

Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut



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16. Abstract (The Post Hurricane Sandy Transportation Resilience Study in New York-New Jersey-Connecticut provides an assessment of the metropolitan region transportation system's resilience to climate, sea level rise and extreme weather. The study leverages lessons learned from Hurricane Sandy and other recent events, as well as future climate projections, to identify strategies to reduce and manage extreme weather vulnerabilities amid the uncertainties of a changing climate. This final report from the study includes information on damage and disruption from Hurricane Sandy on the region's transportation systems, along with that of Hurricane Irene, Tropical Storm Lee, and Halloween Nor'easter Alfred. The report also contains a compilation of climate projections that were used to inform the study and assessments of the vulnerability and risk to the transportation system at three scales: <ul style="list-style-type: none"> • An assessment of the exposure of the transportation system to climate stressors at a regional scale, with information that can be used by transportation agencies in the region to advance more detailed vulnerability and risk assessments. • A vulnerability and risk assessment in three subareas: two multimodal corridors (one in Connecticut and one in New Jersey) and a coastal network of critical transportation facilities (in New York). • Engineering-informed assessments of climate vulnerabilities and risks and evaluation of potential adaptation strategies for a selection of transportation facilities—roads, bridges, tunnels, rail, and ports—that can be considered for these and similar facilities. The report is intended to inform transportation agency efforts to address changing climate conditions and extreme weather events from a regional planning level to facility level assessments.			
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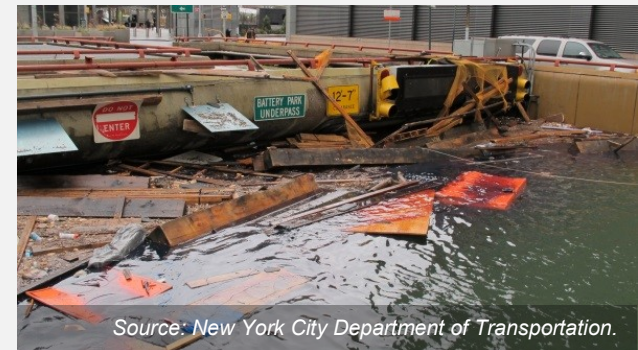
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Post-Hurricane Sandy Transportation Resilience Study Overview

Just as hurricane season was winding down in the fall of 2012, Hurricane Sandy was winding up—charging up the Atlantic Coast, causing havoc for communities along its way. A record-setting storm surge pummeled shoreline communities large and small from New Jersey to New York and Connecticut—destroying homes and businesses and leaving millions without power. Sandy also levied a heavy toll on the region’s transportation systems—knocking out bridges, flooding tunnels, submerging or washing out roads and rail, and closing airports. For a few days, the nation’s largest economic hub ground to a halt, and the rebuilding continues years later.

The Federal Highway Administration (FHWA) launched the Post-Hurricane Sandy Transportation Resilience Study (Post-Sandy Study) to enhance the New York-New Jersey-Connecticut metropolitan region’s resilience to climate change, sea level rise and extreme weather in the longer term, while informing the ongoing recovery process. Building from an FHWA-sponsored New Jersey vulnerability assessment pilot, performed in 2011, the FHWA collaborated with partners in Connecticut, New Jersey, and New York (see Figure 1.1) to leverage the lessons learned from Hurricane Sandy and other recent events, as well as future climate projections, to develop feasible, cost-effective strategies to reduce and manage extreme weather vulnerabilities amid the uncertainties of a changing climate.

The Post-Sandy Study team compiled information on damage and disruption wrought by Hurricane Sandy on the region’s transportation systems, along with that of Hurricane Irene, Tropical Storm Lee, and a severe Halloween Nor’easter nicknamed “Alfred” all in the previous year. The impacts of these four weather events varied across the region and considering them together provides a wide range of potential weather-related consequences for the transportation system. The team also compiled climate projections for use in the Post-Sandy Study and continuously monitored updates from the scientific community as the study progressed.



Source: New York City Department of Transportation.

Although Hurricane Sandy was unlike any storm in recorded history, weather-related disasters will continue to threaten the region. A changing climate could lead to increased flooding from storm surges as sea levels continue to rise, intensifying the impacts of more routine weather and heightening the devastation wrought by extreme storms—tomorrow’s Sandys.

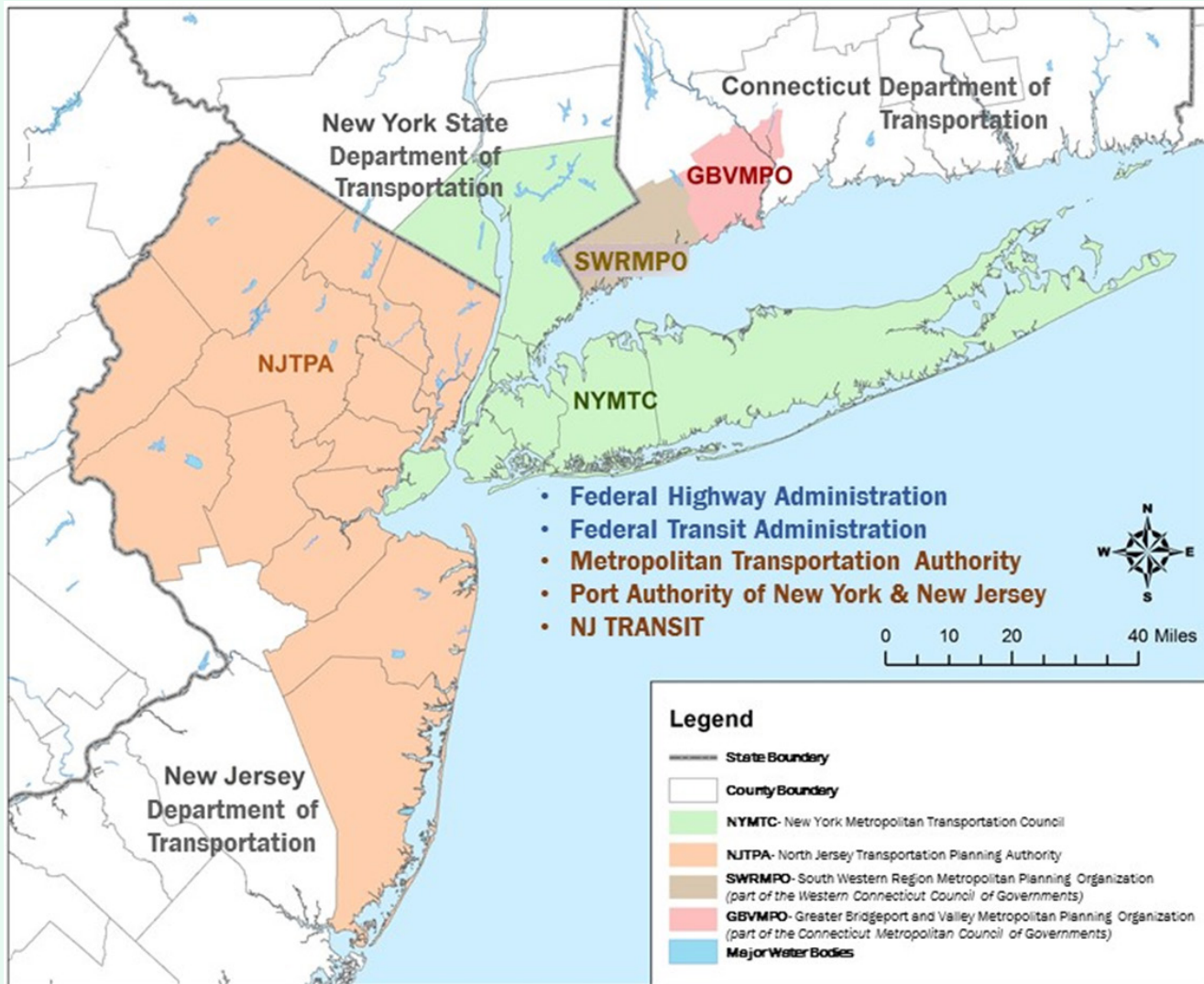


Figure 1.1. Map. Study area and project partners.

(Source: Cambridge Systematics, Inc.)

With an understanding of past impacts and future climate conditions, the Post-Sandy Study assessed vulnerability and risk to the transportation system in the region at three scales:

- **Regional Level.** The study assessed the exposure of the transportation system to climate stressors at a regional scale, developing information that can be used by transportation agencies in the entire study area to advance more detailed vulnerability and risk assessments.
- **Subarea Level.** The study team tested a vulnerability and risk assessment approach at the scale of three “subareas”: two multimodal corridors (one in Connecticut and one in New Jersey) and a coastal network of critical transportation facilities (in New York).
- **Facility Level.** The region’s transportation agencies chose a selection of transportation facilities—roads, bridges, tunnels, rail, and ports—for engineering-informed assessments of climate vulnerabilities and risks and evaluation of potential adaptation strategies that could be applied to these and similar facilities.

Data and resources compiled as part of the Post-Sandy Study, coupled with results and lessons learned from the facility level and subregional assessments, will help transportation agencies in the three-state metropolitan region, and beyond, improve the resilience of our transportation system now and in the future.

1.1 Study Context

The Post-Sandy Study is part of a series of research projects funded by FHWA with a goal of mainstreaming the consideration of climate vulnerability and risk in transportation decision-making. The Post-Sandy Study is intended to inform our collective understanding on how to integrate climate resilience at multiple levels: in planning, during the project development process, and as part of operations and maintenance strategies, including asset management and emergency management.

The project took place amidst a number of statutory and regulatory changes addressing resilience, as well as numerous new initiatives and partnerships, including:

- The Fixing America's Surface Transportation (FAST) Act, signed into law in December 2015, included a number of provisions addressing the resilience of the nation’s transportation system. The FAST Act expands the scope of the planning process for state Departments of Transportation and Metropolitan Planning Organizations to “improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation.” (23 CFR 450.206(a)(9) and 23 CFR 450.306(b)(9)). The FAST Act also requires that metropolitan transportation plans assess capital investment and other strategies that reduce the vulnerability of the existing transportation infrastructure to natural disasters. (23 CFR 450.324(f)(7)).
- The Moving Ahead for Progress in the 21st Century Act (MAP-21) requires States to develop risk-based asset management plans for the National Highway System (NHS). MAP-21 section 1315(b)(1) also requires the “evaluation of reasonable alternatives for roads, highways, or bridges that repeatedly require repair and reconstruction activities from emergency events”. In October 2016, FHWA published a Notice of Final Rulemaking in the Federal Register

describing the process for developing these asset management plans, including addressing the risks associated with current and future environmental conditions, extreme weather events, and climate change. The process also includes addressing the risks related to recurring damage and costs as identified through the evaluation of facilities repeatedly damaged.

