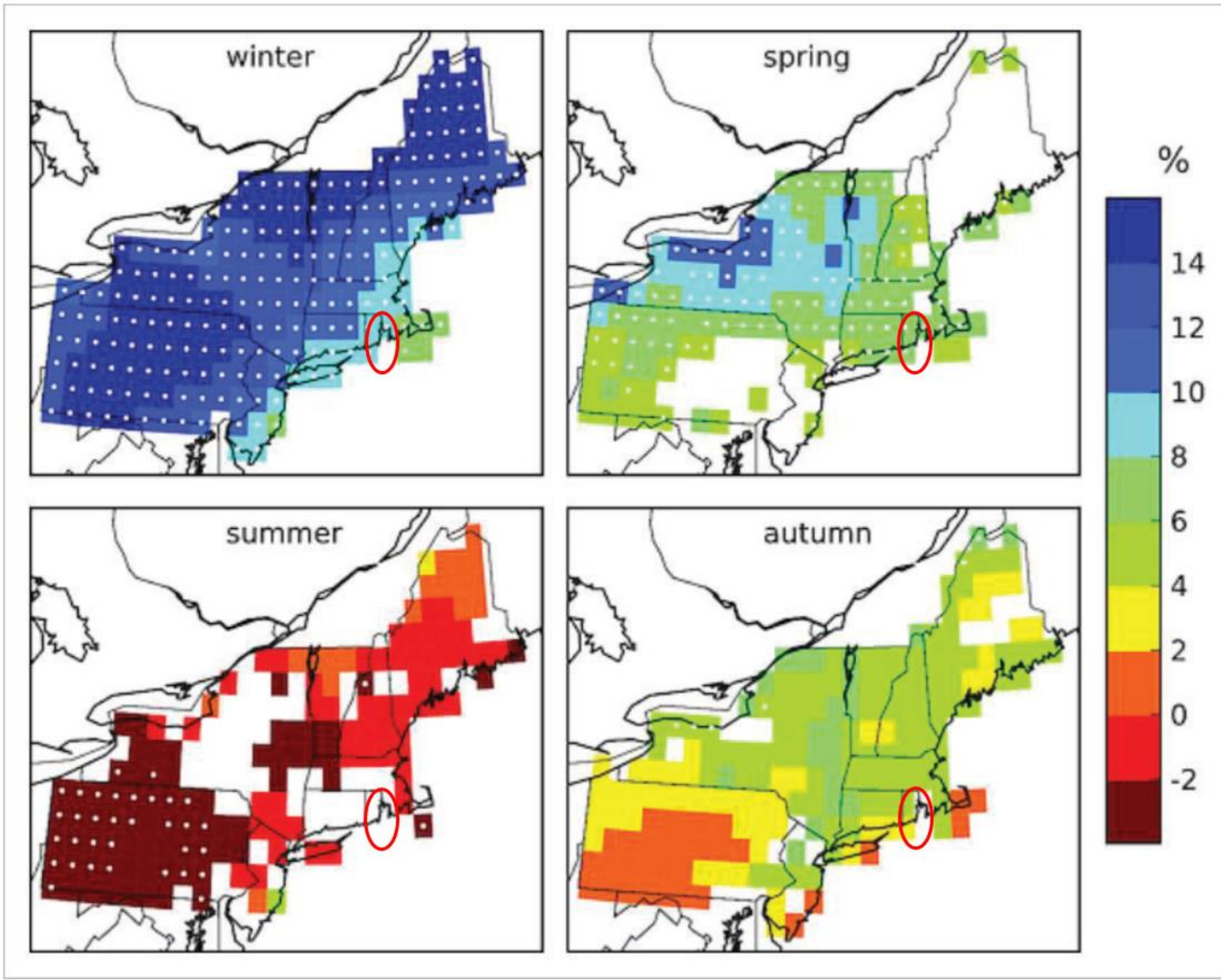


Figure B 5-5: Projected changes in seasonal precipitation volumes, 1971-2000 compared with 2041-2070, as a percent of 1971-2000 precipitation volumes (Rawlins et al. 2012). The RI Coastline study area is indicated with a red oval.

Similar to NCA4, NOAA reported average annual average precipitation is projected to increase in Rhode Island over the 21st century, with those increases coming in the winter and spring. In addition, NOAA reported that the number of extreme precipitation events was projected to increase, potentially increasing flooding risks.

Streamflow: Observations

NCA4 (Wehner et al, 2017 in Wuebbles et al, 2018) indicated a possibility of increased frequency of large storms. The response in runoff to precipitation was less readily apparent:

- The winter snow-deposition season appeared to be shrinking over time, so there would be less snow to melt, generating runoff, in the spring.
- The mix of rain to snow was changing (more rain, less snow, so the sudden rain-on-snow snowmelt runoff events would occur with less total runoff being generated, and more opportunities for water to seep into the soil as opposed to increasing the measured runoff.
- For hurricanes and tropical storms, which are an important driver of flooding events in the eastern United States, the expected drier conditions in the summer months would serve to promote hydrologic losses such that intense thunderstorms might produce substantial precipitation, but more of this would be lost to infiltration.

NCA4 noted that possible deforestation, urbanization, dams, floodwater management activities, or changes in agricultural practices were important factors in statistics connecting runoff and precipitation. The report noted “Projection of future changes is thus a complex multivariate problem.”

Kalra et al (2008) reviewed historical streamflow data for 1951-2001 and found no statistically significant trend in the New England Region for either annual or seasonal streamflow. Small et al (2006) studied flow records in 1948-1997, essentially confirming this “no-trend” finding, but noting also that two stations had a statistically significant decrease in low flows. Armstrong et al (2012) reviewed 23 gage records at “undisturbed” sites and noted that for 22 of the sites, low-magnitude floods were increasing in frequency and magnitude, and that the result was significant at $p<0.1$ for 10 of the stations. Hayhoe et al (2007) reviewed peak spring runoff data since 1950, noting that the peak was occurring earlier by approximately 0.3 days per decade over 1950 to 2000, but with no significance stated; runoff volumes and 7-day annual minimum values presented less clear results.

Hodgkins et al (2003) used a more robust measure of peak flow timing at 27 New England stations (center-of-volume date for the January-through-May winter-spring period and the center-of-volume date for the June-through-December summer-fall period) in the 20th century. Half of these stations (14 of 27) exhibited a $p<0.1$ significant trend of earlier dates for winter/spring; four of the stations also had earlier summer/fall dates. The NCIA (Frumhoff et al, (2007)) noted that in the Northeast Region over the 20th century the date of spring thawing of lake ice had shifted earlier by 9 days in the northern part of the region to 16 days over the southern region.

The U.S. Geologic Survey (USGS) (Zarriello et al (2012)) reviewed the multiple-week high-flow events in much of Rhode Island in the spring of 2010, seeking to establish exceedance probabilities for the rainfall/snowmelt/runoff events that had been observed, through a review of relevant USGS gage data at 44 gages: 21 in Rhode Island, 9 in Massachusetts, and 14 in Connecticut. Zarriello et al (2012) noted that the event appeared to have an annual exceedance probability (AEP) of between 0.002=1/500 and 0.02=1/50. The study noted caveats concerning the changing degree of urbanization (potentially increasing runoff in a given rainfall event) and the extent of regulation upstream from many of the gages (potentially reducing runoff through upstream storage and slower releases), and added a section on nonstationarity and review of recent trends in which “the magnitude of a flood with a given exceedance probability, on average, would be 6, 13, and 21 percent greater in 10, 20, and 30 years, respectively. Trends and their effects can only be ascertained by continued monitoring of streamflow and the continued development of the science of nonstationarity in flood frequency analysis.” The conclusions included that a 1/100-year storm, assuming a continuation of linear trends over the previous 30 years, was likely to have a 1/73-year AEP in 10 years; a 1/55-year AEP in 20 years; a 1/43-year AEP in 30 years.

NOAA has published a set of individual state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future conditions of sea level and coastal flooding. With respect to flooding in Rhode Island, NOAA reported as follows (Runkle et al 2022):

> *“Since 2000, summer precipitation was above average until the most recent 6-year period (2015–2020), which was below average. Rhode Island experienced the largest number of 2-inch extreme precipitation events in the 10-year period of 2005–2014. In 2010, major rainfall from a nor’easter in late March caused the worst flooding in the state’s history. This event set an all-time monthly precipitation record in Providence of 16.34 inches, superseding the previous record of 15.38 inches, which was recorded in October 2005. The flooding of 2010 resulted in an estimated $43 million in national flood insurance claims in the state.”*

Streamflow: Projections

The NCA4 report (Wehner et al (2017) in Wuebbles et al (2018)) made reference to a report by Tebaldi et al (2006), prepared for the Federal Insurance and Mitigation Administration of Federal Emergency Management Agency (FEMA). Tebaldi et al (2006) had developed a regression-based approach of scaling river gauge data based on seven commonly used climate change indices from the Coupled Model Intercomparison Project (CMIP5) database and found that at the end of the 21st century the 1% annual change exceedance floodplain area would increase in area by about 30%. NCA4 noted also that AECOM (2013) had indicated that there would be larger changes in the Northeast and Great Lakes regions and smaller changes in the central parts of the country and the Gulf Coast.

Thomson et al (2005) used two GCMs with various input assumptions to model flows across the United States. For the New England region, the results indicated little to no change over time, and the small change that was indicated, forecast as water yield, was positive in one case and negative in the other, but appeared to register differences smaller than 15 mm in either case.

Hagemann et al (2013) reviewed runoff trends based on a set of GCM simulations. The models indicated runoff increases of up to 3.1 inches per year, with larger increases in the winter and smaller increase in the spring. For the New England region, however, the modeled projections demonstrated appreciable uncertainty, based on setting the starting boundary conditions (seeding), as well as with the models' GCM assumptions.

Frumhoff et al. (2007) noted changes in seasonal timing of runoff (10 days shift for the spring peak flow by 2100), and that the probability of high-flow events may increase by up to 80%, especially in Maine, New Hampshire, and Vermont. Drought frequency was expected to increase due to reductions in summer runoff and soil moisture, with a reduction of 10% for the 7-day annual minimum low flow that occurs with an average return period of 1 year (7Q1).

USACE (2015) summarized a two-model GCM study with estimates of 60 to 200 mm increase (approximately 2.5 to 8 inches) in annual runoff expected for the USACE planning horizon 2071-2100, compared to the period 1971-2000.

The runoff response to extreme storms (for example, 100-year or larger) was less clear, and USACE (2015) includes the statement, "There is little consensus in the literature regarding future projections of annual streamflow volumes, but in general spring streamflow peaks are expected to arrive earlier in the year and may increase in volume."

Both USACE (2015) and CDM Smith (2012) cautioned that hydrologic parameters were a significant source of uncertainty.

Summary: Recent climate literature indicates that there is evidence of observed, increasing mean air temperature trends in the study region. Winter temperatures may be increasing faster than in other seasons. The literature points to an increasing trend in the number and temperature of extreme heat days. Mean temperatures are projected to rise by 5.3 to 9.1 °F by the end of the 21st century.

Total precipitation and the occurrence of extreme storm events is increasing over time. Precipitation, especially winter precipitation, is expected to increase. Two studies projected an increase during the 21st century in winter precipitation of 1 inch per month for the months of December to April. Snowmelt and the spring thaw of lake ice have been observed to occur earlier in the year.

Despite the observations of increasing precipitation over the 20th century, there is little evidence of significant increases in streamflow over the same period. One study citing results of multiple GCM models and scenarios could not definitively project a change in expected peak flows in the New England region.

USGS reviewed recent flooding and concluded that there did appear to be a trend of increasing flooding over time.

NOAA reported that average annual precipitation was projected to increase in the Rhode Island over the 21st century, particularly during winter and spring. Corresponding increases in temperature would increase the proportion of precipitation falling as rain rather than snow. In addition, extreme precipitation was projected to increase, potentially increasing the frequency and intensity of floods.

The findings are summarized for the New England region in **Figure B 5-6**.

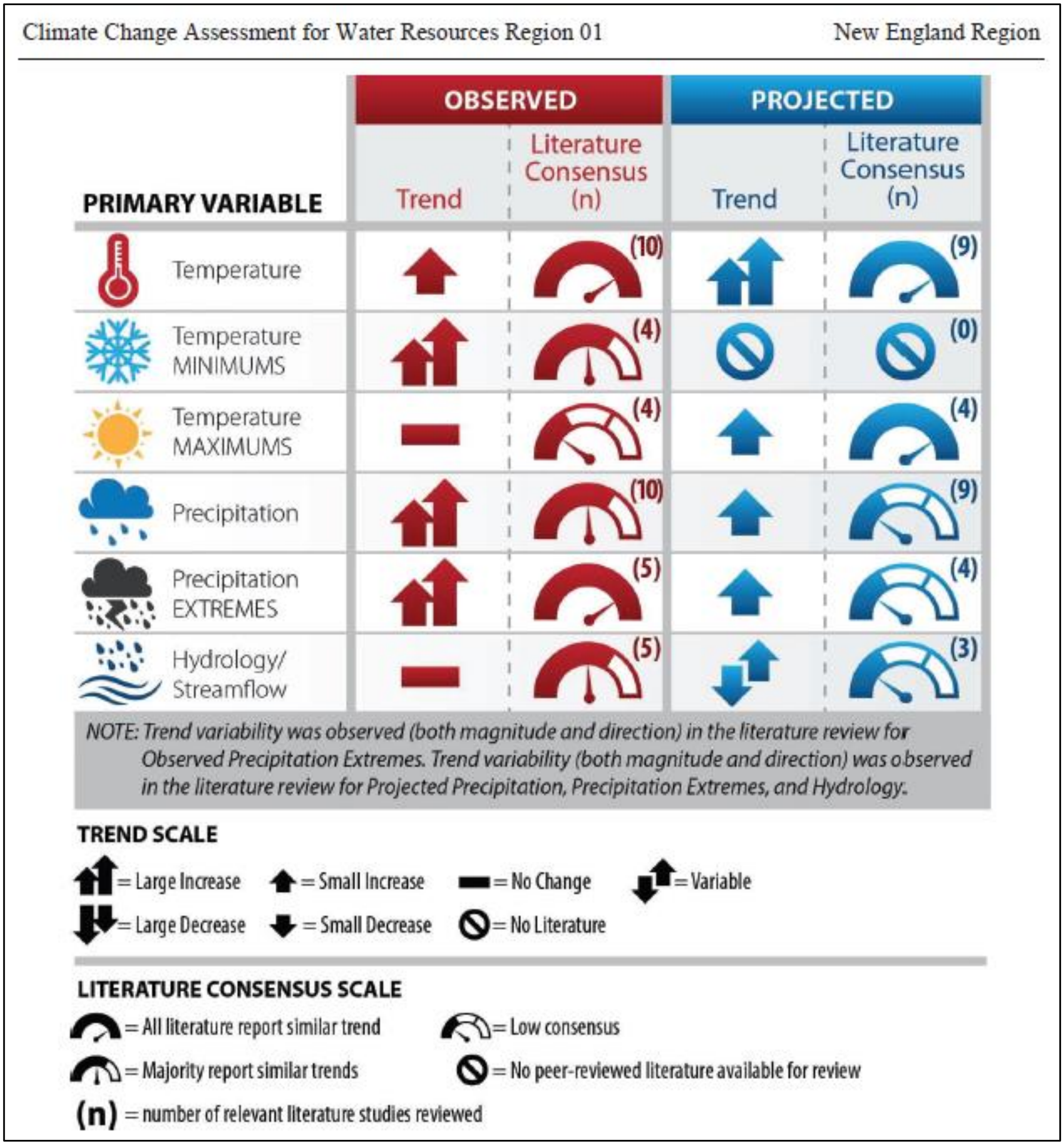


Figure B* 5-6*: Summary matrix of observed and projected climate trends (USACE 2015)

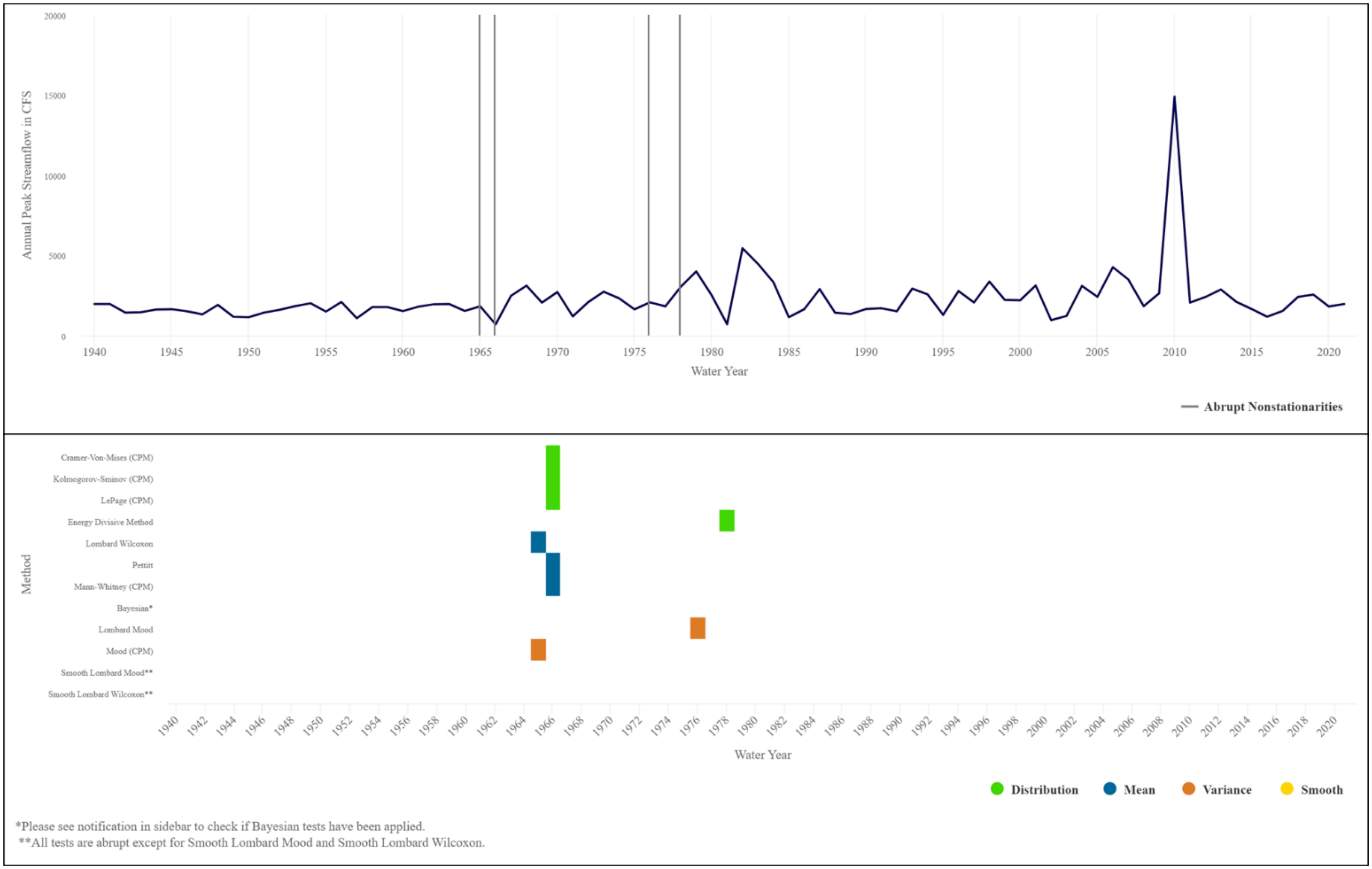
5.2. Nonstationarity Detection

The assumption that discharge datasets are stationary (their statistical characteristics are unchanging) in time underlies many traditional hydrologic analyses. Statistical tests can be used to test this assumption using techniques outlined in Engineering Technical Letter (ETL) 1100-2-3. The Nonstationarity Detection (NSD) tool is a web-based tool to perform these tests on datasets of annual peak streamflow at USGS stream gages. Although this study's focus is coastal storm risk management, the potential for riverine flooding was also investigated for structural measures where pump stations were considered. Therefore, peak streamflow was used to represent future trends and is the primary focus of this assessment.

