US Army Corps of Engineers®

Fox Point Storm Surge Barrier System Vulnerability Assessment

Interim Response to Section 1218 of Public Law 115-270, America's Water Infrastructure Act of 2018

April 2026

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Executive Summary

This analysis evaluates the ability of the Fox Point storm surge barrier system to maintain its functionality and effectiveness over the long term in the face of unpredictable severe weather events. The Fox Point storm surge barrier manages risk to Providence, Rhode Island, from coastal storms by blocking storm surge from entering the Providence River to reduce damage to property and infrastructure. The analysis reviewed the barrier's existing design and present operations and maintenance (O&M) procedures, with specific attention to impacts from sea level change (SLC) and precipitation on the design. Maintaining barrier performance under projected future changes is critical to the city's continued economic prosperity and regional leadership.

The Fox Point Hurricane Shore Protection Project, herein titled Fox Point storm surge barrier system, is a federally authorized and constructed coastal storm risk management (CSRM) project on the Providence River approximately 1,000 feet upstream of the confluence of the Providence and Seekonk Rivers. The city of Providence and the U.S. Army Corps of Engineers (USACE) jointly maintain the feature. After the feature was constructed, USACE turned it over to the city of Providence for O&M through a local cooperation agreement. The city operated and maintained the entire feature until February 2010, when the portion of the feature crossing the Providence River was returned to USACE for O&M. The city retained O&M for the cooling water intake trash rack system, intake canal retaining walls, the fish passage and appurtenances, and the fish passage pipe on the north wall of the structures. At the time of this report, the USACE New England District Operations Division had O&M responsibility for the USACE segment of the project, managed from the Cape Cod Canal Office. The city of Providence is the local sponsor for the Providence segment, and the Providence Department of Public Works (DPW) performs O&M for the Providence segment under the direction of the City Engineer.

Overall Findings and Recommendations

Despite its successful performance against its design coastal storm in modeling exercises, the system is susceptible to future operational risks, specifically, an increased frequency of closure events for the Tainter gate and other low-lying components is anticipated as a result of changes in water levels associated with sea level rise. This situation may contribute to operational fatigue and reduce the available time for maintenance. Modeling also shows future sea levels resulting in water elevations exceeding the closure threshold more frequently during normal tidal cycles.

Additionally, the pumping system may be vulnerable to future rainfall events when the Tainter gates are closed from coastal storm surge in conjunction with a rainfall event. This vulnerability may manifest as increased Tainter gate closure and exceedance frequencies and a corresponding increase in the operational demands placed on the Providence River pumping system.

Specific recommendations include the following:

- Optimize the current closure elevation (either upward or downward) threshold through a CSRM study to refine the future operational frequency through updates to the O&M manual or the water control manual (WCM). USACE guidance allows many potential actions for addressing changes to a project due to design deficiencies or changing conditions, generally termed post-authorization change (PAC) reports.

- Consider nonstructural flood risk management measures within the city of Providence to accommodate additional water when the Tainter gates are not closed based on a higher closure threshold elevation.

Study Background and Drivers

The Fox Point storm surge barrier system was initially constructed to provide CSRM to approximately 280 acres of downtown Providence. The system is central to managing hurricane risk, and since its construction, it has protected the vulnerable areas in Providence. However, projected SLC and other weather patterns may create a significantly different operational environment than the conditions studied as part of the original design and evaluation. SLC may make the design elevation of the level of protection by the system inadequate for higher expected storm surge levels. In addition, the extent of paved surfaces in the watersheds of both the Woonasquatucket and Moshassuck Rivers has considerably increased since the features construction, which may increase the volume of stormwater arriving at the barrier and exceed the pumping capacity of the system during rainfall events.

The city’s commercial area sustained extensive damage from significant flood depths during the 1938 hurricane and Hurricane Carol in 1954. Damages from the 1938 hurricane amounted to $16.3 million, and damage from Hurricane Carol amounted to $25.1 million. The area contains numerous critical structures, including various emergency services, colleges and universities, schools, chemical facilities, power generation facilities, and other facilities. Failure of the Fox Point storm surge barrier during a storm emergency could result in life loss and more than $2.4 billion in economic damages in 2014 dollars, equivalent to $3.2 billion in June Fiscal Year (FY) 2025 dollars (USACE 2022).

In response to Congressional direction in America’s Water Infrastructure Act of 2018 (Public Law 115-270) § 1218, which mandated an assessment of the durability and resilience of North Atlantic Division (NAD) storm surge barriers and harbors of refuge, USACE conducted an interim analysis in 2019 (USACE 2019b). This report expands on that interim analysis and evaluates the feature against more recent rates of sea levels, design storms, and potential increases in stream discharge and precipitation.

Study Approach and Objectives/Results

This study evaluated the Fox Point storm surge barrier system for failure potential at multiple points, including the top of the barrier, the Tainter gate closure threshold, the vehicular gate egresses, the stormwater systems within the barrier, and the riverine pumping systems, against the low, intermediate, and high sea level scenarios in Engineer Regulation (ER) 1100-2-8162, *Incorporating Sea Level Change in Civil Works Programs* (USACE 2019a), as well as against variations in precipitation under plausible scenarios of changing hydrometeorological conditions. While the system remains robust against potential water elevations caused by coastal storms to 2100, including the design storm from the project’s formulation over 50 years ago, vulnerabilities exist in other components.

The Fox Point storm surge barrier is projected to remain resilient and continue providing CSRM against the design coastal storm event after accounting for increases in water levels due to future SLC, which modeling suggests will not overtop the crest of the system until after 2100. However, flooding in Providence is possible with coastal storm surge in conjunction with extreme precipitation associated with future climate events.

Precipitation events were modeled to show the sensitivity of the upstream watershed to increases in precipitation events and the impact to the pumping system. These results show that the Fox Point pumping system, with the Tainter gates closed, can convey water through the barrier to reduce riverine flooding impacts in the downtown Providence area, but the model showed upstream flooding for more extreme events related to plausible scenarios of hydrometeorological change. Extreme precipitation events, associated with Representative Concentration Pathway 8.5 (RCP), exceeded the pumping capacity of the Fox Point system, and flooding was recorded upstream of the barrier.

The study had five objectives that supported the main inquiry, which specified timeframes and scenarios to evaluate for SLC and precipitation. The assessment’s results for these specific questions are as follows:

1. Assess current and future vulnerability of the Fox Point storm surge barrier system to overtopping (+24.2 ft NAVD88) and flanking from tropical and extratropical storms by considering the design storm plus three rates of SLC for low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

   The current design of the Fox Point barrier system is robust against future coastal storms and SLC to 2100, and is overtopped by the design storm plus the high USACE sea level scenario in 2130 (Figure 41)

2. Assess changes in the Fox Point storm surge barrier system critical elevation exceedance thresholds and operational frequency under low, intermediate and high USACE sea level scenarios and changes in future watershed hydrology against critical elevation exceedance thresholds of +5.2 ft NAVD88.

   SLC will exceed the current Tainter gate closure elevation threshold of +5.2 ft NAVD88, requiring either increasing closure frequency or accepting the increased risk of threshold exceedance (Table 17). The pumps will likely be running whenever the Tainter gate is closed from a coastal storm event and create additional wear and tear and maintenance above the current operations.

3. Assess impacts to vehicular gates at Allens Avenue (+11.2 ft NAVD88), India Street (+9.0 ft NAVD88), South Main Street (+14.1 ft NAVD88), and Rhode Island Energy Power Station Street (+8.2 ft NAVD88) under low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

   The Allens Avenue vehicular gate and South Main Street gate are situated at elevations that make them less vulnerable to SLC impacts, but the Rhode Island Energy Power Station Street gate and India Street vehicular gate are likely vulnerable to most high SLC scenarios starting in 2075–2100.

4. Assess impacts to the five sewer gates/tunnels that prevent high tides from backing up through the sewer lines by considering the design storm against the low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

   The Phase 1 sewer gate is the most vulnerable gate compared to the other gates, with impacts to that gate beginning in 2050 for the intermediate and high sea level scenarios.

5. Assess changes to riverine flooding behind the closed Fox Point storm surge barrier system for the pumping system and electrical system/generator against the *Precipitation Frequency Atlas of*

the Unites States, Volume 10 (*Atlas 14*) (Perica et al. 2019) frequency events (10, 20, 50, 100, and 500 years) plus representative concentration pathway (RCP) 8.5 output from the Comprehensive Hydrology Assessment Tool (CHAT) (USACE n.d., a) for 24-/72-hour events to the minimum, lower quartile, median quartile, upper quartile, and maximum in cubic feet per second (cfs) and stage to 2100.

The pumping capacity of the current system is able to convey water through the barrier when the Tainter gate is closed for most scenarios, up to RCP 8.5 for the lower quartile 24-hour rainfall event (Table 10, Table 11). This analysis did not assess the pump efficiency at higher head levels on the discharge side of the barrier, which may be affected by higher sea level in the future. Increased water levels on the discharge side of the barrier could reduce pump efficiency by 10 percent, causing pumping discharge thresholds to be exceeded more often than the current assessment. Analysis of the RCP 8.5 24-hour scenario indicates that the system's pumping capacity is insufficient to manage water levels at the median, maximum, and upper quartile precipitation projections. Water levels from flooding do not reach the elevation of the backup generator system on the interior section of the barrier for these events based on overland flow, but this analysis did not assess stormwater conveyance. These events also see flooding to the west of the Interstate 95 Bridge on the Woonasquatucket River near the vicinity of Atwells Avenue, Valley Street, and Westminster Steet.

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1. Introduction

1.1. Study Authority(ies)

Two authorities govern the construction and present evaluation of the Fox Point storm surge barrier system:

- Congress authorized the original construction, as described in the Report of the USACE Chief of Engineers on July 3, 1958, in the Flood Control Act, Public Law (P.L.) 85-500.
- In 2018, America's Water Infrastructure Act of 2018 (P.L. 115-270), § 1218, directed USACE to assess the harbors of refuge and storm surge barriers (formerly referred to as hurricane barriers):

> NORTH ATLANTIC DIVISION REPORT ON HURRICANE BARRIERS AND HARBORS OF REFUGE. Not later than 1 year after the date of enactment of this Act, the Secretary, in consultation with State and local experts in the North Atlantic Division of the Corps of Engineers, shall submit to Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Environment and Public Works of the Senate a report on the durability and resiliency of existing hurricane barriers and harbors of refuge in the North Atlantic Division, giving particular consideration as to how such barriers and harbors will survive and fully serve their planned levels of protection under current, near, and longer term future predicted sea levels, storm surges, and storm strengths.

As described in Appendix 1 of P.L. 115-270, § 1218, a report is to be provided to the Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Environment and Public Works of the Senate no later than 1 year after its enactment on October 23, 2018. Due to a lack of appropriations, however, an interim report was completed and submitted to Congress (USACE 2019b).

The interim report showed that the storm surge barriers are relatively robust to overtopping from changing sea levels through 2070, and with one exception, through 2120. However, the analysis did not capture changes in tide, storm surge, waves, and precipitation since the time the barriers were designed. Therefore, the level of CSRM provided by these projects may be further diminished when these factors are fully considered. The current analysis accounts for the vulnerabilities the 2019 interim report identified.

This study presents a comprehensive analysis of the Fox Point storm surge barrier system, accounting for weather-related risks that contribute to added stressors on the system and its components. These components include pumps, gates, vehicular access, and the frequency and criteria governing closure operations. At the time of this report, the USACE New England District Operations Division had O&M responsibility for the USACE segment of the project, managed from the Cape Cod Canal Office. The city of Providence is the local sponsor for the Providence segment, and the Providence Department of Public Works (DPW) performs O&M for the Providence segment under the direction of the City Engineer.

1.2. Background of the 2019 Interim Report

USACE oversees eight storm surge barriers within the North Atlantic Division (NAD), including six in New England: Boston, Massachusetts; New Bedford, Massachusetts; Providence (Fox Point), Rhode Island; Pawcatuck, Connecticut; New London, Connecticut; and Stamford, Connecticut. (Figure 1).

Figure 1. Storm surge barriers within New England district (USACE 2019).

The 2019 interim report initially evaluated seven of the eight NAD storm surge barriers (Port Monmouth was not constructed) for their ability to retain functionality against sea level change (SLC) scenarios to 2100. Five storm surge barriers (Fox Point, Pawcatuck, New London, New Bedford, and Stamford) showed minimal navigation impacts under the low SLC scenario through the year 2120 (USACE 2019b). Under the high SLC scenario, the Fox Point and Pawcatuck barriers are not impacted significantly until the late century, while the New London, Stamford, and New Bedford barriers will begin to see significant navigation impacts by mid- to late century (2063–2072). The barriers are projected to retain from 82–90 percent of design structure height at 2070 and from 53–73 percent at 2120 under the USACE high SLC scenario.

1.3. Quality Reviews of the Current Study

Engineer Regulation (ER) 1165-2-217, *Civil Works Quality and Review Policy* (USACE 2021), establishes the review framework for Civil Works decision documents. USACE currently employs several review types for quality and safety, including District Quality Control (DQC), agency technical review (ATR), independent external peer review (IEPR), and safety assurance review (SAR). An ATR is mandatory for all draft and final decision documents and most implementation products, and an IEPR is conducted on project studies and produces feasibility reports and any other studies associated with modifying a water resources project. A SAR's external panels assess the critical decisions and criteria of the preconstruction, engineering, and design (PED) or construction activities prior to initiating physical construction and periodically thereafter until construction activities are completed.

As the scope of this analysis was limited to assessment and included no decision-making, implementation, construction, or modification of any infrastructure, a DQC and quality assurance (QA) review were deemed sufficient for this report.

2. Study Area

2.1. Location

The study area is on the Providence River, a tidal estuary in the northern portion of Narragansett Bay within the state of Rhode Island. The main barrier and structures are within the city limits of Providence, as shown in Figure 2 and Figure 3. The city of Providence has a population of 190,934 residing in 73,854 housing units, encompassing a land area of 18.4 square miles (United States Census Bureau n.d.). The state of Rhode Island is represented by Senators Jack Reed and Sheldon Whitehouse and Representatives Gabe Amo in the first District and Seth Magaziner in the second District.

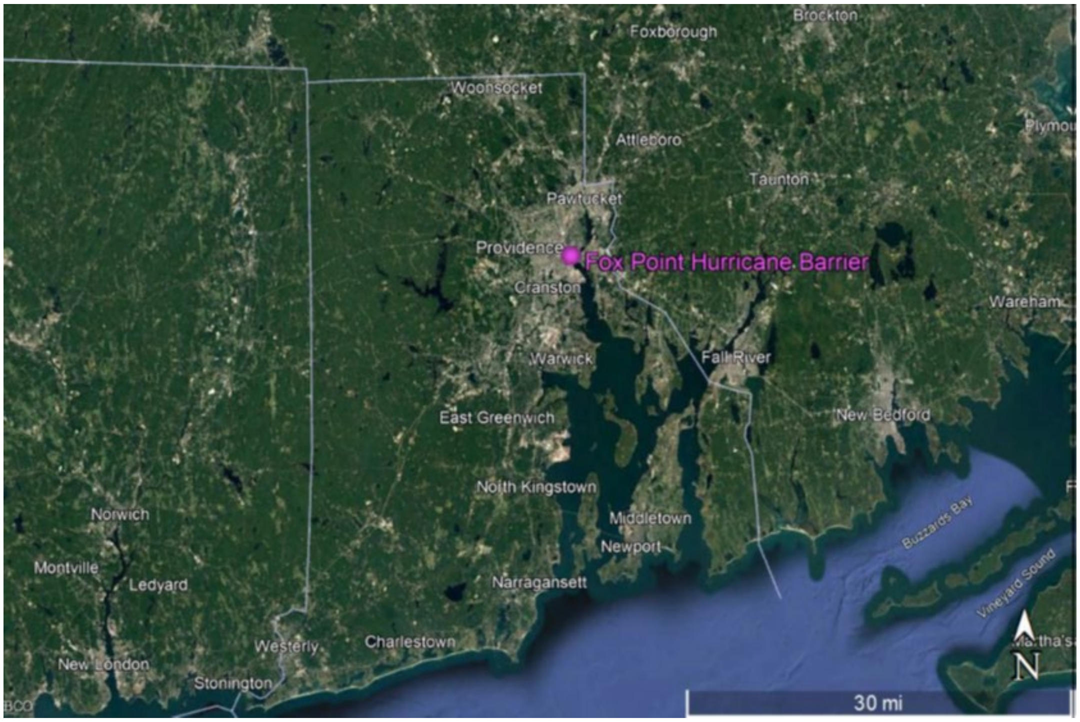


Figure 2. Fox Point storm surge barrier system study area.

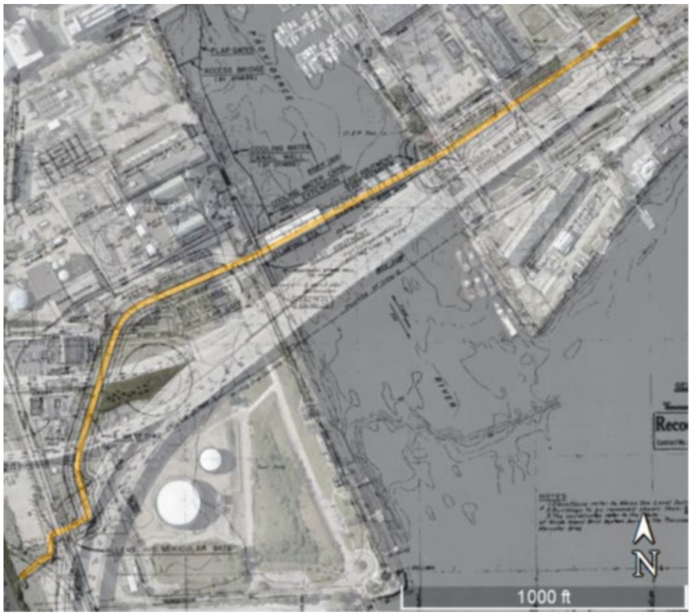


Figure 3. Overview plan of the original Fox Point Storm surge barrier system.

2.2. Storm Surge Barrier System Details

The Fox Point storm surge barrier system, shown in Figure 4, is in the city of Providence, Rhode Island, and is a federally authorized and constructed coastal storm risk management (CSRM) project. The system is in an area known as Fox Point on the Providence River, approximately 1,000 feet upstream of the confluence of the Providence and Seekonk Rivers. The feature is immediately south of the Rhode Island Energy power plant, about 0.2 miles north of Fox Point and one mile south of downtown Providence. The system provides CSRM against storm surge flooding from hurricanes and other coastal storms to approximately 280 acres of downtown Providence. Construction began in July 1960 and was completed in January 1966, at a cost of $15 million (equivalent to $163,000,000 in July 2025). The U.S. Army Corps of Engineers (USACE) Cape Cod Canal Project Office operates and maintains barrier elements that are within the Providence River banks, while the city of Providence operates and maintains the rest of the structure.

The area behind the barrier includes a commercial and industrial center, transportation facilities, public utilities, and many homes. The barrier itself is a 700-foot-long concrete structure with an elevation of +24.2 feet referenced to North American Vertical Datum of 1988 (NAVD88). The structure extends westward across the Providence River from Tockwotton Street near Fox Point to Globe Street near the power plant. The structure contains three Tainter gate openings that prevent floodwaters from entering the bay when closed and allow the passage of small vessels when open. An earthfill dike flanks each side of the barrier. The eastern dike is 780 feet long and the western dike is 1,400 feet long.

Figure 4. Fox Point storm surge barrier system with Providence in the background.

2.3. Historic Climatology

Design Memorandum (DM) No. 2, *Hydrology for the Fox Point Hurricane Barrier* (USACE 1959) found that the Providence River basin is subject to general types of storms, including tropical and extratropical systems. The rapidly moving storms that cross the basin from the west or southwest produce frequent periods of rainfall but are not extremely severe. Storms of the stationary frontal type are apt to be more critical, producing appreciable rainfall over a given area on several successive days. Thunderstorms may be the frontal type associated with continental storms or the local type that can produce high rainfall intensities, but the most severe storms in the area are the hurricane type, of tropical origin (USACE 1959).

The historic storms of September 1938 (+15.0 ft NAVD88), September 1944 (+8.2 ft NAVD88), and August and September 1954 (+13.9 ft NAVD88) were the most extreme on record for this area for coastal storm surge, representing the top three surge events recorded at the Providence tide gage (Table 1). The September 1938 storm, where the greatest part of the rainfall occurred during the 4-day period before the hurricane crossed the coast of Connecticut, is an example of pre-hurricane precipitation. Approximately 90 percent of the total rainfall recorded at Providence during this storm was pre-hurricane rainfall. Damages from the 1938 hurricane amounted to $16.3 million, and damage from Hurricane Carol in 1954 amounted to $25.1 million. Failure of the Fox Point storm surge barrier during a storm emergency could result in life loss and more than $2.4 billion in economic damages in 2014 dollars, equivalent to $3.2 billion in June Fiscal Year (FY) 2025 dollars (USACE 2022)

Other examples of rainfall coincident with hurricanes are September 1944, September 1954 (Hurricane Edna), and August 1955 (Hurricane Diane). Hurricane rainfall is responsible for the majority of record floods on the smaller river basins and tributaries in New England, as well as serious flooding on major rivers that extended over a long period or followed a period of antecedent precipitation. The storm surges in the study area from 1938–1955 were the main drivers for constructing the barriers in Providence, RI, and throughout New England.

Table 1
Top ten surge events at the Providence tide gage 8454000 (National Oceanic and Atmospheric Administration [NOAA] n.d., b).

Rank	+ ft NAVD88	Date
1	15.0	September 20, 1938
2	13.9	August 31, 1954
3	8.2	September 14, 1944
4	7.6	January 20, 1978
5	7.5	August 19, 1991
6	7.2	January 8, 1978
7	7.1	September 12, 1960
8	7.0	November 30, 1963
9	6.7	December 23, 2022
10	6.7	December 18, 2023

- **September 1938 Flood** – Many sections of New England were saturated with as much as 4 inches of rainfall, with very little surface runoff, from September 12–16. Precipitation occurred again on September 17 and increased in intensity until September 21, when the hurricane arrived. Although Providence recorded only 3.1 inches of rain during this period, storm centers near Buck, Connecticut, and Barre, Massachusetts, experienced as much as 17 inches during the storm. Had this storm been centered on the Providence River drainage, major river flooding would have added more damage and destruction to that already caused by the hurricane winds and storm surge

- **August 31, 1954, Flood (Hurricane Carol)** – Rainfall from this hurricane started early in the morning of August 31 in southern New England and ended during the afternoon in northern Maine. Precipitation during this storm ranged between 2–4.5 inches, with the maximum recorded in southern New Hampshire. Providence experienced fewer than 3 inches of rainfall but was damaged by the hurricane's storm surge, which inundated the city.