- The Federal government has provided financial and technical resources to support recovery and resilience measures in the three state metropolitan region. Under the Disaster Relief Appropriations Act (Pub. L. 113–2), Congress provided \$10.9 billion for FTA’s Emergency Relief Program for recovery, relief and resilience efforts in areas affected by Hurricane Sandy. FTA had allocated approximately \$10.1 billion in multiple tiers for response, recovery and rebuilding, for locally prioritized resilience projects, and for competitively selected resilience projects as of December 2016.
- The U.S. Department of Housing and Urban Development (HUD), in partnership with the Municipal Art Society, Regional Plan Association, NYU’s Institute for Public Knowledge, and The Van Alen Institute, and with support from The Rockefeller Foundation and other philanthropic partners, launched an innovative multi-stage competition called “Rebuild by Design” in the aftermath of Hurricane Sandy. Rebuild by Design guided participants through in-depth research, cross-sector, cross-professional collaboration, and iterative design. Participants collaborated with community and local government stakeholders to ensure each stage of the competition were based on the best knowledge and talent and final proposals would be realistic and replicable.

The Post-Hurricane Sandy Transportation Resilience Study builds on a wealth of previous work, including a FHWA-sponsored vulnerability and risk assessment performed in 2011 by the New Jersey Department of Transportation (NJDOT) and the North Jersey Transportation Planning Authority (NJTPA). Many of the assets damaged or disabled during Hurricane Sandy (as well as Hurricane Irene) were highlighted as potentially vulnerable in the previous study.

After receiving 41 original concepts, Rebuild by Design is currently funding seven projects in the three-state metropolitan region. These include:

- “The Big U” project to protect Lower Manhattan from floodwater, storms, and other impacts of a changing climate;
- The “New Meadowlands” project in New Jersey, focusing on flood risk reduction projects in Bergen County in the towns of Little Ferry and Moonachie, which experienced the most damage during Sandy; and
- “Resilient Bridgeport” (in Connecticut), a comprehensive approach to protecting against climate change and storm surge and rainfall flooding that is also designed to stimulate environmental restoration, economic development, and neighborhood revitalization.

Also, during the recovery period following Hurricane Sandy, state, regional, and local transportation agencies have accelerated existing resilience programs or embarked on new projects including assessments to rebuild infrastructure and prepare for future storms. These include the following:

- On September 22, 2014, New York Governor Andrew Cuomo signed into law the Community Risk and Resiliency Act (CRRRA). The purpose of the bill is to ensure that certain state monies, facility-siting regulations and permits include consideration of future climate risk due to sea level rise, storm surge and inland

flooding. Consistent with the provisions of the CRRRA, the New York State Department of Environmental Conservation (DEC) adopted science-based sea-level rise projections into regulation in February 2017. These projections will be updated at least every five years.

- The NYS2100 Commission, appointed by Governor Cuomo after Hurricane Sandy, released its report “Recommendations to Improve the Strength and Resilience of the Empire State’s Infrastructure” in early 2013. The Commission’s report includes recommendations on strengthening and increasing the resiliency of the state’s infrastructure through short- and long-term strategies. The sectors addressed include transportation, land use, energy, insurance, and infrastructure financing and also includes cross-cutting recommendations that are common to these sectors. The recommendations are part of the effort to help protect New York from future storms and natural disasters.
- New York State initiated the “NY Rising Community Reconstruction (NYRCR) Program.” The Governor’s Office of Storm Recovery (GOSR) has allotted more than \$700 million in federal funds to support the planning and implementation of community-developed projects in more than 124 communities severely damaged by Hurricane Sandy, Hurricane Irene, and Tropical Storm Lee, including many communities in the study area for this effort.
- Connecticut Department of Transportation received funding through the U.S. Department of Housing and Urban Development’s (HUD) National Disaster Resilience Competition (NDRC) to advance resilience planning and implementation in the Sandy-affected region of the state.
- The Metropolitan Transportation Authority (MTA) embarked on a “Fix & Fortify” program to repair damaged infrastructure and install flood protection measures and other measures to make the subway system more resilient to future storm events.
- The State of New Jersey and local municipalities have undertaken their own resilience initiatives in the wake of Hurricane Sandy. Several coastal communities have fortified dunes and other protections against coastal storms.
- NJ TRANSIT undertook a comprehensive review of vulnerability and risks to the NJ TRANSIT rail network and is already progressing on repair and replacement projects identified through that effort. NJ TRANSIT developed a semi-quantitative method to help determine the risks facing Transit. From a number of internal interviews, they developed eight criticality criteria. They focused on exposure, sensitivity, and adaptive capacity. NJ TRANSIT was able to secure 80% of the funding requested from Federal Transit Administration for repairs.
- The Port Authority of New York & New Jersey is incorporating climate resiliency into their design guidance. The guidelines address higher temperatures, extreme precipitation, and sea level rise. The guidelines also lay out a series of steps to help engineers establish flood protection criteria for a project. The Authority bases the effectiveness of the design on how quickly the asset can be returned to service in the wake of a disruptive event. The Authority felt they needed a process (rather than set criteria) for knowing what to protect. The process they developed made sure that they look at an asset from all angles and then do a cost-benefit analysis for major projects (>\$10 million).

1.2 Study Objectives and Work Plan

The objectives of the Post-Sandy Study were to:

- Enhance the three state metropolitan region’s resiliency to climate change, sea level rise and extreme weather events in the longer term, while informing the ongoing Hurricane Sandy recovery and rebuilding process;
- Identify feasible, cost-effective strategies to reduce and manage extreme weather vulnerabilities amid the uncertainties of a changing climate; and
- Advance the state of knowledge and develop methods to assist agencies in the region—and nationwide—that are seeking to plan and invest for long-term climate resilience.

The FHWA is undertaking this research with the broader goal of helping transportation agencies mainstream how they consider climate change resilience in transportation decision-making. The Post-Sandy Study is informing a collective understanding of how to best integrate climate resilience at multiple levels of analysis and at multiple points in the cycle of transportation planning, programming, implementation, and monitoring.

Figure 1.2 shows the core elements of the Post-Sandy Study work plan. The project began with a compilation of damage and disruption information from Hurricane Sandy and three other major storm events that impacted the region. The Post-Sandy Study used a system-level vulnerability assessment to identify parts of the regional transportation network that were particularly vulnerable and could benefit from further analysis. The project partners selected three subareas to test the vulnerability and risk assessment on a corridor-level or a network of transportation assets within a sub-area.



Project Guidance Committee Members

- CTDOT - Connecticut
- Department of Transportation
- FHWA - Federal Highway Administration
- FTA - Federal Transit Administration
- GBVMPO - Greater Bridgeport and Valley Metropolitan Planning Organization (part of the Connecticut Metropolitan Council of Governments)
- MTA - Metropolitan Transportation Authority
- NYSDOT - New York State Department of Transportation
- NJDOT - New Jersey Department of Transportation
- NYMTC - New York Metropolitan Transportation Council
- NJ TRANSIT
- NJTPA - North Jersey Transportation Planning Authority
- PANYNJ - Port Authority of New York and New Jersey
- SWRMPO - South Western Region Metropolitan Planning Organization (part of the Western Connecticut Council of Governments)

The project partners identified ten facilities for a detailed vulnerability and risk assessment that included an engineering-informed assessment of potential adaptation strategies. The lessons learned from these facility-specific analyses helped the study team recommend changes to the vulnerability and risk assessment framework used throughout the study.

1.3 Stakeholder Engagement

The Post-Sandy Study team engaged regional stakeholders and technical experts through two groups:

- A Project Guidance Committee (PGC), consisting of the Federal Highway Administration and Federal Transit Administration, the three state Departments of Transportation and four Metropolitan Planning Organizations in the study area, the Metropolitan Transportation Authority (MTA), NJ TRANSIT and the Port Authority of New York & New Jersey, met seven times over the course of the study to provide feedback into work products completed to date and to provide input to guide forthcoming tasks. Table 1.1 shows the meeting dates and objectives.
- A Technical Experts Group (TEG) met three times over the course of the study at key milestones to discuss technical issues related to climate data and assessment of adaptation strategies, and identify opportunities to integrate results of the study in transportation decision-making. The TEG participants included PGC members as well as additional stakeholders in the study region and subject matter experts. Table 1.2 shows the meeting dates and objectives of the TEG meetings.

Table 1.1. Project Guidance Committee (PGC) meetings.

Meeting	Date	Topics
1	August 20, 2013	<ul style="list-style-type: none"> • Project Goals and Context • Data Collection Process/Priorities for Extreme Weather Impacts Assessment • Proposed Facilities for Engineering-Informed Adaptation Assessments
2	November 19, 2013	<ul style="list-style-type: none"> • Draft Results of Damage Assessment • Review of Existing Climate Data • Selection of Facilities for Engineering-Informed Adaptation Assessments
3	March 25, 2014 (via teleconference)	<ul style="list-style-type: none"> • Revised Methodology for Engineering-Informed Adaptation Assessments • Plan for Pilot of Assessment Methodology • Results of Damage Assessment
4	September 23, 2014	<ul style="list-style-type: none"> • Climate Forecasts • Status of Engineering-Informed Adaptation Assessments and Lessons Learned to Date
5	June 9, 2015	<ul style="list-style-type: none"> • Review of Completed Engineering-Informed Adaptation Assessments • Discussion of Proposed Scope of Work for Subarea Assessments of Climate Vulnerability and Risk
6	December 9, 2015	<ul style="list-style-type: none"> • Lessons Learned from Engineering-Informed Adaptation Assessments • Use of Benefit-Cost Analysis Tool in Adaptation Assessments • Review of Refined Scope of Work for Subarea Assessments of Climate Vulnerability and Risk and Initial Work Completed to Date
7	May 4, 2016	<ul style="list-style-type: none"> • Regional Transportation System Vulnerability Assessment • Selection of Subareas for Assessments of Climate Vulnerability and Risk • Proposed Process and Products of Subarea Assessments

Table 1.2. Technical Expert Group (TEG) meetings.

Meeting	Date	Objectives
1	April 22, 2014	<ul style="list-style-type: none"> • Review project background and objectives • Extreme Weather Events and Climate Projections • Opportunities for Integrating Climate Data into Transportation Decision-Making <ul style="list-style-type: none"> – Long-Range/Strategic Planning and Investment Decision-Making; – Design and Engineering; and – System Maintenance and Management (operational) • Review of Regional Damage Assessments • Review and Discuss Engineering-Informed Adaptation Assessments
2	December 11, 2014	<ul style="list-style-type: none"> • Overview of U.S. Army Corps of Engineers' North Atlantic Coast Comprehensive Study (NACCS) • Review Progress of Engineering-Based Adaptation Assessments • Review Assessments Underway by Region's Operating Agencies • Summarize Available FHWA Technical Guidance to Support Climate Vulnerability and Risk Assessment • Gather Technical Input on the Regional Vulnerability Assessment in Task 5.
3	December 7, 2016	<ul style="list-style-type: none"> • Review the project's draft final report. • Discuss integration of climate risk and vulnerability assessment into agencies' existing policies and processes for planning, project development, operations/emergency management, and asset management.