For this study, the NSD tool was applied using annual peak streamflow data from USGS gage 01116500, Pawtuxet River at Cranston, RI. This gage was selected given it captures the largest drainage area, 200 square miles, of the USGS stream gages in the study area. The USGS water year summary states that flows are regulated by powerplants and Scituate Reservoir 13 mi upstream, Flat River Reservoir, and other reservoirs. This is similar to other gages within the study area which are also regulated by upstream diversions to water supply and reservoirs. While the basin areas for the Scituate (94 square miles) and Flat River (58 square miles) Reservoirs are sizeable, there is still a significant drainage area above the Pawtuxet River gage which is unregulated. Annual peak data has been collected since 1939. The NSD tool applies analysis to the period of record from 1940 to 2021.

As shown in **Figure B 5-7**, USGS gage 01116500 has strong evidence of a nonstationarity about water years 1965 and 1966. A strong nonstationarity is one that demonstrates a degree of consensus, robustness, and a significant increase or decrease in the sample mean and/or variance. The 1965-1966 nonstationarity is identified by multiple tests targeted at identifying a change in the overall statistical distribution (see green bars in **Figure B 5-7**), indicating consensus. The 1965-1966 nonstationarity can be considered robust because tests targeted at identifying nonstationarities in different statistical properties identify a change in overall distribution (green bars), mean (blue bars), and variance (orange bar) in **Figure B 5-8**. The magnitude of the mean annual peak flow increases considerably from 1,600 cfs between 1940 and 1964 to 2,600 cfs between 1967 to 2021, as shown in **Figure B 5-8**. The Energy Divisive Method identified a distribution change in water year 1978 and the Lombard Mood test identified a variance change in water year 1976. However, without consensus or robustness from other tests, there is insufficient evidence to reject the null hypothesis of statistical stationarity at this site.

The strong nonstationarity in water years 1965-1966 indicates that it could be beneficial to analyze the data as two subsamples. Analyzing the subset of record from 1940 to 1964 found no statistically significant trends using the Mann-Kendall (p-value = 0.43>0.05) and Spearman Rank Order (p-value = 0.44>0.05) tests applied using a 0.05 level of significance, nor additional nonstationarities. As shown in **Figure B 5-9**, no strong nonstationarities were detected in the subset of record from 1967 to 2021. The Smooth Lombard Wilcoxon test identified a smooth change between 2012 and 2014, but without consensus or robustness from other tests, there is insufficient evidence to reject the null hypothesis of statistical stationarity at this site. Additionally, no monotonic trends are detected in the peak streamflow dataset between 1967 and 2021 using the Mann-Kendall (p-value = 0.79>0.05) and Spearman Rank Order (p-value = 0.74>0.05) tests applied using a 0.05 level of significance.



5.3. Figure B 5-7: Output of the Nonstationarity Detection Tool for USGS Gage 01116500, Pawtuxet River at Cranston, RI

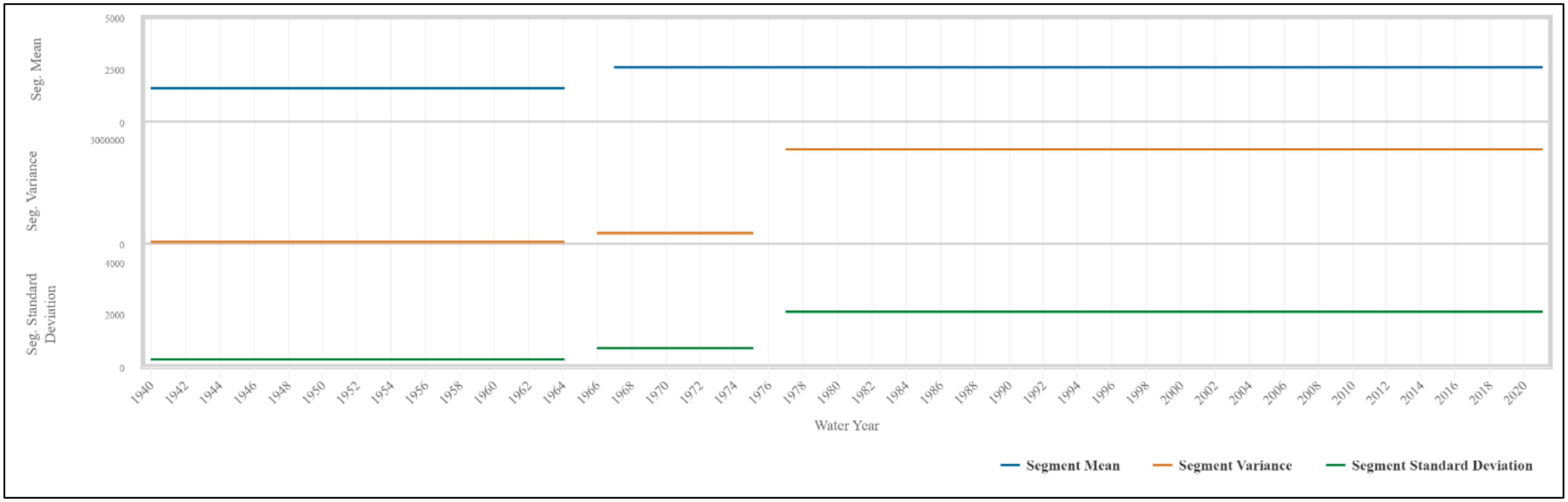


Figure B 5-8: Segment statistics from Nonstationarity Detection Tool for USGS Gage 01116500, Pawtuxet River at Cranston, RI

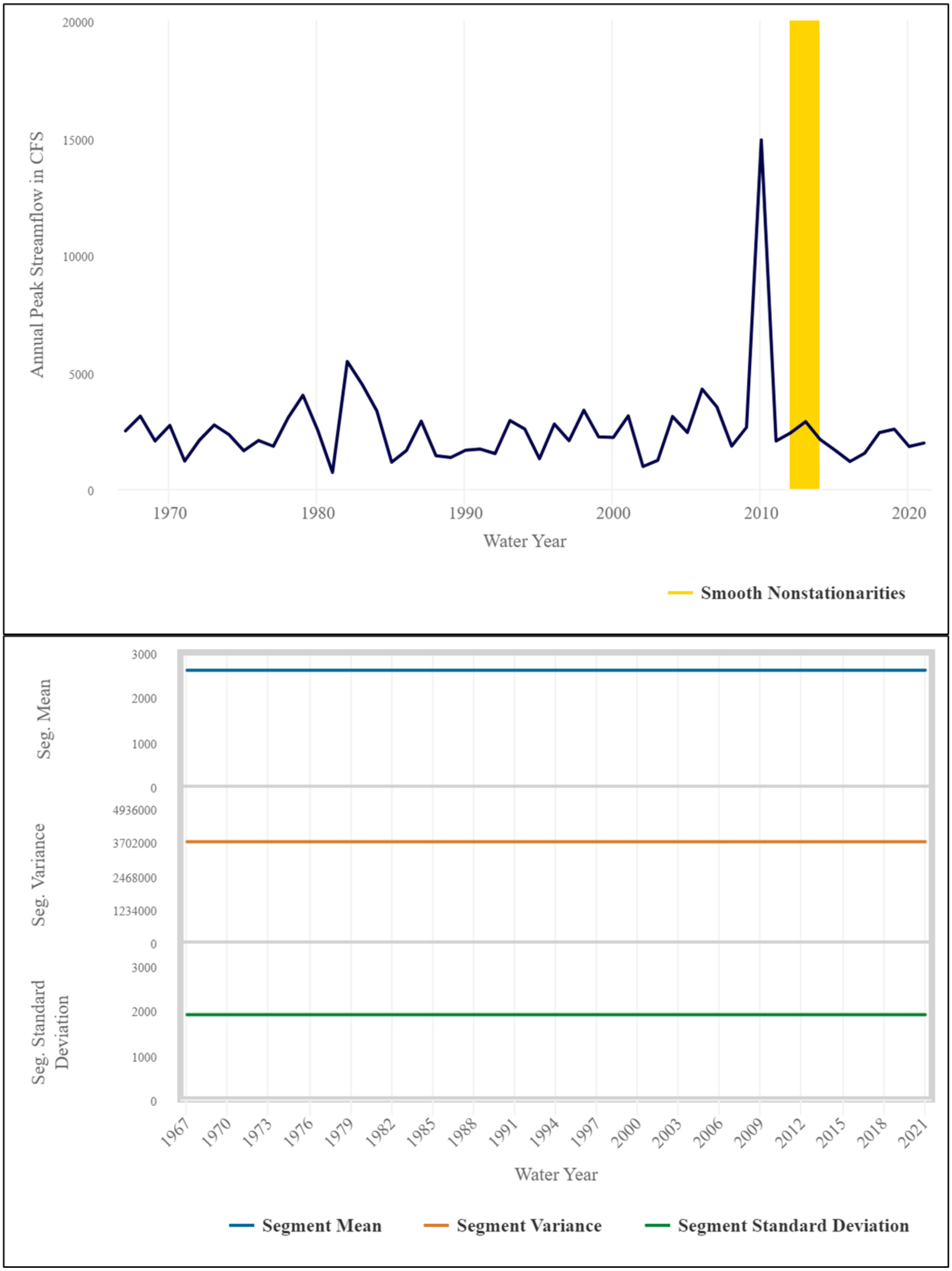


Figure B **5-9:** Output of the Nonstationarity Detection Tool for USGS Gage 01116500, Pawtuxet River at Cranston, RI, for the subset of record water years 1967 to 2021

5.4. Climate Hydrology Assessment Tool

The USACE Climate Hydrology Assessment Tool (CHAT) can be used to assess projected, future changes to streamflow, precipitation, and temperature in the watershed. Projections are at the spatial scale of a HUC-8 watershed, with flows generated using the U.S. Bureau of Reclamation (USBR) Variable Infiltration Capacity (VIC) model from temperature and precipitation data, statistically downscaled from 32 GCM models using two different sets of assumptions regarding accelerated CO_2 levels as greenhouse gas outputs.

While the NSD tool focuses on change points and the presence of a trend in observed data, the CHAT allows for analysis of the magnitude and significance of the trends in simulated, unregulated historical and projected, future data. The CHAT displays spatially-downscaled, hydrologically-simulated and statistically-aggregated CMIP5 GCM outputs available at daily temporal resolution for calendar years 1950-2099. Baseline historic simulations span the timeframe 1950-2005; these historic simulations assume greenhouse gas emissions to be equivalent to a reconstruction of historically-observed greenhouse gas emission levels. Projected future simulations span the timeframe 2006-2099, which represent projected, climate-changed meteorology where various representative concentration pathways (RCP) (aka "scenarios") of greenhouse gas emissions are assumed. CHAT utilizes projected future GCM simulations that were based on accelerated CO_2 levels for RCP 4.5 and RCP 8.5. RCP 4.5 represents rising radiative forcing stabilizing at 4.5 W/m^2 before 2100, and RCP 8.5 represents rising radiative forcing pathway leading to 8.5 W/m^2 in 2100, where radiative forcing expresses the change in energy in the atmosphere due to greenhouse gas emissions.

The RI Coastline study area is largely situated in HUC 01090004 (Narragansett, in the Massachusetts-Rhode Island Coastal HUC 0109). **Figure B 5-10** shows the range of output presented in the CHAT using 64 combinations of GCMs and RCPs applied to generate the climate-changed hydrology using the USBR VIC model. For both the earlier 1950-2005 and the later 2006-2099 periods, the range of data is indicative of the uncertainty associated with projected, climate-changed hydrology (each is the result of combined outputs from the 32 models).

Figure B 5-11 shows the results of the trend analysis for the modeled timeseries from the CHAT. For the Narragansett HUC (HUC 01090004), both the pre-2006 and post-2006 tests appeared to have a positive slope (on average, more flow from year to year). However, there was significant change in the slopes of the computed trendlines; in the outputs, the pre-2006 slope value was approximately 0.11; and the three standard tests failed to detect a trend at the selected alpha = 0.05 level. For the later post-2006 section, the gradient of the computed trend line was more steeply positive, with a slope of 4.51; t-Test, Mann-Kendall, and Spearman Rank-Order statistical significance tests all yielded significance values well below alpha = 0.05, indicating detection of a statistically significant trend. Therefore, although there is not enough evidence to suggest a trend in the simulated, historic variable values, the statistically significant change in projected future variable values suggests that there will be changes in the future without project conditions due to climate change for the

Narragansett HUC 01090004 watershed in the Massachusetts-Rhode Island Coastal HUC 0109.

It is important to recognize that although there may be significant trends in the inter-model mean value of simulated variable data, there is still a wide range of projected future hydroclimate conditions. Therefore, it is recommended that the trend analysis shown in **Figure B 5-11** be viewed in conjunction with **Figure B 5-10** which shows the inter-model range of simulated hydroclimatology.

As seen in **Figure B 5-12** and **Figure B 5-13**, similar trends were modeled for the neighboring Cape Cod (HUC 01090002) and Pawcatuck-Wood (HUC 01090005) HUCs, of which the south coast of Little Compton and Block Island are parts, respectively.

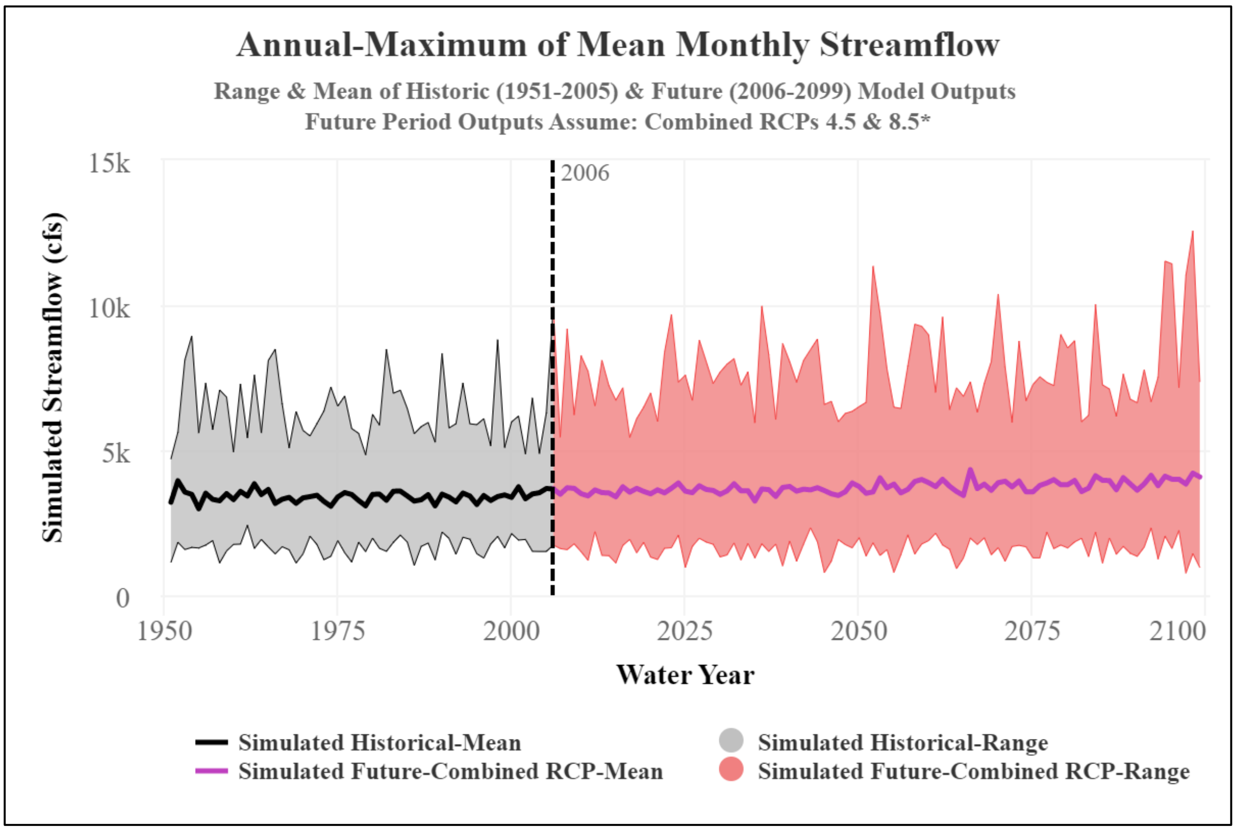
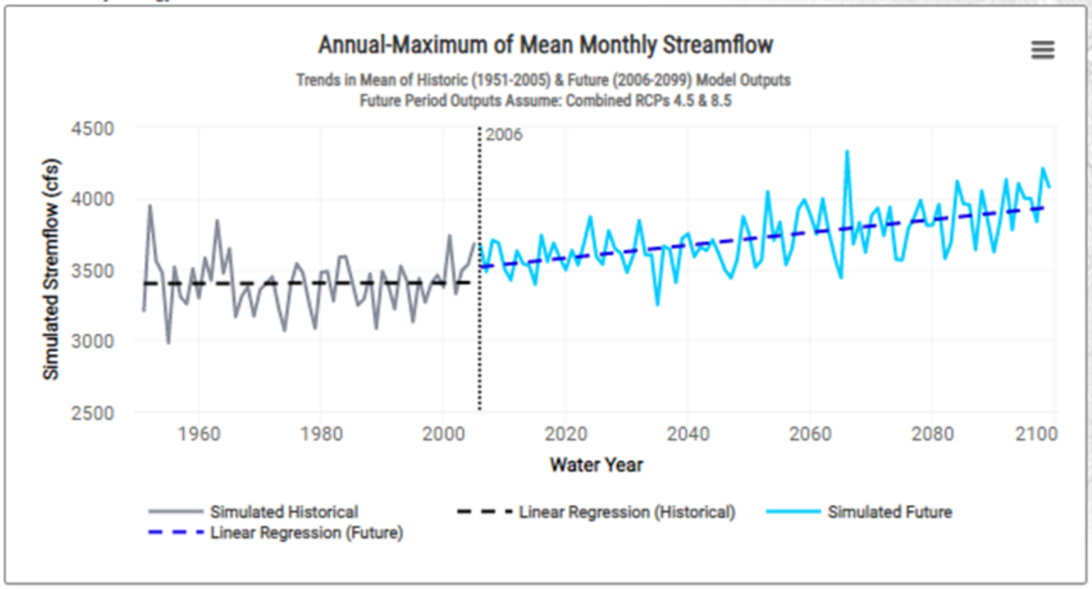


Figure B 5-10: Range of 64 Climate-Changed Hydrology Model Output for Narragansett watershed (HUC 01090004)