- **September 11, 1954, Flood (Hurricane Edna)** – The rainfall associated with this hurricane amounted to about 4.4 inches at Providence and 6.3 inches at Woonsocket, Rhode Island. Very little antecedent precipitation occurred, but the high concentration of rainfall in about a 6-hour period produced serious flooding on many streams. This flood was the maximum of record for the Woonasquatucket River at Centerdale, Rhode Island, with a peak discharge of 1100 cubic feet per second (cfs). The computed total flow from the Moshassuck and Woonasquatucket Rivers at Providence was estimated to have a maximum discharge of about 6,000 cfs.

- **August 19, 1955, Flood (Hurricane Diane)** – Torrential rains accompanied this hurricane, falling on ground already saturated by the heavy precipitation which accompanied Hurricane Connie during the previous week (August 11–15). In less than a 2-day period, over 6 inches of rain were recorded in Providence and 10.4 inches at Woonsocket. Despite the heavy rain, the total runoff measured at Centerdale represented only about 0.4 inches for the entire 38.3 square miles of drainage. Runoff computations indicate that this flood may have been the largest of record in the lower Woonasqwatucket River. The maximum discharge for the entire drainage area above the project site was estimated to be about 6,400 cfs.

- **October 29, 2012, Flood (Hurricane Sandy)** – This storm impacted Rhode Island, causing widespread power outages and coastal flooding due to storm surge, though the worst damage was concentrated in southern coastal areas and Narragansett Bay. In Providence, the Fox Point storm surge barrier was activated to protect the downtown area, while communities south of the barrier experienced flooding. Sandy brought high winds and coastal flooding to southern New England. Easterly winds gusted to 50–60 mph for interior southern New England; 55–65 mph along the eastern Massachusetts coast and along the I-95 corridor in southeast Massachusetts and Rhode Island; and 70–80 mph along the southeast Massachusetts and Rhode Island coasts. The very large waves on top of the storm surge caused destructive coastal flooding along stretches of the exposed Rhode Island south coast. (National Weather Service [NWS] 2012). The peak water elevation for Hurricane Sandy was approximately +6.7 ft NAVD88 (Figure 5).

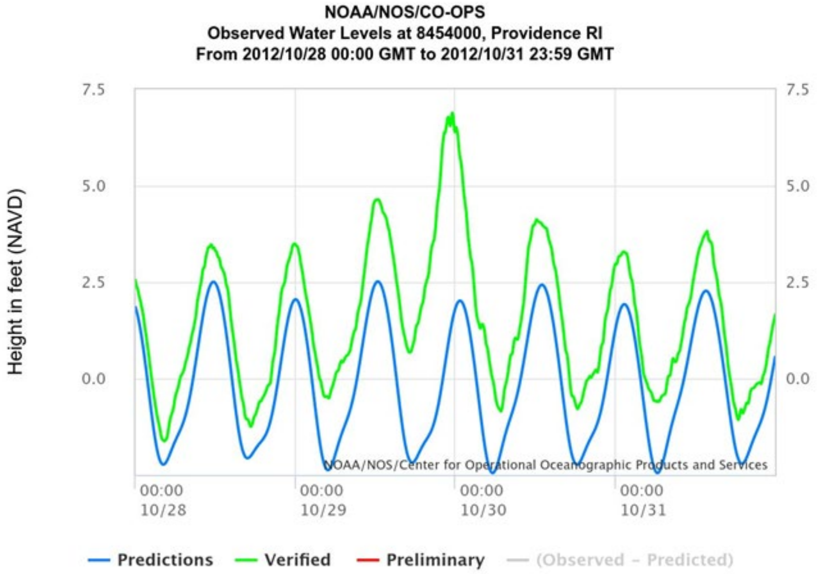


Figure 5. Hurricane Sandy, Providence tide gage,(NOAA, 2026).

2.4. Historic Events

The hurricane of 1938 continues to be the storm of record for elevated water levels at the Providence tide gage 8454000 (NOAA n.d., b), at +15.0 ft NAVD88. Since construction, the project has never been tested with a flood height near that produced by this storm. On August 19, 1991, Hurricane Bob's water level was +7.5 ft NAVD88, approximately 7 feet below the 1938 storm surge. Hurricane Sandy ranked as the 11th highest event for that gage with an elevation of +6.7 ft NAVD88 (USACE 2007).

2.5. Design Coastal Storm

Decades ago, USACE used a design storm approach, as opposed to the current life-cycle approach that considers a range of hypothetical and historical extratropical and tropical cyclones. DM No. 4, *Fox Point Hurricane Barrier* (USACE 1960), identified the design storm for the Fox Point storm surge barrier system as the hurricane of 1938. The September 1938 storm produced the highest surge and rainfall associated with a hurricane and flooding in southern New England (Figure 6). The maximum precipitation for this storm was concentrated over Portland (Buck), Connecticut, about one mile south of Middletown, where a total of 17 inches was recorded for September 17–21.

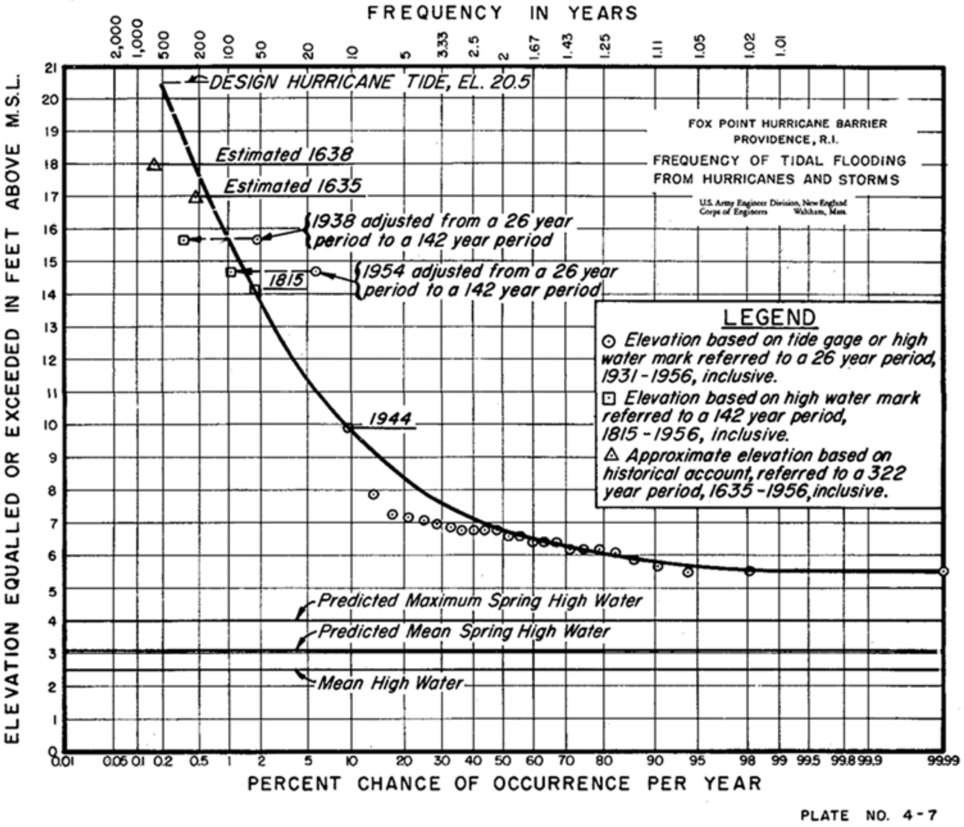


Figure 6. Storm frequency curve from the original DM.

2.6. Standard Project Riverine Flood

DM No. 2 identified the standard project flood (SPF) for the area in accordance with Civil Engineer Bulletin 52-8, *Standard Project Flood Determination* (USACE 1952), with adopted unit hydrographs for the basin subdivisions. The DM stated that while Providence has not experienced a major river flood coincident with a damaging storm surge within the period of record, the physical possibility exists with every future hurricane. Therefore, studies were made of various storms experienced in New England that could be considered associated with hurricanes. A rainfall excess of 9.12 inches was developed from 48 hours rainfall of 12.0 inches, with maximum losses of 0.1 inches per hour. The peak of the SPF for the total drainage area would be about 24,000 cfs. The assumption was that the flood runoff would not coincide with a hurricane storm surge requiring that the Tainter gates be closed; instead, this flow tested the capacity of the gated openings through the barrier to confirm that the restriction would not contribute to damage during a major river flood with normal high tide conditions.

2.7. Datums

The Fox Point storm surge barrier spans decades of datum references and changes to how water elevations, storm elevations, and feature heights are recorded. Per ER 1110-2-8160, this study references the latest datums in the National Spatial Reference System, which are the North American Vertical Datum of 1988 (NAVD88) for geodetic heights and the 1983–2001 National Tidal Datum Epoch for tidal water levels, for all elevation measurements. Figure 7 shows how these elevations compare to each other at the Providence gage in the 1983–2001 period.

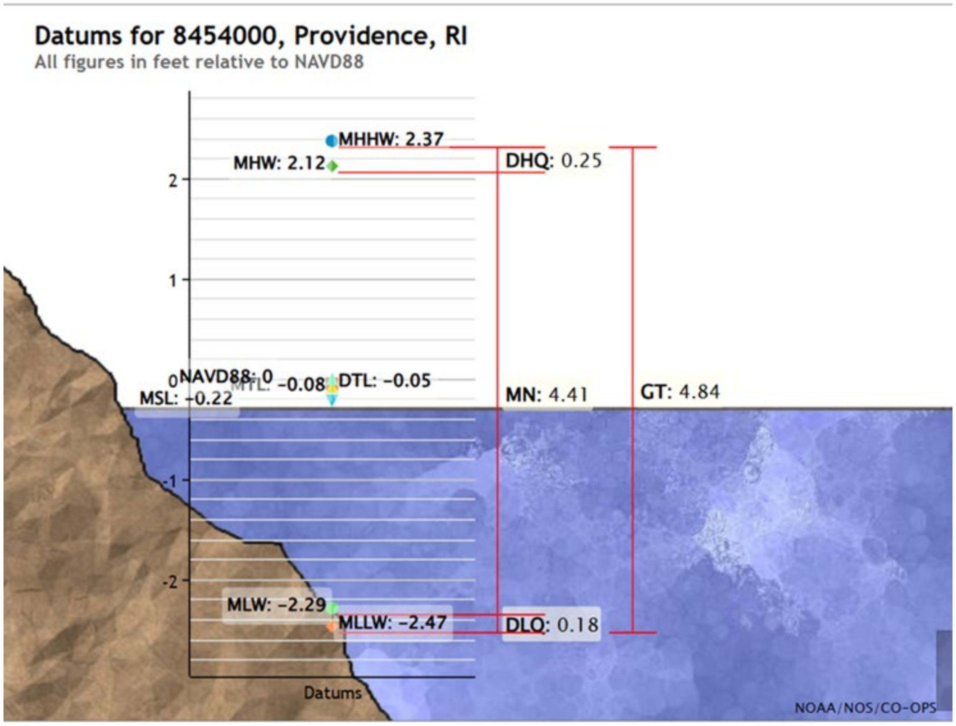


Figure 7. Datum elevations at the Providence gage.

Table 2 lists the datum elevation differences relative to NAVD88.

Table 2
Datum height differences from NAVD88 (datum accepted April 17, 2003).

Datum	Datum Name	Height Difference (feet)
HAT	Highest Astronomical Tide (October 9, 2033)	+3.78
MHHW	Mean Higher High Water	+2.37
MHW	Mean High Water	+2.12
NAVD88	North American Vertical Datum of 1988	0
MTL	Mean Tide Level	−0.08
MSL	Mean Sea Level	−0.22
MLW	Mean Low Water	−2.29
MLLW	Mean Lower Low Water	−2.47
LAT	Lowest Astronomical Tide (January 14, 2036)	−3.6

3. Problems, Opportunities, Objectives and Constraints

Planning studies typically begin with a preliminary assessment to identify problems, opportunities, objectives, and constraints.

- **Problems** help identify the water resource issue the team is trying to solve.
- **Opportunities** usually present the options to resolve that problem.
- **Objectives** identify the specific timing duration, location, and effect to define the analysis parameters.
- **Constraints** are issues that limit the analysis parameters for costs and time

This approach establishes metrics for evaluating the study’s progress and, ultimately, assessing its effectiveness in addressing problems, capitalizing on opportunities, achieving stated objectives, and mitigating constraints. This helps the project development team (PDT) develop comprehensive assessments.

Sections 3.1 to 3.4 identify the study’s problems, opportunities, objectives, and constraints.

3.1. Problems

- Evaluate the existing Fox Point Storm Surge Barrier System to determine the resilience of the feature against storm surge, SLC, and variations in precipitation.

3.2. Opportunities

- Evaluate the resilience of the Fox Point Storm Surge Barrier System.
- Recommend further studies or confirm the resilience of the system through small adjustments to the system as part of normal operations and maintenance (O&M).
- Recommend a post-authorization change (PAC) report to review the completed project for large-scale changes to the system or to make recommendations and modifications to the O&M of the system.

3.3. Objectives

This study’s objectives specify timeframes and scenarios to evaluate for SLC and precipitation.

- SLC projections were based on USACE low, medium, and high projections defined in ER 1100-2-8162, adjusted to the observed rate of change at the Providence gage (4.6 mm/yr between 1985–2025).

- The rainfall projections used adjustment factors based on simulations under representative concentration pathway (RCP) 8.5 applied to the precipitation totals from the *Precipitation Frequency Atlas of the United States, Volume 10* (*Atlas 14*) (Perica et al. 2019) for 10-, 25-, 50-, 100-, and 500-year storms for 24-hour and 72-hour duration events.

- The study timeframe was established from the current date to 2100 to synchronize projections with USACE resilience tools, notably the Comprehensive Hydrology Assessment Tool (CHAT) (USACE n.d., a) and the Sea Level Analysis Tool (SLAT) (USACE n.d., b). This synchronization aligns the tools' projected outyears (the projections in the CHAT extend to 2100).

Based on these adjustments, the following five objectives are specific to timing, location, duration, and effect:

1. Assess current and future vulnerability of the Fox Point storm surge barrier system to overtopping (+24.2 ft NAVD88) and flanking from tropical and extratropical storms by considering the design storm plus three rates of SLC for low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

2. Assess changes in the Fox Point storm surge barrier system critical elevation exceedance thresholds and operational frequency under low, intermediate, and high USACE sea level scenarios and changes in future watershed hydrology against critical elevation exceedance thresholds of +5.2 ft NAVD88.

3. Assess impacts to vehicular gates at Allens Avenue (+11.2 ft NAVD88), India Street (+9.0 ft NAVD88), South Main Street (+14.1 ft NAVD88), and Rhode Island Energy (+11.4 ft NAVD88) under low, intermediate, and high USACE scenarios at the Providence tide gage to 2100.

4. Assess impacts to the five sewer gates/tunnels that prevent high tides from backing up through the sewer lines by considering the design storm against the low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

5. Assess changes to riverine flooding behind the closed Fox Point storm surge barrier system for the pumping system and electrical system/generator against the *Atlas 14* frequency events (10, 20, 50, 100, and 500 years) plus RCP 8.5 output from the CHAT tool for 24-/72-hour events to the minimum, lower quartile, median quartile, upper quartile, and maximum in cfs and stage to 2100.

3.4. Constraints

- Funding (studies of this size and type are usually limited in funds).

- Timeframe (the projection was limited to 2100 based on the model capabilities).

4. Weather Considerations

4.1. Recent Weather-Related Trends

The study team evaluated observed and projected trends in temperature and precipitation using data and assessments from authoritative sources, including the following:

- The Climate Explorer website (NOAA & National Environmental Modeling and Analysis Center [NEMAC] n.d.).

- *State Climate Summaries 2022: Rhode Island* (NOAA 2022).

The National Sea Level Explorer website (EPA, DHS, FEMA, NASA, NOAA, USACE, DoD, and USGS n.d.).

- *Fifth National Climate Assessment: Chapter 21: Northeast* (Whitehead et al. 2023).

- *Recent US Climate Change and Hydrology Literature Applicable to US Army Corps Engineers Missions: New England Region 01* (Civil Works Technical Series [CWTS]-2015-20) (USACE 2015).

These sources summarize the latest science, including observed and projected temperature, precipitation, and changes in sea levels.

The Fifth National Climate Assessment reports that the Northeast United States continues to be confronted with extreme weather, most notably extreme precipitation, which caused problematic flooding across the region and heat waves (very likely, high confidence). In response, adaptation and mitigation efforts, including nature-based solutions, have increased across the region (high confidence), with a focus on emissions reductions, carbon sequestration, and resilience building (medium confidence) (Whitehead et al. 2023).

The NOAA state climate summary for Rhode Island (NOAA 2022) predicts increases in temperature, sea level, and precipitation and documents the effects of extreme storms in the state. Temperatures in Rhode Island have risen almost 4 °F since the beginning of the 20th century, and 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. Annual precipitation in Rhode Island has increased since 1895 and 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.

Total annual precipitation for Rhode Island was generally above average in recent decades. The driest multiyear periods were the 1940s and the latter half of the 1960s, and the wettest period was the 2000s, although precipitation has been predominantly above average since the 1970s. The driest consecutive 5 years was the 1962–1966 interval, and the wettest 5-year period was 2005–2009, with an annual average of 54 inches of precipitation, which was about 8 inches more than the long-term average. Since 2000, summer precipitation was above average until the most recent 6-year period (2015–2020), which was below average (NOAA 2022).

Civil Works Technical Series (CWTS-2015-20) discusses a strong consensus in the recent literature toward an increase in annual temperature in the New England Region over the past century, particularly in the latter part of the century. Several studies indicate cooling during some seasons, or cooling throughout the year in northern New England. Winter temperatures may be increasing at a faster rate than other seasons. The literature also points toward an increasing trend in the number and temperature of extreme heat days. The literature also has good consensus that total precipitation and the occurrence of extreme storm events have increased over the past century in the study region. However, despite the increased precipitation in the region, little evidence is available of significant increases in streamflow over the same period. This paradox is discussed by Small, Islam, and Vogel (2006), who attribute it largely to seasonal differences in the timing of the changes in precipitation vs. streamflow, and other studies note that snowfall is decreasing. Several studies indicate that seasonal streamflow timing is shifting even as annual volumes may not be changing. Results presented here also suggest that increasing temperatures may play an additional role in the lack of streamflow sensitivity to precipitation changes in the region (USACE 2015).

The literature has a strong consensus that air temperatures will increase in the study region and throughout the country over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of up to approximately 3 °C (5.4 °F) by the latter half of the 21st century for the New England Region. Some studies anticipate the largest increases in summer, and others predict the greatest warming in winter. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past. Projections of precipitation and hydrology in the New England Region are less certain than those associated with air temperature. However, in general, the literature indicates increases in precipitation through the 21st century. Extreme high-water events (storms and floods), in particular, are projected to increase. The literature has little consensus 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. Simultaneously, summer low flow volumes may be reduced, and some studies indicate increased drought frequency (USACE 2015).

Sea level trends were evaluated for the gages nearest to Fox Point and for the region as a whole. The local Providence tide gage 8454000 (NOAA n.d., b) reports a relative sea level trend of + 2.56 millimeters/year (mm/yr) with a 95 percent confidence interval of +/− 0.23 mm/yr based on monthly mean sea level (MSL) data from 1938–2023, which is equivalent to a change of 0.84 feet in 100 years (NOAA n.d., b).

SLAT facilitates the application of ER 1100-2-8162 and Engineer Pamphlet (EP) 1100-2-1, *Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation* (USACE 2019c), which provide guidance for incorporating SLC into USACE projects.

The SLAT tool provides two observations from SLC at the Providence tide gage, the period from January 1985 to December 2024 and the period from June 1938 to December 2024. Based on these observations, the relative sea level change (RSLC) at the Providence gage recently increased from 2.62 mm/yr from the historic record to 4.6 mm/yr in the more recent 40-year timeframe from January 1985 to December 2024.

Many aspects of weather-related risk are likely to impact the Fox Point study area in the future related to increases in temperature, fluctuations in precipitation and riverine discharge, SLC, and coastal storms. Key factors affecting the Fox Point system include projected SLC and precipitation impacting Tainter gate closure exceedances and the barrier's function against coastal storms. These factors are evaluated to understand the vulnerability of the Fox Point storm surge barrier system to weather-related risks. Additional details on SLAT and CHAT are in Appendix A, Hydrometeorological-Related Risks.

4.2. Weather-Related Thresholds and Tipping Points

Critical thresholds are water surface elevations (WSEs) at which structural condition deteriorates or system performance is compromised, and a tipping point is the point beyond which stability and/or performance rapidly declines, leading to significantly increased impacts. The study team identified multiple thresholds and tipping points within the Fox Point storm surge barrier system to evaluate against weather-related risks (Table 3). They evaluated these thresholds and tipping points against multiple scenarios related to precipitation, SLC, and stream discharge that may impact the primary function of the Fox Point system's ability to reduce storm damage (USACE 2020).

The thresholds and tipping points for the Fox Pont system include the top of the storm surge barrier, the Tainter gate closure elevation threshold, and the numerous street gates and stormwater systems that must be operated during storm events to reduce the storm risk to the city of Providence. The critical elevation thresholds of the Fox Point system are listed in Table 3.

Table 3
Major thresholds and tipping points of the Fox Point storm surge barrier system.