1.4 Contents and Organization of the Report

The remainder of this report is organized as follows:

- Section 2 summarizes the damage and disruption to the multimodal transportation system of the three-state metropolitan region caused by recent major storms;
- Section 3 catalogs key climate variables and summarizes the tools used to conduct the vulnerability, risk, and adaptation assessments;
- Section 4 describes how a generalized vulnerability and risk assessment process can be applied at a regional scale, at the level of a corridor or small network, and for specific facilities in the region's multimodal transportation network; and
- Section 5 provides examples of how a climate vulnerability and risk assessment and related information can be incorporated into an agency's policies, plans, and programs, and the information can help deliver better adaptation projects.

There are six Appendices to the report:

- Appendix A provides additional detail about the compilation of damaged and disrupted assets.
- Appendix B details a process that was developed for this study to assess vulnerability and risk at the scale of a facility.
- Appendix C contains a complete set of maps and related analysis of exposure to climate stressors at the regional level.
- Appendix D contains three subarea assessments of vulnerability and risk.
- Appendix E contains ten facility-level assessments of vulnerability and risk.
- Appendix F contains a compilation of resources and tools that can be used to assist in a vulnerability and risk assessment.

2

Storm Conditions, Damage, and Disruption

Hurricane Sandy (2012), Hurricane Irene (2011), Tropical Storm Lee (2011), and Nor'easter Alfred (2011) together claimed dozens of lives, caused countless injuries, and resulted in tens of billions of dollars in damage, disruption, and economic impact. This chapter summarizes how these events caused damage and disruption to the multimodal transportation system of the three state metropolitan region.

- Section 2.1 summarizes the weather conditions associated with each storm.
- Section 2.2 summarizes the damage each storm caused to transportation facilities.
- Section 2.3 summarizes disruption caused by each storm.
- Appendix A contains details about the storm surge, wind, rainfall, and stream gage observations before, during, and after each storm, as well as the full damage and disruption assessment conducted early in this study.

2.1 Storm Conditions

Figure 2.1 shows the paths of the storm centers for Irene, Lee, Alfred, and Sandy. Irene, Lee, and Alfred all moved in a northeasterly direction. Sandy, however, approached from the southeast and moved west-northwest into New Jersey, a turn that was responsible for the extreme storm surge and widespread wind damage in the region. Irene was the only storm whose center moved directly over the study area.

Hurricane Sandy, also known as “Superstorm Sandy,” caused catastrophic damage to much of the study area. A storm surge that coincided with the highest tide of the month caused sea levels along the New Jersey coast, along the south shore of Long Island, and in New York Harbor to rise higher than ever before in recorded history. In fact, the surge was so significant that rising water and waves destroyed the tide gage at Sandy Hook (see Figure 2.2). Many critical transportation facilities were inundated (some tunnels from floor to ceiling), and transit and roadway facilities were shut down, some for weeks.

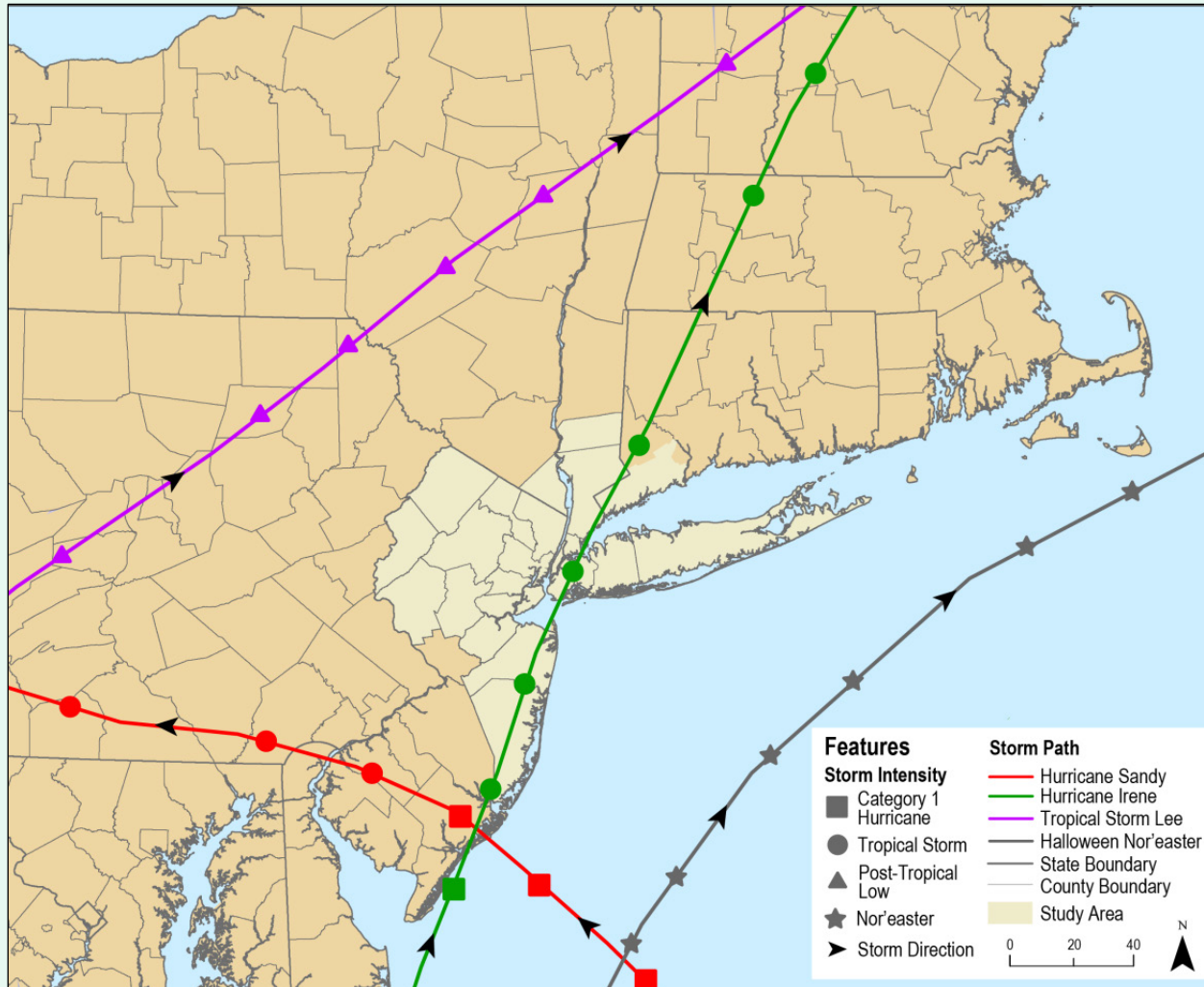


Figure 2.1. Map. Path of storm centers—Sandy, Irene, Lee, and Alfred.

(Source: National Oceanic and Atmospheric Administration, Office for Coastal Management. DigitalCoast Historical Hurricane Tracks data.)

The impacts of the corrosive salt water on electrical components are still being felt more than four years later and will cause long-lasting impacts on the reliability of the region's multimodal transportation system. Major power generating stations, electrical substations, emergency backup generators, oil refineries, fuel storage facilities, and other critical components of the region's electrical and fuel distribution system also were impacted, with associated immediate and long-term impacts to the transportation system.

The one-two punch of Hurricane Irene and Tropical Storm Lee, which arrived in the region within two weeks of each other during the summer of 2011, caused significant (primarily inland) flooding and wind-related damage in northern New Jersey and the Lower Hudson Valley (see Figures 2.3 through 2.5 for a comparison of stream gage readings in New Jersey for Sandy, Irene, and Lee). Little Falls stream gage on the Passaic River, which has a median daily discharge of less than 400 cubic feet of water per second, experienced about 1,300 cubic feet per second after Sandy, which had a relatively modest cumulative rainfall total of just over one inch at Newark Airport. After Irene dumped nearly 9 inches of rain (a 100-year rainfall event), Little Falls saw more than 20,000 cubic feet of water per second. Saturated soils in the Passaic River basin meant that Lee's 2 inches of rain less than two weeks later resulted in more than 12,500 cubic feet of water per second at Little Falls.

While these storms caused extensive damage in upstate New York and Vermont, within the Post-Sandy Study area, some roadways and transit lines were also damaged by floods and debris from Irene's winds and rain, then re-submerged when the same rivers and streams flooded again after Lee. In some cases, trees that survived Irene's winds were unable to withstand a second storm, as waterlogged soils were unable to support the roots of larger trees once Lee arrived.

Alfred followed two months after Irene and Lee in October 2011, but this third storm followed a more southeasterly track, and therefore had its greatest impacts in Connecticut. In the portion of the study area covering Southwest Connecticut and Westchester County, New York, Alfred dumped unusually large amounts of snow on trees still covered with leaves relatively early in the Fall season. The winds associated with this storm toppled large numbers of trees, blocking area roadways and train lines, and tearing down power lines that supplied electricity to Metro-North Railroad as well as traffic signals and street lights. Parts of Connecticut, primarily in the northern region (outside of the study area), were without electricity for over a week.