HUC 01090004 - Narragansett

Climate Hydrology Assessment Tool v2.2



Trend Lines

Simulated Historical (1951 to 2005)	Simulated Future (2006 to 2099)
0.1075 Traditional Slope	**4.5118** Traditional Slope

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.9471
Mann-Kendall	0.69505
Spearman Rank-Order	0.77602

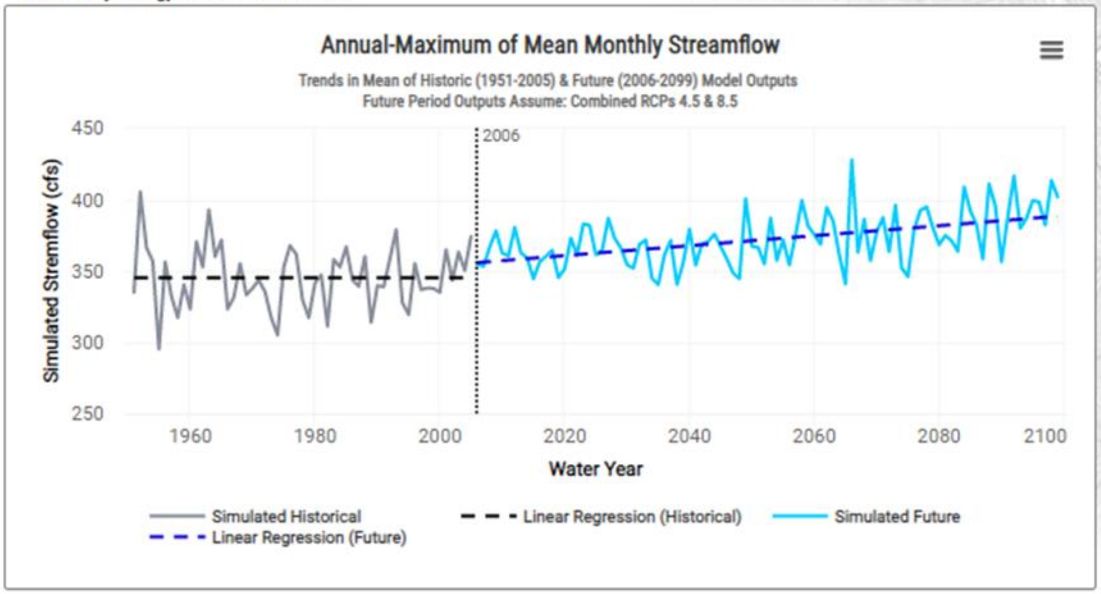
Statistical Signficance Tests (Future)

Test	p-value
t-Test	1.0831e-1< 2.2e-16**
Mann-Kendall	< 2.2e-16**
Spearman Rank-Order	1.7543e-1< 2.2e-16**

Figure B 5-11: Projected annual maximum of mean monthly flows for the Narragansett watershed (HUC 01090004) (Pre-and Post-2006 Time Periods)

HUC 01090002 - Cape Cod

Climate Hydrology Assessment Tool v2.2



Trend Lines

Simulated Historical (1951 to 2005)

2e-04
Traditional Slope

Simulated Future (2006 to 2099)

0.3496
Traditional Slope

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.99921
Mann-Kendall	0.8276
Spearman Rank-Order	0.78888

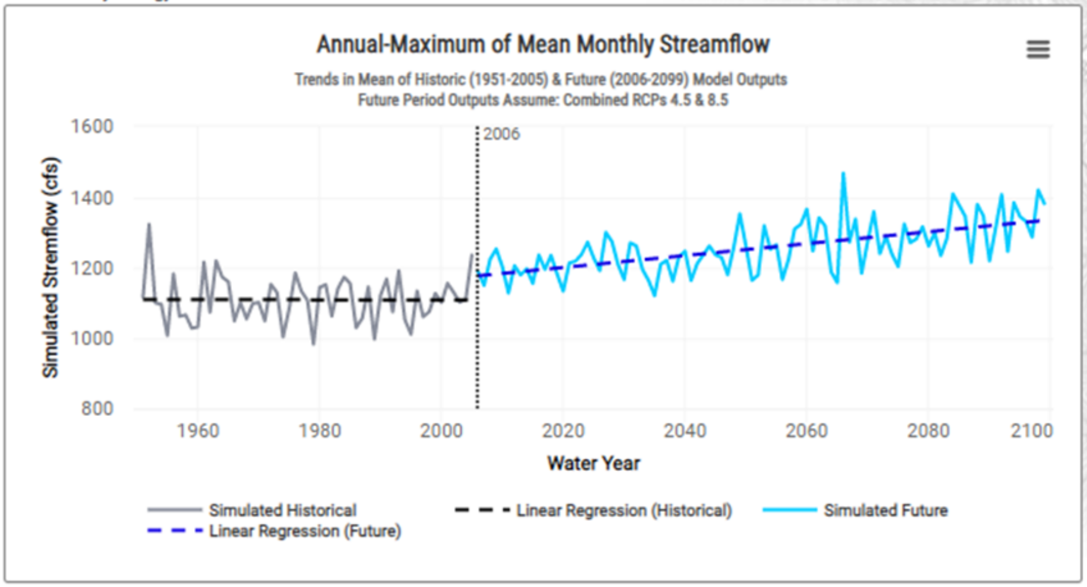
Statistical Signficance Tests (Future)

Test	p-value
t-Test	1.4159e-07**
Mann-Kendall	9.5367e-07**
Spearman Rank-Order	2.6652e-07**

Figure B 5-12: Projected annual maximum of mean monthly flows for the Cape Cod watershed (HUC 01090002) (Pre-and Post-2006 Time Periods)

HUC 01090005 - Pawcatuck-Wood

Climate Hydrology Assessment Tool v2.2



Trend Lines

Simulated Historical (1951 to 2005)	Simulated Future (2006 to 2099)
-0.0391 Traditional Slope	**1.6909** Traditional Slope

Statistical Significance Tests (Historical)

Test	p-value
t-Test	0.94556
Mann-Kendall	0.63185
Spearman Rank-Order	0.61976

Statistical Signficance Tests (Future)

Test	p-value
t-Test	1.4515e-11**
Mann-Kendall	< 2.2e-16**
Spearman Rank-Order	1.2604e-11**

Figure B 5-13: Projected annual maximum of mean monthly flows for the Pawcatuck-Wood watershed (HUC 01090005) (Pre-and Post-2006 Time Periods)

5.5. Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment (VA) Tool facilitates a screening-level, comparative assessment of the vulnerability of a given business line and HUC-4 watershed to the impacts of climate change, relative to the other HUC-4 watersheds within the continental United States (CONUS). It uses the CMIP5 GCM-BCSD-VIC dataset (2014) to define projected hydrometeorological inputs, combined with other data types, to define a series of indicator variables to define a vulnerability score.

Vulnerabilities are represented by a weighted-order, weighted-average (WOWA) score generated for two subsets of simulations (wet—top 50% of cumulative runoff projections; and dry—bottom 50% cumulative runoff projections). Data are available for three epochs. The epochs include the current time period ("Base") and two 30-year, future epochs (centered on 2050 and 2085). The Base epoch is not based on projections and so it is not split into different scenarios. For this application, the tool was applied using its default, National Standard Settings. In the context of the VA Tool, there is some uncertainty in all of the inputs to the vulnerability assessments. Some of this uncertainty is already accounted for in that the tool presents separate results for each of the scenario-epoch combinations rather than presenting a single aggregate result.

As shown in **Figure B 5-14**, the Massachusetts-Rhode Island Coastal Basin (HUC 0109) watershed is not considered vulnerable to climate change impacts for the flood risk reduction business line, since it is not among the 20% most vulnerable watersheds for this business line in the CONUS (202 HUC04s). This is true for both the wet and dry scenarios and both the 2050 and 2085 epochs. Although the HUC 0109 watershed is not considered vulnerable in a relative sense to impacts from climate change, it may still be vulnerable in an absolute sense.

The primary drivers of the flood risk vulnerability assessment for wet scenarios under the two epochs are indicators **568C** and **568L**, both titled Flood Magnification. **568C** (cumulative) is a ratio of flood runoff to monthly runoff exceeded 10% of the time (including freshwater inputs); **568L** (local) is the same ratio, but it does not include upstream watershed). Other indicators were: **590**, the number of urban acres within the 500-year floodplain; the **277** runoff-precipitation ratio; and **175C** annual covariance (an index comparing monthly mean runoff and monthly mean precipitation).

In both projected epochs, and for both the wet and dry scenarios, the VA/WOWA score remained below the level of the top 20% of vulnerabilities. The score for the wet scenario was roughly 10% greater than for the dry scenario in each epoch. The scores increased by approximately 5% between the earlier and the later epochs, for both the wet and the dry scenarios. The increases over time indicate that there might be a later epoch (than the late 21st century) in which the vulnerability of the Massachusetts-Rhode Island Coastal Basin (HUC 0109) to climate change impacts with respect to the flood risk business line would result in a "vulnerable" assessment, scored in comparison to other HUC-4 basins. The scores are summarized in **Table B 5-1**, and the indicators themselves are listed in **Table B 5-2**.

Neighboring VA analyses, for adjacent HUC-4 basins, had the same “0 HUC(s) vulnerable” overall result.

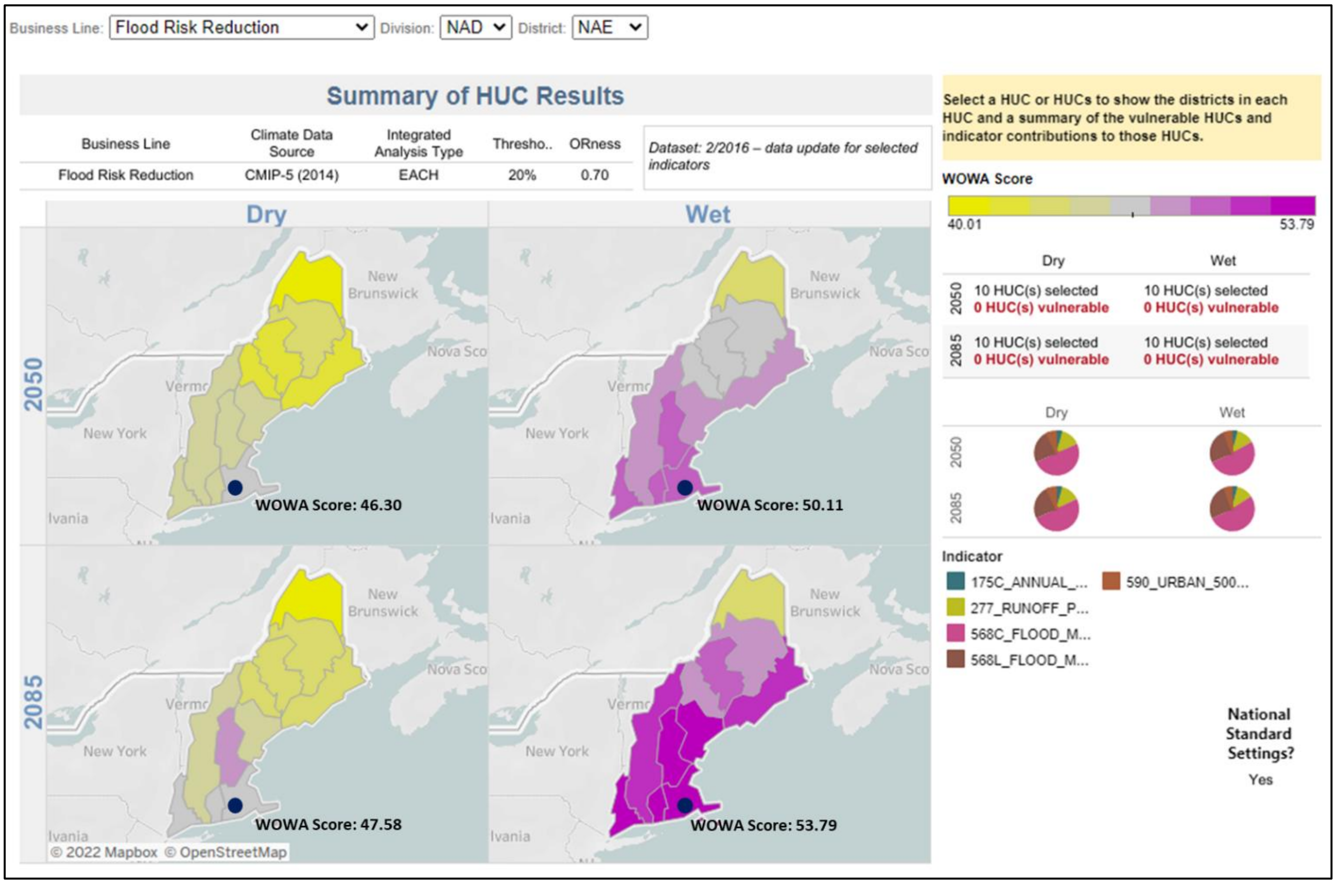


Figure B 5-14: Output of the VA Tool indicates the Massachusetts-Rhode Island Coastal Basin watershed is not among the 20% most vulnerable CONUS watersheds for the Flood Risk Reduction business line under wet and dry scenario projections in both the 2050 and 2085 epochs

Table B 5-1: Projected Vulnerability with respect to Flood Risk Reduction

HUC4 Watershed	Projected Vulnerability with Respect to Flood Risk Reduction			
	Flood Risk Reduction Vulnerability Score			
	2050 Dry	2050 Wet	2085 Dry	2085 Wet
Massachusetts-Rhode Island Coastal Basin (0109)	46.30	50.11	47.58	53.79

Table B 5-2: Comparison of Different Indicators for the Massachusetts-Rhode Island Coastal Basin

Massachusetts-Rhode Island Coastal Basin (0109)				
Indicator	**Indicator Contributions to WOWA Flood Risk Reduction Vulnerability Score (percentages)**			
	2050 Epoch		**2085 Epoch**	
	Dry	**Wet**	**Dry**	**Wet**
568C Flood Magnification – change in flood runoff: ratio of indicator 571C (monthly runoff exceeded 10% of the time, including upstream inputs) to 571 in base period. *See* ***Footnote***	48.12	49.22	48.28	49.96
568L Flood Magnification – change in flood runoff: ratio of indicator 571L (monthly runoff exceeded 10% of the time, excluding upstream freshwater inputs) to 571L in base period. *See* ***Footnote***	15.80	24.87	15.85	25.25
590 Urban 500-year Floodplain Area – Acres of urban area within the 500-year floodplain	24.39	14.94	24.51	14.37
277 Runoff Precipitation – Median of: deviation of runoff from monthly mean times average monthly runoff divided by deviation of precipitation from monthly mean times average monthly precipitation	8.76	8.22	8.38	7.73
175C Annual Covariance – long-term variability in hydrology: ratio of the standard deviation of annual runoff to the annual runoff mean. Includes upstream freshwater inputs (cumulative)	2.92	2.76	2.69	1.45

Footnote:
The 568C and 568L *indicator values* are the same, but their *importance weights* are not. The overall WOWA score (vulnerability score) accounts for the *indicator value* and the *importance weights* to compute the vulnerability score. This is why the WOWA scores listed in the VA tool have different values.
"Some indicators are more directly relevant to a business line than others, so giving every indicator the same weight would be inappropriate – Instead, the tool uses subjective weights that assign more weight to indicators that are highly relevant or important." – VA User Manual

5.6. Conclusion

Recent climate science literature indicates observed trends of rising mean and extreme temperatures. The literature indicates observed precipitation mean and extreme values show rising trends. The literature is equivocal, however, on projected stream runoff trends. As a result, projections of future streamflows are mixed and depend on the climate model and its assumptions. Observed trends in streamflow vary by season, but some evidence exists of increasing flows on average.

Observed annual peak streamflow data from 1940 to 2021 was reviewed within the NSD. The nonstationarity analysis did identify a strong nonstationarity in water years 1965-1966. The source of the nonstationarity is unknown, as both the Scituate and Flat

River Reservoir dams were in operation prior to the USGS gage's installation and other dams along the river are unregulated and run-of-the-river. Analysis of subsets of the record from 1940 to 1964 and from 1967 to 2021 detected no strong nonstationarities or statistically significant trends.

The CHAT HUC-8 review of simulated annual peaks of streamflows indicated, however, that the peak flows in the Narragansett and neighboring watersheds of the RI Coastline study area were increasing over time. The pre-2006 record had no detectable trend. The post-2006 record, which included forecast estimates to the year 2100, appeared to have a statistically significant monotonic trend of increasing flows over time, but with improbably small alpha-test results. The watershed is not vulnerable in the flood risk management business line relative to other CONUS watersheds. The watershed may still be vulnerable to the impacts of climate change in an absolute sense, as well as sea level change.

As a result, projections of future streamflows are mixed and depend on the climate model and its assumptions (the literature review rather than the site-specific data review). Observed trends in streamflow vary by season, and there is not a consensus of increasing flows on average. There has, however, been an increase in the number of extreme precipitation events. Projected increases in annual precipitation, along with increases in temperature and precipitation falling as rain (rather than snow) may potentially increase the frequency and intensity of floods.

6. EXISTING CONDITIONS

6.1. 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 6-1**, 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 6-2**, are caused by irregular fluctuations in coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents (El Nino). This plot shows the interannual variation of monthly mean sea level and the 5-month running average. The average seasonal cycle and linear sea level trend have been removed.