Feature	Critical Elevation Threshold	Hazard	Harm	Qualitative Likelihood
Top Elevation of Fox Point Feature	+24.2 ft NAVD88	Increased water elevations overtopping the structure during storm events	Flooding In Providence behind closed gates	Not Likely
Tainter Gate Barrier Closure Elevation Threshold	+5.2 ft NAVD88	Increased closure frequency with SLC and/or increased damages	Increased operational costs, gate maintenance	Very Likely
River Pumps (Five @ 1400 cfs)	7,000 feet per second	Increase in discharge requirements as a result of streamflow increases	Flooding in Providence with Barriers closed from inability of pumps to evacuate streamflow	Indicated/ Plausible

Identifying thresholds and tipping points within the impacted project area informs both selecting adaptation options and decision-timing strategies. Determining tipping points that generate a necessary action in the future is an essential element of alternative development with respect to SLC. These critical elevations were evaluated against projections of future precipitation and SLC to assess the system's resilience to these changes. The team evaluated these elevations against future projections of SLC and precipitation with USACE certified tools and models, including the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), the HEC River Analysis System (HEC-RAS), SLAT, and the Gate Operations Analysis Tool (GOAT) to determine future weather-related hazards to the Fox Point barrier.

4.3. Correlation Between Storm Surge and Rainfall/Runoff

Correlation analysis reveals the relationship between interior/riverine and exterior/coastal forcing. No specific correlation analysis supported the Fox Point location, but one was performed nearby, for New Haven, Connecticut. Due to the generally similar weather patterns, the conclusions from the New Haven analysis applied to Fox Point.

Based on available data, the New Haven analysis demonstrated a weak correlation between rainfall and elevated coastal water levels. But this is not a case of complete non-coincidence; though rare, high rainfall and elevated coastal water level can occur simultaneously. High tide conditions only prevail for about 10 percent of the time, so an intense storm is more likely at mid or low tide. Predicting the coincidence of rainfall and elevated coastal water level is uncertain. Independence was demonstrated by a condition where the coastal water level does not appear in any way reliably related to or predicted by the rainfall (or vice versa).

Analysis relied on the available historic datasets. In areas where extratropical storms are present, like Providence, the length of the historic dataset is not sufficient to fully understand the statistical relationship. Since a rigorous analysis of joint probabilities was beyond the scope of this study, practitioner judgement selected marginal probabilities for precipitation and coastal water level.

DM No. 2 supports the lack of correlation between coastal storm and riverine flooding. This DM discussed that the probability of a major river flood coincident with a hurricane tide is remote. The hurricanes of September 1938 and August 31, 1954 (Hurricane Carol) caused the greatest historic tidal damage in Providence, but in both storms the total precipitation in the area was only about 3 inches. The reverse was true in the cases of the hurricane of September 1954 (Hurricane Edna) and August 19, 1955 (Hurricane Diane). During these storms that caused the greatest river flooding, tides were only slightly above normal and caused no serious damages in Providence. However, the DM indicated that although Providence has not experienced simultaneous major river flooding and damaging hurricane tides within the period of record, each hurricane presents the physical possibility of large tidal surge occurring in combination with extreme precipitation.

5. HEC-HMS Modeling

HEC-HMS simulates the complete hydrologic processes of dendritic watershed systems for the study area. The software includes many traditional hydrologic analysis procedures, such as event infiltration, unit hydrographs, and hydrologic routing. HEC-HMS also includes procedures for continuous simulation, including evapotranspiration, snowmelt, and soil moisture accounting. This study's hydrologic model used HEC-HMS version 4.12. The model characterized the watershed, its soil properties, and potential discharge changes resulting from projected precipitation increases in the Woonasquatucket and Moshassuck Rivers.

5.1. Watershed Delineation

The Rhode Island watershed was delineated using HEC-HMS from a digital elevation model (DEM) of terrain. Delineation resulted in 10 subbasins.

The watershed is very urban and developed in the southeastern half, which covers much of the city of Providence. The northwestern half is more suburban and forested (Figure 8). Several small ponds, dams, and reservoirs are within the watershed. The watershed outfall is at the southeast corner, at the Fox Point barrier. The areas in orange and brown are higher in elevation; areas in green are lower. The Woonasquatucket River and the Moshassuck River converge into the Providence River, on which the Fox Point storm surge barrier is situated.

Observed data is available for use within the watershed. Each river in the watershed has a gage: the Woonasquatucket River gage 01114500 (USGS n.d., c) in Centerdale and the Moshassuck River gage 01114000 (USGS n.d., a) in downtown Providence. The Woonasquatucket gage has discharge data available dating from 1987–2025 (present) and the Moshassuck gage has discharge data available dating from 1990–2025 (present).

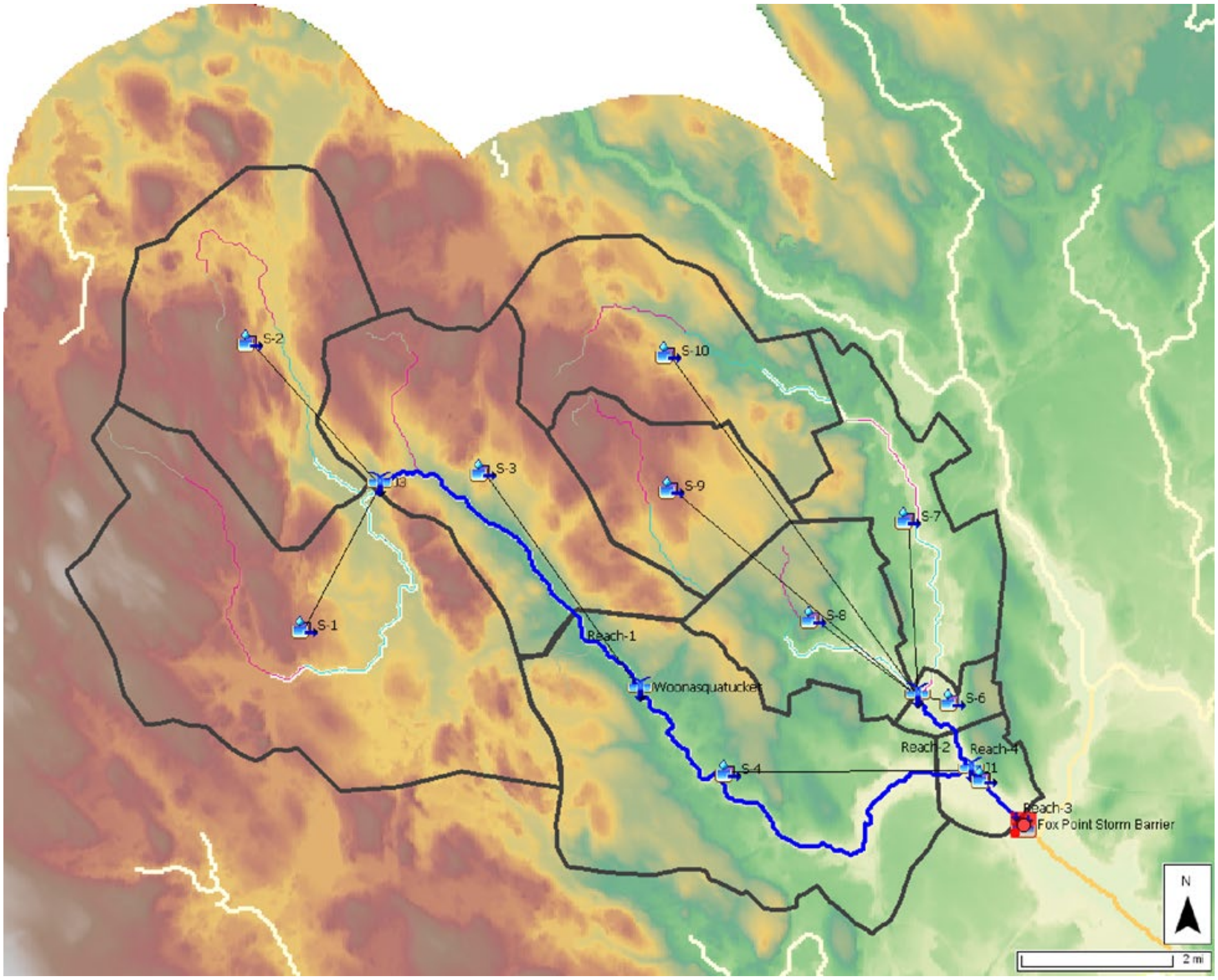


Figure 8. Watershed delineation with terrain elevation visualization.

5.2. Initial Basin Conditions

5.2.1. Loss Parameters

The loss method for the hydrologic model was the initial and constant method (USACE n.d., c).. This method has three main inputs: initial loss, constant rate (loss), and percent imperviousness. Constant loss rate parameters were generated using a weighted average of different soil groups A, B, C, and D. ratios. The amount of area in each soil group was determined using USDA Web Soil Survey data for the state of Rhode Island (USDA n.d.). The weighted average was computed for all 10 delineated subbasins. Percent imperviousness for each subbasin was determined from the watershed information in USGS's StreamStats database (USGS n.d., b). In the calibration process, initial loss and constant rate parameters are altered in an iterative process to converge on accurate values. The initial values are shown in Table 4.

Table 4
Soil group constant rate values were estimated using the following table SCS soil groups and infiltration (loss) rates (Natural Resources Conservation Service 1986; Skaggs and Khaleel 1982).

Soil Group	Description	Range of Loss Rates (inches/hour)
A	Deep sand, deep loess, aggregated silts	0.30–0.45
B	Shallow loess, sandy loam	0.15–0.30
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.05–0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00–0.05

5.2.2. Transform Parameters

The Clark unit hydrograph method considers the translation of excess precipitation throughout the watershed as well as the attenuation of the discharge due to temporary storage within the watershed. This analysis used the Modified Clark (ModClark) hydrograph. The ModClark method explicitly accounts for variations in travel time to the watershed outlet using a gridded representation of the watershed to route excess precipitation to the subbasin outlet (Kull and Feldman 1998; USACE n.d., d). The two parameters for the ModClark transform method are

- Tc (time of concentration) – The time for excess precipitation to travel to hydraulically.

- R (storage coefficient) – The attenuation due to storage effects in the watershed.

(Kull and Feldman 1998).

Initial values for Tc and R were calculated using basin characteristics and then modified based on the calibration efforts.

5.2.3. Baseflow Parameters

The recession baseflow method was selected primarily because it is for event simulation. Initial discharge is needed and can be readily obtained for calibration events by using the two USGS gages in the watershed. Recession constant and ratio-to-peak values were estimated and then modified during calibration.

5.2.4. Routing Parameters

The Muskingum Routing method was used. Using channel dimensions and rating curves for both rivers, travel time was calculated as one of the inputs. The Muskingum x value is dimensionless and not easily calculated. Initial x values were chosen and changed through the iterative calibration process (Figure 9, Figure 10).

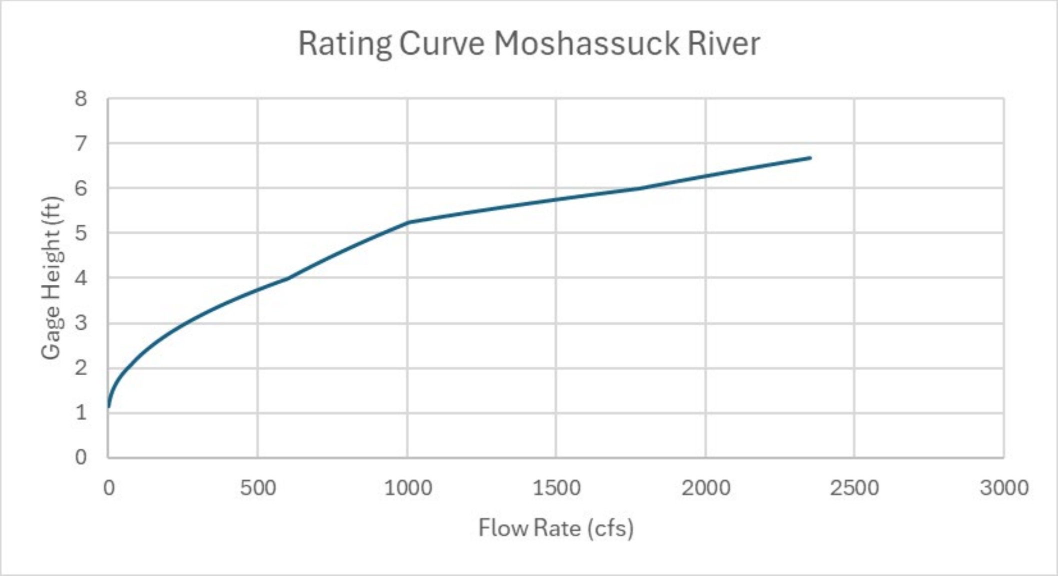


Figure 9. Moshassuck rating curve.

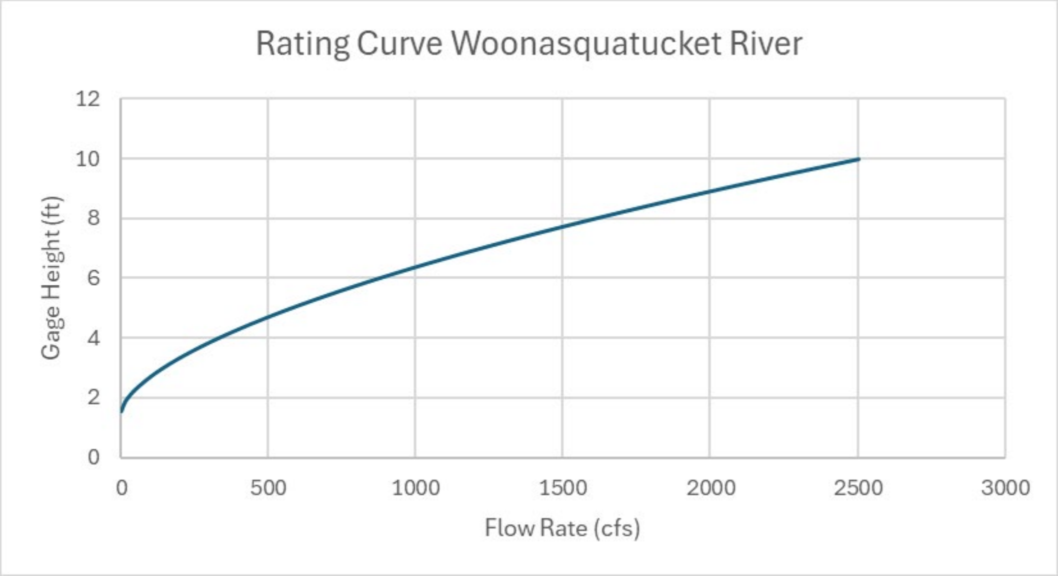


Figure 10. Woonasquatucket rating curve.

5.3. Calibration and Validation Events

The model's parameters (loss, transform, baseflow, routing) were modified in an iterative process so that the results of the simulation closely resembled observed data for calibration events. Two calibration events were used: July 4, 2023, and March 24, 2024. These events were chosen to avoid periods of snowmelt in the Northeastern United States. The observed data is from the two gages, one on each river in the watershed: the Woonasquatucket River gage 01114500 (USGS n.d., c) and the Moshassuck River gage 01114000 (USGS n.d., a).

- The July 4, 2023, calibration event recorded 1 inch of rain in the watershed; however, the previous week had 3 days with a half-inch of rainfall, likely causing the soil conditions to become more saturated, resulting in a peak flow of 1,400 cfs in the Moshassuck River (baseflow 30 cfs before event) and 140 cfs in the Woonasquatucket River (baseflow 30 cfs before event) .

- The March 24, 2024, event occurred after almost 2 weeks of minimal rainfall. The last significant rain event occurred on March 9 at 1.6 inches of precipitation. On March 23, the Providence area received 3.1 inches of rain causing the flows in the Moshassuck River to peak at 2,200 cfs (baseflow 45 cfs before event) and flows in the Woonasquatucket River to peak at 550 cfs (baseflow 120 before event).

The loss parameters in the HEC-HMS model skew higher than typical. The initial loss rates were far too low to account for all of the runoff seen in the results. Originally these low initial loss rates were combatted by increasing loss rates to reduce runoff, but it required increasing the loss rates beyond what was reasonable. Loss rates were reduced back into reasonable ranges, and transform parameters were altered to reduce the runoff in the model to match observed river discharge in the calibration process.

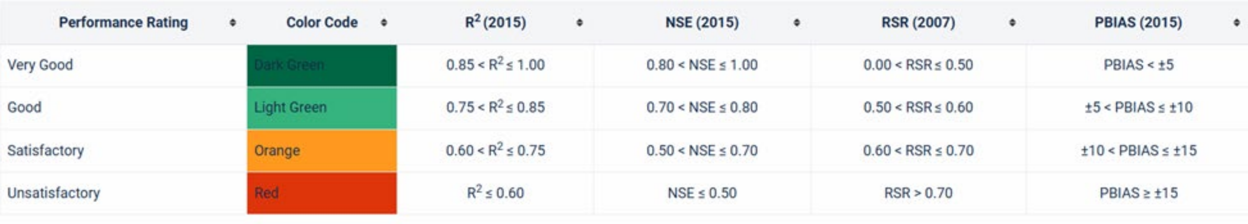
Two validation events were also simulated: July 28, 2012, and August 13, 2014. Parameters in validation runs are created by averaging the parameters from both calibration events. Parameters for validation events are not adjusted like in calibration events save for initial river discharge and initial losses, which change based on antecedent conditions for each event. Initial losses and initial discharge are unique for each validation run and are the only parameters that change. For these events, precipitation data is entered into the model, and the simulation results should closely match the observed data without adjusting any parameters other than initial discharge for the baseflow and initial losses used in deficit and constant loss method.

- The July 28, 2012, validation event recorded 0.88 inches of rain in the watershed. In previous 10 days two prior rain events of 1.74 inches and 0.55 inches occurred which likely saturated the soil, resulting in a peak flow of 1,280 cfs in the Moshassuck River and 150 cfs in the Woonasquatucket.

- The August 13, 2014, validation event recorded 1.06 inches of rain in the watershed. The previous two weeks saw almost no rainfall. The peak runoff for the event was 1,300 cfs in the Moshassuck and 210 cfs in the Woonasquatucket River.

5.4. Calibration and Validation Results

For model simulation results, HEC-HMS can display two metrics that determine model accuracy: a Nash-Sutcliffe score and percent-bias. The following table summarizes the Moriasi et al. 2015 report from the HEC-HMS user's manual. (Figure 11). The charts showing results vs. observed data (Figure 12, Figure 14) and the Nash-Sutcliffe scores (Figure 13, Figure 15), summarized in Table 5, suggest that the calibration results fall well within an acceptable range for this analysis based on the criteria in the Nash Sutcliffe Efficiency (NSE) column of the table in Figure 11. Peak timing and magnitude for the HEC-HMS-simulated events also closely match the observed data. Subsequent validation events also had Nash-Sutcliffe scores within an acceptable range.



Performance Rating	Color Code	R^2 (2015)	NSE (2015)	RSR (2007)	PBIAS (2015)
Very Good	Dark Green	$0.85 < R^2 \le 1.00$	$0.80 < NSE \le 1.00$	$0.00 < RSR \le 0.50$	PBIAS < ±5
Good	Light Green	$0.75 < R^2 \le 0.85$	$0.70 < NSE \le 0.80$	$0.50 < RSR \le 0.60$	±5 < PBIAS ≤ ±10
Satisfactory	Orange	$0.60 < R^2 \le 0.75$	$0.50 < NSE \le 0.70$	$0.60 < RSR \le 0.70$	±10 < PBIAS ≤ ±15
Unsatisfactory	Red	$R^2 \le 0.60$	$NSE \le 0.50$	$RSR > 0.70$	PBIAS ≥ ±15

Figure 11. HEC-HMS performance ratings for summary statistics.