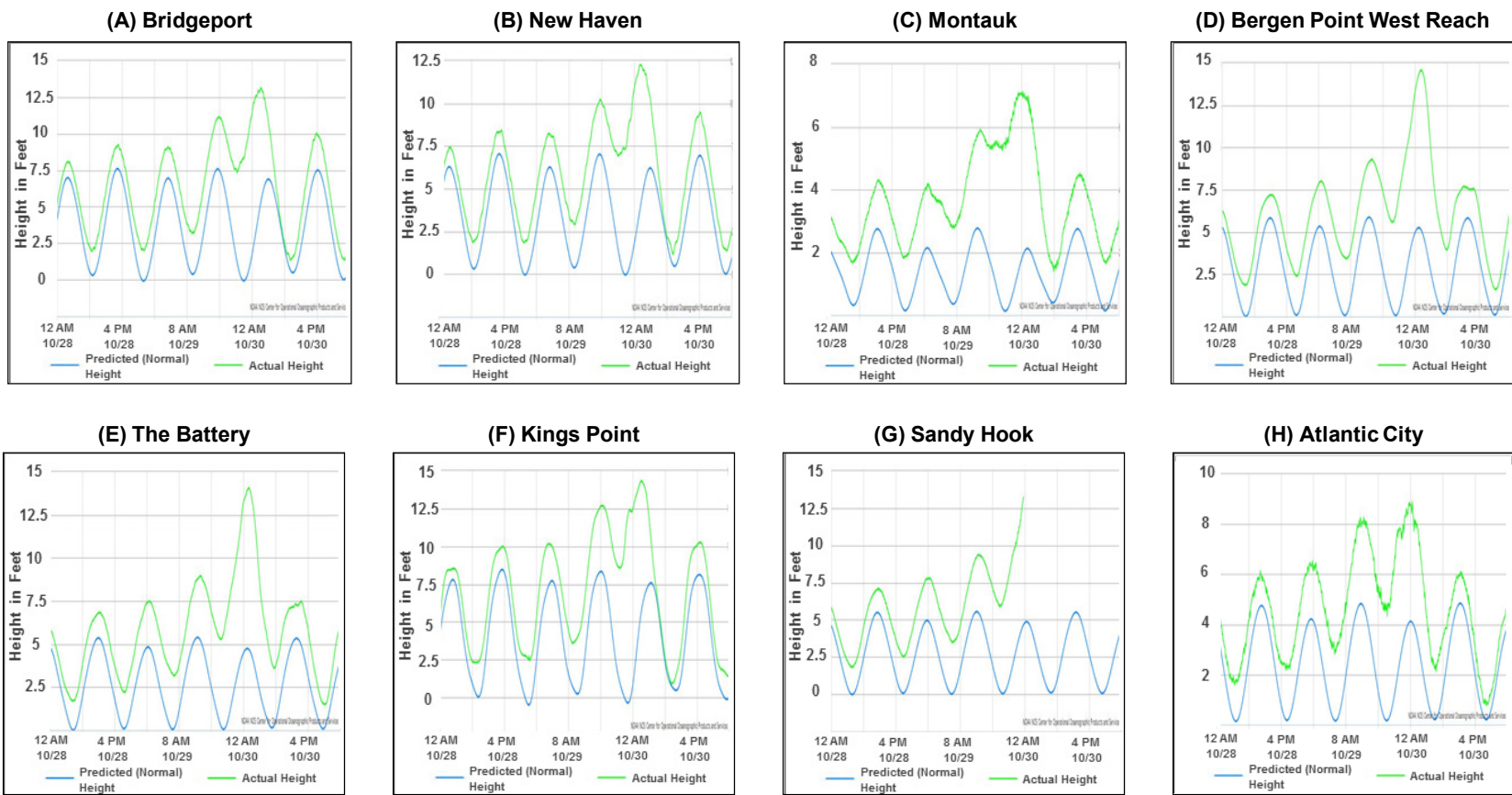


Figure 2.2. Chart. Hurricane Sandy tidal readings.

(Source: National Oceanic and Atmospheric Administration’s National Ocean Service – Center for Operational Oceanographic Products and Services.)

Notes: Blue lines indicate predicted (normal) water heights while green lines indicate actual heights.

Tide gage data represent the 72-hour period from 12 AM on October 28th, 2012 through 12 AM on October 30th, 2012. Tide readings show the normal tide height in blue, and the actual reading during the storm in green. The greatest surge heights generally occurred around midnight on October 30th along the New Jersey coast and at Montauk, while peak heights were observed slightly after midnight at all other gages.

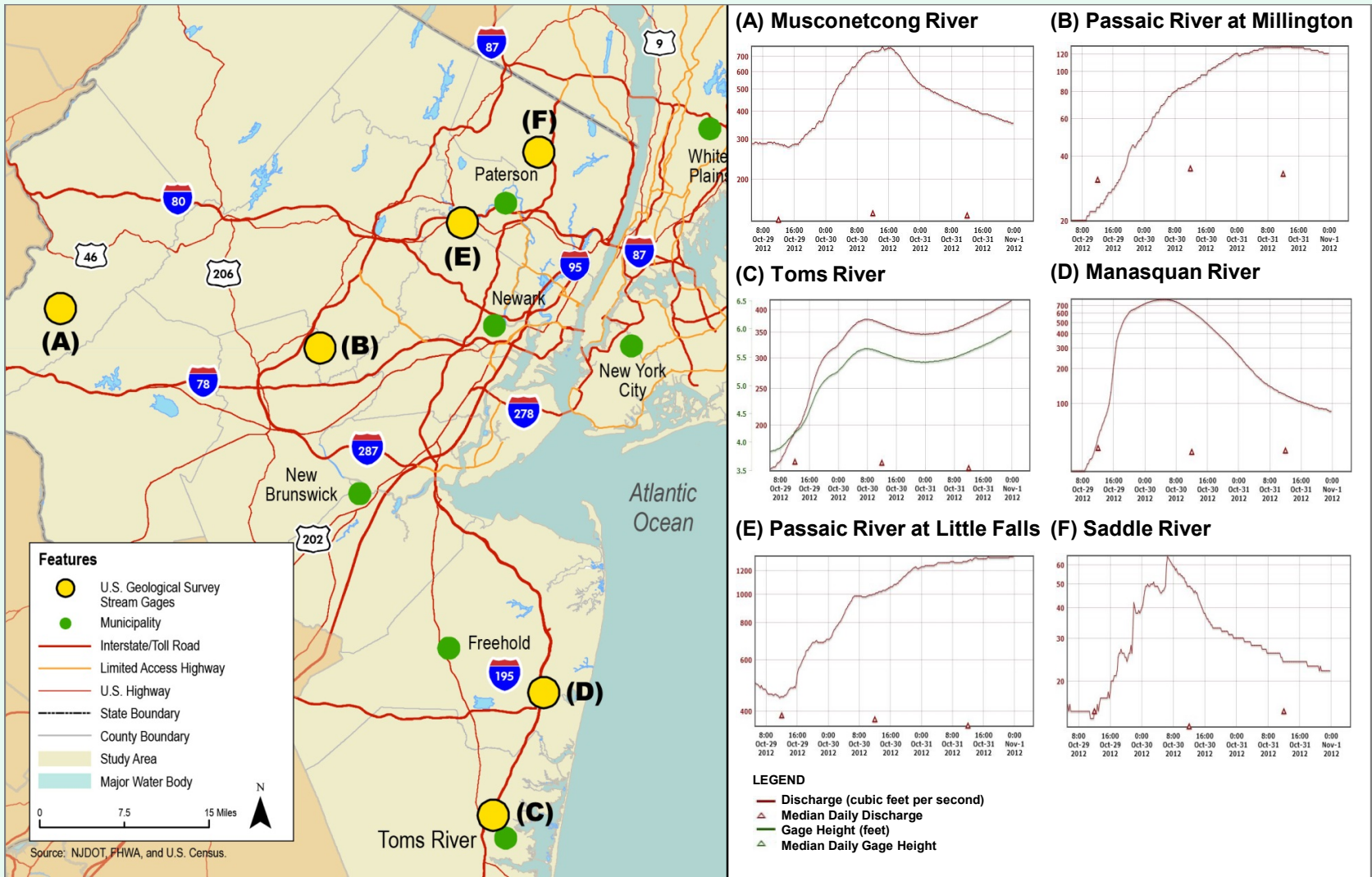


Figure 2.3. Map and charts. Hurricane Sandy stream gauge observations: New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

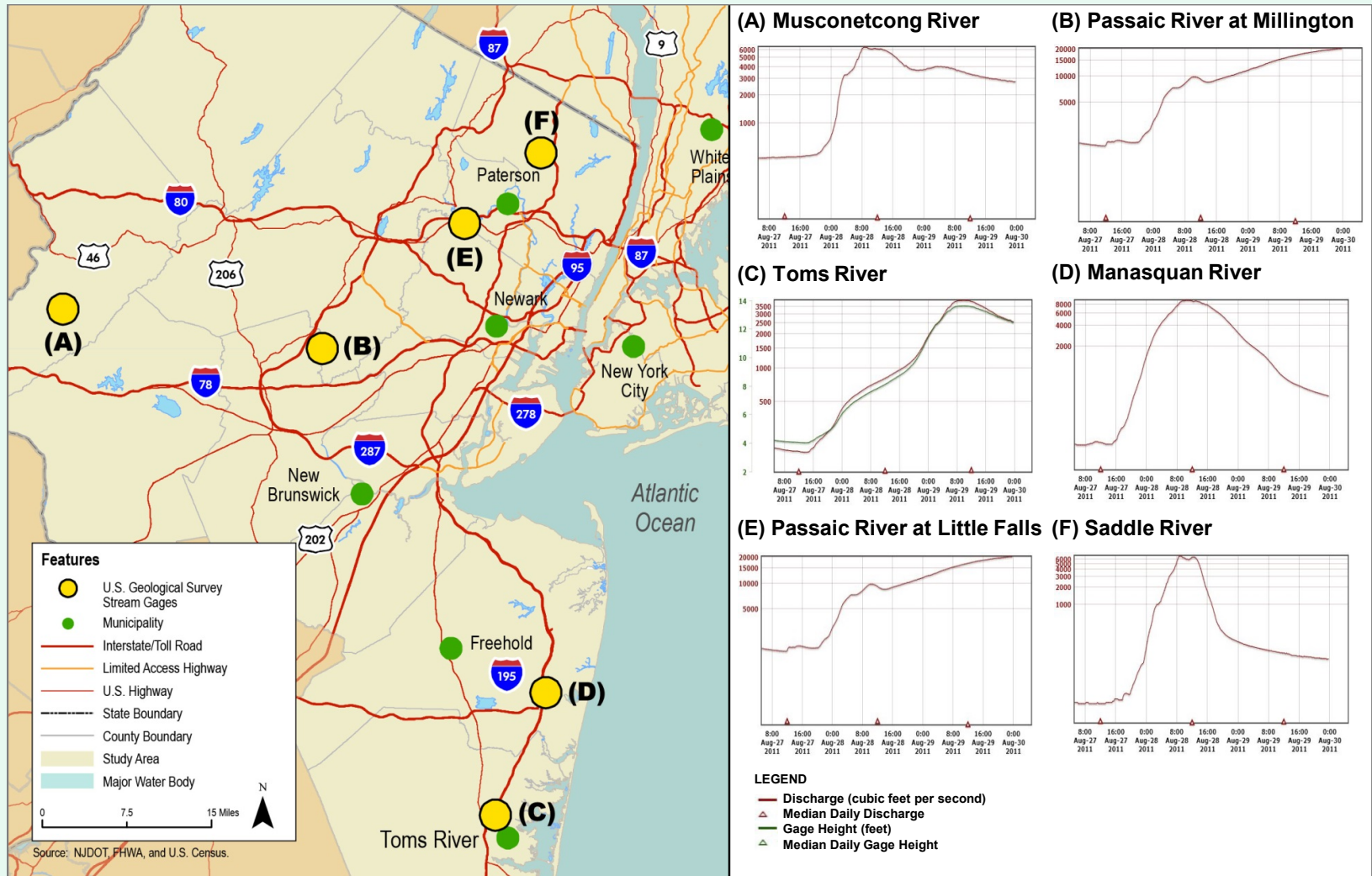


Figure 2.4. Map and charts. Hurricane Irene stream gauge observations: New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