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

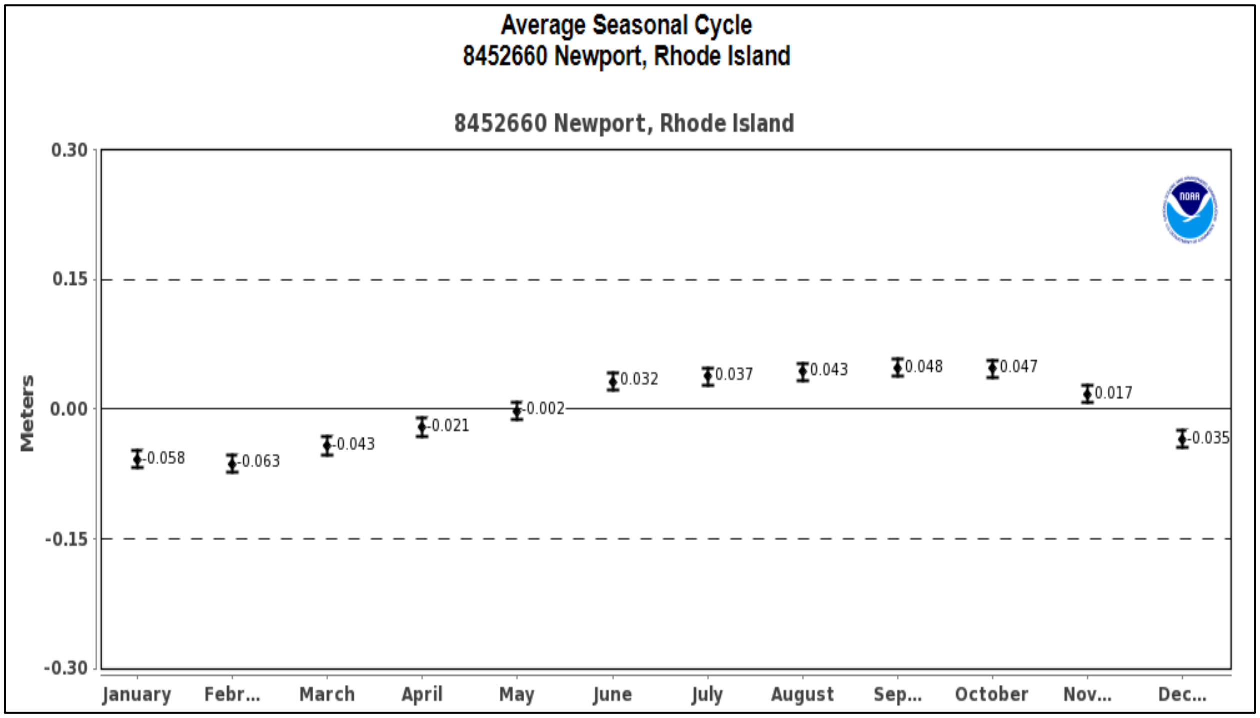


Figure B 6-1: Average seasonal cycle of mean sea level at Newport, RI

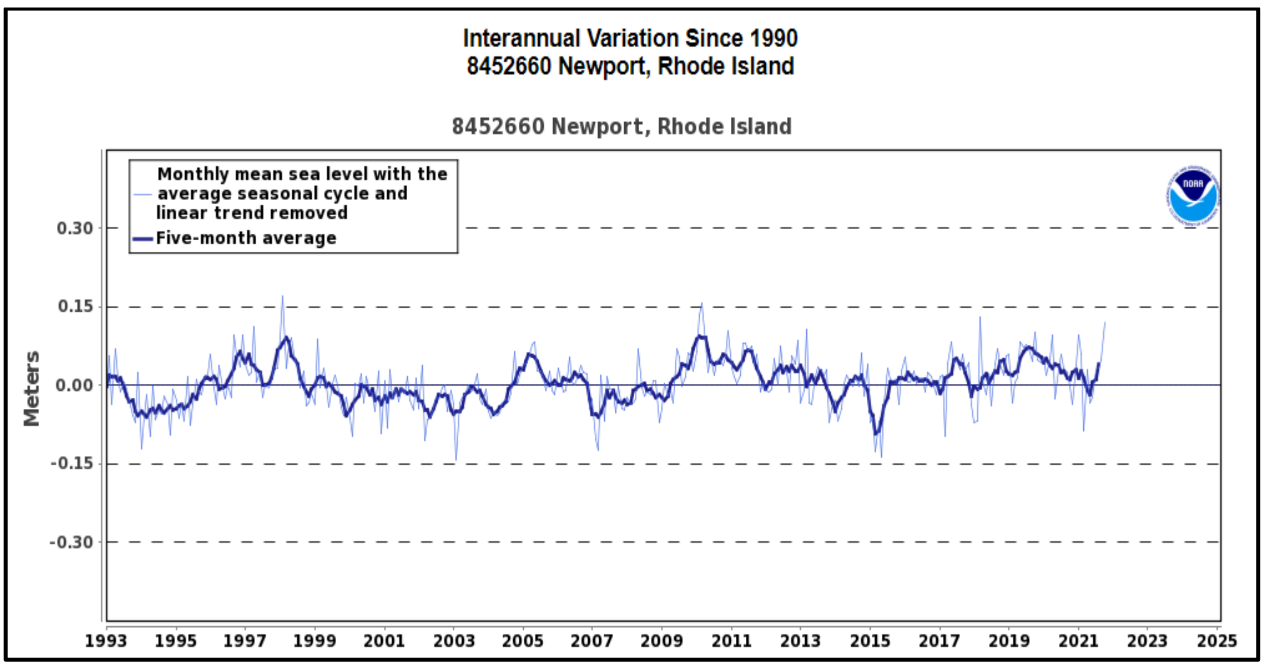


Figure B 6-2: Interannual variation in sea level at Newport, RI

6.2. 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 not including wave action. 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 Rhode Island coastline and increase linearly with distance from the mouth to the head of the bay.

6.2.1. Historic Storms

The study area has experienced flooding from both tropical cyclones and extratropical cyclones. **Table B 6-1** displays the top ten historical storms 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 6-1: 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.

6.2.2. 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 6-2**.

Table B 6-2: 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:

<u>Newport:</u>

- 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 (**Figure B 6-3**).

- 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 (**Figure B 6-4**).

- 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 evacuations of some lower lying areas. Alternate routes may be required as coastal roads become impassable.

Figure B 6-3: Flood stage contours for the Common Fence Point area of Portsmouth

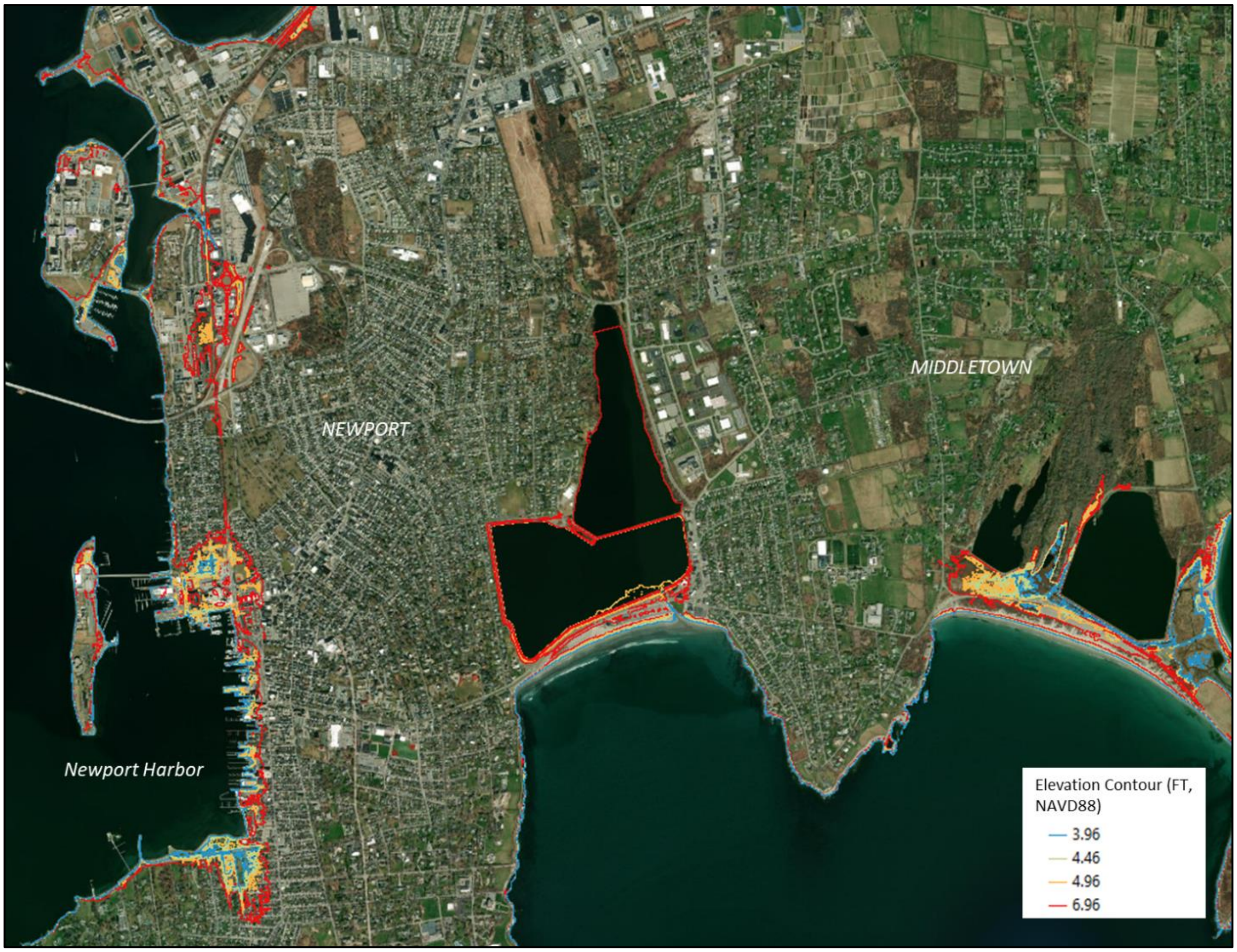


Figure B 6-4: Flood stage contours for Newport Harbor and Newport and Middletown beaches

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 (**Figure B 6-5**), 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 evacuations 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.

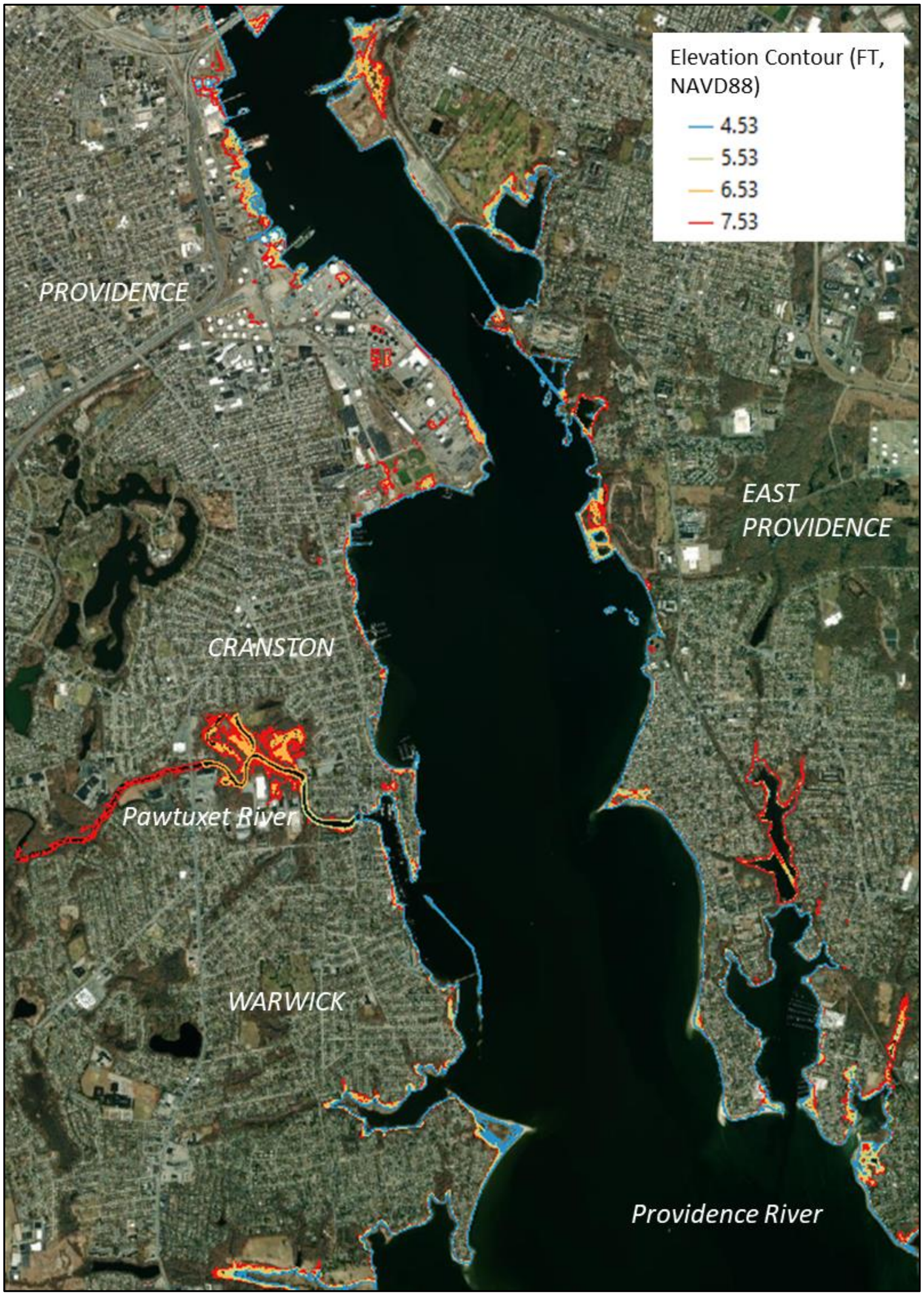


Figure B 6-5: Flood stage contours along the Providence River

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 (**Figure B 6-6**). 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 (**Figure B 6-7**). In Bristol, impacts occur in the vicinity of Bristol Harbor, Route 114, Colt State Park, and the East Bay Bike Path (**Figure B 6-8**). 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.