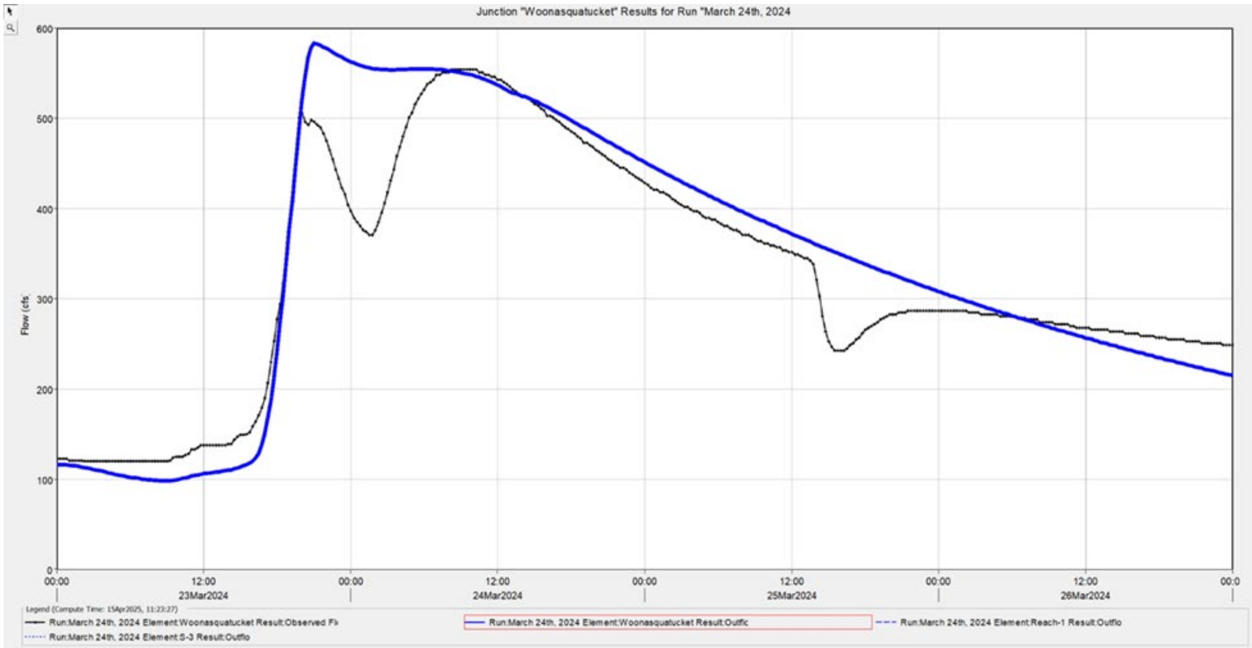
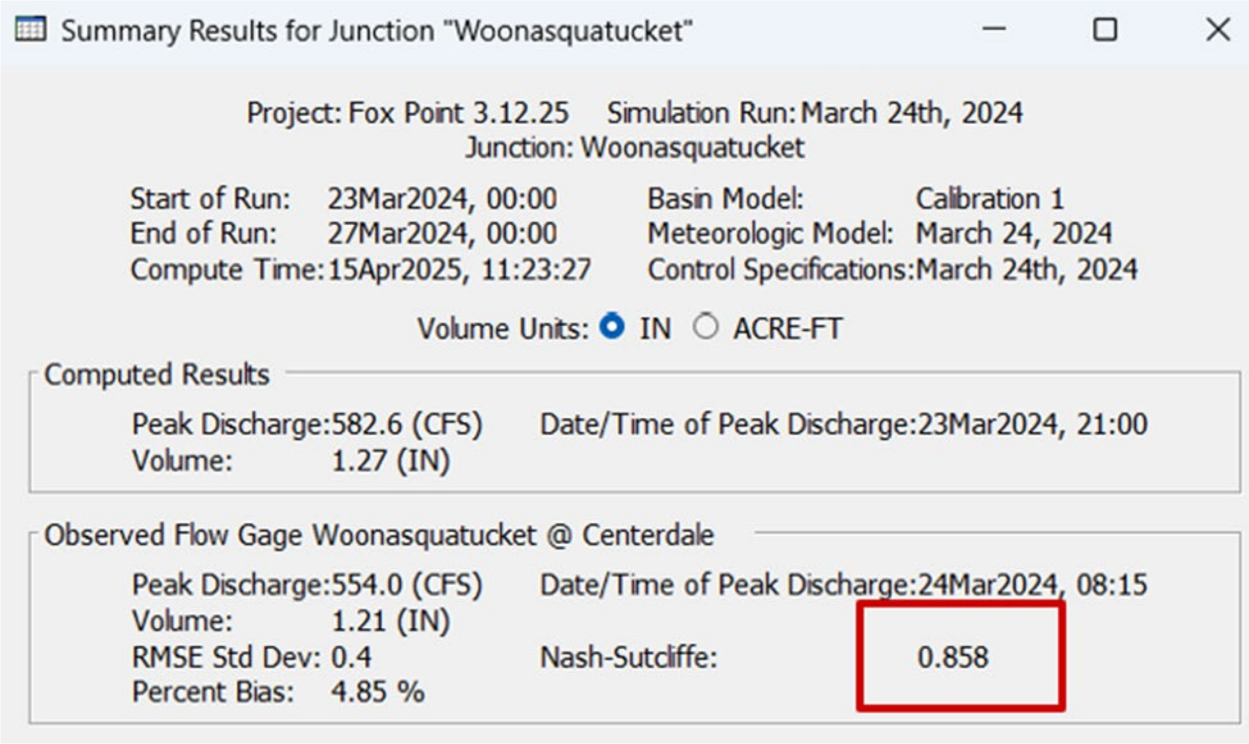


Figure 12. HEC-HMS simulation results vs. observed data at the Woonasquatucket River gage 011114500 (USGS n.d., c) in Centerdale.



Summary Results for Junction "Woonasquatucket"

Project: Fox Point 3.12.25 Simulation Run: March 24th, 2024
Junction: Woonasquatucket

Start of Run: 23Mar2024, 00:00
End of Run: 27Mar2024, 00:00
Compute Time: 15Apr2025, 11:23:27
Basin Model: Calibration 1
Meteorologic Model: March 24, 2024
Control Specifications: March 24th, 2024

Volume Units: ● IN ○ ACRE-FT

Computed Results

Peak Discharge: 582.6 (CFS)
Date/Time of Peak Discharge: 23Mar2024, 21:00
Volume: 1.27 (IN)

Observed Flow Gage Woonasquatucket @ Centerdale

Peak Discharge: 554.0 (CFS)
Date/Time of Peak Discharge: 24Mar2024, 08:15
Volume: 1.21 (IN)
RMSE Std Dev: 0.4
Nash-Sutcliffe: 0.858
Percent Bias: 4.85 %

Figure 13. Woonasquatucket calibration results for March 24, 2024.

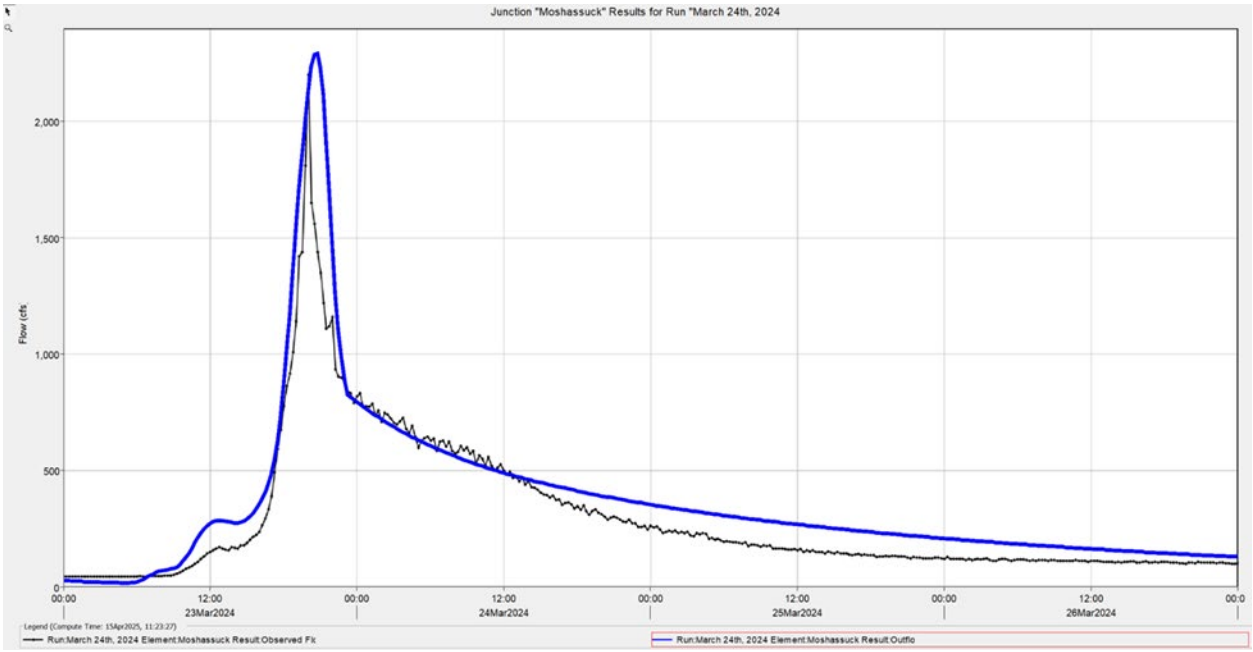
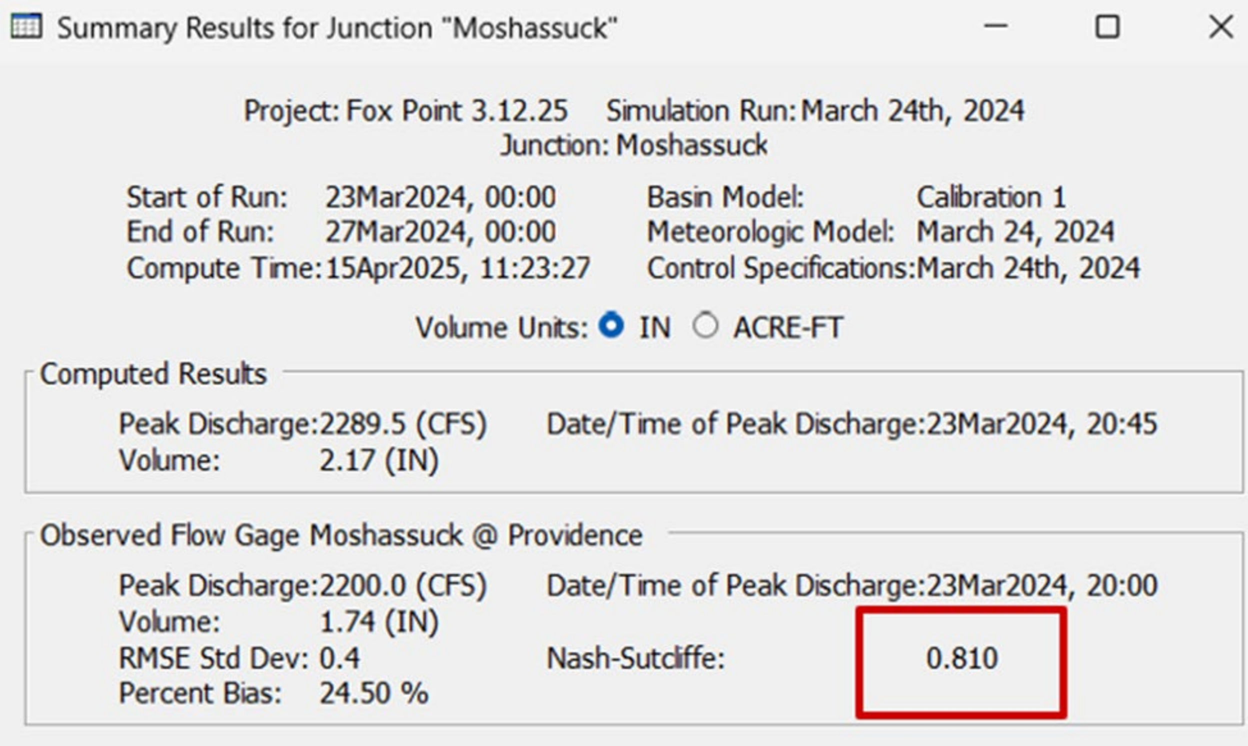


Figure 14. HEC-HMS simulation results vs. observed at the Mossassuck USGS gage (USGS n.d., a).



Summary Results for Junction "Moshassuck"

Project: Fox Point 3.12.25 Simulation Run: March 24th, 2024
Junction: Moshassuck

Start of Run: 23Mar2024, 00:00
End of Run: 27Mar2024, 00:00
Compute Time: 15Apr2025, 11:23:27

Basin Model: Calibration 1
Meteorologic Model: March 24, 2024
Control Specifications: March 24th, 2024

Volume Units: ● IN ○ ACRE-FT

Computed Results

Peak Discharge: 2289.5 (CFS) Date/Time of Peak Discharge: 23Mar2024, 20:45
Volume: 2.17 (IN)

Observed Flow Gage Moshassuck @ Providence

Peak Discharge: 2200.0 (CFS) Date/Time of Peak Discharge: 23Mar2024, 20:00
Volume: 1.74 (IN)
RMSE Std Dev: 0.4 Nash-Sutcliffe: 0.810
Percent Bias: 24.50 %

Figure 15. Moshassuck calibration results for March 24, 2024.

Table 5
Calibration and validation results.

River	Woonasquatucket River	Moshassuck River
July 4, 2023, Calibration		
Nash Sutcliffe Score	0.76	0.73
Percent Bias (%)	-1.72	64
Observed Peak Flow (cfs)	141	1470
Comp. Peak Flow (cfs)	91.3	1659
Observed Volume (in.)	0.16	0.42
Compared Volume (in.)	0.15	0.7
March 24, 2024, Calibration		
Nash Sutcliffe Score	0.86	0.81
Percent Bias (%)	4.86	24.5
Observed Peak Flow (cfs)	554	2200
Comp.Peak Flow (cfs)	583	2289
Observed Volume (in.)	1.21	1.74
Comp. Volume (in.)	1.27	2.17
July 28, 2012, Validation		
Nash Sutcliffe Score	0.74	0.82
Percent Bias (%)	-11	14
Observed Peak Flow (cfs)	152	1280

River	Woonasquatucket River	Moshassuck River
Compared Peak Flow (cfs)	76	1032
Observed Volume (in.)	11	0.37
Comp. Volume (in.)	0.09	0.42
August 13, 2014, Validation		
Nash Sutcliffe Score	0.65	0.86
Percent Bias (%)	28.4	33
Observed Peak Flow (cfs)	208	1280
Comp. Peak Flow (cfs)	185	1122
Observed Volume (in.)	0.19	0.54
Comp. Volume (in.)	0.24	0.72

5.4.1. Production Runs

Production runs were simulated using a model developed from the two calibration events. The parameters in both calibration events are averaged – loss, transform, baseflow, and routing. The full table of parameters is documented in Appendix B, Hydrology.

The program modeled changes in watershed hydrology and precipitation to determine the Fox Point storm surge barrier system's capacity to operate effectively under future conditions and varying precipitation scenarios. The current pumping capacity behind the Fox Point Barrier is 7,000 cfs when all five pumps are fully operational pumping 1,400 cfs each. That is at full capacity, with the five pumps transporting water from behind the barrier to the ocean/bay side of the barrier when the Tainter gate is closed during a coastal storm event. Increases in precipitation are projected to increase run-off amounts, potentially stressing the pump system capacity.

The study team modeled 24- and 72-hour rainfall events for the 10-, 25-, 50-, 100-, and 500-year rainfall storms anticipated for the RCP 8.5 scenario. RCP 8.5 is a high-emission, "business-as-usual" scenario for the future that assumes continued, unmitigated increases in greenhouse gas (GHG) emissions to year 2100.

5.4.2. Representative Concentration Pathway 8.5 Results

The study used *Atlas 14* annual maximum storm (AMS) precipitation frequency estimates (Table 6) with 90 percent confidence intervals for the Providence area to assess the impacts from precipitation changes on at the study location (latitude 41.8484° and longitude −71.4389°). CHAT estimated future precipitation. CHAT found and applied RCP 8.5 modifiers (Table 7) to the *Atlas 14* AMS point depths. The RCP 8.5 scenario models high future GHG emissions and concentrations above current levels. RCP values were found for both a 24-hour and 72-hour duration storm for five recurrence intervals: 10-, 25-, 50-, 100-, and 500-year events (Table 8, Table 9). RCP 8.5 is a very conservative upper estimate for predicted rainfall in this region. The *Atlas 14* annual maximum point depths, as well as the modified point depths are shown below.

Table 6
Atlas 14 AMS estimates.

Recurrence (years)	24-Hour (inches)	72-Hour (inches)
10	5.04	6.27
25	6.14	7.67
50	6.95	8.69
100	7.82	9.78
500	10.3	12.9

Table 7
Percent 8.5 change in annual max: Modifiers to create the future point depths.

Event	Minimum	Lower Quartile	Median	Upper Quartile	Maximum
24-hour	0.01	0.12	0.22	0.29	0.38
72-hour	0	0.13	0.25	0.33	0.47

Table 8
24-hour duration point depth (in) with RCP 8.5 modification.

Recurrence (years)	Minimum (inches)	Lower Quartile (inches)	Median (inches)	Upper Quartile (inches)	Maximum (inches)
10	5.09	5.64	6.15	6.50	6.96
25	6.20	6.88	7.49	7.92	8.47
50	7.02	7.78	8.48	8.97	9.59
100	7.90	8.76	9.54	10.09	10.79
500	10.40	11.54	12.57	13.29	14.21

Table 9
72-hour duration point depth (in) with RCP 8.5 modification.

Recurrence (years)	Minimum (inches)	Lower Quartile (inches)	Median (inches)	Upper Quartile (inches)	Maximum (inches)
10	6.27	7.09	7.84	8.34	9.22
25	7.67	8.67	9.59	10.20	11.27
50	8.69	9.82	10.86	11.56	12.77
100	9.78	11.05	12.23	13.01	14.38
500	12.90	14.58	16.13	17.16	18.96

Future point depths were input into the hypothetical storm events for the five recurrence intervals for 24- and 72-hour storms, for a total of 50 simulations. Peak flows were recorded downstream of the observed gages at the study location. Summaries of these peaks are in Table 10 and Table 11.

Table 10
24-hour duration peaks at barrier (cfs).

Recurrence (years)	Minimum (inches)	Lower Quartile (inches)	Median (inches)	Upper Quartile (inches)	Maximum (inches)
10	2,115	2,486	2,803	3,034	3,340
25	2,836	3,287	3,699	3,990	4,367
50	3,381	3,896	4,374	4,711	5,138
100	3,977	4,566	5,104	5,486	5,974
500	5,702	6,500	7,226	7,736	8,423

Table 11
72-hour duration peaks at barrier (cfs).

Recurrence (years)	Minimum (inches)	Lower Quartile (inches)	Median (inches)	Upper Quartile (inches)	Maximum (inches)
10	785	971	1,127	1,233	1,441
25	951	1,334	1,523	1,671	1,975
50	1,337	1,572	1,858	2,058	2,408
100	1,563	1,912	2,251	2,480	2,894
500	2,447	2,956	3,466	3,831	4,551

5.5. HEC-HMS Discussion and Consideration

The hydrologic analysis does not forecast or predict future events. The link between precipitation (rainfall) and impacts to stream hydrology is not certain; not all increases in precipitation lead to increases in stream discharge, due to factors related to variability of the timing of events and soil moisture, among others.

The model results show that the 7,000 cfs Fox Point pump capacity threshold is only exceeded for the 24-hour rainfall event during the 500-year storm in the RCP 8.5 scenario for the median, upper quartile, and maximum model runs.

A Bulletin 17C analysis was performed for the gages on both rivers. A regional skew for the New England area was applied: 0.37 for skew coefficient and 0.414 mean squared error (MSE) (USGS 2019). Findings indicate that HEC-HMS results for the Woonasquatucket River are close to the results of the 17C analysis. However, the HEC-HMS results for the Moshassuck River show an overestimated peak for higher annual exceedance probability (AEP) events, such as the 500-year, when compared to the 17C analysis. HEC-HMS results are still within the confidence bounds but are near the upper end of the range. Comparison tables are in Appendix B- Hydrology.

6. HEC-RAS Introduction

HEC-RAS is an integrated system of software that simulates one-dimensional steady and unsteady flow of river hydraulics, calculates water surface profiles, and maps inundation. The modeling program determined flood extent and depth behind the Fox Point barrier, considering both the projected increases in precipitation and closure of the Tainter gate from a coastal storm. This model is truncated from an updated USGS version of a FEMA flood insurance study model.

This model for this effort included the Fox Point hurricane barrier and supporting pump station. The model covers downtown Providence, including part of the harbor at the outfall of the Providence River. For the upper extent, the inflow on the Woonasquatucket River begins at Centerdale.

The model is fully one-dimensional. Manning's roughness coefficients range in value from 0.032 to 0.035 for the main channel, with a median of 0.032, and from 0.052 to 0.085 for the overbank areas, with a median value of 0.075. The HEC-RAS model assessed the hydrologic impacts of forecasted precipitation increases within the Providence area and surrounding watershed, based on RCP scenarios from CHAT (Figure 16).

Figure 16. Fox Point storm surge barrier and vicinity.

Woonasquatucket is the primary river reach in the model, with the Moshassuck tributary modeled as a lateral inflow hydrograph. The USGS version of the model included this area but omitted the Fox Point storm surge barrier. This current modeling effort implemented the barrier as well as its three functioning Tainter gates. The gate openings are 40 feet by 40 feet, with the top of the openings at elevation +24.2 ft NAVD88. A ruleset was created for functionality of the gates at specific triggers: The barrier gates are closed when the WSE in the harbor reaches +5.2 ft NAVD88, and they open when WSE drops below 2.2 feet. The pumps are turned off when the gate opens. The gate opening speed is 1 hour 45 minutes, and closing speed is 35 minutes, as stated by the gate operator.

The model included the pump station. Five pumps have a capacity of 1,400 cfs each. The pumps are operated when the upstream flow is high, and the gates are closed due to surge in the harbor. According to the gate operator, the pumps are turned on when upstream flow meets the capacity of the pumps (i.e., when flow is at 1,400 cfs, pump 1 is turned on; when the flow is at 2,800 cfs pump 2 is turned on; etc.). This scheme was modeled in a ruleset for the pump station in the unsteady flow file. Figure 17 and Figure 18 show the pump curves. A limitation of this investigation is that for future MSL values, estimated pump capacity could be reduced as much as 10 percent.

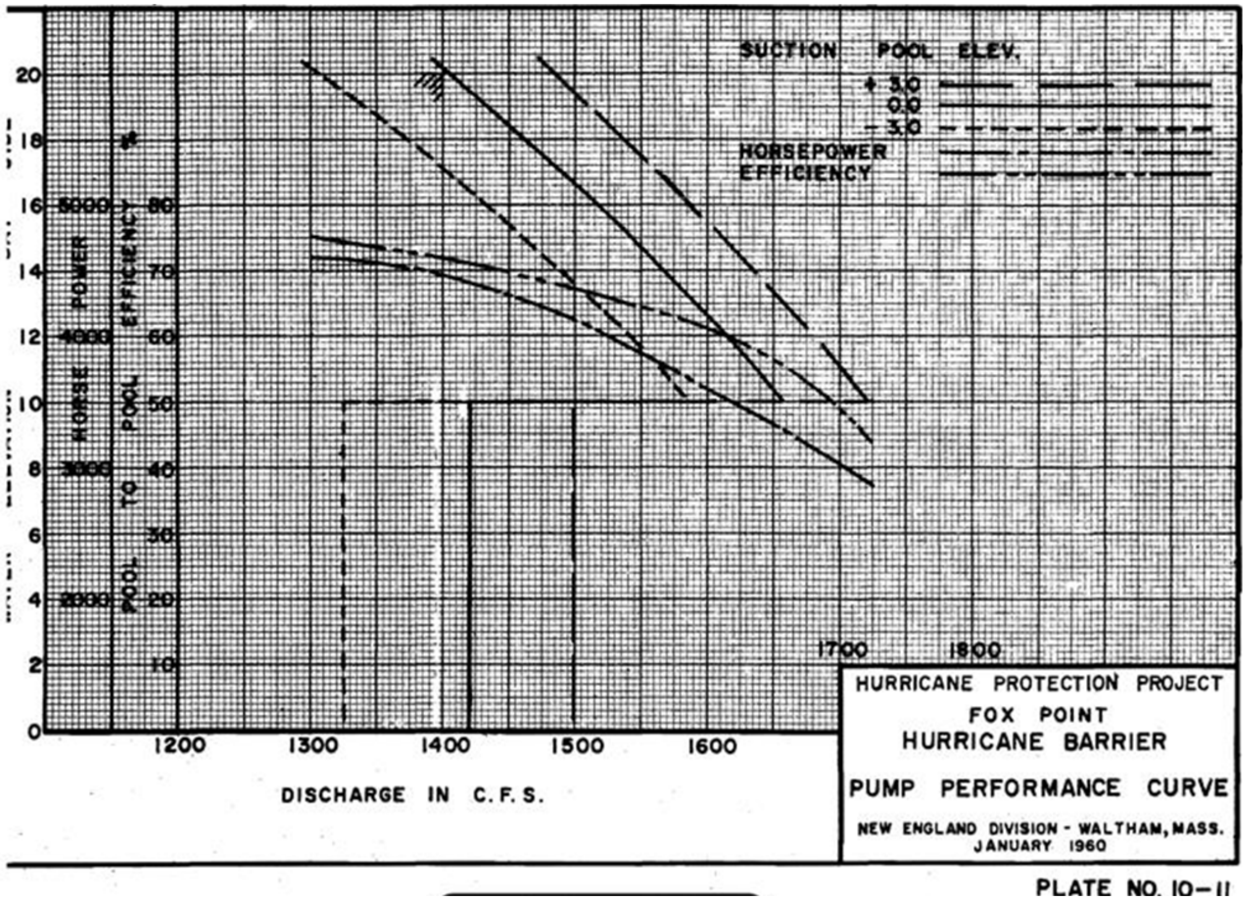


Figure 17. Pump curves (DM No. 4).