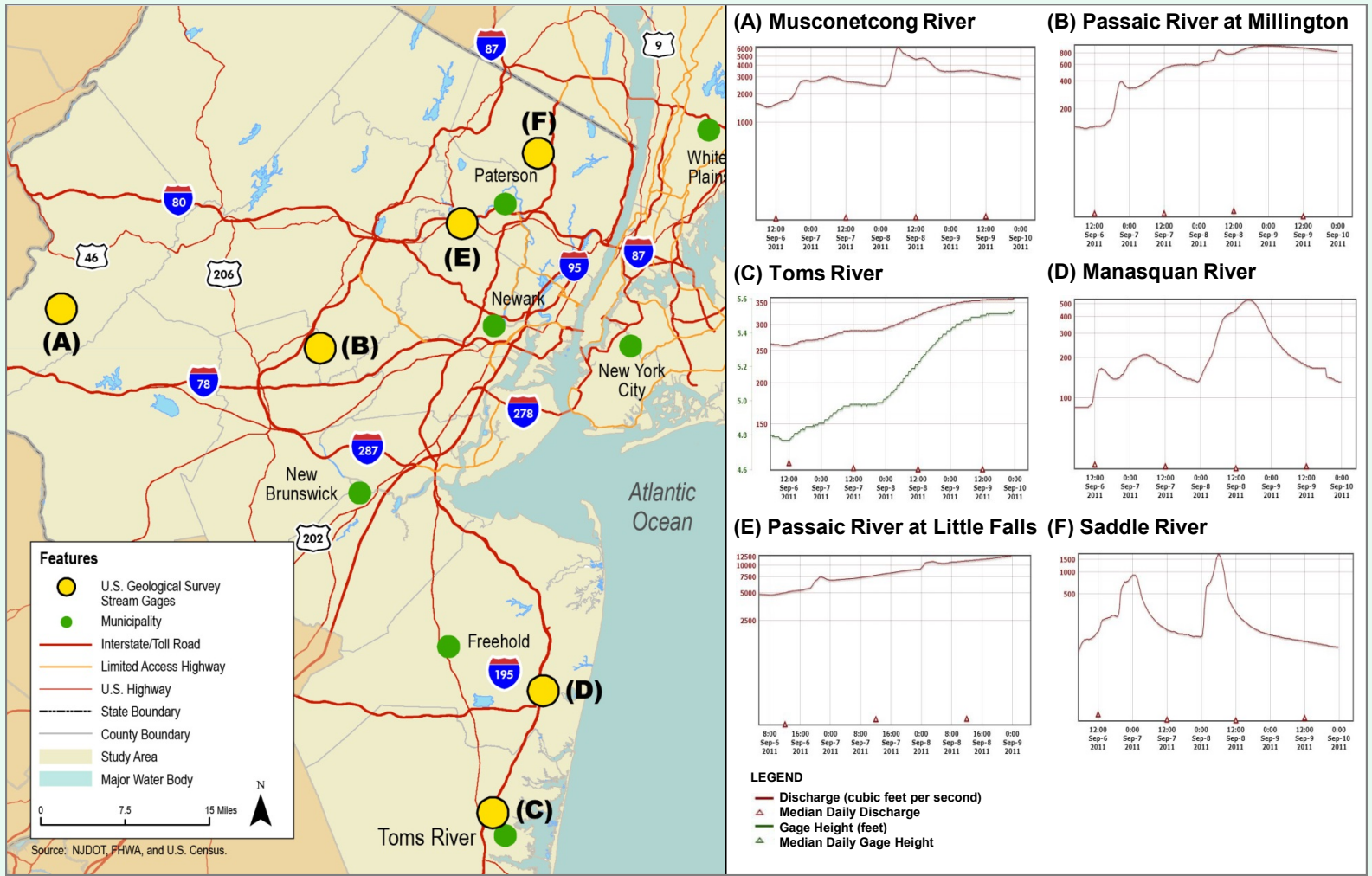


Figure 2.5. Map and charts. Tropical Storm Lee stream gage observations: New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

As with their paths, the strengths of these storms—measured by peak sustained wind speed—varied as well. For example, Hurricane Sandy’s intensity diminished to tropical storm strength (less than 74 mph peak sustained winds) as it made landfall in New Jersey, merging with a winter storm front. However, the shoreward direction of its winds caused sea water to “pile up” in the form of a storm surge along the coast.

Irene—formerly hurricane strength—passed through the study area as a tropical storm. Lee was considered a post-tropical low by the time it entered the study area. Alfred was a low pressure system typically referred to as a “nor’easter.” However, these storms had enough moisture to cause significant impacts to the region.

More details on the weather context of each storm including storm surge, wind, precipitation, and stream gage observations for the periods before and after each storm’s peak, can be found in Appendix A.

2.2 Assessment of Damage to the Regional Transportation System

This section summarizes a compilation of surface transportation assets damaged as a result of these four storms. The study team assembled data on event-related damage to the regional transportation system from FHWA division offices in New Jersey, New York, and Connecticut; respective Departments of Transportation in those states; the Federal Transit Administration; operators of transit systems in the study area; and the Federal Emergency Management Agency.

Damage to the Regional Highway System in the Study Area

Figures 2.6 and 2.7 compare the geographic extent of projects submitted for ER Program reimbursements for Hurricane Sandy as of October 2013, and for the combination of Hurricane Irene and Tropical Storm Lee. Projects are shown by asset class. Figures 2.8 through 2.11 show similar comparisons of projects by climate stressor and failure mode, respectively.

These figures clearly indicate the differences in damage associated with the storms. Hurricane Sandy’s storm surge caused coastal flooding, with extensive washouts and bridge damage along the Jersey Shore and the south shore of Long Island. The storm surge also led to inundation of tunnels crossing the Hudson and East rivers, and low-lying mechanical and electrical equipment were flooded when water levels rose in coastal and near-coastal areas around the region. As water flowed into and out of major channels, bridge piers and foundations were compromised due to scouring of sediment and rocks from

The information presented in this section is not intended to be a comprehensive inventory of damage to the region’s Federal-aid highway system. Instead, by summarizing available information on the types of damage observed from four recent storms, this report is intended to help inform future strategies to enhance the three-state metropolitan region’s resilience to climate change and extreme weather in the long term.

channel bottoms. Hurricane Sandy also caused extensive wind-related damage to roadway appurtenances like signs, guardrails, fences, and lights throughout the region, either due to direct wind-related structural failure or due to damage from wind-blown trees and other debris. Table 2.1 summarizes the top ten most costly projects submitted to FHWA for ER program reimbursements as of October 2013.

The data presented in this section are limited to reported damage to highways in the study area and to the information available at the time the data was collected for this report in October 2013.

The rainfall associated with Hurricane Irene and Tropical Storm Lee, in contrast, caused most of the reported damage, with the most severe impacts near rivers and streams away from the coast in New Jersey. Bridges and culverts spanning these streams were washed out or damaged by the flow of water or by water-carried debris, and stretches of roadways adjacent to fast-running streams or in nearby flood plains were eroded or flooded. Unlike previous heavy rainfall events that have been known to cause occasional floods and minor damage along rivers like the Passaic River, the magnitude of rainfall and subsequent floods from Hurricane Irene and Tropical Storm Lee damaged transportation assets of national significance, including Interstate Highways 80 and 287 and U.S. 46.

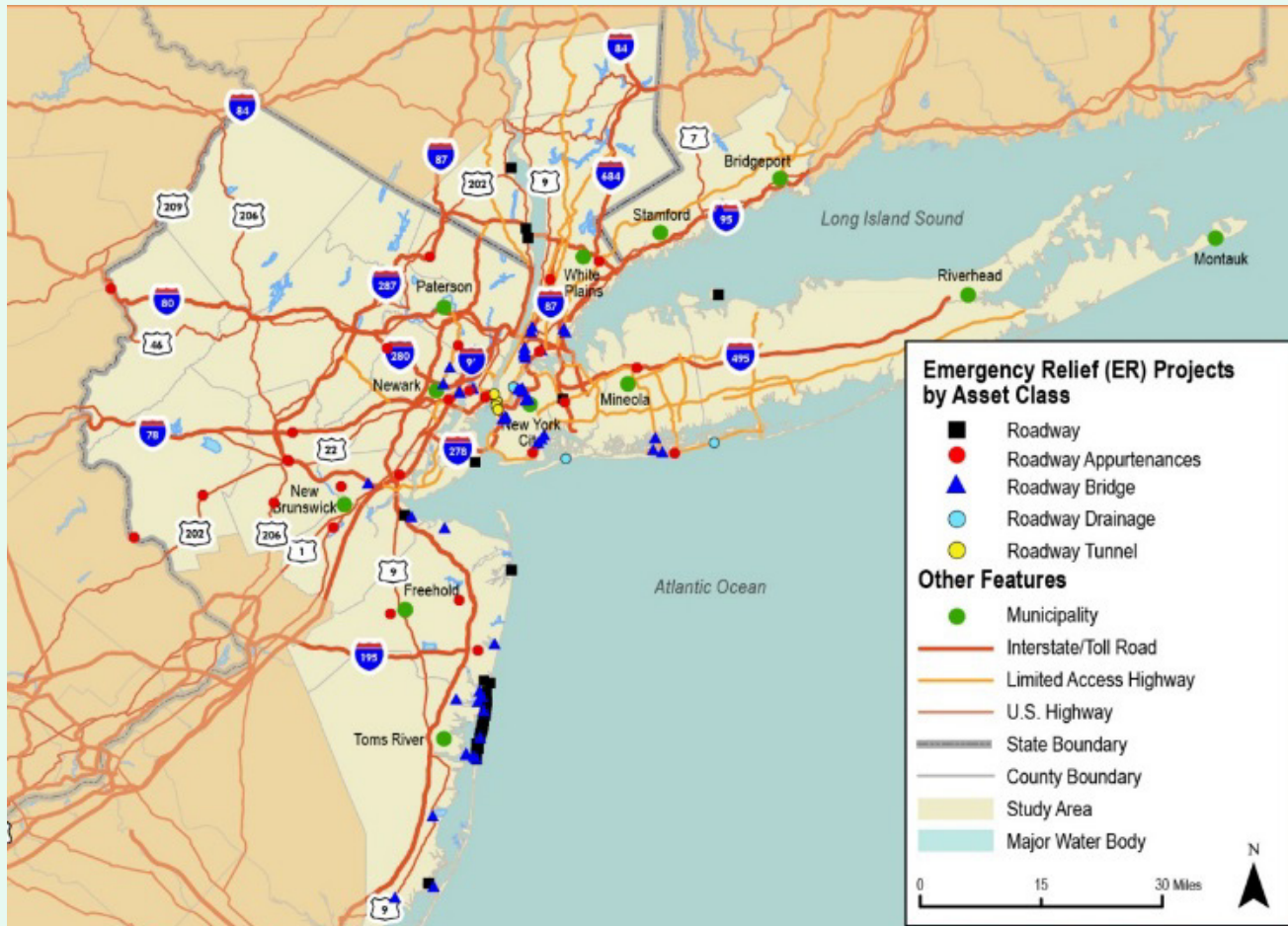


Figure 2.6. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by asset class, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