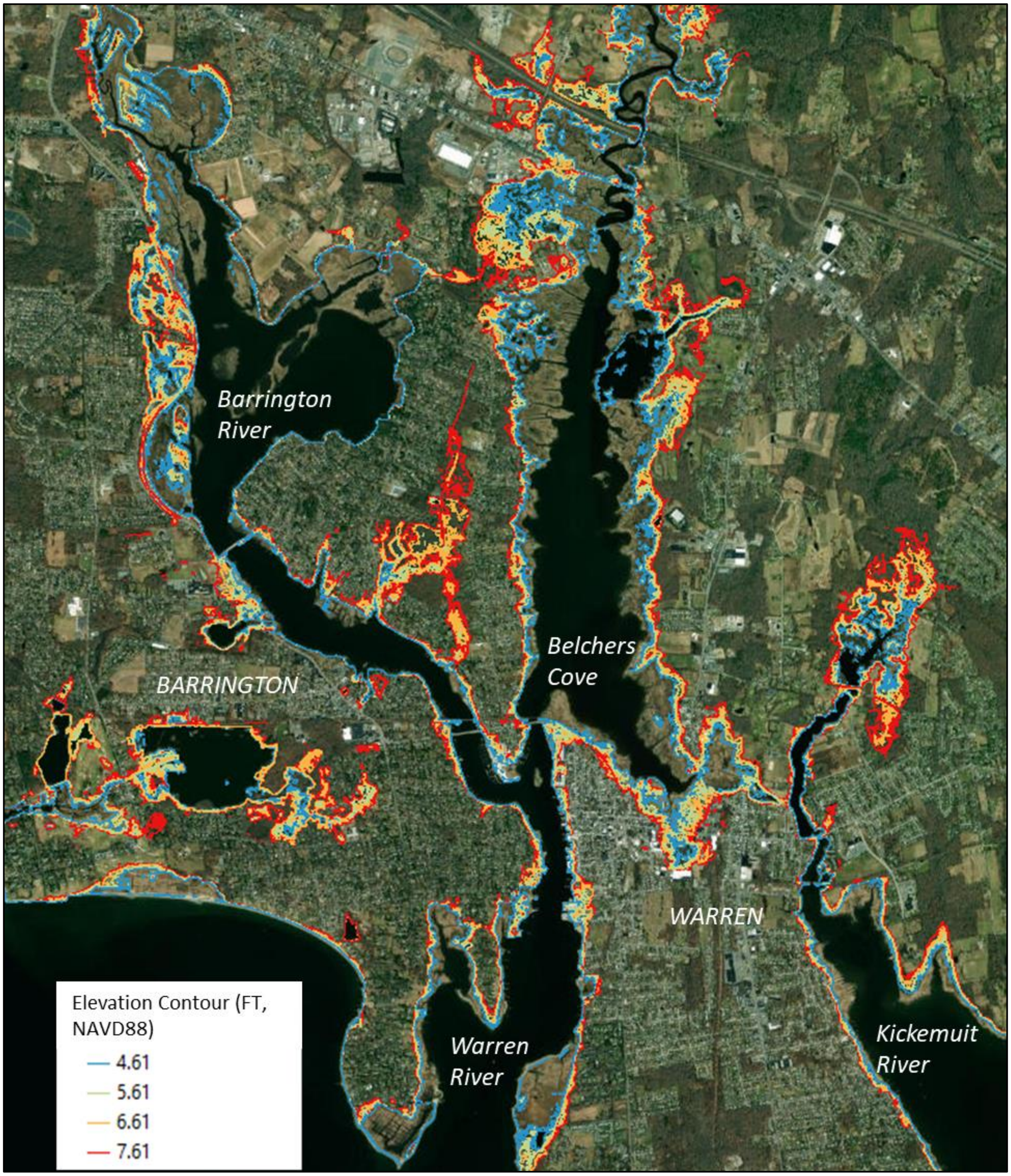


Figure B 6-6: Flood stage contours for Barrington and Warren

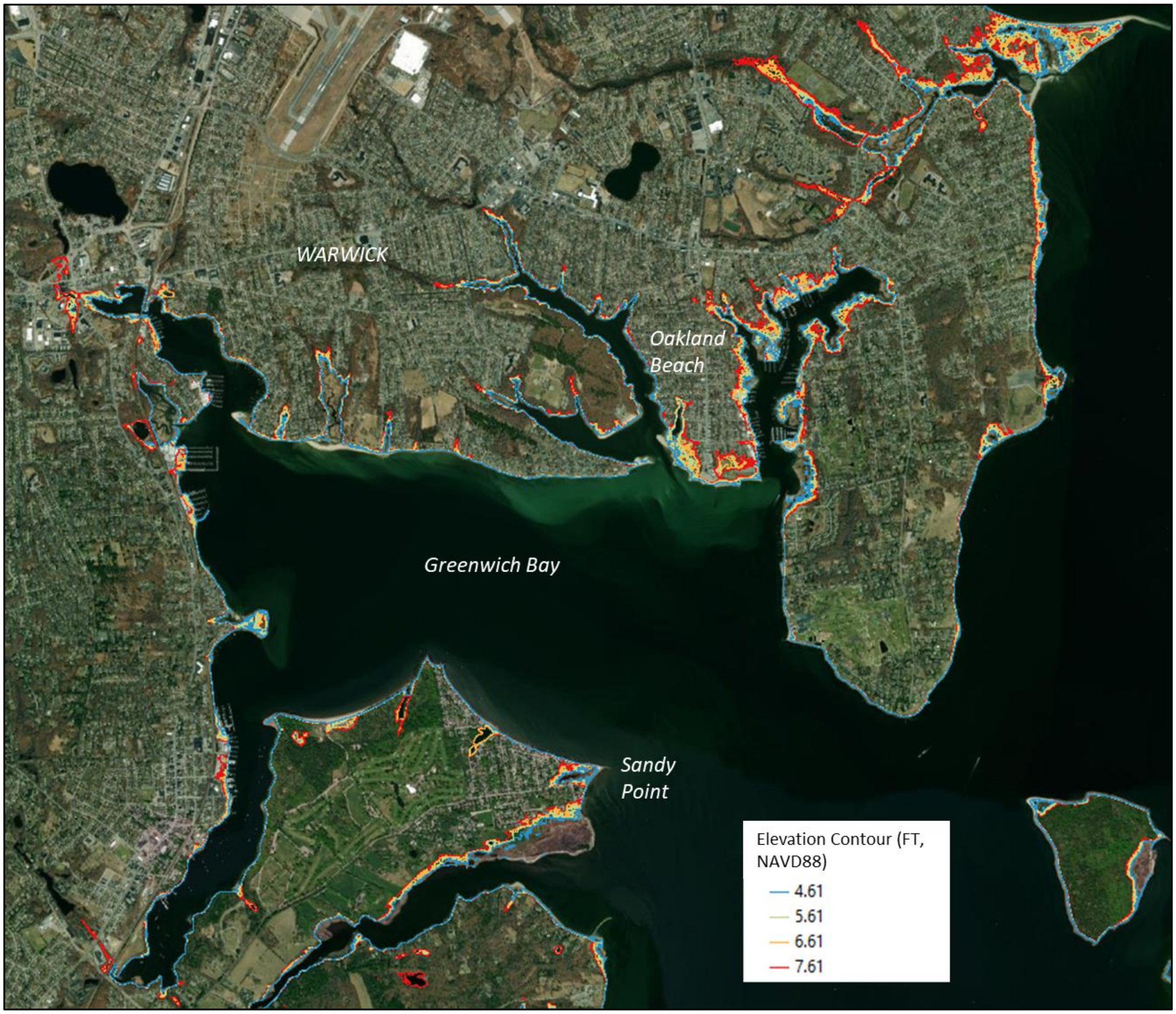


Figure B 6-7: Flood stage contours for Warwick and Greenwich Bay

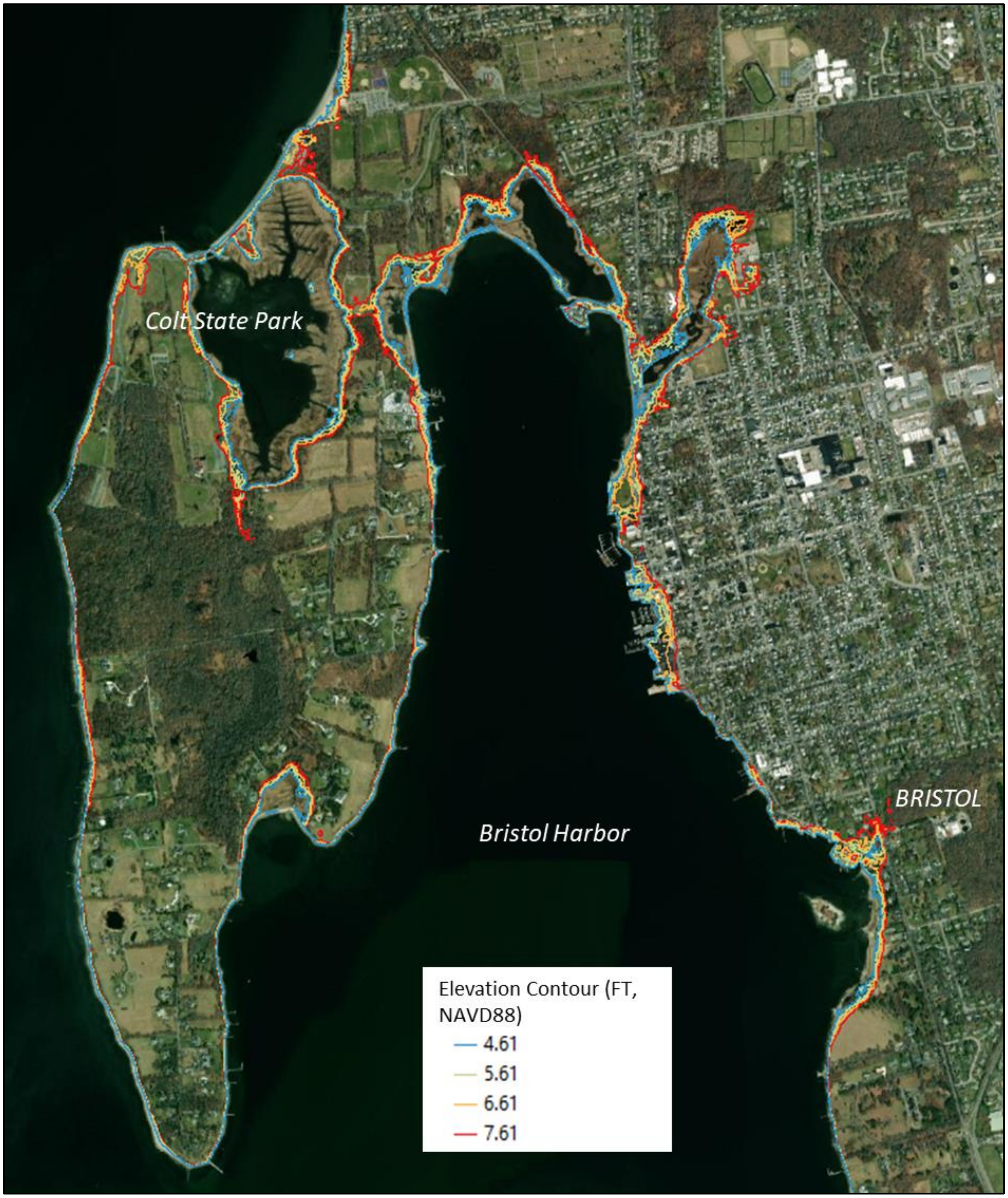


Figure B 6-8: Flood stage contours for Bristol Harbor

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 (**Figure B 6-9**). 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 (**Figure B 6-10**). 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.

Figure B 6-9: Flood stage contours for North Kingstown and Quonset Point

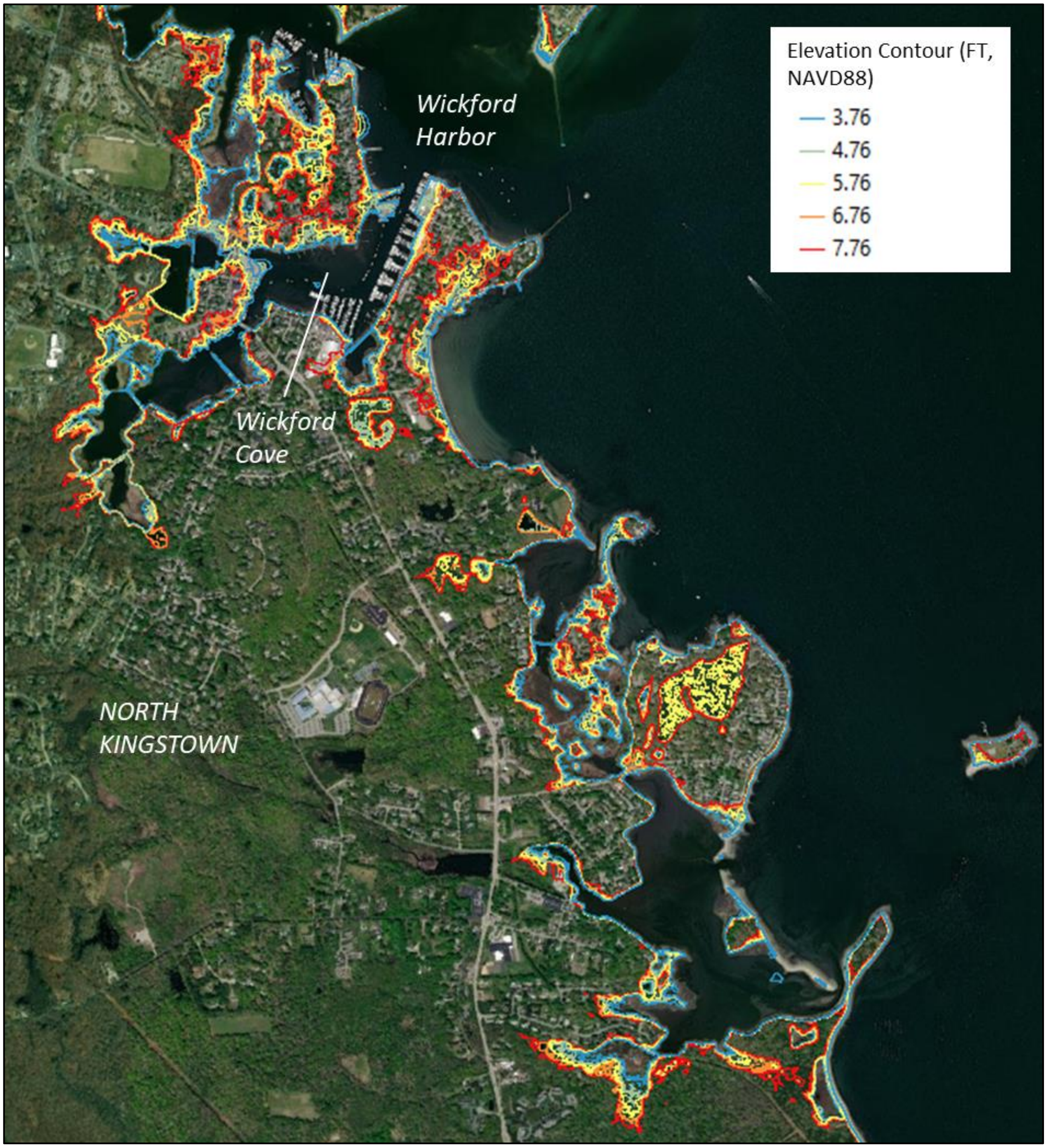


Figure B 6-10: Flood stage contours for North Kingstown and Wickford

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 (**Figure B 6-11**). 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.

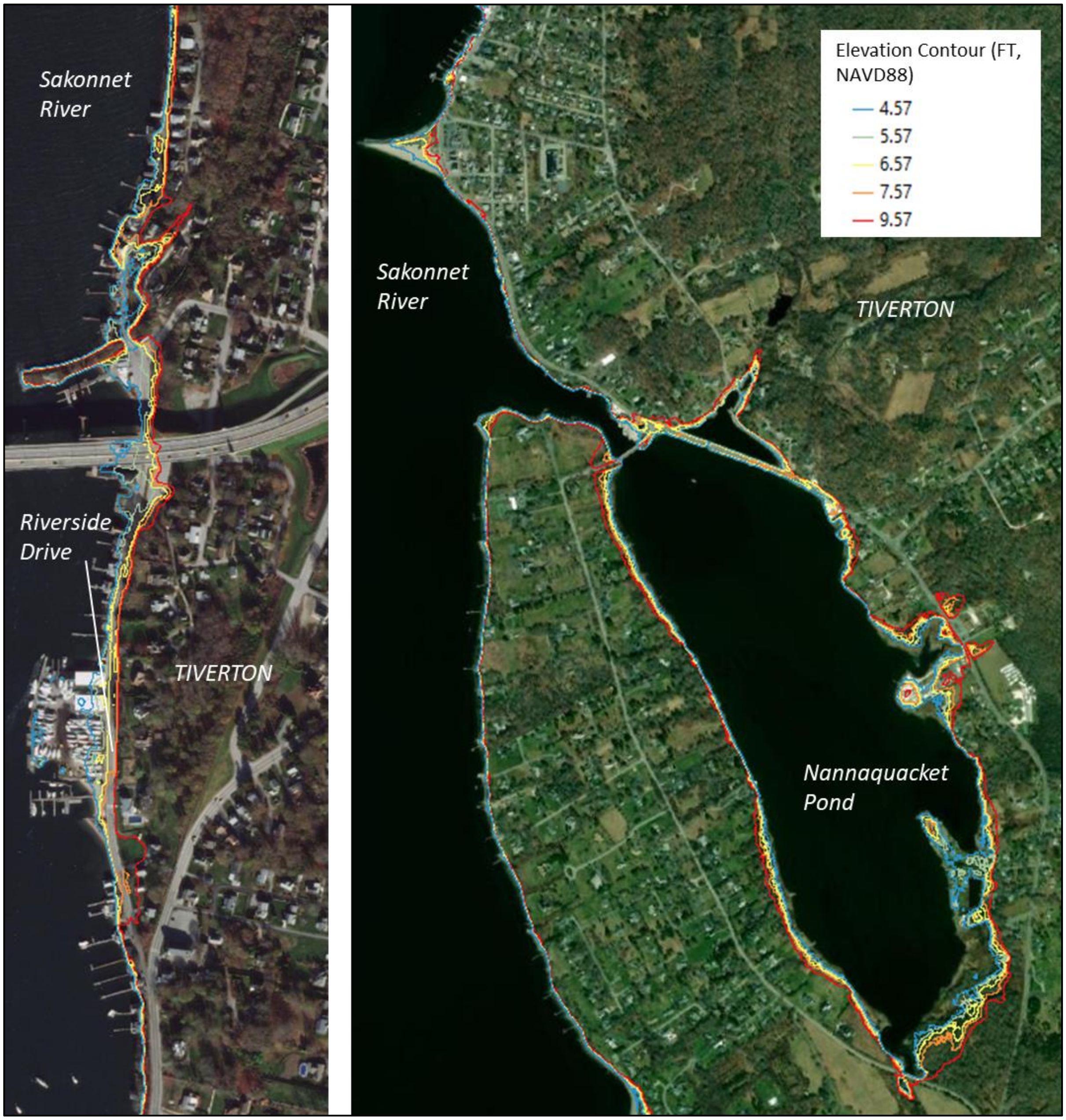


Figure B 6-11: Flood stage contours for Tiverton along Riverside Drive (left) and Nannaquacket Pond (right)

6.2.3. NACCS

The NACCS was authorized under the Disaster Relief Appropriations Act, P. 113-2, in response to Hurricane 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's Coastal and Hydraulics Laboratory (ERDC-CHL) 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.

6.2.4. NACCS Water Levels

NACCS water levels were used directly as coastal forcing inputs to the 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 6-12** depicts the 1-percent annual exceedance probability (AEP) water levels at the mean confidence level at the save points within the study area. The water levels shown do not include sea level rise and are representative of the current NTDE. The amplification in storm surge from south to north within Narragansett Bay is evident.

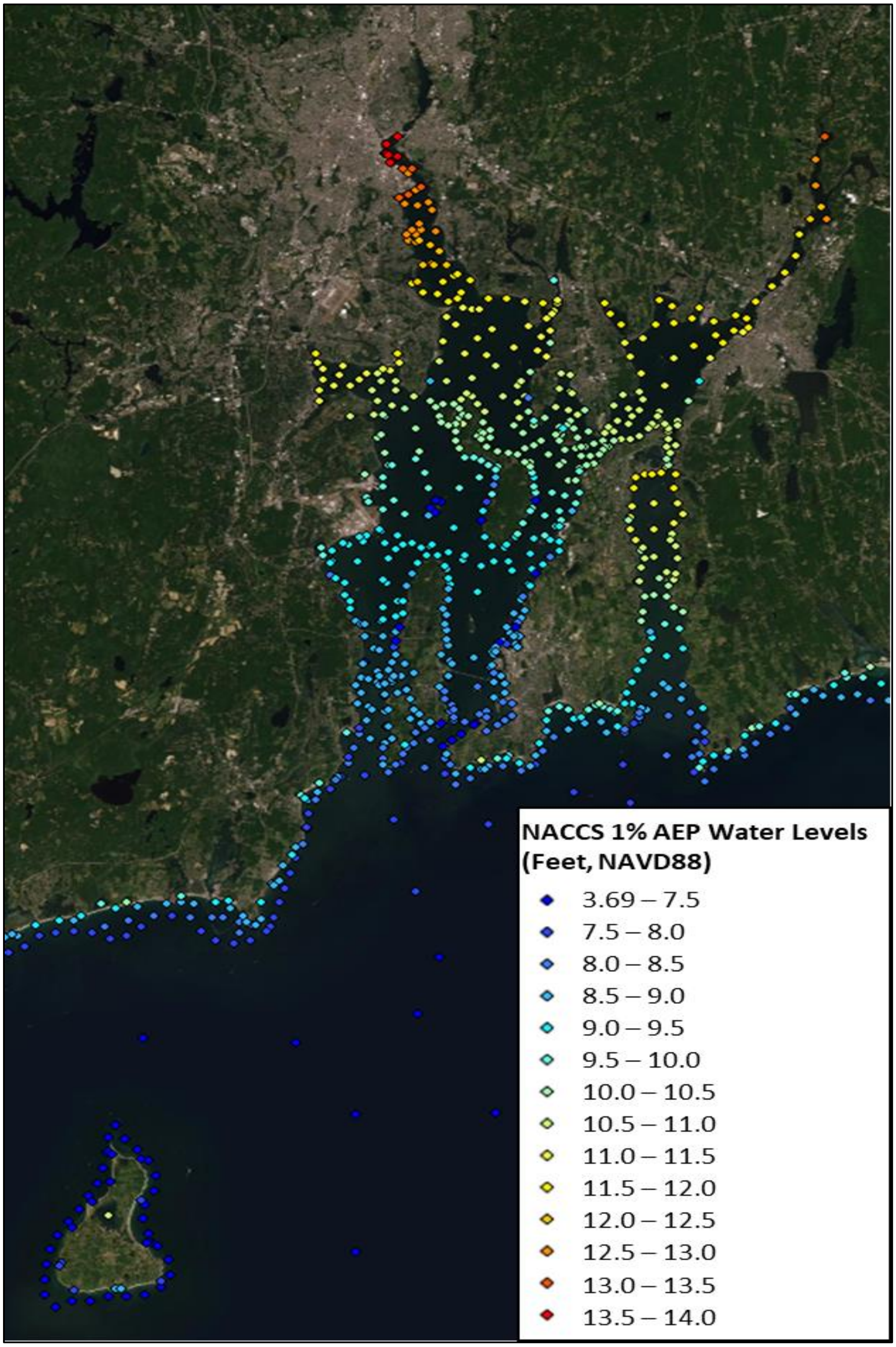


Figure B 6-12: NACCS 1-percent AEP water levels in feet, NAVD88

The study area was discretized into regions known as model areas (MAs) 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 MA, 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 MA. 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 MA such that all 1-percent AEP water levels within a MA 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 MA without overly discretizing the study area appropriate for a planning feasibility study. The MAs and representative save points are shown in **Figure B 6-13**.

Mean and 90% confidence limit AEP water levels for the current NTDE are provided in **Table B 6-3** and **Table B 6-4**, 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 6-13: Study area discretization and representative save points

Table B 6-3: 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	4.85	5.87	6.83	8.08	10.01	11.44	12.92	14.92
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 6-4: 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

6.3. 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 (breaking due to high curvature of short waves). 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 Hurricane 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 6-5** at the representative save points by MA. These wave heights are based on model runs without consideration for sea level change and are reflective of the current national tidal datum epoch. As discussed above, wave heights within Narragansett Bay are lower than those within Rhode Island Sound due to the shallow water and sheltering afforded within the bay.

Although the wave heights presented in **Table B 6-5** are representative of present day sea level conditions and do not include sea level change, sea level change is incorporated within G2CRM. G2CRM adds sea level change to the surge level over the 50-year period of analysis through linear superposition. While wave heights are not recomputed in STWAVE, the sea level rise component is included in the depth-limited wave calculation discussed in Section 7.4.2. This simplified approach is acceptable for planning-level analysis, but does not account for nonlinearities in the wave calculation.

Table B 6-5: NACCS mean 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

7. G2CRM MODELING

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 **Appendix C**, *Economic and Social Considerations,* for more information regarding the development of the G2CRM economic inputs.

7.1. 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).

7.2. 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 6-13**, displayed above, shows the location of the fifteen MAs.

7.3. Protective System Elements

A 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, described further in Sections 8.2 through 8.4 and depicted in **Appendix D**, *Engineering and Design*.

7.4. 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.

7.4.1. 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 MA save point. This storm sampling resulted in a range of 469 to 495 tropical storms per MA. 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 MA. The number of storms sampled for each MA is provided in
Table B 7-1.

While the hydrodynamic modeling completed as part of the NACCS and used in this study was performed in meters, MSL, G2CRM uses units of feet and the NAVD88 vertical datum. Therefore, the NOAA vDatum conversion from MSL to NAVD88 was provided at each of the selected save points within G2CRM.

Table B 7-1: 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)
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)

7.4.2. Wave Generation

G2CRM can represent wave hazards within a MA 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 within the MA. 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 for the MA. Because the NACCS points containing the STWAVE output were located offshore and MAs were typically above MSL, this third approach was used throughout the study area. As such, STWAVE model output was applied directly to all MAs 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.