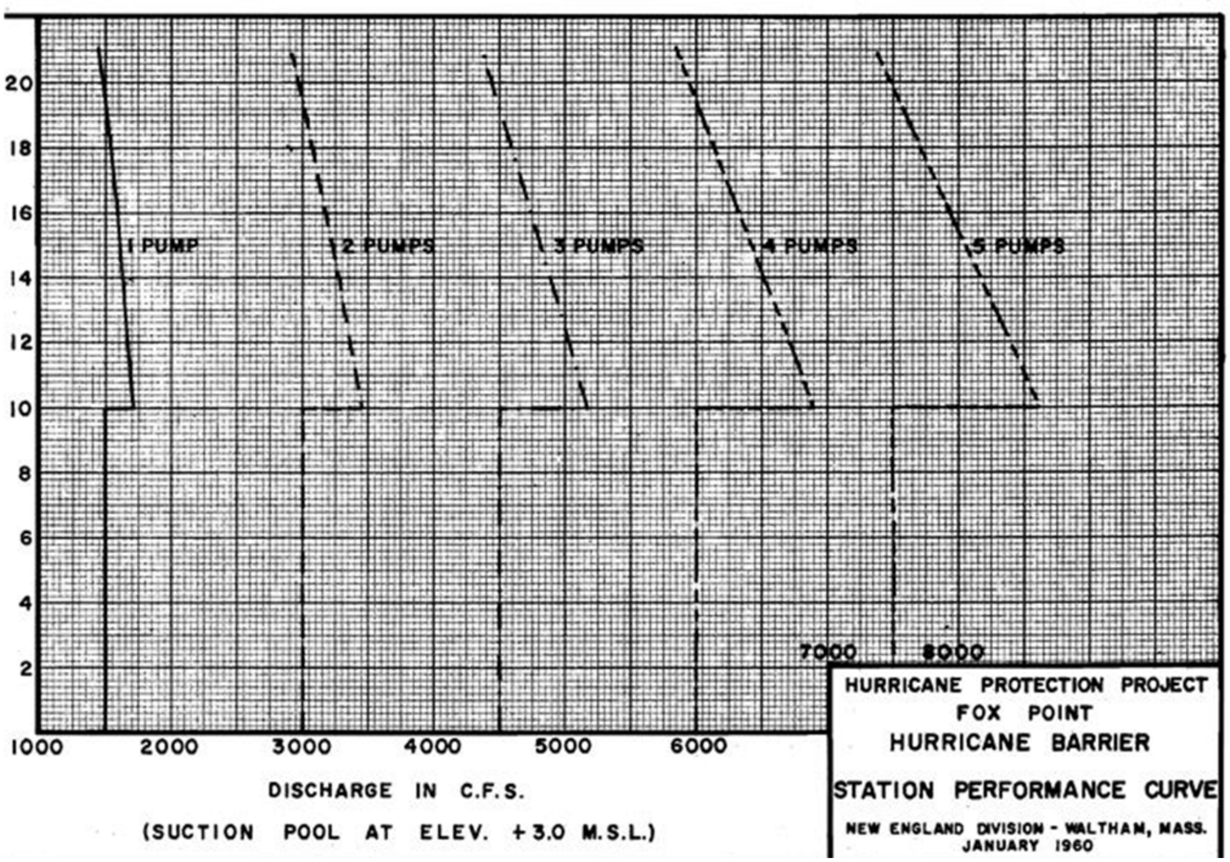


Figure 18. Pump curves (DM No. 4).

6.1. Validation

USGS already calibrated the model, but this effort made some validation runs. A December 17, 2023, event was simulated in the model. For this event the Providence River peaked at roughly 3,100 cfs on December 18 at 5:00 pm. Matching the peak timing and peak magnitude was considered (Figure 19, Figure 20) Ideally, the simulated hydrograph should be as close as possible to the observed hydrograph. With close peak timings and magnitudes, results suggest that model's parameters are within accurate range and the model is functioning as desired, because the simulated hydrograph follows the observed hydrograph for this event.

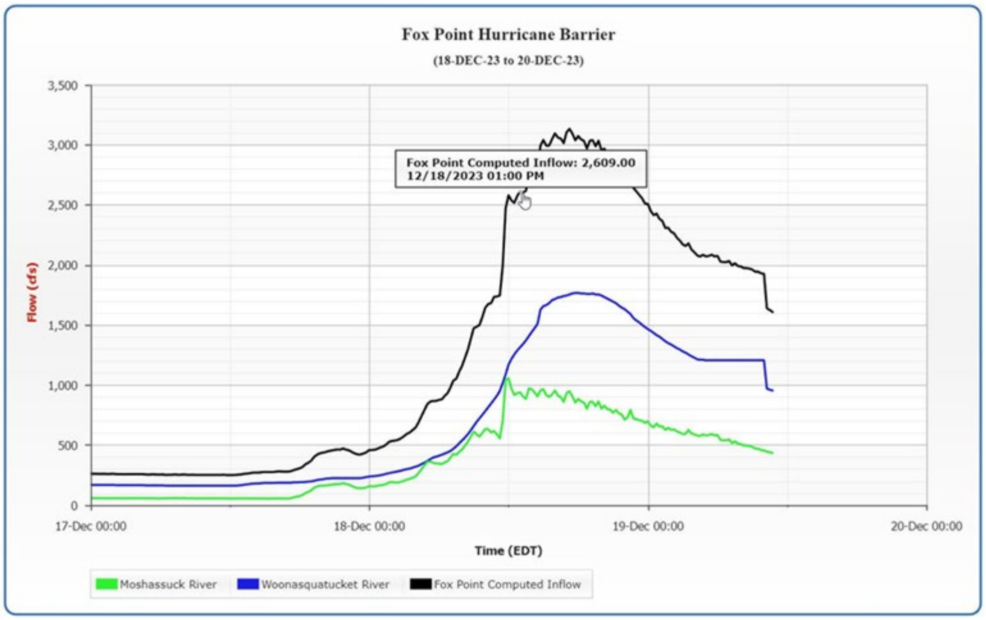


Figure 19. Historical Providence River flow from operator.

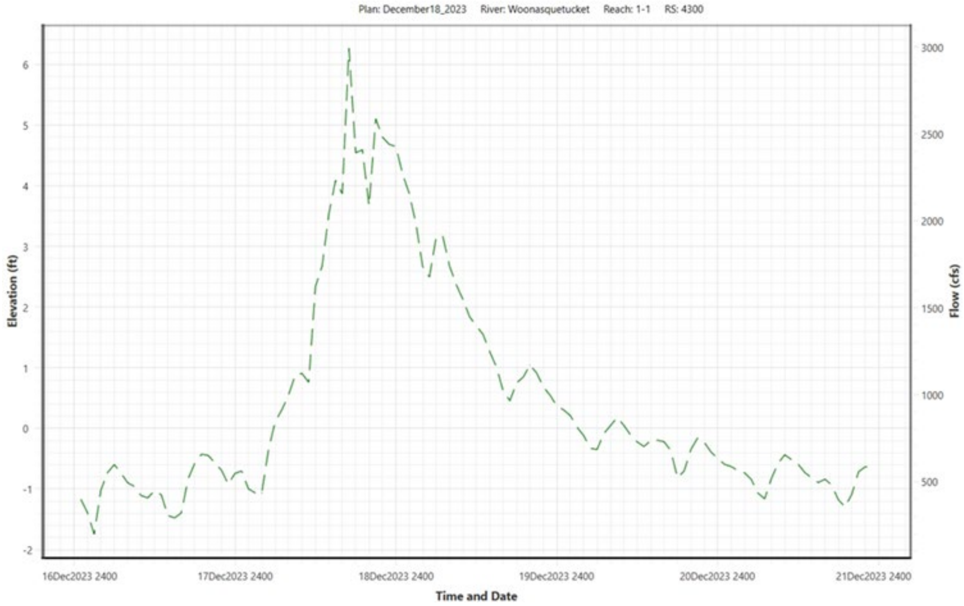


Figure 20. HEC-RAS model flow upstream of barrier, downstream of river confluence.

A second validation event from the HEC-HMS model was simulated in the RAS model: August 13, 2014. Matching the peak timing and peak magnitude was considered. Peak runoff and discharge was measured in the Providence River upstream of the Fox Point barrier. Figure 21 compares the peak runoff from the HEC-HMS model with the discharge seen in the HEC-RAS model. The HEC-RAS model discharge closely matches the HEC-HMS model with timing being fairly close. The minor peaks in the HEC-RAS model result from the tidal boundary condition, a condition not present in the HEC-HMS model.

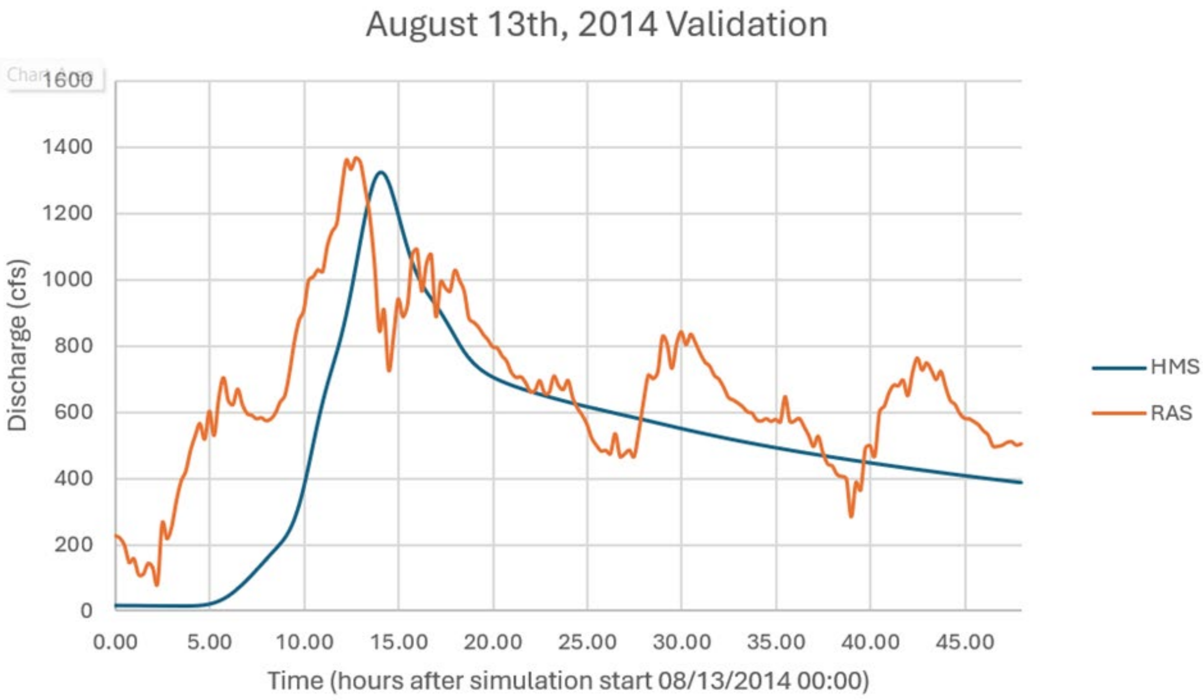


Figure 21. Comparison of HEC-RAS and HEC-HMS hydrographs for the August 13 2014, validation event.

The inflow boundary conditions, from the AEP event hydrographs, use RCP 8.5 GHG emission scenarios. The hydrographs are produced from the previous HEC-HMS hydrologic model. The events have an increased precipitation for future scenarios. For the production runs, the team wanted the following scenarios:

- 24- and 72-hour storm events.
- Rainfall events at five recurrence intervals (0.1, 0.04, 0.02, 0.01, and 0.002).
- A range of RCP 8.5 probabilities (minimum, lower quartile, median, upper quartile, and maximum).

Fifty simulation runs were conducted based on these combined scenarios, using two stage boundaries:

- A hypothetical tidal boundary with a surge that peaks within the first 24 hours for the 24-hour storm scenarios (Figure 22).
- A boundary that peaks on day 3 for the 72-hour storm scenarios (Figure 23).

The surge in the harbor, downstream of Providence River and the Fox Point storm surge barrier, is large enough to trigger a gate closure. The peak runoff timing occurring at the same time as the peak surge in the harbor demonstrates a high strain scenario on the system. Exactly how these timings correlate, however, is unknown. The hydrograph is theoretical, and the peak represents the 100-year 95 percent confidence WSE of 10.18 ft NAVD88 (2026), based on the Providence tide gage 8454000 (NOAA n.d., b). The primary usage of this high surge was to allow the gates to close following the rules defined in the HEC-RAS model.

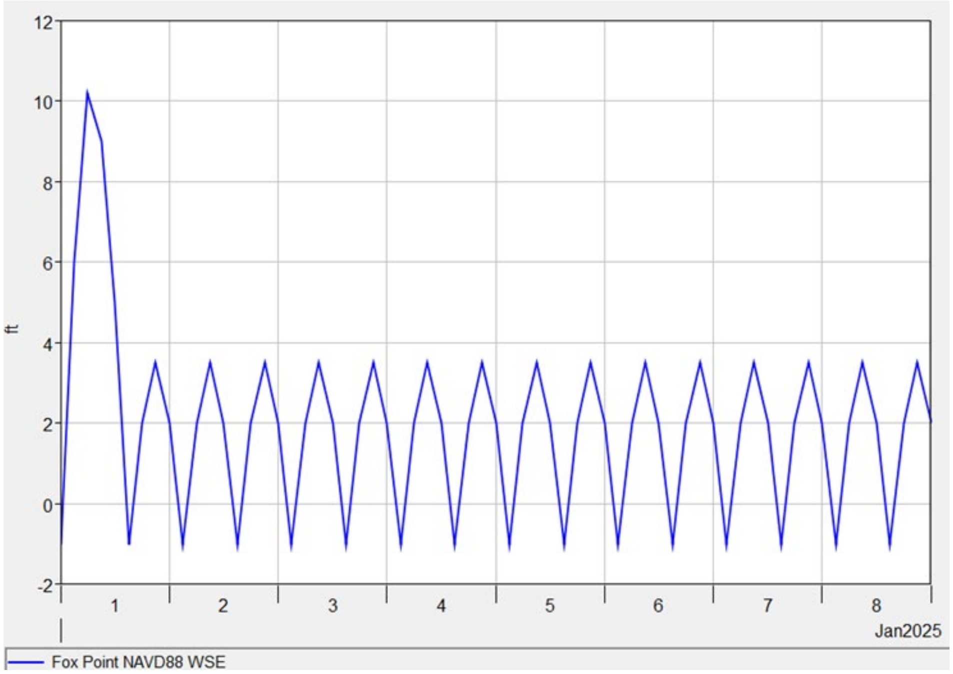


Figure 22. Hypothetical surge event for the stage boundary used for 24-hour rainfall events.

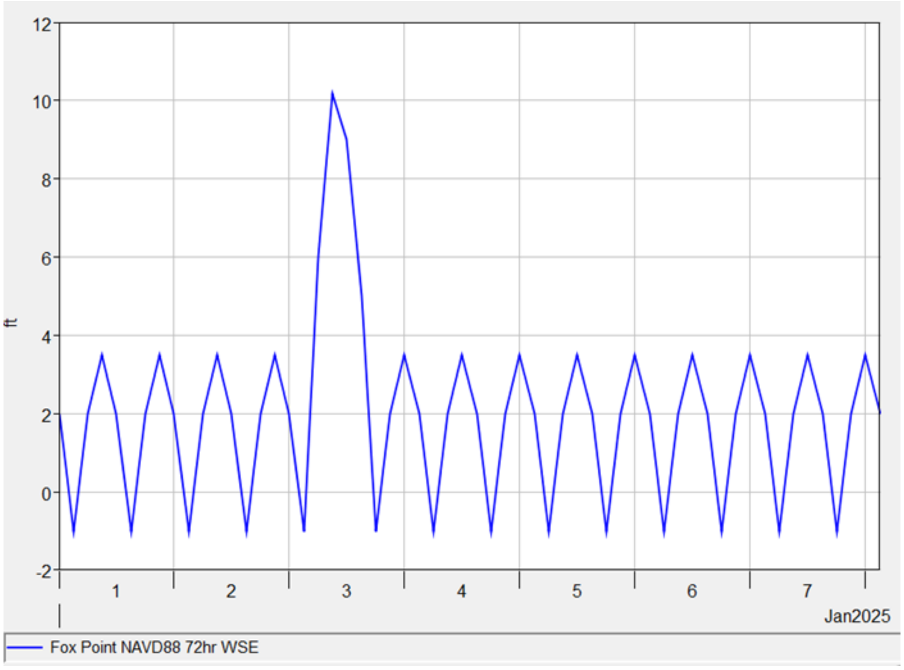


Figure 23. Hypothetical surge event for the stage boundary used for 72-hour rainfall events.

6.2. HEC-RAS Results

For the production runs, HEC-HMS hydrographs produced from hypothetical future rainfall events were used at river boundary conditions. All 50 scenarios were completed. Figure 24 through Figure 30 show the model results as depth grids. For both 100- and 500-year events, the depth maps show flooding in the commercial area along Valley Street and Atwells Avenue. Along Valley Street and Kinsley Avenue, which are both adjacent to the Woonasquatucket River, street flooding ranges from 1–4 feet, which could cause notable property damage. For 500-year 24-hour scenarios, many of these commercial sites (grocery stores, markets, restaurants) show up to 1–3 feet of flooding on site, not just in the street.

Figure 24. Atwells Avenue inundation from a 24-hour 100-year event with the maximum predicted future rainfall increase (RCP 8.5).

Figure 25. Atwells Avenue inundation from a 24-hour 500-year event with the maximum predicted rainfall increase (RCP 8.5).

Figure 26. Valley Street and Westminster Steet inundation from a 24-hour 100-year event with the maximum predicted future rainfall increase (RCP 8.5).

Figure 27. Valley Street and Westminster Steet inundation from a 24-hour 500-year event with the maximum predicted future rainfall increase (RCP 8.5).

Figure 28. Stage comparison near the barrier: 100-year event vs. 500-year event.

Figure 29. Stage comparison near the barrier: 500-year minimum RCP 8.5 estimate vs. 500-year maximum RCP 8.5 estimate.

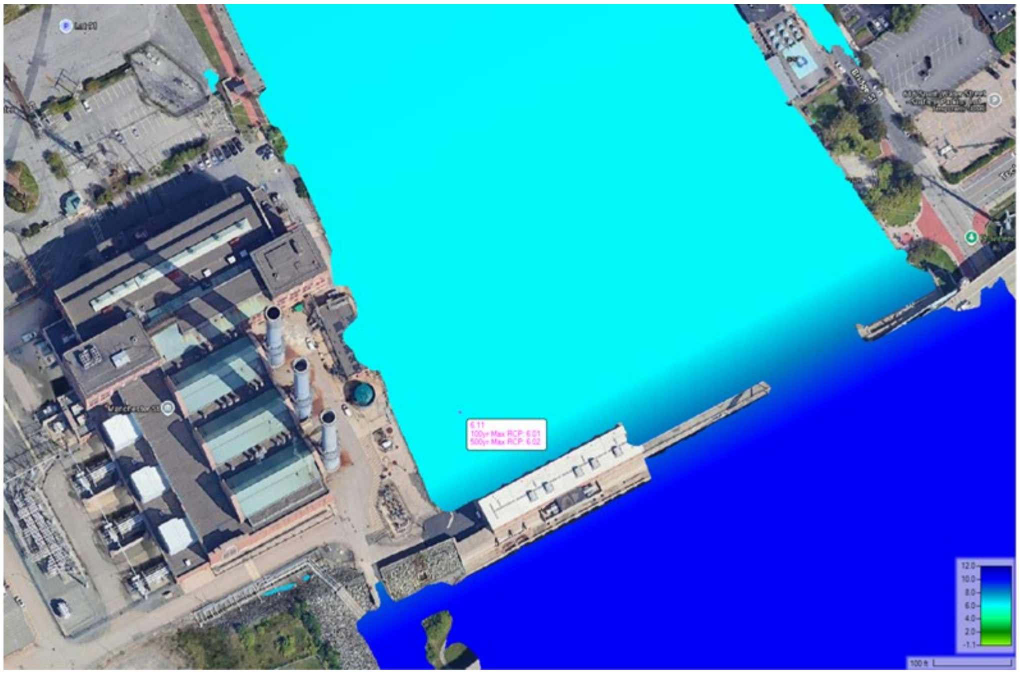


Figure 30. WSE near the barrier: 100- and 500-year (maximum RCP 8.5 rainfall estimate).

Table 12 shows depths and WSEs at two locations: the Valley Street/Helme Street intersection (see Figure 31) and along Eagle Street (see Figure 32). Based on depths seen in Table 12, model results show that the system is more capable of handling the 10-year event with maximum RCP 8.5 estimated rainfall, only showing depths of 0–1 feet in the street. The 25-year event and beyond show much more serious flooding of 2 feet and up.