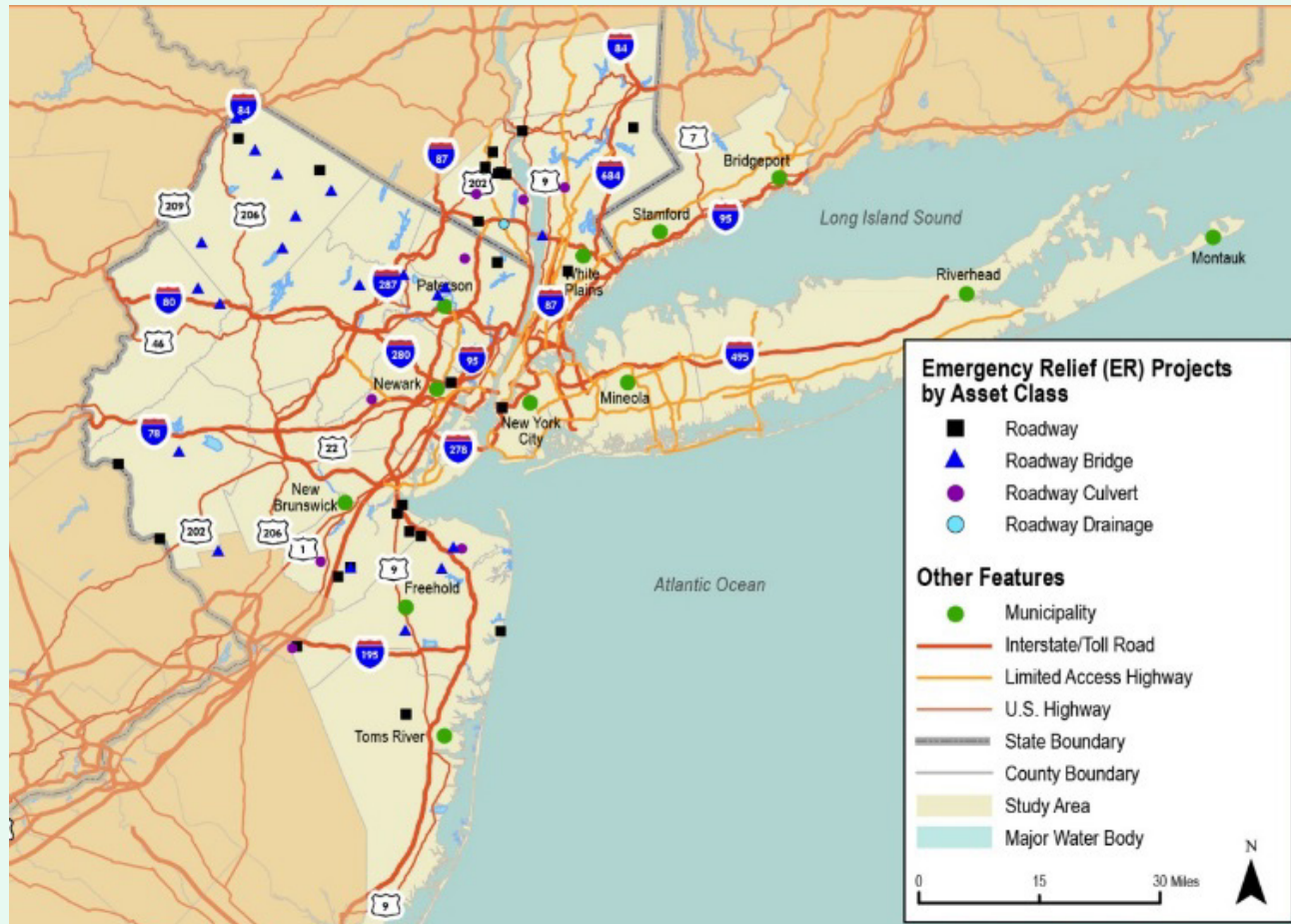


Figure 2.7. Map. Projects Submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by asset class, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

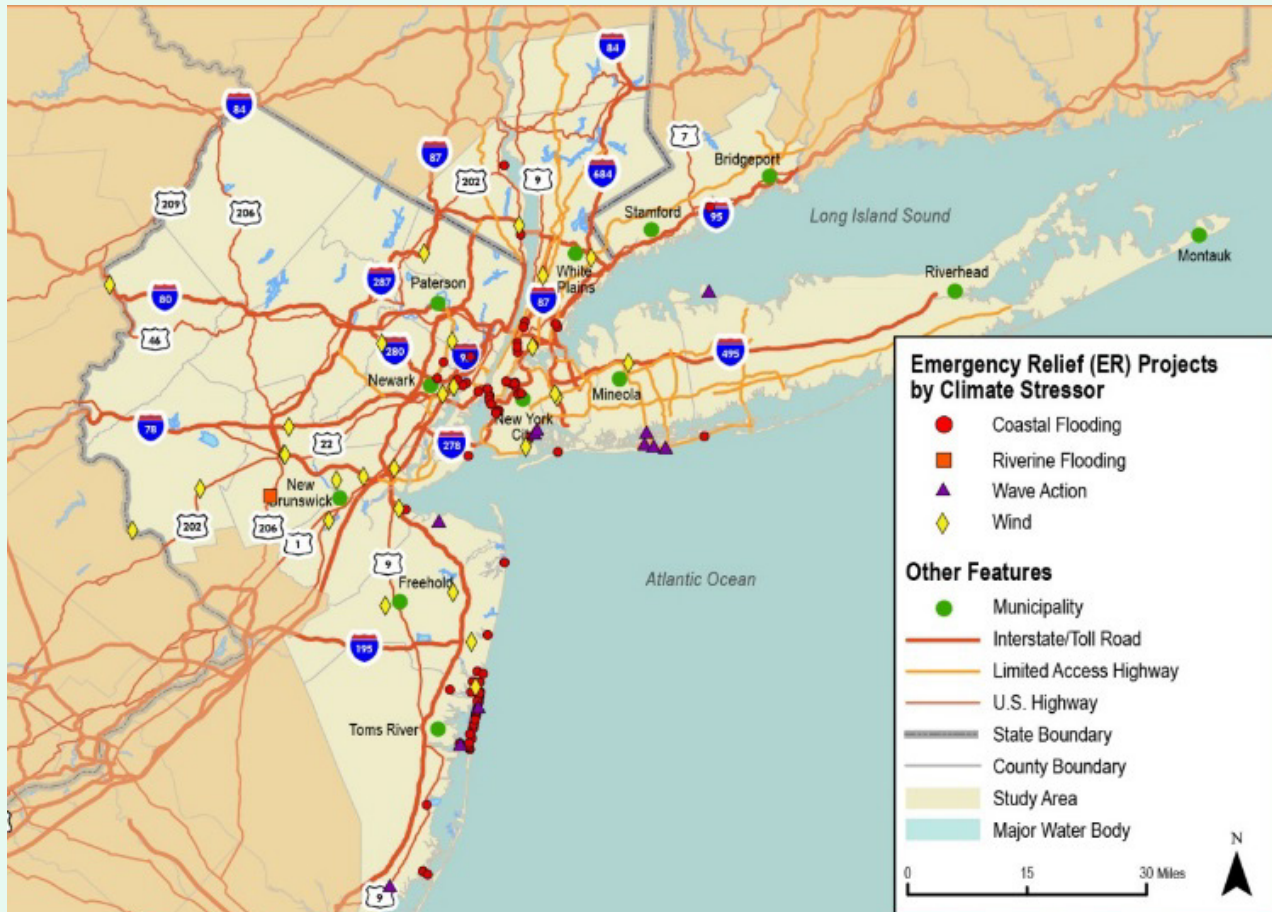


Figure 2.8. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by climate stressor, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

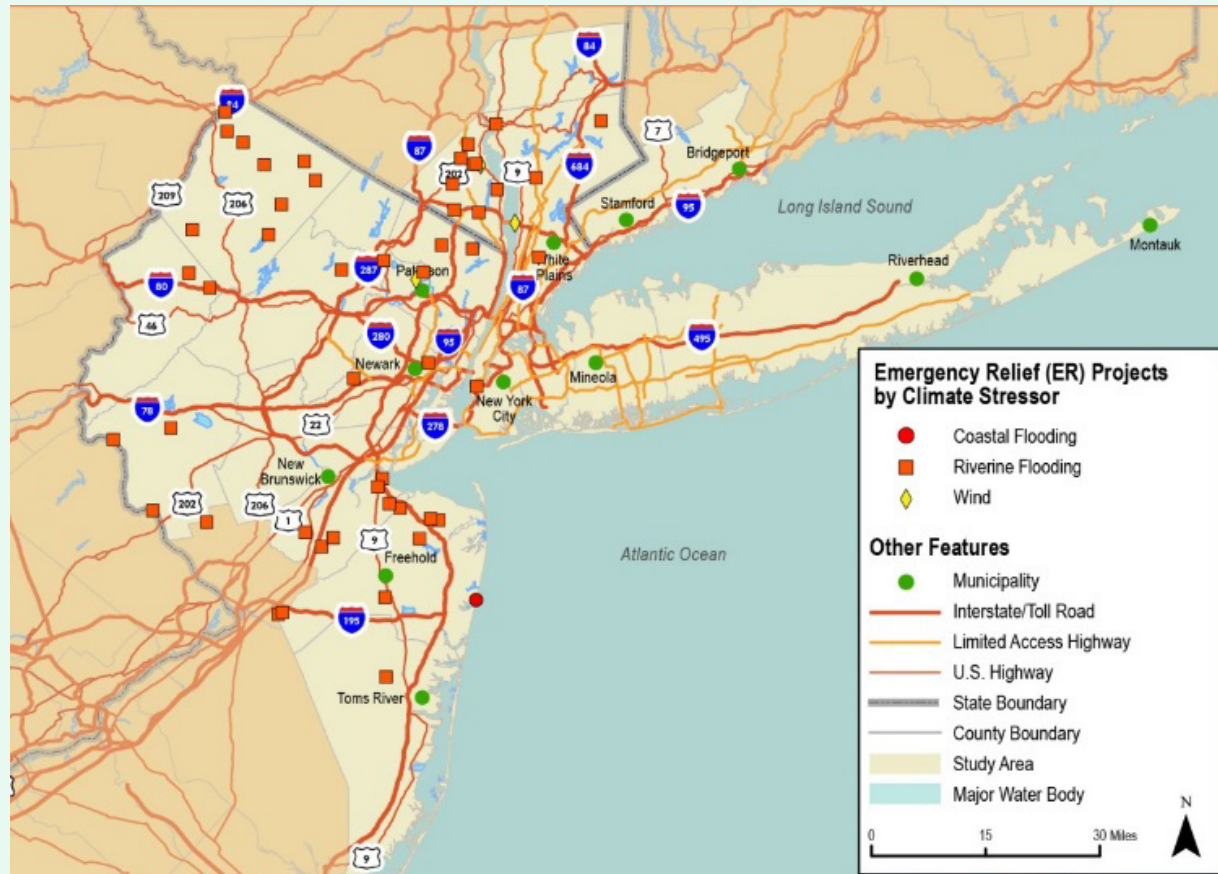


Figure 2.9. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by climate stressor, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