7.4.3. 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. **Table B 7-2** summarizes the season definitions and average number of storms per season.

7.4.4. 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.

7.4.5. Tide Stations

The nearest hydraulically similar tidal prediction station was applied to each MA. The tide station assignments by MA are shown in
Table B 7-1.

7.4.6. 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. This SLC rate was selected at the start of the feasibility study and represents the long-term rate through 2018. Although the sea level change rate has changed slightly since 2018 (2.85 mm/year through 2021), it is not expected to impact the outcome of study findings. For example, if the 2021 rate is used to project RSLC through 2080 under the intermediate scenario, the difference in SLC is 0.02 feet (1.51 feet versus 1.49 feet). While 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 milestone, the TSP was evaluated further under the low and high SLC curves within G2CRM to evaluate the plan's performance under alternate SLC scenarios and to arrive at the recommended plan. Results of the G2CRM runs under alternate SLC scenarios are presented in **Appendix C**, *Economic and Social Considerations*.

Table B 7-2: Storms per season

Season Description	Season Type	Average Storms per Season
Trop Season June	Tropical	0.007038560
Trop Season July	Tropical	0.007038560
Trop Season August	Tropical	0.045750640
Trop Season September	Tropical	0.084462720
Trop Season October	Tropical	0.021115680
Trop Season November	Tropical	0.010557840
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	0.200000000
Etrop Season March	Extratropical	0.160000000
Etrop Season April	Extratropical	0.080000000
Etrop Season May	Extratropical	0.013333333

7.4.7. Stage-Volume Input

G2CRM has an optional data import tool for stage-volume relationships, which is used to represent internal ponding within a MA. If a stage-volume relationship is not employed, G2CRM will instantaneously transmit the stage when it exceeds the input PSE top elevation into the MA. To represent the coastal flooding more accurately within a MA with a PSE in place, G2CRM has an option to use the weir equation to calculate a time-dependent volume transmitted into the MA until the storage capacity within the MA is filled, after which G2CRM transitions back to transmitting the stage unmediated into the MA. Stage-volume relationships were created using the DEM to determine the volume within each MA 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 MA protected by a PSE could be better represented.

8. 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 initially considered to reduce impacts from coastal flooding and wave attack. However, only the following measures were considered within the final array of alternatives. Reference the main report and **Appendix F**, *Plan Formulation,* for additional detail on the various measures and screenings conducted prior to engineering analysis and design.

8.1. 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 8-1**. 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.

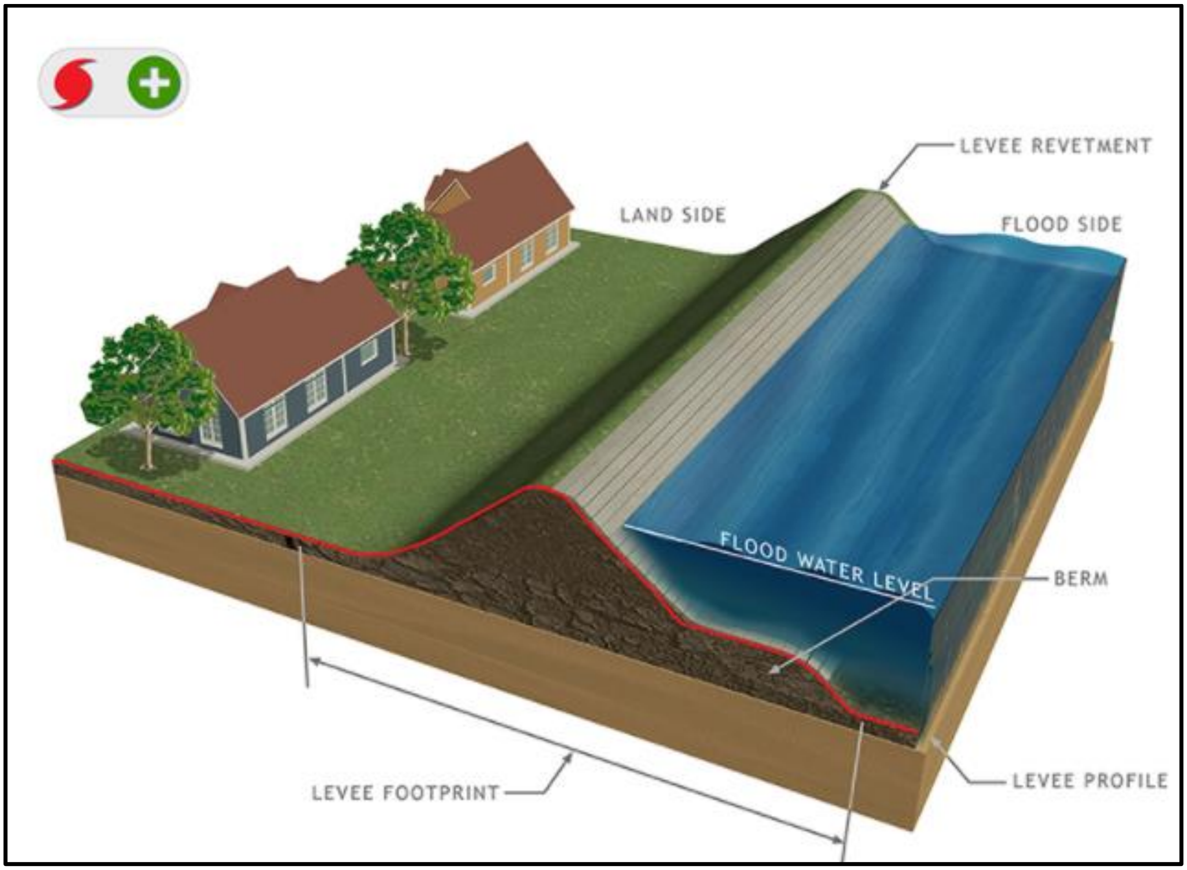


Figure B 8-1: Levee example image

8.2. 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 floodwall 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 floodwall. The combination of steel sheeting, reinforcement, concrete, and pile support make a floodwall a much more costly structural flood risk management measure than a similar length and height levee. A typical floodwall is depicted in **Figure B 8-2**. 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.

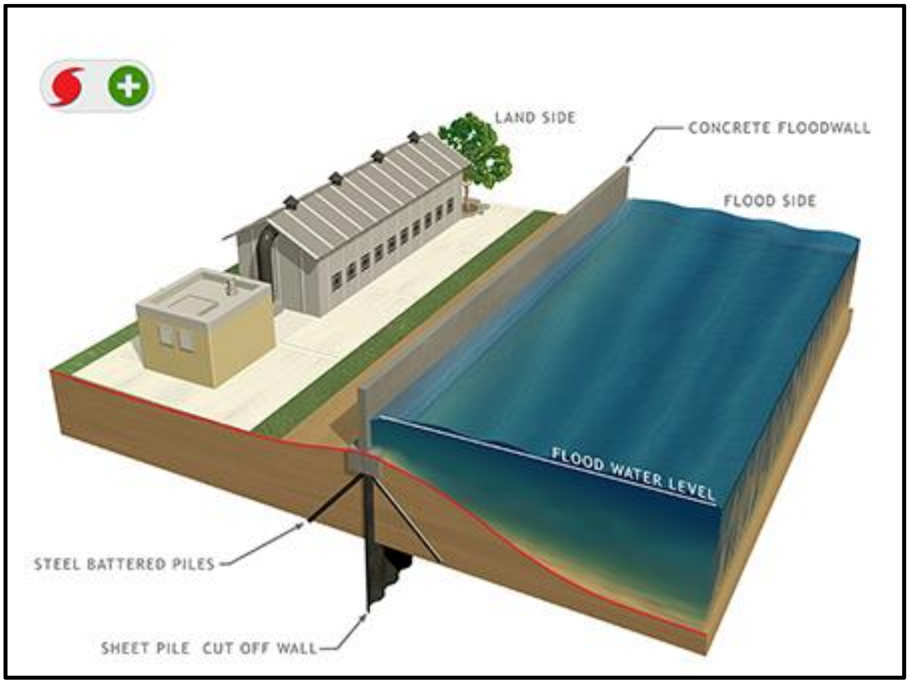


Figure B 8-2: Floodwall example image

8.3. Storm 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 storm surge barrier at Fox Point to reduce flood damage potential for the city of Providence (**Figure B 8-3**). Another example of a storm surge barrier, consisting of a dike and sector gates, is located nearby in New Bedford and Fairhaven, Massachusetts (**Figure B 8-4**).

Figure B 8-3: Fox Point storm surge barrier

Figure B 8-4: New Bedford storm surge barrier

8.4. Structure Elevation

As discussed in the main report, the primary recommendation of this study is to elevate structures in place (**Figure B 8-5**). Structure elevation is a nonstructural technique in which individual structures are elevated vertically to reduce their flood risk. 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, 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 8-5: Structure elevation example

8.5. 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.

8.6. 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.

8.7. 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.

9. 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 storm surge barriers with gates would be costly to construct, difficult to adapt, and in service longer than the 50-year economic period of analysis. 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, and nonstructural measures, such as structure elevations, 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. The optimization of design heights is discussed in **Appendix C**, *Economic and Social Considerations*.

9.1. No Action Alternative

The No Action Alternative or 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 MAs. Each simulation was run using the intermediate sea level change scenario for Newport, RI.

MAs that were not considered for structural measures were set up as unprotected MAs. Where structural measures were considered, MAs were set up as upland MAs with the PSE elevation set to the existing ground elevation along the proposed structural alignment in the FWOP. The damages assigned to each MA 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 **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 9-1** and **Table B 9-2**, respectively. These values were determined by linearly superimposing the 1.49 feet of intermediate SLC on the 1992 NACCS water levels given in **Table B 6-3** and **Table B 6-4**. It is common practice when assessing water levels in coastal studies to separately consider components, such as storm surge, tide, and SLC, before combining them through linear superposition to determine the total water level. The use of linear superposition introduces an error due to the complex nonlinear interaction of the water level components. This error is referred to as the nonlinear residual. Nonlinear residuals were quantified as part of the NACCS hydrodynamic modeling effort. The nonlinear residuals for sea level change plus astronomic tides for the RI Coastline study area are shown in **Figure B 9-1**, with the majority of save points having combined biases of less than 0.1m. This was considered an acceptable level of bias for the study but does introduce some uncertainty in the future water levels.

While the G2CRM economic model uses timeseries water levels, the AEP water levels were used to define the study area and to formulate alternatives.

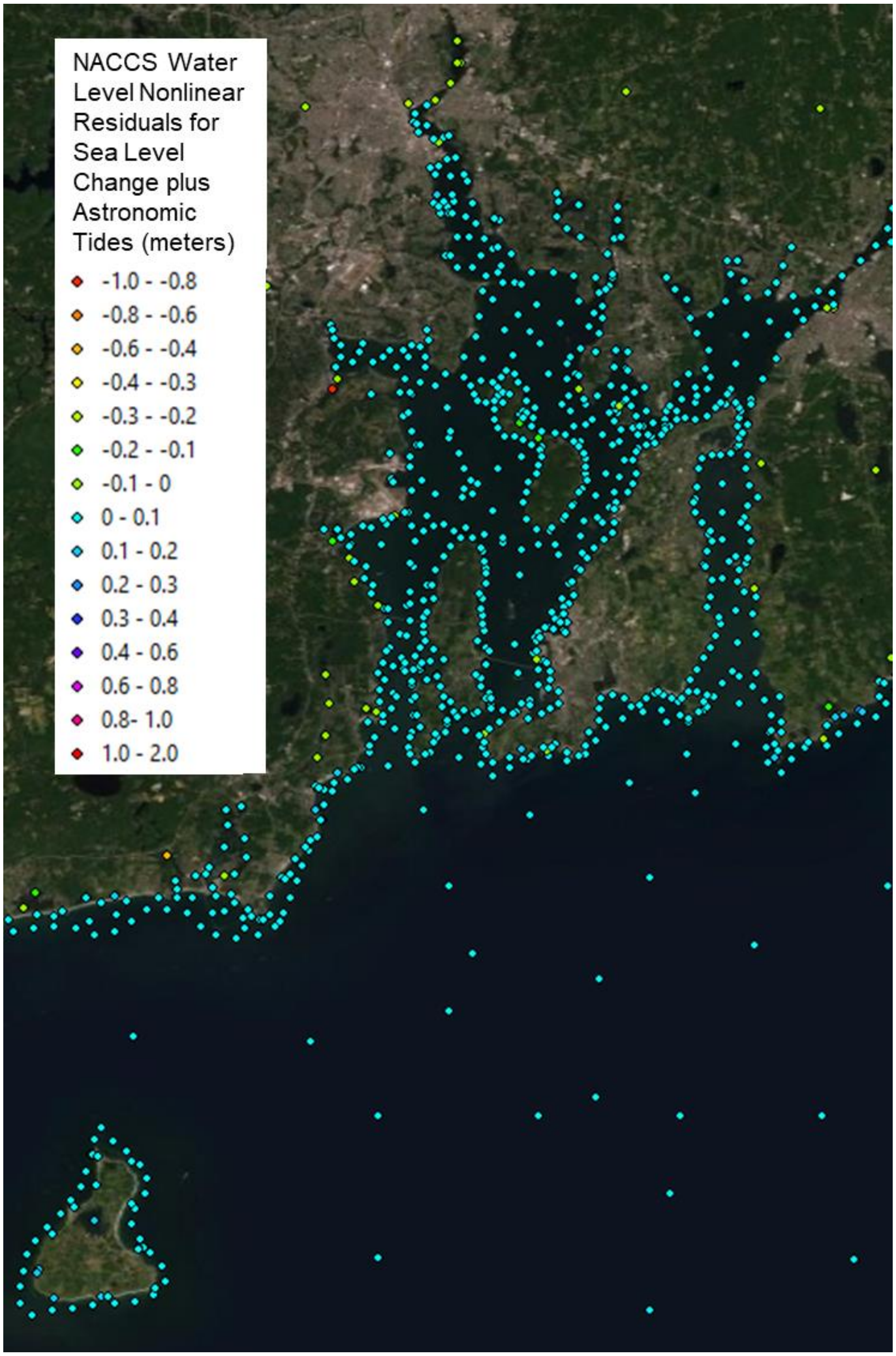


Figure B 9-1: NACCS Nonlinear Residuals within the RI Coastline study area

Table B 9-1: 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	6.34	7.36	8.32	9.57	11.50	12.93	14.41	16.41
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 9-2: 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

Figure B 9-2 through **Figure B 9-7** 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. Vulnerability to coastal flooding is presented by town, with the most vulnerable areas having greatest inundation depths and densities of assets in the floodplain.

Beginning in Narragansett in **Figure B 9-2**, 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 Mackerel 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 9-2** is largely limited to coastal ponds and existing marshlands.

North Kingstown (**Figure B 9-3**) 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 9-4**), 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 storm surge 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 9-4 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 9-5**) 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 Poppasquash 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 Nannaquaket Pond and along Seapowet Cove. Fogland Beach will be overwashed.with most of Fogland Point underwater.

In Little Compton (**Figure B 9-6**), 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 9-7**), 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.

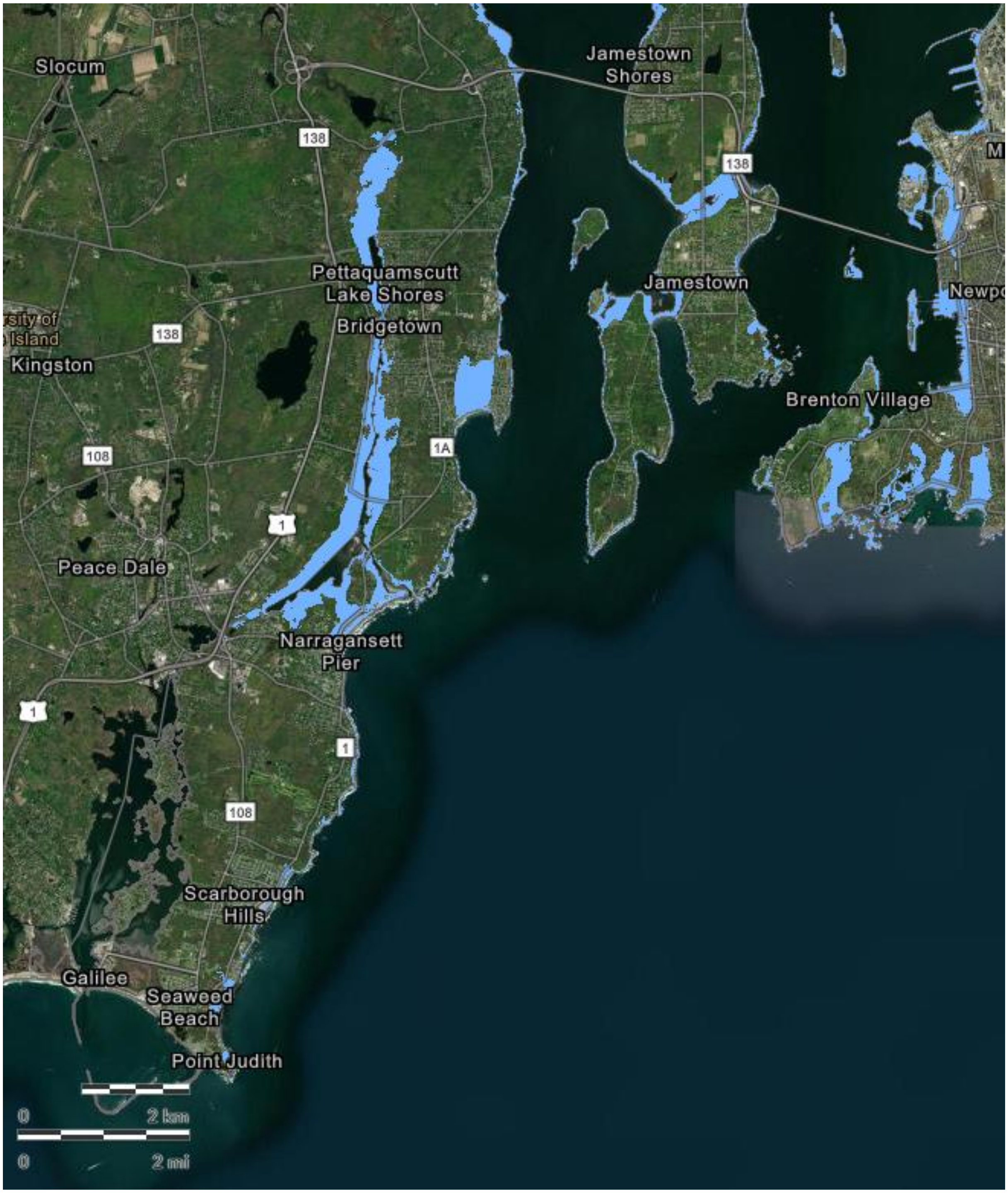


Figure B 9-2: 2080 1-percent AEP inundation under intermediate SLC—Narragansett, South Kingstown, North Kingstown, Jamestown, Newport