Table 12
Comparison of AEP events: depth and WSE.

AEP Max RCP	Valley Street and Helme Street Depth (feet)	Valley Street and Helme Street WSE (feet)	Eagle Street Depth (feet)	Eagle Street WSE (feet)
10	1	15.7	0	N/A
25	2.2	16.9	0.9	10
50	2.7	17.3	1.8	10.8
100	3.3	17.9	2.9	11.9
500	4.4	19	4.2	13.2

Figure 31. Valley Street - Helme Street intersection, indicated by the red circle.

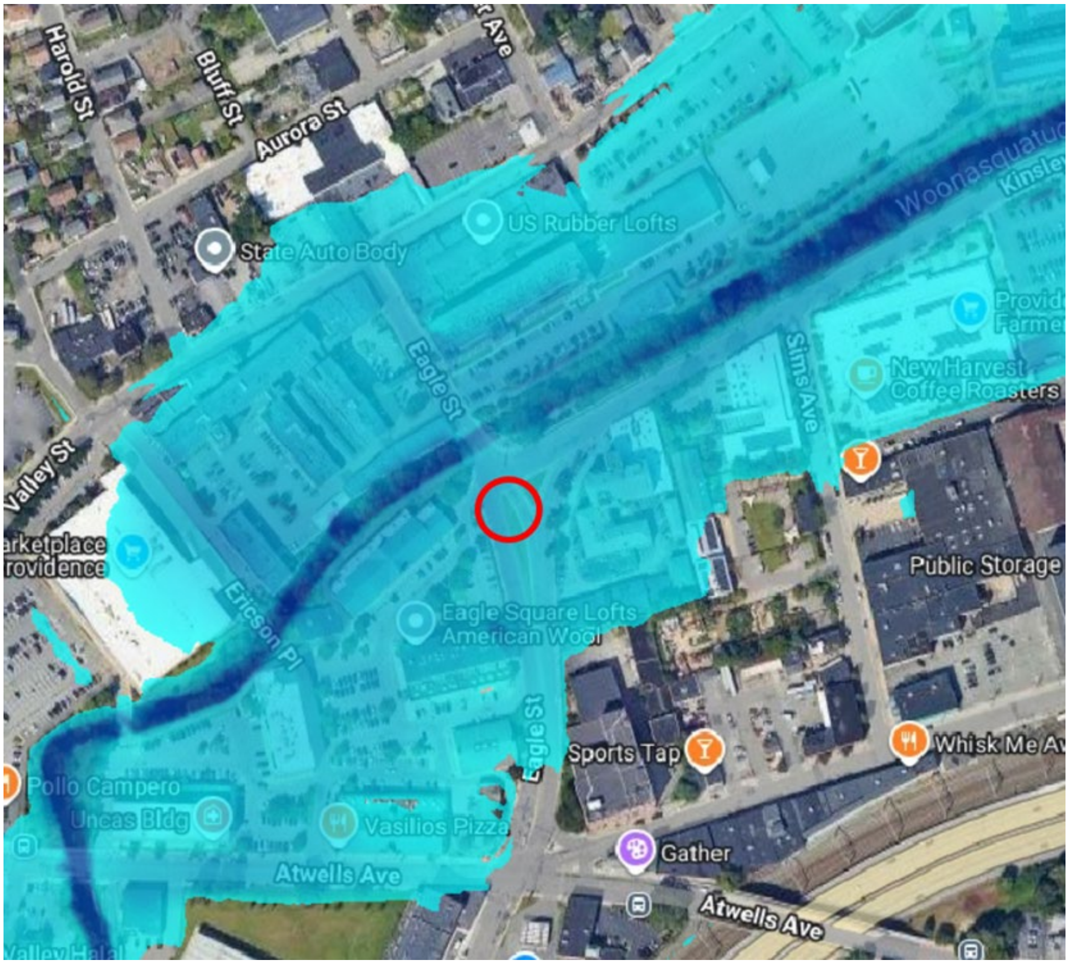


Figure 32. Eagle Street inundation, indicated by the red circle.

The hydrographs seen in Figure 33 and Figure 34 show the relationship between gate flow versus the stage in the harbor. They are produced from the HEC-RAS model runs, and they illustrate closure of the gates and cessation of flow through the gate, while the water level in the harbor is above the threshold of +5.2 ft NAVD88, and the gates being open again at +2.2 ft NAVD88, allowing water to pass again. While the gates are closed, the barrier still has discharge via the pump station.

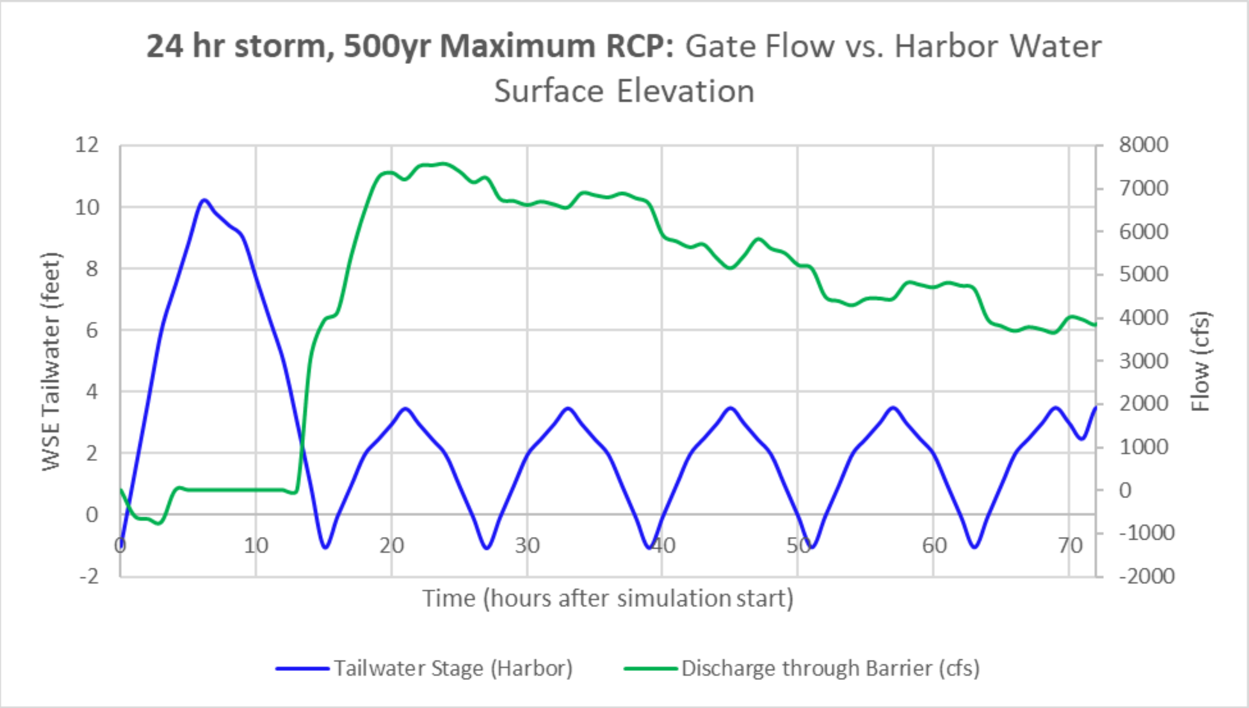


Figure 33. Stage and flow hydrograph at the barrier for a 24-hour 500-year storm with maximum increased future rainfall.

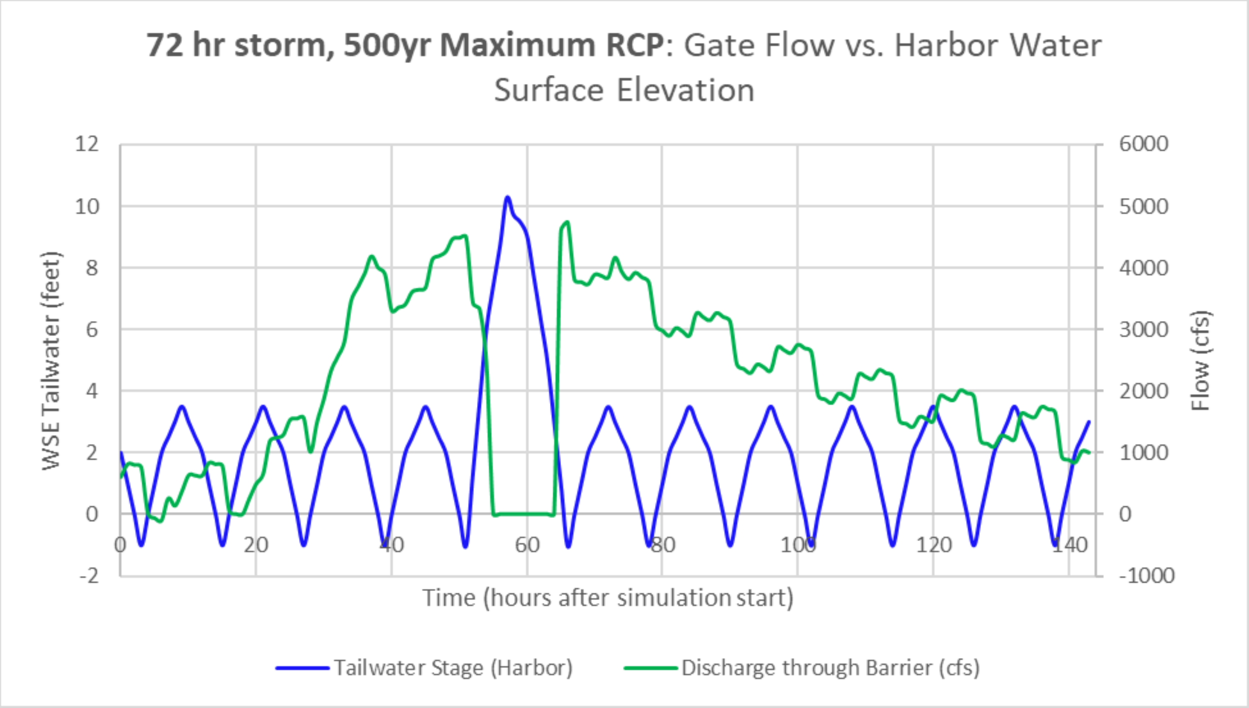


Figure 34. Stage and flow hydrograph at the barrier for a 72-hour 500-year storm with maximum increased future rainfall.

6.3. HEC-RAS Discussion and Consideration

The HEC-RAS analysis indicates that flooding from the extreme RCP scenarios is likely to lead to flooding in the vicinity of Valley and Westminster Streets, as well as upstream from the Fox Point barrier. In the model, the existing pumping system was able to convey water through the storm surge barrier system with the Tainter gate closed, and the flooding was very limited in the vicinity of the barrier. Flooding upstream was more prevalent for the scenarios that were evaluated, and the RCP 8.5 extreme rainfall events caused flooding in these upstream areas for the median, upper quartile, and maximum 500-year (.002) storm events.

The hydrologic analysis does not forecast or predict future events. The link between precipitation (rainfall) and impacts to stream hydrology is not certain; not all increases in precipitation lead to increases in stream discharge, due to factors related to the variability of the timing of events and soil moisture, among others. Additionally, the local stormwater draining systems have also not been accounted for in this study and may be worth considering in the future.

7. Sea Level Analysis

The team determined the potential impacts of coastal water levels on the Fox Point storm surge barrier system’s critical elevation thresholds using SLAT. As discussed, higher water levels in the future are expected to impact the barrier’s Tainter gate closure frequency, the functioning of the vehicular gates, and Providence’s overall storm risk management.

7.1. Impacts of Sea Level Change on the Fox Point Storm Surge Barrier System

This report analyzes historical and projected sea level trends at the Fox Point storm surge barrier. The approach used daily maximum water level data from 1938–2025 from the Providence tide gage 8454000 (NOAA n.d., b) and the O’Brien methodology (O’Brien 2017). The goal was to calculate impacts to critical elevations from SLC and coastal storms to the gate closure threshold exceedances; overtopping of the barrier feature; and impacts to vehicular and sewer gates. The results estimate the frequency of water levels exceeding specified thresholds and incorporate USACE SLC scenarios to provide a range of potential annual exceedances, reflecting both historical trends and anticipated future SLC.

7.2. Critical Elevation Thresholds

The key elevation thresholds were analyzed:

- +24.2 ft NAVD88 – Top elevation of the Fox Point feature
- +5.2 ft NAVD88 – Tainter gate barrier closure elevation threshold
- +11.2 ft NAVD88 – Allens Avenue street gate
- +8.2 ft NAVD88 – Rhode Island Energy Power Station street gate
- +9.0 ft NAVD88 – India Street gate

- +13.9 ft NAVD88 – South Water Street gate
- +14.1 ft NAVD88 – South Main Street gate
- +6.7 ft NAVD88 – Phase 1 sewer gate
- +11.7 ft NAVD88 – Phase 2 sewer gate

The two features of the Fox Point storm surge barrier system that have the greatest risk from the impacts from SLC are the closure threshold for the Tainter gates, the Rhode Island Energy gate, and the Phase 1 sewer gate. The critical elevation thresholds that the sea level analysis identified for those features are discussed in Section 7.4.

7.3. Coastal Water Levels

Tide gage data from Providence (Figure 35) available from 1938–2025 was analyzed using SLAT, which follows the methods outlined in ER 1100-2-8162 and EP 1100-2-1 to evaluate site-specific rates of SLC. These rates, typically expressed in mm/yr, provide a quantitative measure of ongoing SLC and are used as input for downstream modeling that projects navigational gate operations through 2100.

By incorporating observed sea level trends, the model estimates the frequency and likelihood of water levels exceeding operational thresholds. Verified hourly water level height observations from NOAA's CO-OPs (NOAA n.d., a) are the basis for the maximum observed water level for each day. These daily maxima represent the historical daily peak water levels used as model inputs.

The model operates on a daily time step, predicting daily maximum water levels, and makes a binary determination of gate closure for each day based on whether the predicted water level exceeds the closure threshold. The analysis is limited to identifying days with gate closures and does not account for multiple closure events within a given day.

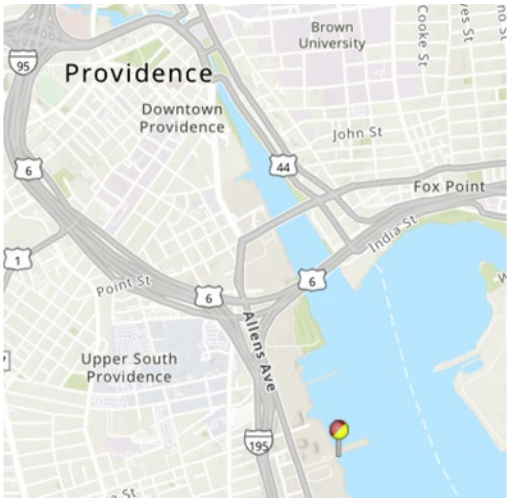
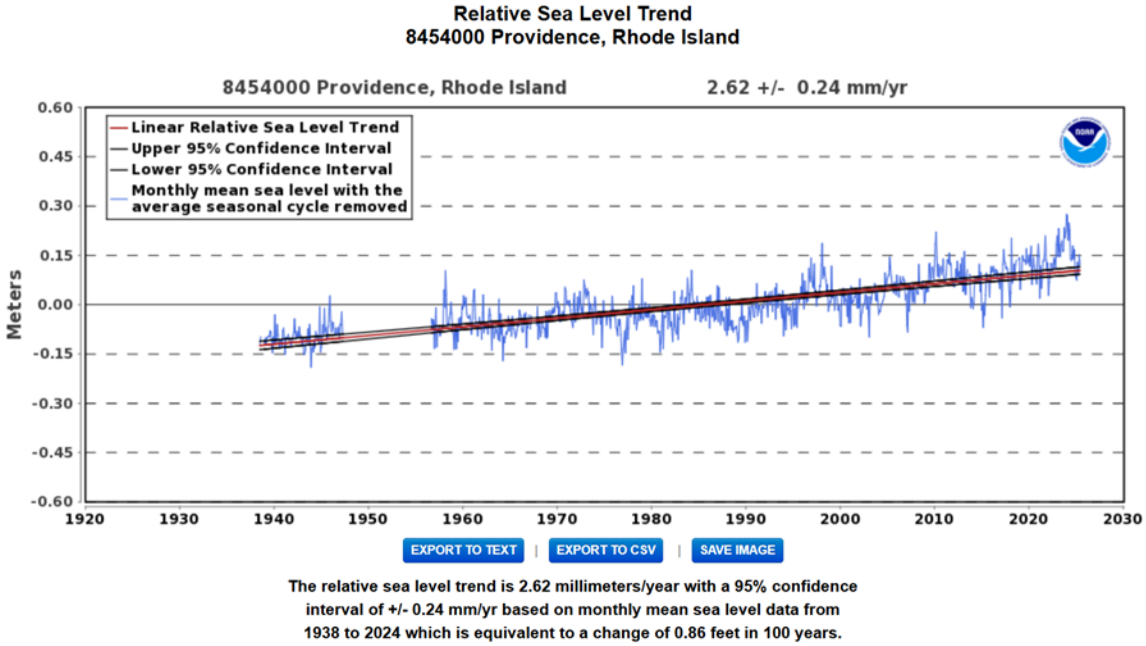


Figure 35. Location of Providence tide gage.

7.4. Scenarios

Planning studies and engineering designs over the project life cycle, for both existing and proposed projects, consider alternatives that are formulated and evaluated for the entire range of possible future rates of SLC. For Fox Point, the range is represented by three scenarios of low, intermediate, and high SLC (USACE 2019b). These scenarios present the range of RSLC based on the Providence tide gage 8454000 (NOAA n.d., b).

ER 1100-2-8162 defines the three USACE SLC scenarios, which are equation-based and use the MSL rate from a tide gage with a published MSL trend. The NOAA long-term from 1938–2024 MSL trend at Providence is 2.56 mm/yr (Figure 36). This trend is an RSLC trend that includes vertical land motion at the tide gage location. The more recent trend from 1985–2025 is 4.6 mm/yr.



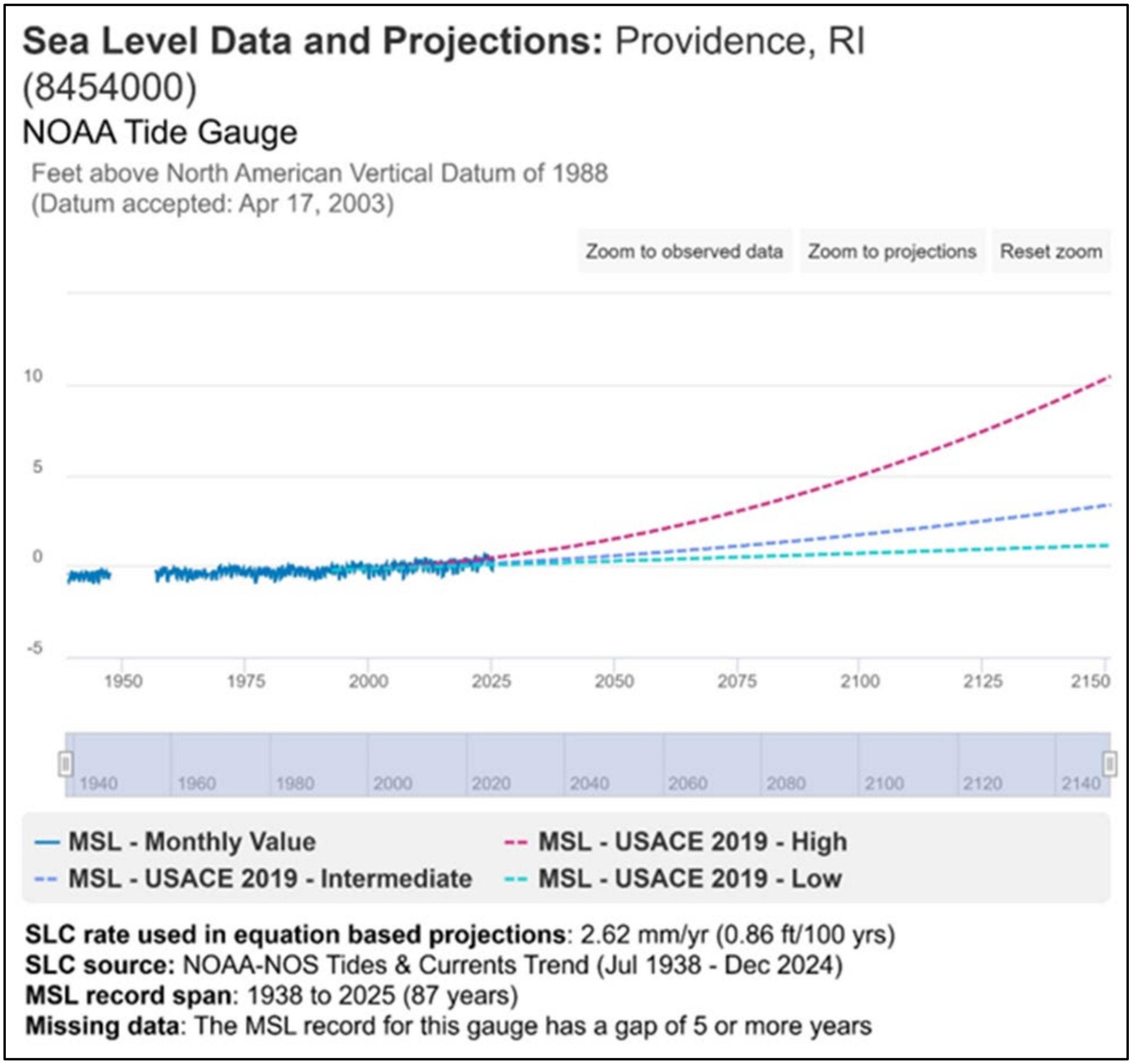
Relative Sea Level Trend
8454000 Providence, Rhode Island

The relative sea level trend is 2.62 millimeters/year with a 95% confidence interval of +/- 0.24 mm/yr based on monthly mean sea level data from 1938 to 2024 which is equivalent to a change of 0.86 feet in 100 years.

Figure 36. MSL trend, Providence tide gage 8454000 (NOAA n.d., b).