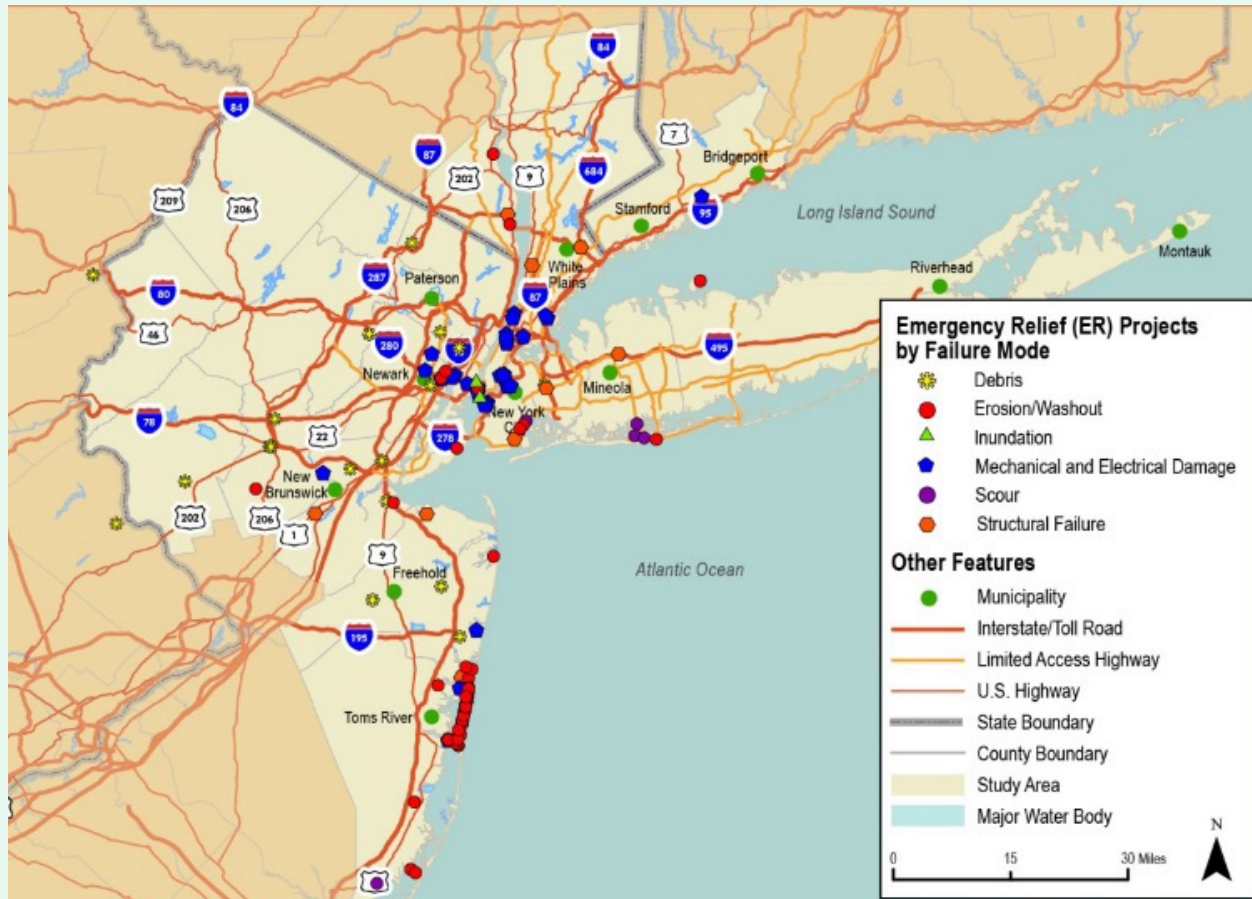


Figure 2.10. Map. Projects Submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by failure mode, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

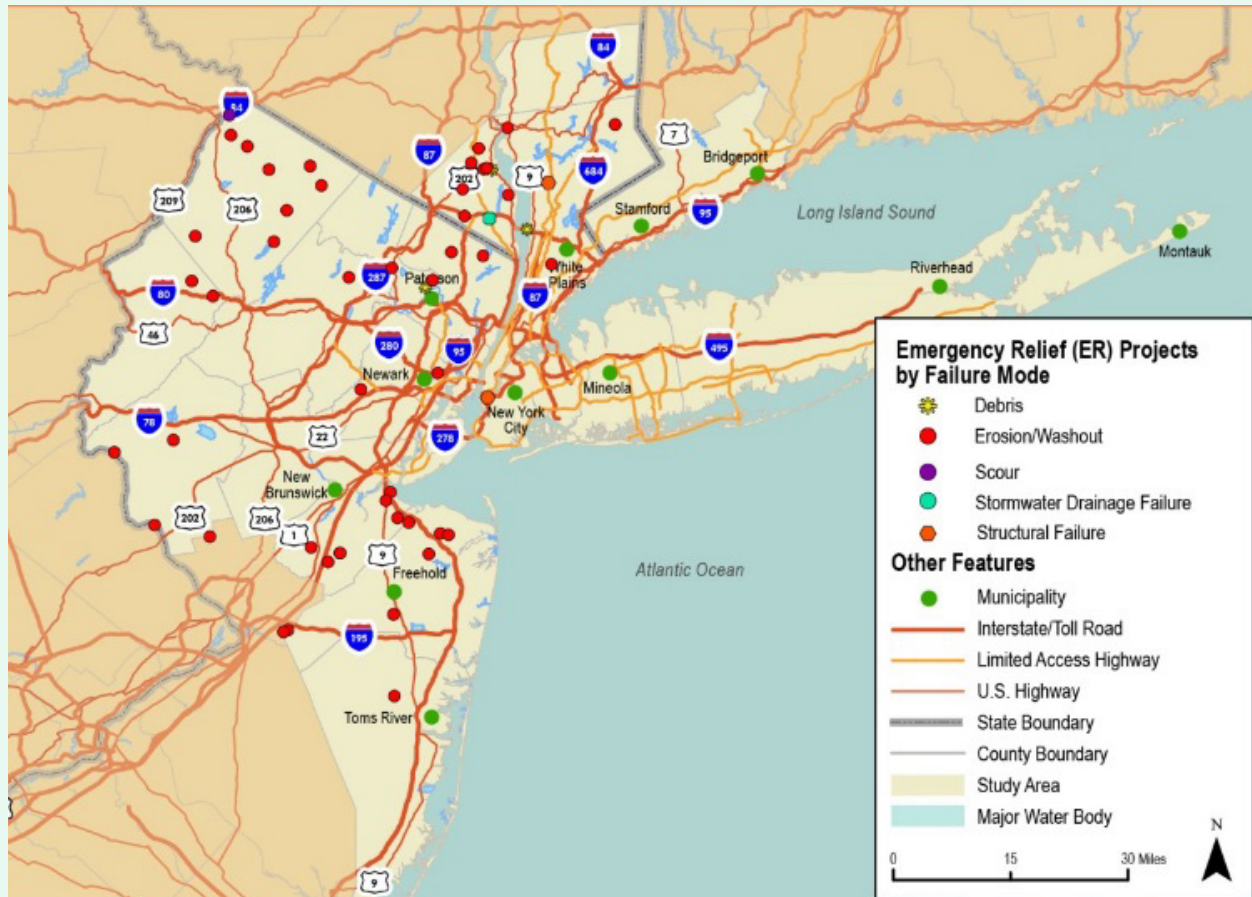


Figure 2.11. Map. Projects Submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by failure mode, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

Table 2.1. Top ten Federal Highway Administration Emergency Relief program reimbursement requests by estimated repair and replacement costs—Hurricane Sandy.

Asset and Damage Description	State	County	Metropolitan Planning Organization	Preliminary Estimates of Total Repair and Replacement Cost
NJ 35: Washouts and erosion due to storm surge	NJ	Ocean and Monmouth Counties	NJTPA	\$217,800,000
Ocean Parkway: Washouts and erosion due to storm surge	NY	Nassau and Suffolk Counties	NYMTC	\$39,700,000
Battery Park Underpass: Mechanical and Electrical Damage due to Storm Surge/Inundation	NY	Manhattan (New York County)	NYMTC	\$33,800,000
Federal-aid roadways in Rockaway Peninsula and Broad Channel, Queens: Washouts and mechanical/electrical damage	NY	Queens	NYMTC	\$22,800,000
Route 9A (West Street), including West Street Underpass: Damage due to wind, debris, and storm surge	NY	Manhattan (New York County)	NYMTC	\$18,300,000
Metropolitan Avenue Bridge over Newtown Creek: Mechanical and electrical damage	NY	Queens	NYMTC	\$9,300,000
Union Street Bridge over Gowanus Canal: Mechanical and electrical damage	NY	Brooklyn (Kings County)	NYMTC	\$4,600,000
Third Street Bridge over Gowanus Canal: Mechanical and electrical damage	NY	Brooklyn (Kings County)	NYMTC	\$3,300,000
207th Street University Heights Bridge: Mechanical and electrical damage	NY	Bronx and Manhattan (New York County)	NYMTC	\$3,200,000
NJ 71 Bridge over Shark River (Belmar): Mechanical and electrical damage	NJ	Monmouth County	NJTPA	\$3,000,000

Source: Federal Highway Administration, October 2013.

Note: Cost estimates are preliminary. Notable projects, such as repairs to the Hugh L. Carey Brooklyn-Battery Tunnel, the Holland Tunnel, and the Queens-Midtown Tunnel are not included in this table because preliminary estimates of repair costs had not been finalized at the time the data was collected by this study team in October 2013.

Damage to the Regional Transit System in the Study Area

The extent of damage wrought by Hurricane Sandy and the difficulty assessing long-term damage caused by the inundation of many key assets by salt water both present challenges to the region's transit service providers and to the Federal Transit Administration (FTA) as they attempt to define specific restoration, repair, and replacement projects and estimate costs associated with these projects. Rather than duplicate the extensive documentation and review of damage to the regional transit system as a result of the four storms covered by this analysis, this section presents a high-level overview of the damage associated with each storm event in an attempt to differentiate the impacts of the storms.

Hurricane Sandy

Table 2.2 summarizes the costs associated with Hurricane Sandy as reported to the FTA by the region's transit operators as of January 2013. A full list of projects in each category can be found in the comprehensive report, "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report." Of the \$10.4 billion that Congress allocated to the FTA Emergency Relief program for response, recovery, and rebuilding in areas affected by Hurricane Sandy under the Disaster Relief Appropriations Act (Pub. L. 113–2), \$5.7 billion (corresponding to the costs shown under the headings "Grouping 1" and "Grouping 2") had been allocated to the agencies via formula as of January 2013. The remaining funding ("Grouping 3") is being allocated to projects addressing longer-term resiliency needs.

Similar to the damage caused to area roadways, the transit system was most heavily impacted by Hurricane Sandy's storm surge. Tunnels and stations flooded and above-ground tracks, rail yards, signals, and switches were inundated or washed out in a broad area covering all three states in the study area. Both New Jersey Transit and Metro-North Railroad also experienced severe wind-related damage, with trees and other debris destroying overhead catenary on rail lines west and north of New York City.

Table 2.3 summarizes the most significant damage reported by each agency as of January 2013.

Table 2.2. Summary of costs associated with Hurricane Sandy recovery, repair, and resiliency projects on the region’s transit system, as of January 2013.