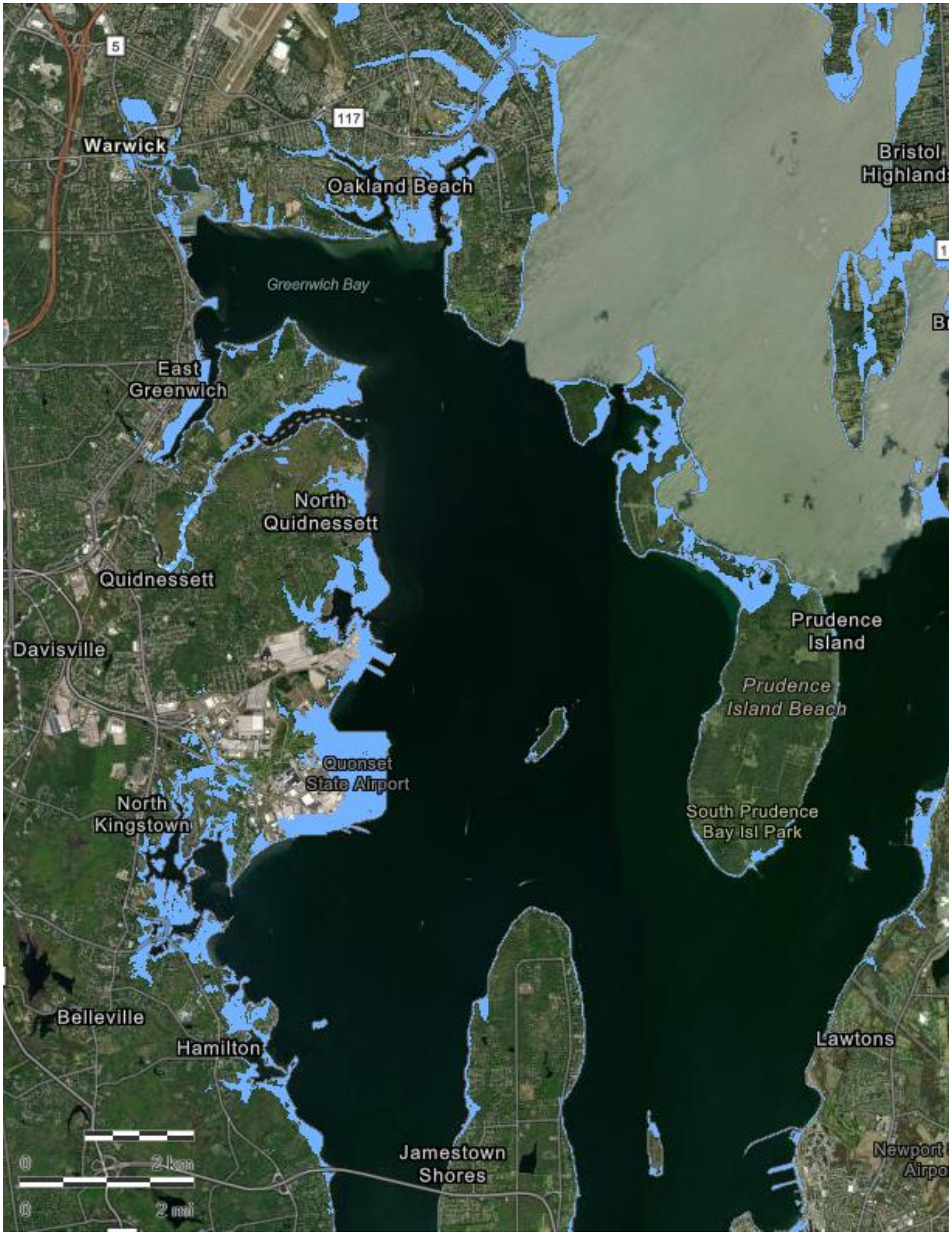


Figure B 9-3: 2080 1-percent AEP inundation under intermediate SLC—North Kingstown, East Greenwich, Warwick, Jamestown, Portsmouth (Prudence Island)

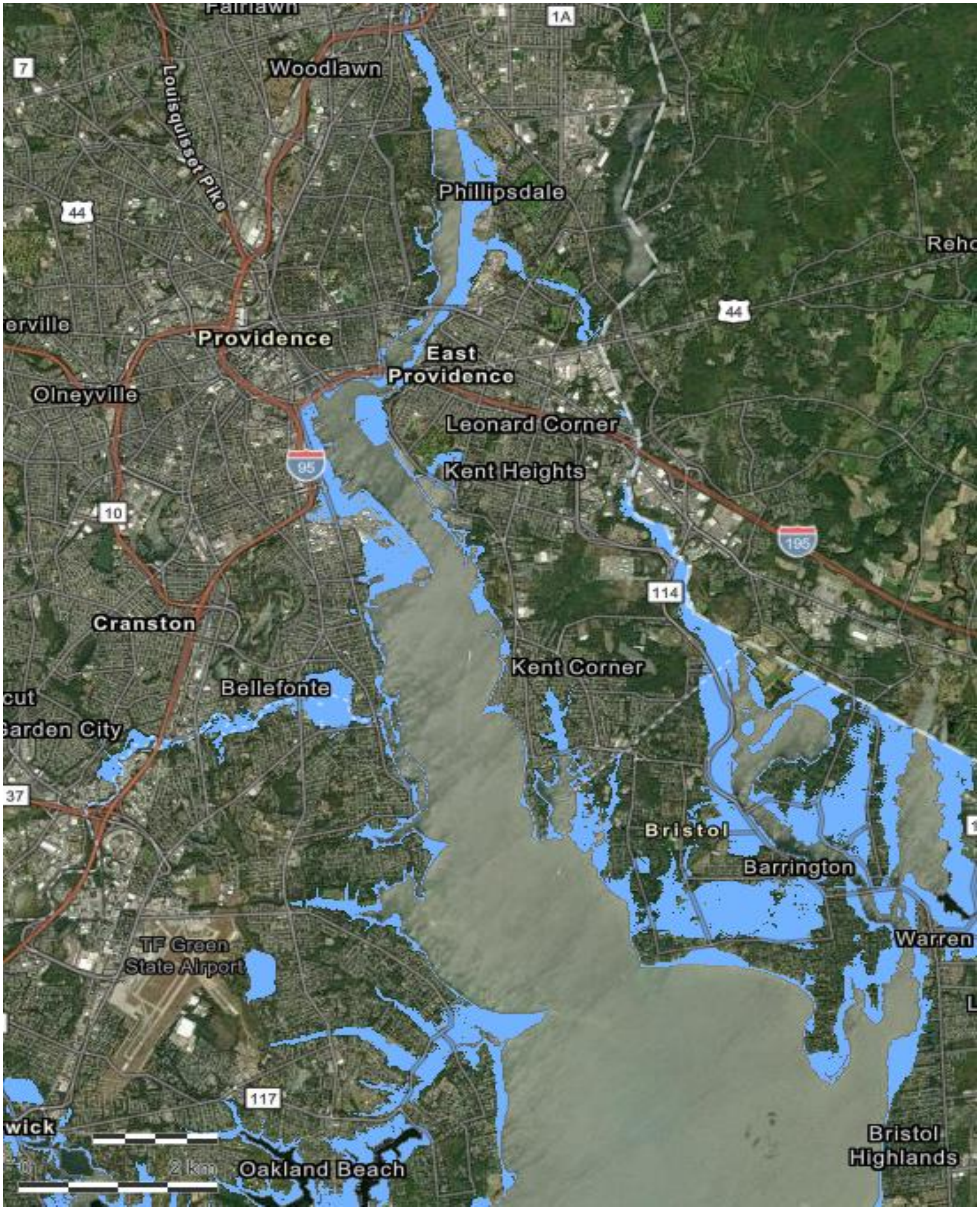


Figure B 9-4: 2080 1-percent AEP inundation under intermediate SLC—Warwick, Cranston, Providence, Pawtucket, East Providence, Barrington, Warren

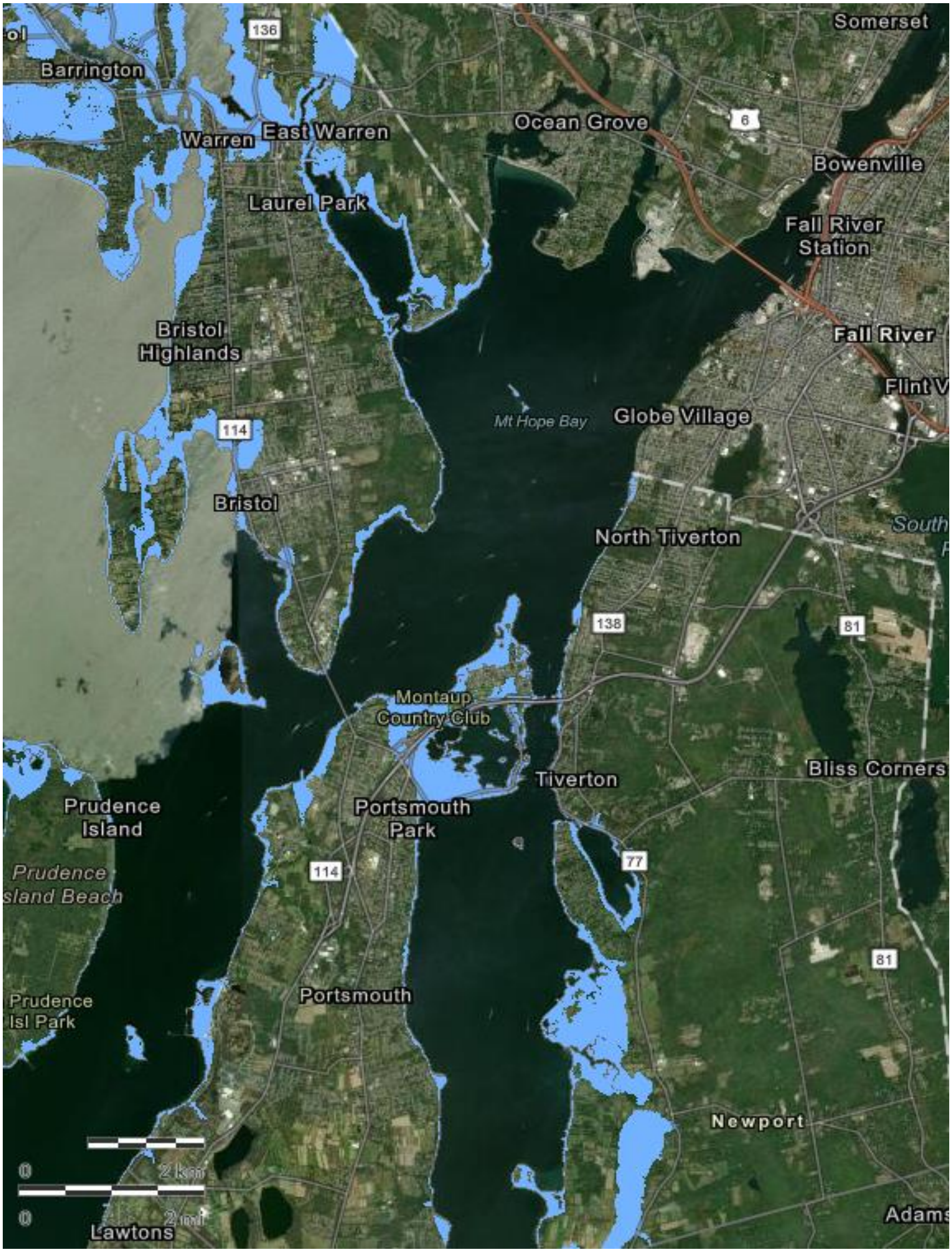


Figure B 9-5: 2080 1-percent AEP inundation under intermediate SLC—Warren, Bristol, Portsmouth, Tiverton

Figure B 9-6: 2080 1-percent AEP inundation under intermediate SLC—Tiverton, Little Compton, Middletown, Newport

Figure B 9-7: 2080 1-percent AEP inundation under intermediate SLC—Block Island

9.2. Warren-Barrington Storm Surge Barrier

9.2.1. 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 storm surge barrier crossing either the Warren River (lower alignment shown in red in **Figure B 9-9**) or the Barrington and Palmer Rivers (upper alignment shown in yellow in **Figure B 9-9)**. 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 0.2-

percent AEP was selected due to the density of structures within the Warren-Barrington area and the lower adaptability of a storm surge barrier system that would be expected to be in service longer than the 50-year economic period of analysis. Further, moving from the 1-percent AEP to the 0.2-percent AEP required only lengthening the tie-ins to higher ground by 250 feet, a small fraction of the total lengths of 6,386 feet for the upper barrier alignment and 3,449 feet for the lower barrier alignment. 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 storm surge 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 Grande 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 storm surge barrier system alignments and design.

An additional length of floodwall would also be needed on the east side of Warren in the vicinity of Serpentine Road to prevent floodwaters from the Kickemuit River and Warren Reservoir from flanking the system.

9.2.2. G2CRM Representation

Within G2CRM, both alignments were represented using a PSE, with a stage-volume relationship for the interior area (**Figure B 9-8**). 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.

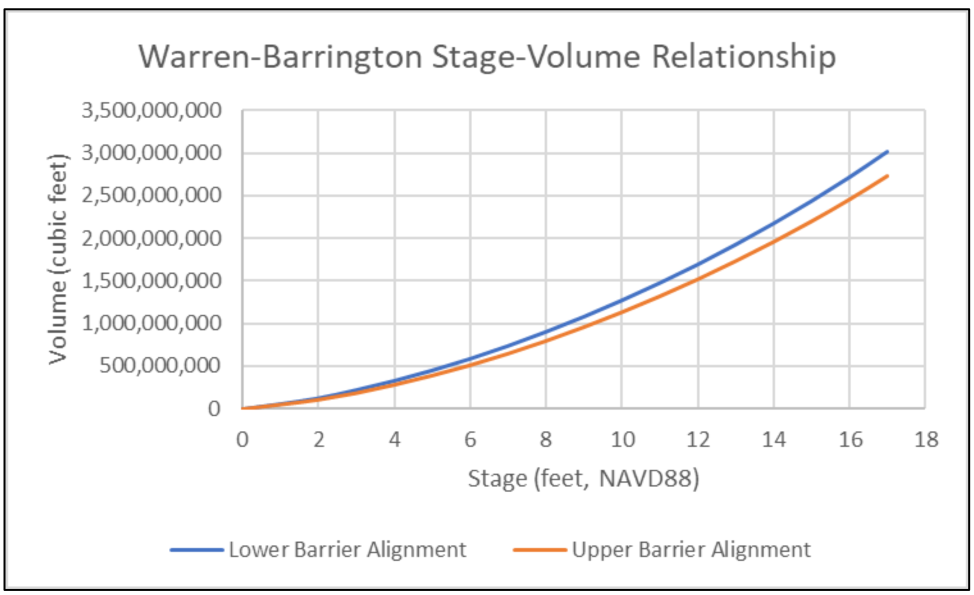


Figure B 9-8: Warren-Barrington G2CRM Stage-Volume Relationship

9.2.3. 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 in **Figure B 9-10**.

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. It should be noted that this pump sizing was computed for present hydrologic conditions and the impacts of climate change were not included as this alternative did not result in a benefit-cost ratio above 1.0.