Two different rates of SLC for Providence were analyzed to explore how different assumptions about long-term change could affect projected water levels. In addition to the full record trend of 2.62 mm/yr, the rate calculated from the most recent 40 years (4.6 mm/yr) was also considered (Figure 38, Figure 37) These figures show elevation in ft NAVD88 on the Y axis and time on the X axis.

The shorter record provides a consistent basis for comparison with other tide gages over the same period and helps highlight recent trends that may differ from the longer-term average. Using historic tide gage data, both rates were applied to develop projections and estimate when certain thresholds might be exceeded through 2100. Showing results for both rates helps illustrate the range of outcomes. To analyze predicted gate closures, the higher rate was a more conservative case, providing insight into conditions that could occur under a faster rate of change (Figure 38).



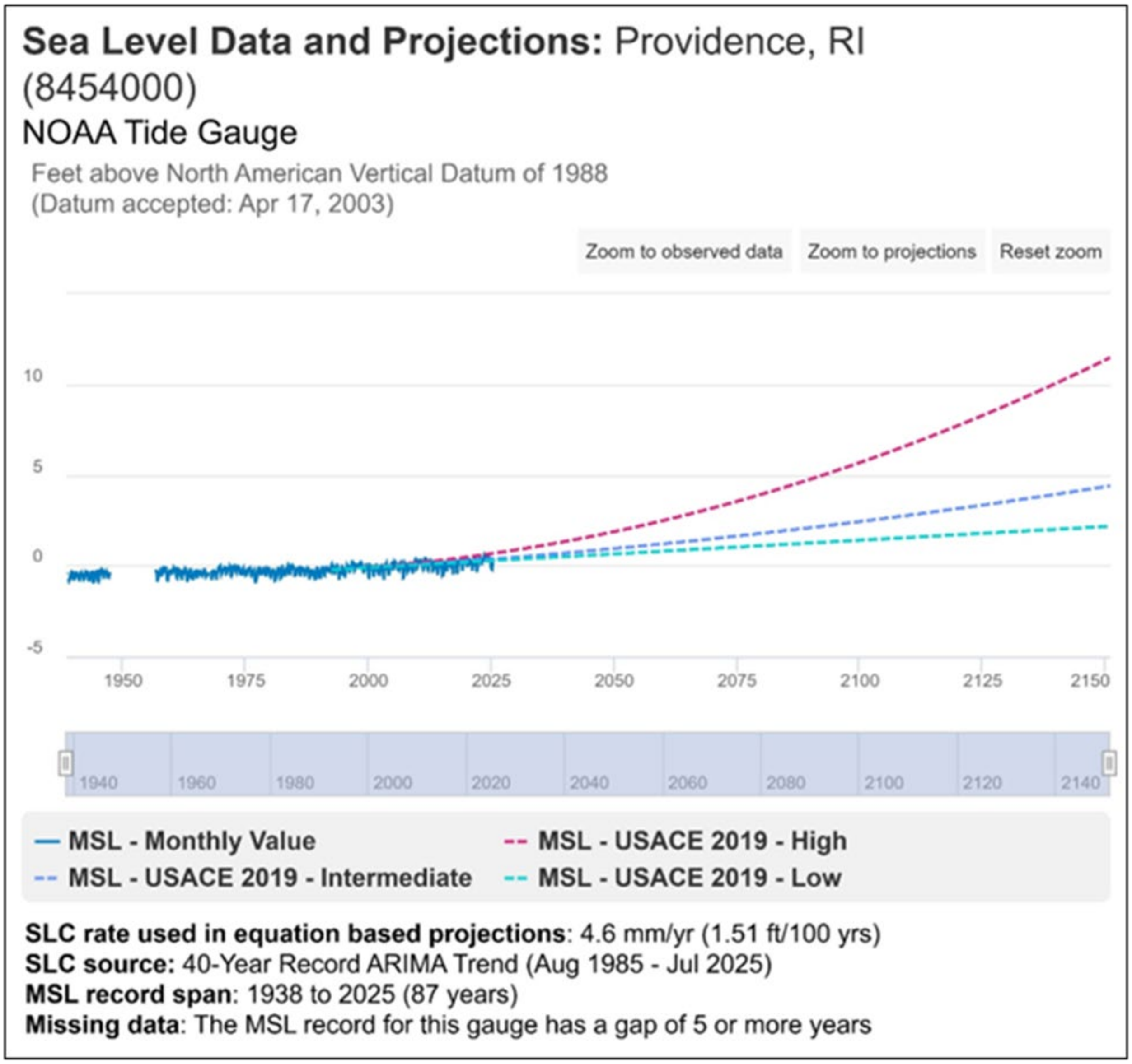
Sea Level Data and Projections: Providence, RI (8454000)

NOAA Tide Gauge

Feet above North American Vertical Datum of 1988
(Datum accepted: Apr 17, 2003)

SLC rate used in equation based projections: 2.62 mm/yr (0.86 ft/100 yrs)
SLC source: NOAA-NOS Tides & Currents Trend (Jul 1938 - Dec 2024)
MSL record span: 1938 to 2025 (87 years)
Missing data: The MSL record for this gauge has a gap of 5 or more years

Figure 37. USACE 2019 scenario projections for Providence, using a SLC rate of 2.62 mm/yr.



Sea Level Data and Projections: Providence, RI (8454000)

NOAA Tide Gauge

Feet above North American Vertical Datum of 1988
(Datum accepted: Apr 17, 2003)

SLC rate used in equation based projections: 4.6 mm/yr (1.51 ft/100 yrs)
SLC source: 40-Year Record ARIMA Trend (Aug 1985 - Jul 2025)
MSL record span: 1938 to 2025 (87 years)
Missing data: The MSL record for this gauge has a gap of 5 or more years

Figure 38. USACE 2019 scenario projections for Providence, using a SLC rate of 4.6 mm/yr.

Table 13 and Table 14 present projected mean water levels in ft NAVD88 for each decade under the low, intermediate, and high USACE 2019 SLC scenarios for each rate of SLC, at each rate of change.

Table 15 shows the estimated timing of critical threshold exceedances, indicating the year each threshold is first likely to be exceeded under the same scenarios. Together, these tables highlight how average water levels are projected to change over time and when key thresholds are crossed, illustrating differences across scenarios and the potential progression of future conditions.

Table 13
USACE SLC scenarios, 1992 to 2150; projections based on the Providence tide gage and full record rate of sea-level change (2.62 mm/yr).

Year	Low (feet)	Intermediate (feet)	High (feet)
1992	-0.22	-0.22	-0.22
2000	-0.15	-0.15	-0.13
2010	-0.07	-0.04	0.05
2020	0.02	0.09	0.31
2030	0.11	0.23	0.64
2040	0.19	0.4	1.05
2050	0.28	0.58	1.53
2060	0.36	0.78	2.08
2070	0.45	0.99	2.71
2080	0.54	1.22	3.41
2090	0.62	1.48	4.18
2100	0.71	1.75	5.03
2110	0.79	2.03	5.96
2120	0.88	2.34	6.95
2130	0.97	2.66	8.03
2140	1.05	3	9.17
2150	1.14	3.36	10.39

Table 14
USACE SLC scenarios, 1992 to 2150; projections based on the Providence tide gage and 40-year record rate of sea-level change (4.6 mm/yr).

Year	Low (feet)	Intermediate (feet)	High (feet)
1992	-0.22	-0.22	-0.22
2000	-0.1	-0.09	-0.08
2010	0.05	0.08	0.17
2020	0.2	0.27	0.49
2030	0.35	0.48	0.89
2040	0.5	0.71	1.36
2050	0.66	0.95	1.9
2060	0.81	1.22	2.52
2070	0.96	1.5	3.21
2080	1.11	1.8	3.98
2090	1.26	2.11	4.82
2100	1.41	2.45	5.73
2110	1.56	2.8	6.72
2120	1.71	3.17	7.79
2130	1.86	3.56	8.92
2140	2.01	3.96	10.13

Year	Low (feet)	Intermediate (feet)	High (feet)
2150	2.16	4.38	11.42

Table 15
Projected Timing of Critical Threshold Exceedance for USACE 2019 Scenarios.

Critical Threshold Description	Critical Elevation (+ ft NAVD88)	RSLC Used for Projections	USACE Low	USACE Int	USACE High
Tainter Gate Barrier Closure Elevation Threshold	5.2	2.62 mm/yr (full record trend)	None	None	2102
Tainter Gate Barrier Closure Elevation Threshold	5.2	4.6 mm/yr (40-year trend)	None	None	2094
Allens Ave Street Gate	11.2	2.62 mm/yr (full record trend)	None	None	None
		4.6 mm/yr (40-year trend)	None	None	2148
RI Energy Power Station Street Gate	8.2	2.62 mm/yr (full record trend)	None	None	2132
		4.6 mm/yr (40-year trend)	None	None	2124
India Street Gate	9.0	2.62 mm/yr (full record trend)	None	None	2139
		4.6 mm/yr (40-year trend)	None	None	2131
South Water Street Gate	13.9	2.62 mm/yr (full record trend)	None	None	None
		4.6 mm/yr (40-year trend)	None	None	None
South Main Street Gate	14	2.62 mm/yr (full record trend)	None	None	None
		4.6 mm/yr (40-year trend)	None	None	None
Phase 1 Sewer Gate	6.7	2.62 mm/yr (full record trend)	None	None	2118
		4.6 mm/yr (40-year trend)	None	None	2110
Phase 2 Sewer Gate	11.7	2.62 mm/yr (full record trend)	None	None	None
		4.6 mm/yr (40-year trend)	None	None	None

8. Forecasted Future Exceedances Under SLC Scenarios using the Gate Operational and Analysis Tool

GOAT modeled the impacts of SLC on critical elevation thresholds through 2100 in 25-year increments. This tool modeled the effects of SLC based on low, medium, and high projections from the Providence tide gage 8454000 (NOAA n.d., b). The simulation combines tidal data with projected SLC scenarios. Future SLC, when superimposed on existing tidal patterns, exacerbates high tides and leads to more frequent nuisance flooding. This increased tidal influence impacts lower critical elevation thresholds, independent of coastal storm events. The complete results are in Appendix C, Gate Operations Analysis Tool.

8.1. Simulation Method

GOAT forecasts future water levels and potential gate closures using a statistical simulation model in the R statistical software package (R Core Team 2025). Historical daily maximum water levels and gate closure records form the basis of the analysis. The model determines the best-fitting statistical distribution for each month of the year, then generates large sets of synthetic water level data adjusted annually for projected RSLC under low, intermediate, and high scenarios. These simulated water levels are combined with an empirical relationship between water level and closure probability to estimate future closure frequencies.

In the absence of historical closure data, a 100 percent exceedance probability is assumed for values at or above the operational threshold. The simulation runs on a daily time step from 1992–2100, generating thousands of independent trials per year. Daily maximum water levels are predicted in each trial, and the mean across trials is used as the predicted daily maximum for gate closure evaluation. Results include mean annual exceedances as well as uncertainty bounds based on the 10 and 90 percent quantiles.

The historic closures of the Fox Point Tainter gate barrier from 1964–2024 are shown in Figure 39. The noticeable spike in closures in 2010 does not indicate a sudden change in system performance. Instead, it reflects the point at which USACE assumed responsibility for operating and maintaining the feature. When USACE assumed control of the barrier in 2010, the function of the river pumps was questionable, and not all pumps were fully operational. In coordination with the city of Providence, the Tainter closure criteria for operating the barrier was lowered until USACE could get the system fully functional (USACE 2010). The 2010–2022 spike in operations is due to these lowered elevations criteria. Since 2022, USACE has reverted to the original Tainter gate closure criteria and is experiencing a reduction in the number of closures per year.

Coordination with the Operations Division at the New England District provided insights into the barrier's operational history. In 2022, the barrier was activated during three winter storms. This operation decreased in 2023, when it functioned for only one winter storm. However, the barrier was used again for three winter storms in 2024. No closure operations were conducted for flood control in 2025.

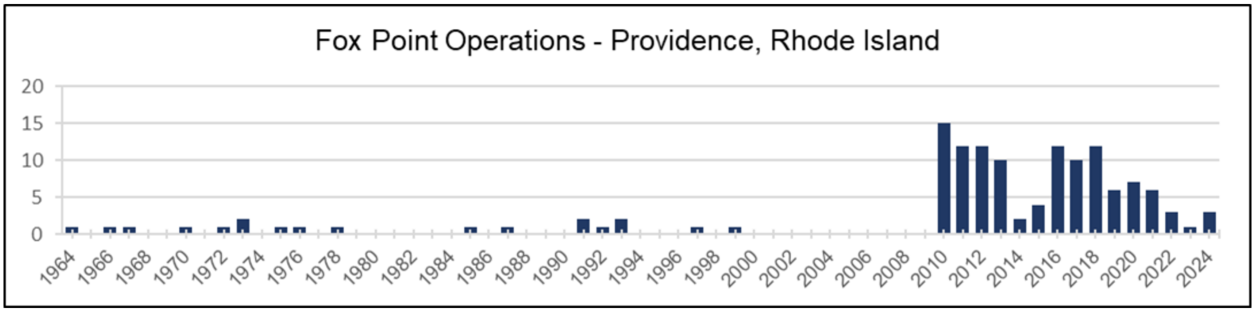


Figure 39. Historic closures of the Fox Point Tainter gate barrier.

Before generating simulated water levels, the historic tide gage record was detrended to a 1992 baseline using a first-degree polynomial regression (Figure 40). The year 1992 was selected because it represents the midpoint of the NOAA national tidal datum epoch (1983–2001), providing a standardized reference for MSL. Detrending to this baseline removes the long-term change signal from the observations, isolating the variability around mean conditions for 1992. This allows projected SLC scenarios to be added consistently, so that simulated values reflect observed variability without double-counting the historic trend.

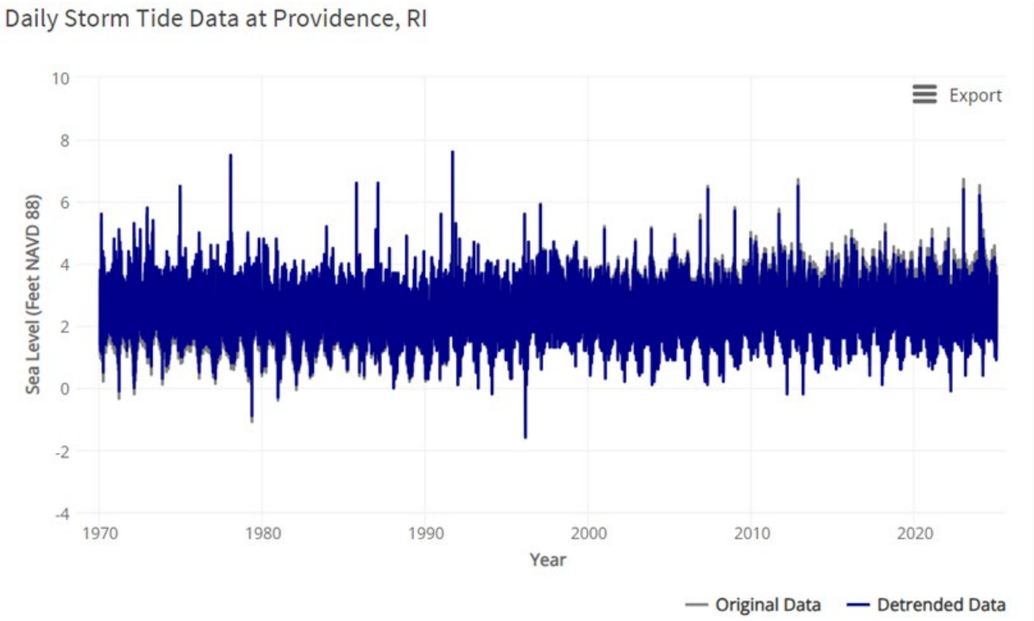


Figure 40. Historic daily storm tide data at Providence from the GOAT.

8.2. Incorporating Sea Level Change

The threshold exceedance model computes SLC for three scenarios: low, intermediate, and high. Projected RSLC for each year was calculated in R based on methods used in SLAT. For every year in the simulation period (1992–2100), the projected annual RSLC was added to the mean of the monthly distribution, effectively shifting the monthly distributions upward each year while maintaining the same shape. These future values incorporate both the projected sea level increases with the natural variability of monthly water levels to represent how mean water levels could realistically fluctuate under each scenario.

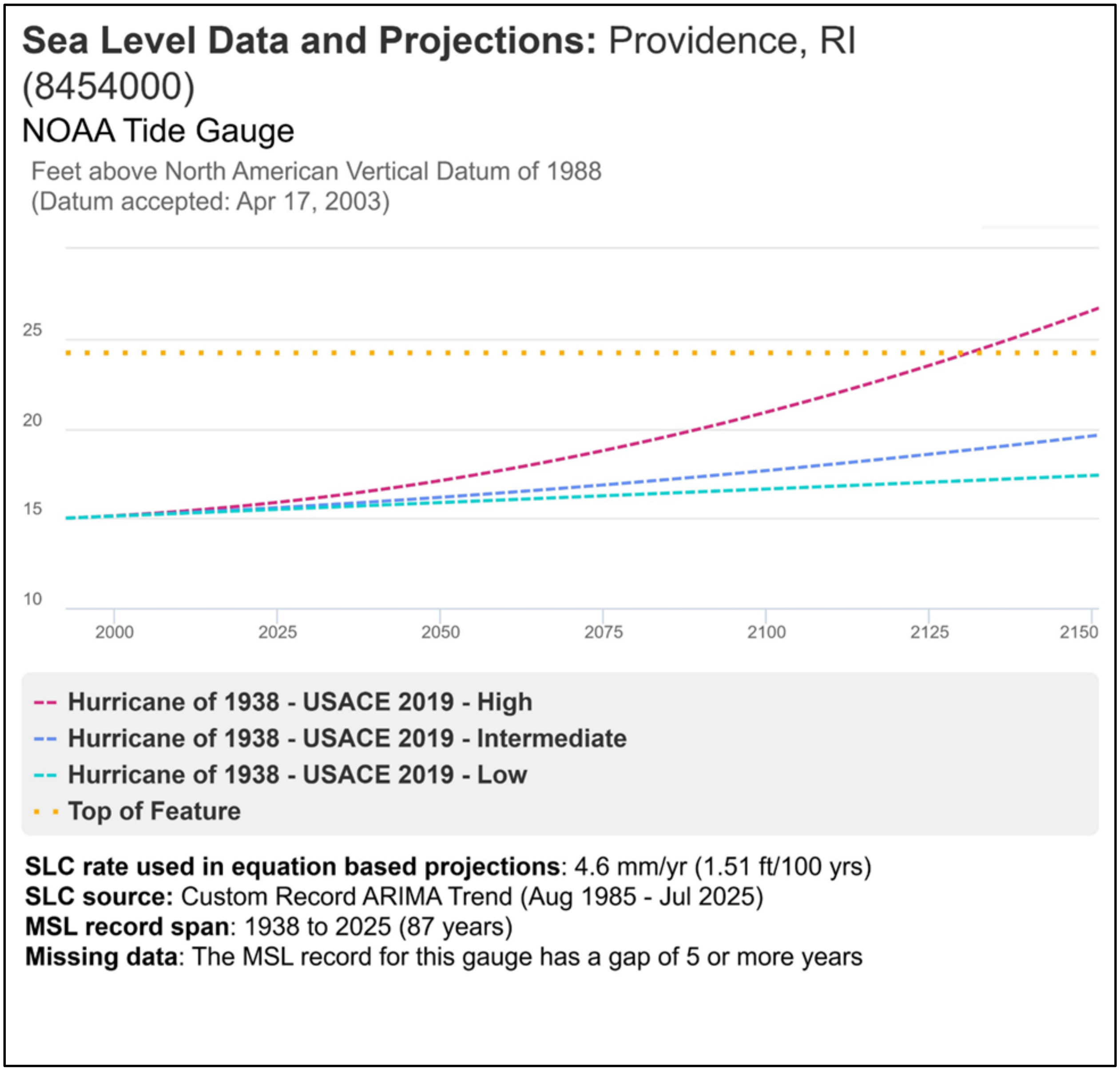
The results show the distribution of simulated monthly water levels across all years in the projection period. Each box represents the variability within a month, while the overlaid lines indicate the monthly averages for 1992 and the projected years 2050, 2075, and 2100. Each scenario has a box plot: low, intermediate, and high. These visualizations highlight both the seasonal variability and the gradual increase in mean water levels over time, showing how the simulations represent typical monthly conditions for 1992 and the projected years 2050, 2075, and 2100. All results are in Appendix C.

9. Simulation Results

9.1. Top Elevation of Fox Point Feature (+24.2 ft NAVD88)

A SLAT analysis assessed potential overtopping of the Fox Point storm surge barrier by combining projected SLC with the water elevation from the barrier's storm of record, the 1938 hurricane (estimated +15.0 ft NAVD88). Outputs from SLAT include the intersections of the storm of record combined with

USACE 2019 low, intermediate, and high SLC scenarios, assuming the 40-year record rate of 4.6 mm/yr as of July 2025 as used in all other analyses for this report (Figure 41).



SLC rate used in equation based projections: 4.6 mm/yr (1.51 ft/100 yrs)
SLC source: Custom Record ARIMA Trend (Aug 1985 - Jul 2025)
MSL record span: 1938 to 2025 (87 years)
Missing data: The MSL record for this gauge has a gap of 5 or more years

Figure 41. USACE 2019 scenario projections for Providence using SLC rate of 4.6 mm/yr (40-year record autoregressive integrated moving average (ARIMA) trend) from both MSL and 15.0 ft NAVD88 storm of record.

Table 16 shows the projected intersections with the top of the barrier for each scenario. For the 1938 hurricane water level, the high scenario results in an intersection in 2112, while the intermediate and low scenarios show no intersections. For the 1 percent AEP high EWL and MSL water levels, no intersections are projected across any of the scenarios, high, intermediate, or low.

Table 16
Projected timing of critical threshold exceedance for USACE 2019 scenarios: Intersections with top elevation of Fox Point feature (+24.2 ft NAVD88).