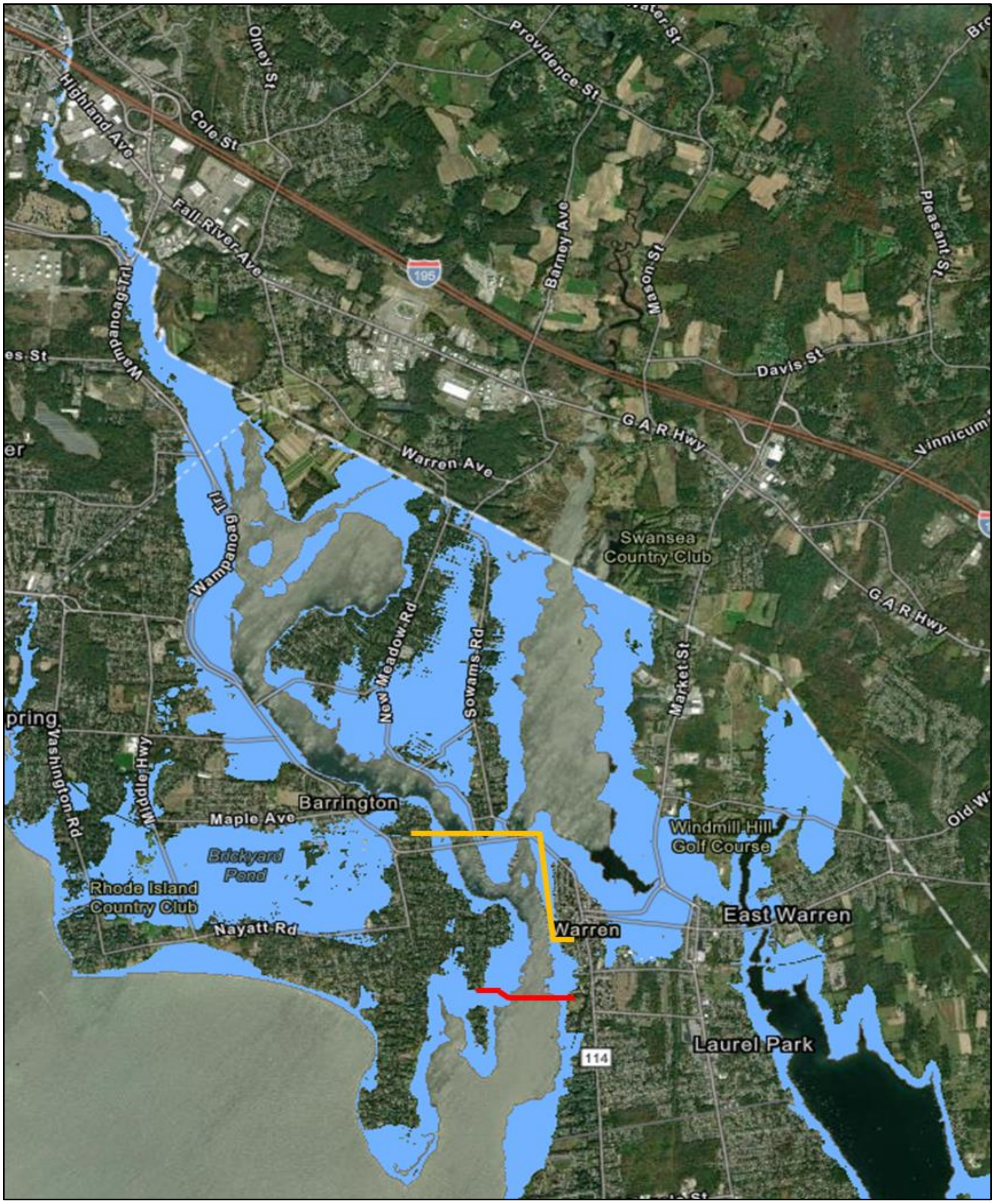


Figure B 9-9: Warren-Barrington storm surge barrier alignments

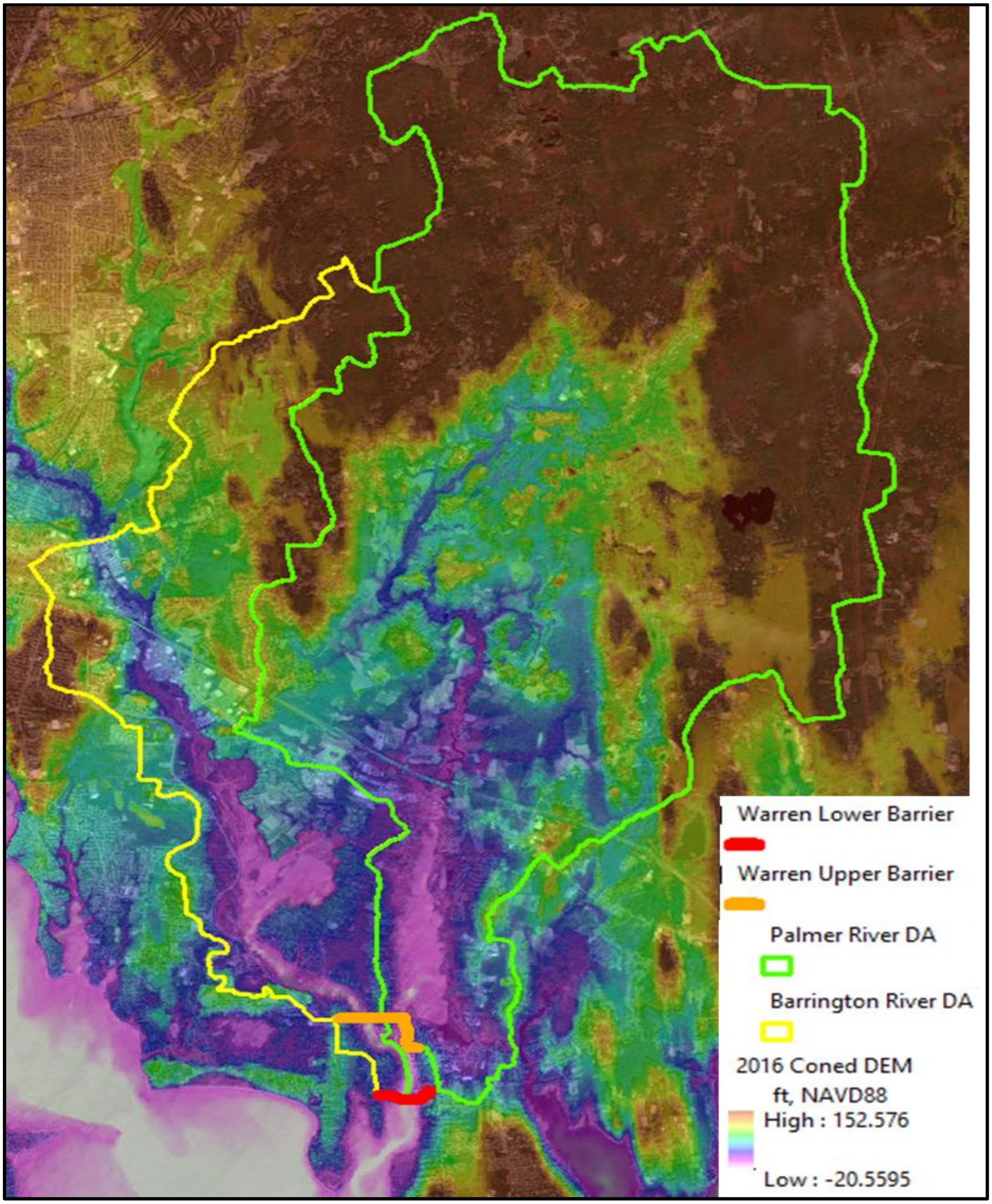


Figure B 9-10: Warren-Barrington storm surge barrier watersheds

9.3. Middlebridge Surge Barrier

9.3.1. Alignment and Geometry

A storm surge barrier across the Narrow River at Middlebridge Road in South Kingstown and Narragansett was designed to prevent storm surge from propagating up the Narrow River and flooding the low-lying residential neighborhoods to the north (**Figure B 9-12**). 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 crests at an elevation of 9 ft NAVD88. Structural engineering analysis determined the bridge could support a storm surge barrier 1 ft above that elevation at 10 ft NAVD88. This elevation corresponds to approximately the 1-percent AEP water elevation with 50% assurance for the year 2080 under the intermediate sea level change scenario (10.13 ft 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.

9.3.2. G2CRM Representation

The Middlebridge storm surge barrier was represented in G2CRM using a PSE with a stage-volume relationship for the interior area (**Figure B 9-11**). 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.

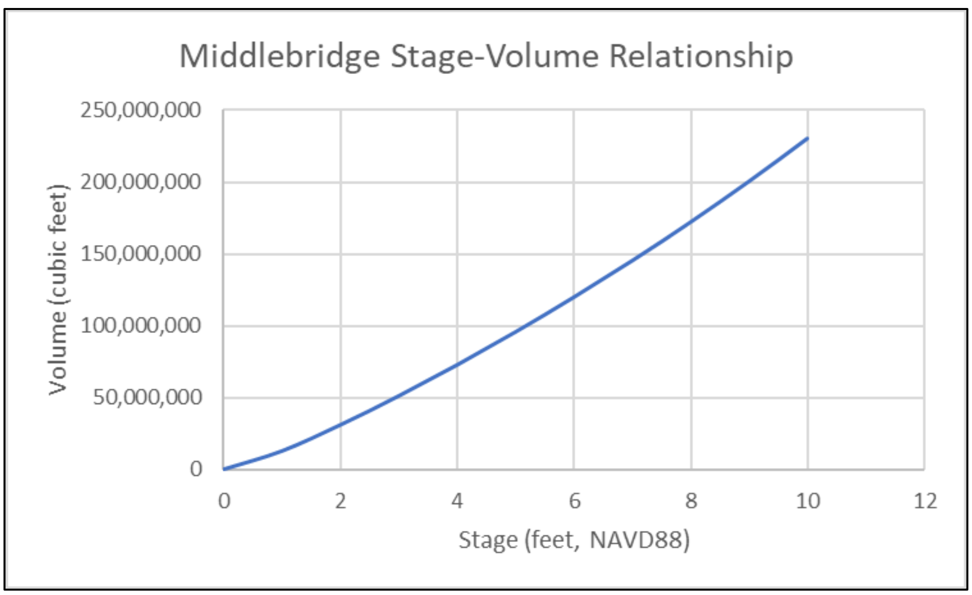


Figure B 9-11: Middlebridge G2CRM Stage-Volume Relationship

9.3.3. Interior Drainage

The interior area at Middlebridge was defined as the interior watershed behind the storm surge barrier, shown **Figure B 9-12**. 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. It should be noted that this pump sizing was computed for present hydrologic conditions and the impacts of climate change were not included as this alternative did not result in a benefit-cost ratio above 1.0.

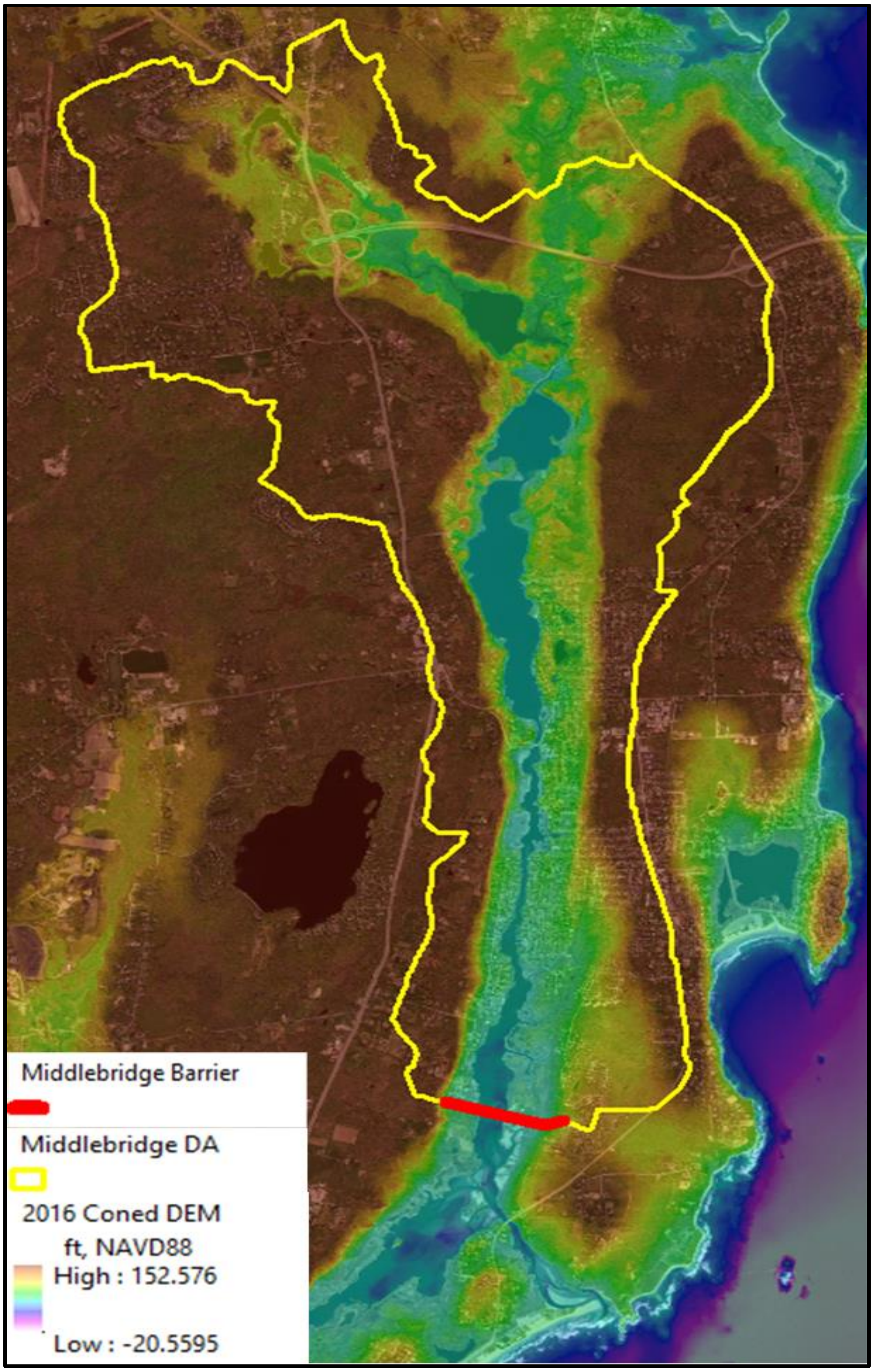


Figure B 9-12: Middlebridge storm surge barrier watershed

9.4. Wellington Floodwall and Levee System

9.4.1. 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 9-13**). 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 9-13: Wellington floodwall and levee alignment with area of risk reduction

9.4.2. 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 (**Figure B 9-14**). 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.

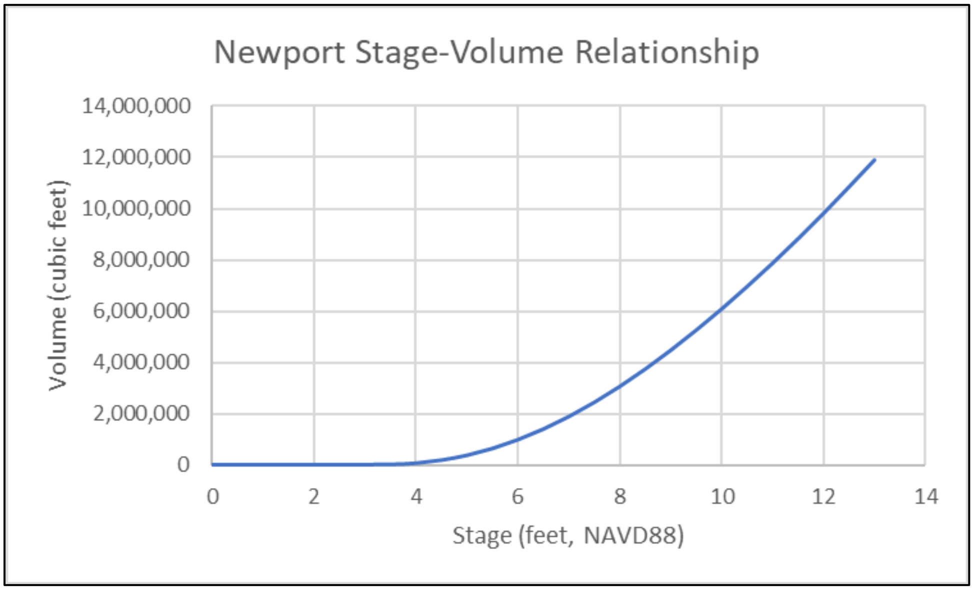


Figure B 9-14: Wellington Avenue G2CRM Stage-Volume Relationship

9.4.3. Interior Drainage

The interior area at Wellington was defined as the interior watershed behind the floodwall and levee system, shown in **Figure B 9-15**. 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 Service (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 SCS 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 U.S. Department of Agriculture Natural Resources Conservation Service (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 of concentration. 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 of concentration 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. It should be noted that this pump sizing was computed for present hydrologic conditions and the impacts of climate change were not included as this alternative did not result in a benefit-cost ratio above 1.0.

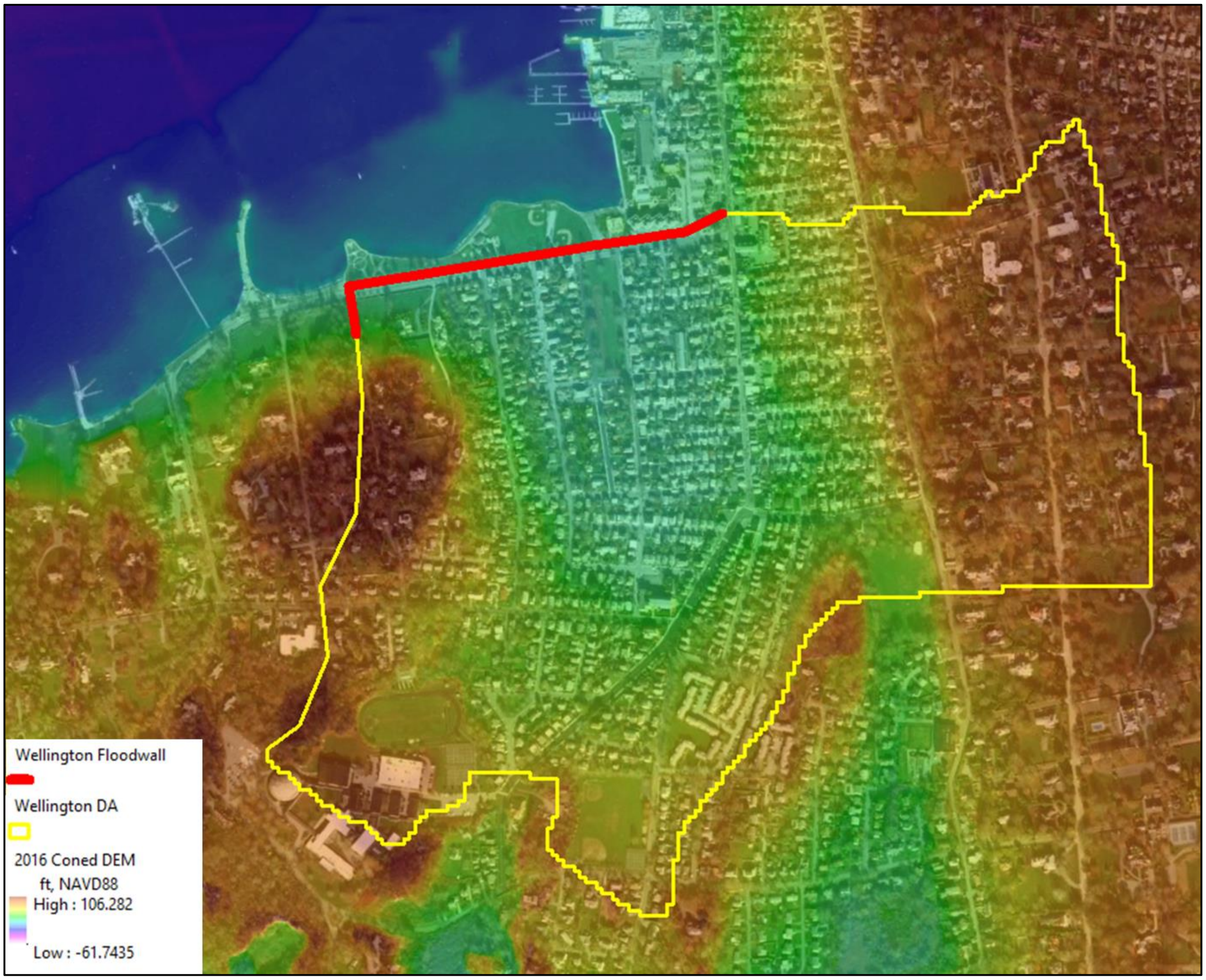


Figure B 9-15: Wellington Avenue floodwall watershed

9.5. Nonstructural Alternative

The nonstructural alternative was considered for all structures within the study area. 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 with 50% assurance + wave contribution + 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). Screening of structures for elevation is detailed in Section 5.5 of **Appendix C**, *Economic and Social Considerations.*

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 feet height was assumed for all measures.

Acquisition was considered for single family residences expected to be inundated by or become inaccessible at the highest annual tide with the year 2080 under the USACE intermediate SLC scenario.

10. RECOMMENDED PLAN

The recommended plan for coastal storm risk management in the RI Coastline CSRM Project is the nonstructural plan which includes 497 total structures – 290 residential recommended for elevation and 206 non-residential recommended for floodproofing.

10.1. 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 1% 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 accounts for the repeated annual exposure to flood risk over time.

The design elevation for the nonstructural plan was the 1% AEP NACCS water level + wave contribution + 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 10-1**. 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. In this conceptualization the design height is unchanged, but its performance is communicated using the 90% confidence interval. The performance that is communicated is lower, but with higher confidence.

As the project performance in **Table B 10-1** assumes sea level change will follow the USACE intermediate scenario, the same level of performance will be surpassed sooner under the high sea level change scenario and later under the low sea level change scenario. The same 1.49 feet of sea level rise that is projected under the intermediate scenario by the year 2080, could occur as soon as the year 2045 under the high sea level scenario or as late as the year 2156 under the low sea level scenario.

Table B 10-1: 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%	3.1%	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%

10.2. Reliability and Life Safety

Nonstructural plans such as the recommended plan 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 recommended 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 NWS 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*.

10.3. Climate Risk

As indicated in **Table B 10-2**, climate change has the potential to result in increased hazard to the recommended plan's structure elevation and floodproofing measures. The residual risk to the plan due to precipitation and temperature increases is classified as low. The risk to the structural elevation and floodproofing measures is low because the climate hydrology analysis resulted in little evidence for increases in peak streamflows in the near term. However, the residual risk to the plan due to sea level rise exceeding the intermediate scenario is higher.

Table B 10-2: Climate Risk Register

Feature or Measure	Trigger	Hazard	Harm	Qualitative Likelihood
Structure elevation and floodproofing	Higher precipitation and temperatures result in more extreme runoff events.	Higher River Discharges Flood Frequency Increase	Compound flooding from rainfall and coastal sources	Low; no significant trend in observations or consensus among projections causing increased streamflow
Structure elevation and floodproofing	Increased sea level	Increased water levels and wave heights	Increased SLR may increase frequency and magnitude of water level and wave loading on structures. Risk reduction level decreases while residual risk increases.	Likely

11. 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 MAs, 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 initial pump sizing. Finally, the design elevation height for the nonstructural analysis was provided to economics for incorporation into G2CRM.

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