Water Level	Source	Scenario	Intersections
1938 Hurricane: +15.0 ft NAVD88	USACE 2019b	High	2112
		Intermediate	None
		Low	None
1% AEP High EWL	USACE 2019b	High	None
		Intermediate	None
		Low	None
MSL	USACE 2019b	High	None
		Intermediate	None
		Low	None

9.2. Tainter Gate Barrier Closure Elevation Threshold (+5.2 ft NAVD88)

Table 17 and Figure 42 present the simulated number of predicted gate closure days for the low, medium, and high SLC scenarios through 2100 with a 4.6 mm/yr rate of observed SLC. Lower and upper estimates, corresponding to the 10 and 90 percent quantiles, indicate the range of possible outcomes based on variability in the simulated water levels. In this context, the 10 and 90 percent quantiles represent values below which 10 and 90 percent of the model results fall, respectively. Together, they define an 80 percent confidence interval that provides a realistic range for the number of closure days in each year, showing how the model's predictions can vary while excluding rare, extreme outcomes.

The results illustrate how the frequency of gate closures is projected to change over time, with higher scenarios showing more frequent closures and an increasing trend in later decades. Differences among scenarios highlight the potential variability in closure frequency under different SLC conditions, while the quantiles capture uncertainty from both seasonal and interannual fluctuations in the simulations.

Table 17
Upper and lower estimates of gate closures for elevation thresholds of +5.2 ft NAVD88.

Year	Level	Lower (10%)	Mean	Upper (90%)
2025	Low	1	4	7
	Intermediate	2	5	8
	High	4	7	11
2050	Low	4	8	11
	Intermediate	6	12	17
	High	49	58	70
2075	Low	7	13	18
	Intermediate	27	35	45
	High	278	288	300
2100	Low	17	23	30
	Intermediate	113	128	144

Year	Level	Lower (10%)	Mean	Upper (90%)
	High	353	357	361

In this framework, the concept of perfect foresight is applied by treating the threshold as an absolute determinant of exceedance. The probability density function is evaluated such that any value above the threshold corresponds to a 100 percent probability of closure, while any value below the threshold corresponds to 0 percent. This binary interpretation assumes complete certainty in the system's response once the threshold is crossed, without accounting for uncertainty or operational discretion.

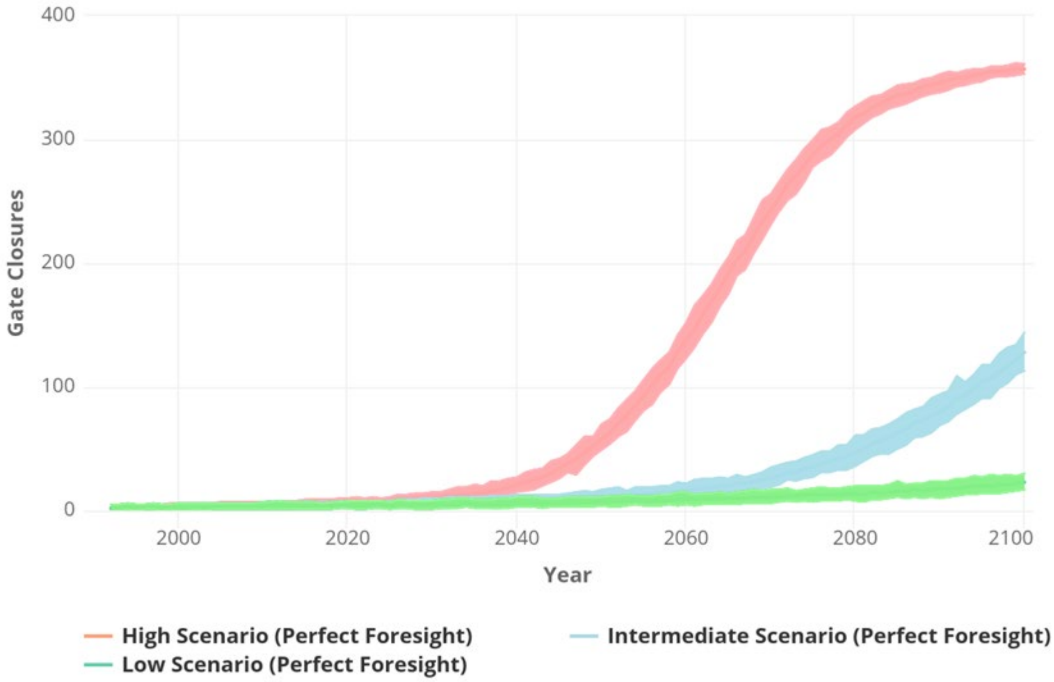


Figure 42. Estimated gate closures by scenario for water levels exceeding +5.2 ft NAVD88 with a 4.6 mm/yr rate of SLC.

Figure 43 shows projected sea level on the left axis and predicted gate closures on the right axis. Decadal boxplots represent the distribution of simulated mean water levels within each decade, capturing the variability across months and years. A line overlaid on the right axis shows the total number of predicted gate closure days for each decade, summed across all years within that period. This visualization enables comparison of how changes in sea level relate to the frequency of gate closures, highlighting both the range of possible water levels and the projected trend in closures over time. The complete charts and boxplots for the critical elevation thresholds are in Appendix C.

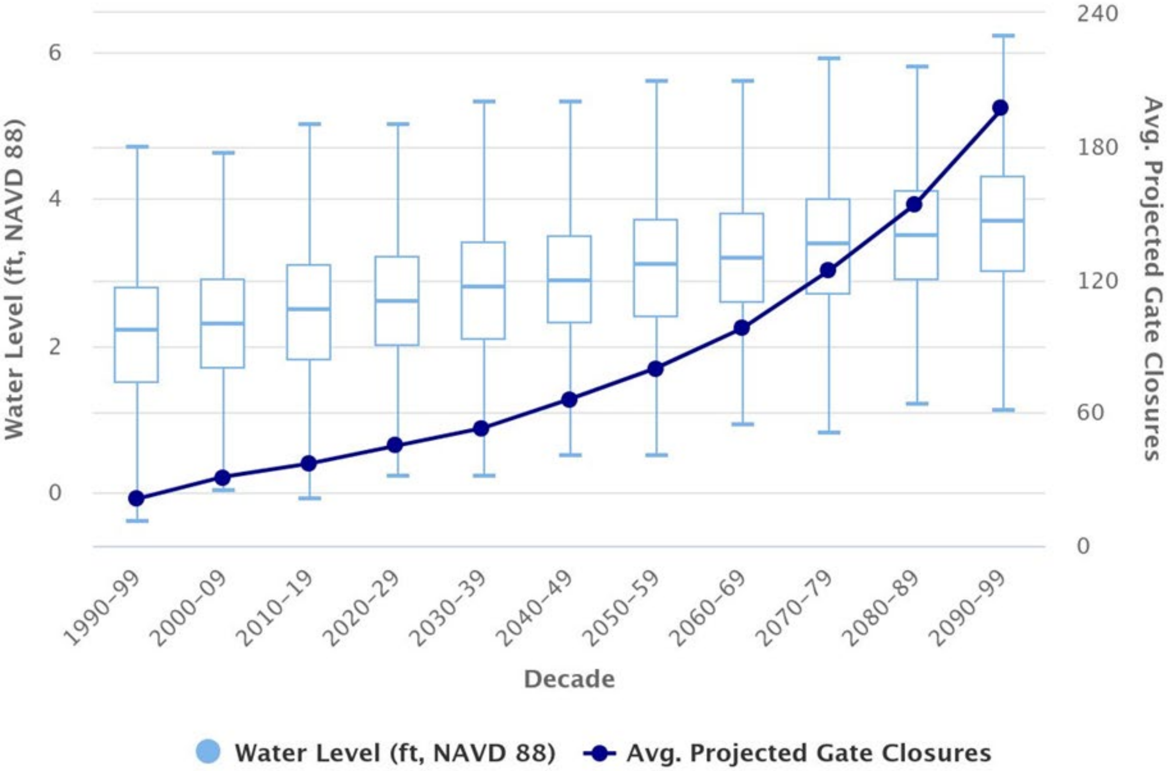


Figure 43. Projected water levels by decade vs. projected gate closures for the low scenario with a 4.6 mm/yr rate of observed SLC.

9.3. Vehicular and Sewer Gates Summary

A similar water level analysis was performed for the critical elevation thresholds, including the street and sewer gates. The gates at Allens Avenue, Rhode Island Power Station, India Street, South Water Street, South Main, and two sewer gates were also evaluated. The results of this analysis are compiled in Appendix C.

The India Street gate and the Phase 1 sewer gate, both lower gates, are projected to experience the most frequent impacts from SLC by 2100. The India Street gate is impacted by the high rate of SLC in 2100, and the Phase 1 sewer gate shows impacts from the high rate of SLC in 2075. Both gates of the Fox Point storm surge barrier system are relative low points of the feature and would be impacted sooner than other features from rising water levels.

10. Conclusions of the Vulnerability Assessment

10.1. Overall

The Fox Point storm surge barrier system was evaluated for coastal storm risks in the face of future weather-related events. The system was modeled against its potential vulnerability to coastal storms, future SLC, and increases in precipitation.

The barrier system provides robust risk management against overtopping during the design coastal storm event while accounting for future rates of SLC based on low, medium, and high USACE sea level scenarios to 2100. Beyond that, modeling indicates that the system may be overtopped with the high rate of SLC superposed with the design storm in the 2130s, without accounting for waves.

The interior pumping system, which conveys water through the barrier with Tainter gate closures, is vulnerable to increases in precipitation based on its current pumping capacity for RCP 8.5 for the 500-year rainfall event. The increases in river discharge associated with the modeled increase in precipitation exceed the pumping threshold of 7,000 cfs for these events. While riverine water does not exceed the banks of the river for some of the more frequent events, the hydraulic capacity of the stormwater system may be reduced, resulting in localized flooding. Relatedly, if the study area experiences these more extreme rainfall events as the RCP 8.5 scenario projects, floodwater behind the closed Tainter gate will accumulate further upstream than the Fox Point barrier in Providence and likely cause flooding.

Analysis indicates the Tainter gate operations and lower vehicular gate closure mechanisms represent the most vulnerable components of the feature with regard to projected SLC impacts. The current Tainter gate closure elevation threshold will be exceeded more often in the future due to SLC, independent of any changes in coastal storm frequency or magnitude. Projected SLC, when combined with typical tidal fluctuations, is anticipated to cause the operational elevation threshold to be exceeded multiple times per year. This may require revising the current operational plan to accommodate an increased closure frequency. The current operational plan may require either significantly increasing Tainter gate operational frequency or adjusting the closure threshold elevation to maintain current closure rates.

The height of the Fox Point storm surge barrier system appears to manage the risk of overtopping, even considering SLC. However, future SLC poses a significant vulnerability to the gate closure system, increasing the likelihood of exceeding the Tainter gate closure threshold and frequency. The interior hydraulic and hydrologic modeling also indicates that extreme future rainfall may compromise the system's pumping capacity and cause upstream flooding while the Tainter gate is closed during tropical and extratropical events.

10.2. Results for Specific Objectives

10.2.1. Objective 1

> Assess current and future vulnerability of the Fox Point storm surge barrier system to overtopping (+24.2 ft NAVD88) and flanking from tropical and extratropical storms by considering the design

> storm plus three rates of SLC for low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

The current design of the Fox Point Barrier System is robust against future coastal storms and SLC to 2100 and is overtopped by the design storm plus the high USACE sea level scenario in 2130 (Figure 41).

10.2.2. Objective 2

> Assess changes in the Fox Point storm surge barrier system critical elevation exceedance thresholds and operational frequency under low, intermediate, and high USACE sea level scenarios and changes in future watershed hydrology against critical elevation exceedance thresholds of +5.2 ft NAVD88.

SLC will exceed the current Tainter gate closure elevation threshold of +5.2 ft NAVD88, requiring either increasing closure frequency or accepting the increased risk of threshold exceedance (Table 17). The pumps will likely be running whenever the Tainter gate is closed from a coastal storm event and create additional wear and tear and maintenance above the current operations.

10.2.3. Objective 3

> Assess impacts to vehicular gates at Allens Avenue (+11.2 ft NAVD88), India Street (+9.0 ft NAVD88), South Main Street (+14.1 ft NAVD88), and Rhode Island Energy Power Station Street (+8.2 ft NAVD88) under low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

The Allens Avenue vehicular gate and South Main Street gate are at elevations that make them less vulnerable to SLC impacts, but the Rhode Island Energy Power Station Street gate and India Street vehicular gate are likely vulnerable to most high SLC scenarios starting in 2075–2100.

10.2.4. Objective 4

> Assess impacts to the five sewer gates/tunnels that prevent high tides from backing up through the sewer lines by considering the design storm against the low, intermediate, and high USACE sea level scenarios at the Providence tide gage to 2100.

The Phase 1 sewer gate is more vulnerable than other gates, with impacts to that gate beginning in 2050 for the intermediate and high sea level scenarios.

10.2.5. Objective 5

> Assess changes to riverine flooding behind the closed Fox Point storm surge barrier system for the pumping system and electrical system/generator against the *Atlas 14* frequency events (10, 20, 50, 100, and 500 years) plus RCP 8.5 output from CHAT for 24-/72-hour events to the minimum, lower quartile, median quartile, upper quartile, and maximum in cfs and stage to 2100.

The pumping capacity of the current system is able to convey water through the barrier system when the Tainter gate is closed for most scenarios up to RCP 8.5 for the lower quartile 24-hour rainfall event

(Table 10, Table 11). This analysis did not assess the pump efficiency at higher head levels on the discharge side of the barrier, which may be affected by higher sea level in the future. Increased water levels on the discharge side of the barrier could reduce pump efficiency by 10 percent, causing pumping discharge thresholds to be exceeded more often than the current assessment. Analysis of the RCP 8.5 24-hour scenario indicates that the system’s pumping capacity is insufficient to manage water levels at the median, maximum, and upper quartile precipitation projections. Water levels from flooding do not reach the elevation of the backup generator system on the interior section of the barrier for these events based on overland flow, but this analysis did not assess stormwater conveyance.

11. Study Limitations

This vulnerability assessment is limited as to the extent to which modifications can be made to the Fox Point storm surge barrier system, the nature and limitations of the modeling outputs, and the assumed correlation between coastal surge events and simultaneous precipitation events during a storm.

Modifications to the Fox Point storm surge barrier system may be accomplished within existing USACE authorities for completed projects, but they cannot be accomplished within this limited study. While USACE has the capability to model climate change and precipitation scenarios, major construction or the replacement of a storm surge barrier cannot be supported as a federal interest at this time. The scope and schedule for this study are inadequate to change the operations or make recommendations for modifications to the feature. Changes to the operations plan, closure thresholds, or the height of the feature can only be accomplished through a detailed study or modifications to the water control manual (WCM). Physical modifications to the Fox Point storm surge barrier system would only be recommended after a more detailed effort that includes a cost benefit analysis, peer review, a detailed design and cost estimate, and internal approvals through a series of milestones and checkpoints with a full National Environmental Policy Analysis (NEPA) review. This assessment’s hydrologic analysis was also limited to overland flow from precipitation. This effort did not assess impacts to stormwater conveyance, which may be affected by increased water held behind the barrier when the Tainter gate is closed.

This vulnerability assessment also assumes simultaneous surge events from coastal storms and heavy precipitation events, which may not be true for future storms. Correlation studies between coastal surge events and precipitation events performed in the Connecticut area are useful to understand the relationship to coastal surge and rainfall events (USACE 2025). The Fairfield/New Haven CSRM project is in the vicinity of three rivers, the West, Mill, and Quinnipiac, and this study performed a correlation analysis to examine the relationship between rainfall and coastal water levels and the dependence of rainfall and coastal water levels. For the Fairfield/New Haven Site, rainfall and elevated coastal water levels are not physically related. Since no consistent relationship exists from one to the other, rainfall cannot predict coastal water levels. The analysis showed a weak correlation to no correlation between rainfall and coastal water levels. Therefore, the design coastal storm is unlikely to occur simultaneously with the maximum precipitation event as modeled in this Vulnerability Assessment.

12. Recommendations

The vulnerability assessment indicates that the storm surge barrier is robust against the design coastal storm event but an increase in sea levels may make it vulnerable to operational fatigue from the frequency of the Tainter gate closures and pump operations. Additionally, the pumping system may be vulnerable to future rainfall events when the Tainter gates are closed from coastal storm surge in conjunction with a rainfall event. An update to the WCM and/or updates to the O&M of the facility can further assess these vulnerabilities. More significant initiatives, such as constructing a new storm surge barrier at a different location, require a new feasibility study. The present analysis indicates that a new barrier is likely unnecessary to manage risk from coastal flooding in the existing project area at the present time, since the existing barrier is not expected to be overtopped during the design coastal storm event while accounting for sea level rise over the next hundred years. Any new start study requires substantial funding and resources from the Federal Government as well as support from a non-federal sponsor. The study team and the home district believe that the most reasonable approach for the Fox Point system is to change the O&M manual and/or update the WCM.

12.1. Changes to the O&M Manual

The most immediate risks to the Fox Point storm surge barrier system derive from increased Tainter gate closure frequency associated with SLC and increased frequency of pumping. These risks can be partly managed through minor modifications to the O&M manual and operational guidance.

The study area has seen an increase in the rate of SLC in the observed record, as demonstrated by the difference between the +2.6 mm/yr rate of change observed over the full historic period to the +4.6 mm/yr rate for the 1985–2025 timeframe. The greatest impact of further rises in sea level is to the operation of the barrier's Tainter gates. The GOAT analysis indicates that the elevation closure threshold of +5.2 ft NAVD88 would be exceeded between 23 and 357 days per year on average under the low and high sea level scenarios, respectively, by 2100 (Table 16) which is an increase from the present closures per year that the New England District Operations team reported (Figure 39).

Since returning to the original closure criteria in 2022, the New England team has maintained a low yearly average of only 0–3 flood control closures of the Tainter gates. Adjusting the closure threshold upward from +5.2 ft NAVD88 to accommodate increased sea level is likely to decrease the gate closure frequency but may expose the areas behind the barrier to residual damages and nuisance flooding. This flooding, in the absence of coastal storms, can likely be mitigated through nonstructural measures like elevating or floodproofing critical infrastructure or private property. This also requires understanding how higher basin levels impact stormwater conveyance to determine if the change induces flooding.

12.2. Water Control Manual Updates

WCMs are typically prepared for more complex structures and major structures that require an attendant during unusual or extreme hydro meteorological conditions. The main purposes of the manuals are to document the water control plan and to provide a reference source on project issues, authorities, data, schedules, and all other information to regulate a project. A manual should help regulate water management and consider all foreseeable conditions that may affect a project or system.

The governing manuals and regulations that outline the process for updates to a water control plan or manual are Engineer Manual (EM) 1110-2-3600, *Management of Water Control Systems* (USACE 2017), ER 1110-2-8156, *Preparation of Water Control Manuals* (USACE 2018), and ER 1110-2-240, *Water Control Management* (USACE 2016). These documents outline guidelines for managing and preparing water control systems. They also offer direction to field offices about the content and processes for creating and updating water management practices at all USACE-owned and -operated water control projects.

ER 1110-2-8156 recommends considering complete updates at regular intervals to incorporate additional hydrologic data and any other new information. EM 1110-2-3600 also states that as water control plans and water management plans are developed or updated, they should include integrated strategies for adaptation and mitigation to manage climate variability and impacts.

The New England District is currently updating its Fox Point storm surge barrier system WCM. The findings of this vulnerability assessment and the literature review show that the hydrometeorological conditions in the study area, particularly relating to precipitation and sea levels, are anticipated to experience foreseeable changes in the future. These changes will impact the daily and future operations of the Fox Point feature and shall be considered for the updates to the WCM. Consideration should also be given to nonstructural flood risk management measures within the city of Providence to accommodate additional water when the Tainter gates are not closed based on a higher closure threshold elevation.

In summary, although the Fox Point storm surge barrier demonstrated successful performance against the design coastal storm during modeling exercises, the system faces potential operational risks. Specifically, an increased frequency of closure events for the Tainter gates and other low-lying components is expected due to rising water levels associated with SLC and potential increases in precipitation during extreme rainfall events that could exceed the system pumping capacity. SLC and increases in precipitation may contribute to operational fatigue of the Tainter gates and reduce the available time for maintenance activities during periods when the coastal water levels exceed the closure thresholds and cause exceedances of the pumping capacity during extreme rainfall events.

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Acronym List

AEP	Annual Exceedance Probability
AMS	Annual Maximum Storm
API	Application Programming Interface
ARIMA	Autoregressive Integrated Moving Average
ASABE	American Society of Agricultural and Biological Engineers
ATR	Agency Technical Review
C	Celsius
cfs	Cubic Feet per Second
CHAT	Comprehensive Hydrology Assessment Tool
CHL	Coastal and Hydraulics Laboratory
CSRM	Coastal Storm Risk Management
DEM	Digital Elevation Model
DHS	Department of Homeland Security
DM	Design Memorandum
DoD	Department of Defense
DPW	Department of Public Works
DQC	District Quality Control
ECB	Engineering and Construction Bulletin
EM	Engineer Manual
EP	Engineer Pamphlet
EPA	Environmental Protection Agency
ER	Engineer Regulation
ERDC	Engineer Research and Development
ETL	Engineer Technical Letter
EWL	Extreme Water Level
F	Fahrenheit
FEMA	Federal Emergency Management Agency
FY	Fiscal Year
GHG	Greenhouse Gas
GOAT	Gate Operations Analysis Tool
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
HOR	Harbor of Refuge
HSPP	Hurricane Shore Protection Project
IEPR	Independent External Peer Review
MSE	Mean Squared Error
MSL	Mean Sea Level
NAD	North Atlantic Division
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NEMAC	National Environmental Modeling and Analysis Center
NEPA	National Environmental Policy Analysis
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash Sutcliffe Efficiency
NWS	National Weather Service
O&M	Operations and Maintenance
PAC	Post-Authorization Change
PDT	Project Development Team

PED	Preconstruction, Engineering, and Design
P.L.	Public Law
QA	Quality Assurance
RAS	River Analysis System
RCP	Representative Concentration Pathway
RSLC	Relative Sea Level Change
SAR	Safety Assurance Review
SIR	Scientific Investigations Report
SLAT	Sea Level Analysis Tool
SLC	Sea Level Change
SPF	Standard Project Flood
U.S.	United States
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WCM	Water Control Manual
WSE	Water Surface Elevation