Grantee/Applicant	Grouping 1: Priority Projects	Grouping 2: Other Restoration and Repair	Grouping 3: Resiliency	TOTAL
MTA NYC Transit	\$2,328,712,549 ^a	\$1,020,500,000	\$6,380,000,000	\$9,729,212,549
MTA Metro-North Railroad	\$232,397,000	\$105,400,000	\$812,000,000	\$1,149,797,000
MTA Long Island Rail Road	\$176,107,725	\$114,892,275	\$488,000,000	\$779,000,000
MTA Capital Construction	\$44,091,355			\$44,091,355
NYCDOT	\$36,792,662		\$6,100,000	\$42,892,662
PANYNJ	\$1,287,431,630		\$1,396,262,500	\$2,683,694,130
NJ TRANSIT	\$475,741,086		\$1,055,187,500	\$1,530,928,586
Counties ^b	\$4,366,308			\$4,366,308
TOTAL	\$4,585,640,315	\$1,240,792,275	\$10,137,550,000	\$15,963,982,590

^a NYC Transit identified an additional \$19,687,451 in response to the FTA’s Notice of Funding Availability which is not included in this initial damage assessment.

^b Includes costs identified by municipal transit operators in Putnam, Rockland, Westchester, and Nassau Counties, and costs submitted by New York State Department of Transportation on behalf of state-supported bus operators in FTA’s Region II.

Source: FTA report: “Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report” January 2013.

Table 2.3. Selected damage to regional transit network from Sandy.

Transit Agency	Summary of Damage from Hurricane Sandy
MTA NYC Transit ^{a, b}	<ul style="list-style-type: none"> ● Eight subway tunnels flooded, some completely from floor to ceiling ● Rockaway Line in Queens, including bridges over Jamaica Bay, completely submerged. Multiple portions washed out, and two full breaches of the embankment and causeway connecting the Rockaways to Howard Beach. ● Sea Beach Line in Brooklyn, including nine above-ground stations, experienced severe flooding, resulting in damage to submerged infrastructure. ● South Ferry (1) and Whitehall (R) Stations in lower Manhattan completely submerged; Rector Street (R), Rector Street (1), Broad Street (J,Z), and Bowling Green (4,5) severely flooded. ● Dyckman Street (A) and 207th Street (A) Stations in Upper Manhattan and 148th Street (3) Station in Harlem severely flooded. ● Coney Island Stillwell Terminal in Brooklyn severely damaged. ● Switches and other equipment at rail yards and maintenance shops at Coney Island, Rockaway Park, 148th Street, and 207th Street under water and damaged. ● 15 miles of damaged or destroyed signaling. ● 10 escalators, three elevators, and 500 fare collection devices damaged. ● Staten Island Railway (SIR) signals, switch controls, relays, and other components damaged at St. George Terminal. SIR Clifton Shop sustained structural damage, as well as damage to electrical, heating, and other systems. ● MTA Bus Far Rockaway Depot flooded; equipment and office space damaged.
MTA Metro-North Railroad ^{a, d}	<ul style="list-style-type: none"> ● Hudson Line flooded in numerous locations adjacent to the Hudson River. ● Moderate flooding at Harmon Yard in Croton-on-Hudson impacted two locomotives, 11 passenger cars, and other equipment. ● Trees down on New Canaan branch of New Haven Line damaged catenary.
MTA Long Island Rail Road ^a	<ul style="list-style-type: none"> ● East River Tunnels flooded, damaging signals and communications equipment. ● Mid-town Manhattan storage yard just west of Penn Station flooded. ● Long Beach branch extensively damaged.

^a FTA report: “Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report” January 2013.

^b Testimony of Joseph J. Lhota, Chairman and CEO of the New York Metropolitan Transportation Authority, to the United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.

^c Testimony of Testimony of James Weinstein, Executive Director NJ TRANSIT Corporation, to United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.

^d Reuters, “New Jersey railway put trains in Sandy flood zone despite warnings,” published November 17, 2012.

Table 2.3. Selected damage to regional transit network from Sandy (continuation).

Transit Agency	Summary of Damage from Hurricane Sandy
NJ TRANSIT ^{a, b, c}	<ul style="list-style-type: none"> ● More than 630 trees fell on rights-of-way system-wide. ● More than 23 miles of catenary power and other wire damaged or destroyed. ● Nine bridges, including two major draw bridges, suffered severe damage. ● Nearly eight miles of track and roadbed washed out. ● Key electrical substations destroyed. ● Signal and communication systems and other critical systems damaged systemwide (all 12 rail lines). ● Hoboken Terminal and adjacent rail yard flooded. ● 71-acre Meadowlands maintenance and repair facility flooded; 261 rail cars, approximately 25 percent of NJ TRANSIT's fleet, and 62 locomotives, approximately one third of the fleet, damaged or destroyed. ● Damage to the rights of way of three light rail lines. ● Minor to moderate damage at 17 bus garages statewide.
Port Authority-Trans Hudson Railroad (PATH)	<ul style="list-style-type: none"> ● World Trade Center, Exchange Place, and Hoboken Stations submerged. ● Several miles of track, signals, switches, and communications equipment flooded from World Trade Center to Grove Street, and near Hoboken Station. ● Electrical substations flooded.
NYC Department of Transportation ^a	<ul style="list-style-type: none"> ● Staten Island Ferry's St. Georges Terminal damaged by debris and flooding.
Long Beach Transit	<ul style="list-style-type: none"> ● Long Beach bus garage and maintenance facility flooded.

^a FTA report: "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report" January 2013.

^b Testimony of Joseph J. Lhota, Chairman and CEO of the New York Metropolitan Transportation Authority, to the United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.

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^d Reuters, "New Jersey railway put trains in Sandy flood zone despite warnings," published November 17, 2012.

Hurricane Irene and Tropical Storm Lee

Within the study area, Hurricane Irene and Tropical Storm Lee in 2011 caused significant damage to the region's transit system as well, but the most significant damage occurred to a stretch of the Port Jervis Metro-North Railroad line in Rockland and Orange Counties, where three 1,000 foot stretches of track and one 4,000 foot stretch were washed out by flooding of the Ramapo River caused by rainfall.

Irene and Lee also caused minor flooding of rail yards and maintenance areas along the Hudson River, including NJ TRANSIT's Hoboken Terminal in Hudson County and Metro-North Railroad's Harmon maintenance facility and rail yards in Westchester County. Metro-North stations in in Valhalla, Ossining and Croton-on-Hudson all experienced flooding, with minor damage. NJ TRANSIT's Bound Brook station flooded, and MTA's Coney Island Rail yard flooded.

NJ TRANSIT reported that between 300 and 400 downed trees were cleared from tracks systemwide after Irene. Bus garages in Oradell Bus and Paterson flooded, and more than 350 buses were relocated. NJ TRANSIT's Route 23, Willowbrook, and Mother's Park/Ride lots closed temporarily due to flooding after Irene.

Nor'easter Alfred

Alfred, the Halloween Nor'easter of 2011, brought snow that was trapped in leaf-covered trees early in the Fall season. Accompanying high winds caused the top-heavy trees to fall in large numbers, particularly north and east of New York City. Metro-North Railroad's New Canaan, Waterbury, and Danbury branches experienced damage from downed trees and debris.

2.3 Disruption Assessment

While damage to the transportation system as a whole has resulted in billions of dollars (and counting) in repair costs, other factors such as flooding, debris and snow-clogged roads, loss of electric power, a regional shortage of gasoline and diesel fuel, and wind also contributed to massive disruptions in service to the travelling public. Lost productivity added significantly to the overall costs of these events.

The following two sections summarize the disruptions to the highway and transit systems caused by the four storm events. As with the damage assessment above, this disruption assessment is not intended to be a comprehensive inventory, but rather to serve as an illustration of major categories of disruptions associated with the four storm events.

Regional Highway System Disruptions

Hurricane Sandy

Hurricane Sandy caused extensive damage to coastal roads in New Jersey and New York, and several roadways and tunnels in lower Manhattan flooded or were extensively damaged by storm-related debris. Notable closures that caused disruption on a regional scale are shown in Figure 2.8 and include the following:

- Sandy's storm surge caused major erosion or full washouts at nearly 40 locations on a 12.5-mile stretch of NJ 35. New Jersey Department of Transportation was able to reopen NJ 35 to limited traffic in January 2013, two months after the storm, but full reconstruction of the roadway was completed in a series of projects starting in 2013 and ending in 2015.
- Stretches of Ocean Parkway in Nassau and Suffolk Counties, NY, adjacent to the Atlantic Ocean also were washed out by Hurricane Sandy's wave action and storm surge. Washed out sections of Ocean Parkway reopened in April 2013.
- An estimated 86 million gallons of water flooded the Hugh L. Carey Brooklyn-Battery Tunnel between Manhattan and Brooklyn. The tunnel reopened to automobile traffic in late November 2012, nearly one month after the storm.
- The Holland and Midtown Tunnels flooded. The Holland Tunnel reopened to bus traffic on November 2 and to all traffic days later. The Midtown Tunnel was closed to all traffic until November 8.
- Although most bridges used to access barrier islands in New Jersey and New York were able to accommodate traffic within hours or days after the passage of the storm, many remained closed to all traffic except emergency vehicles and supply trucks for days or weeks to facilitate emergency response and disaster recovery in hard-hit areas.
- Prior to and during periods of sustained winds over 60 miles per hour, major bridge crossings in the region were closed to all traffic during Hurricanes Sandy. These included the George Washington Bridge, Tappan Zee Bridge, all bridges operated by MTA Bridges and Tunnels, some bridges operated by New York City DOT, and the Bear Mountain Bridge, operated by the NYS Bridge Authority. Trucks and high-profile vehicles were restricted from using these crossings when wind gusts regularly exceeded 60 miles per hour.

In addition to closures of roadway infrastructure, much of the region experienced a shortage of diesel and gasoline in the days after the storm. New York Harbor was closed to navigation by the U.S. Coast Guard for six days from October 30 to November 4. Due to storm-surge-related flooding that impacted three of the region's largest refineries and several fuel storage facilities, the region's fuel distribution system did not have capacity to transport enough fuel to the region's gas stations to meet demand. Motorists and truck drivers in New Jersey, New York City, and Long Island waited in hours-long lines attempting to refuel in the days after the storm. Often, gas stations ran out of fuel before waiting motorists could refuel. The Governors of New York and New Jersey and the Mayor of New York

City imposed “even-odd” gasoline rationing at all gas stations in northern New Jersey, Long Island, and New York City. Rationing ended November 13 in New Jersey, November 17 on Long Island, and November 23 in New York City.

Power outages also caused failure of traffic signals, street lights, intelligent transportation systems infrastructure, and communications systems used to support emergency response. The Lower Manhattan street grid and major regional arterials functioned at very low levels of service with reduced capacity for days. As shown in Figure 2.12, downed trees, downed power lines, and debris also blocked traffic on major regional routes for several days as state and local agencies and utilities cleared roads, sidewalks, and parking lots.

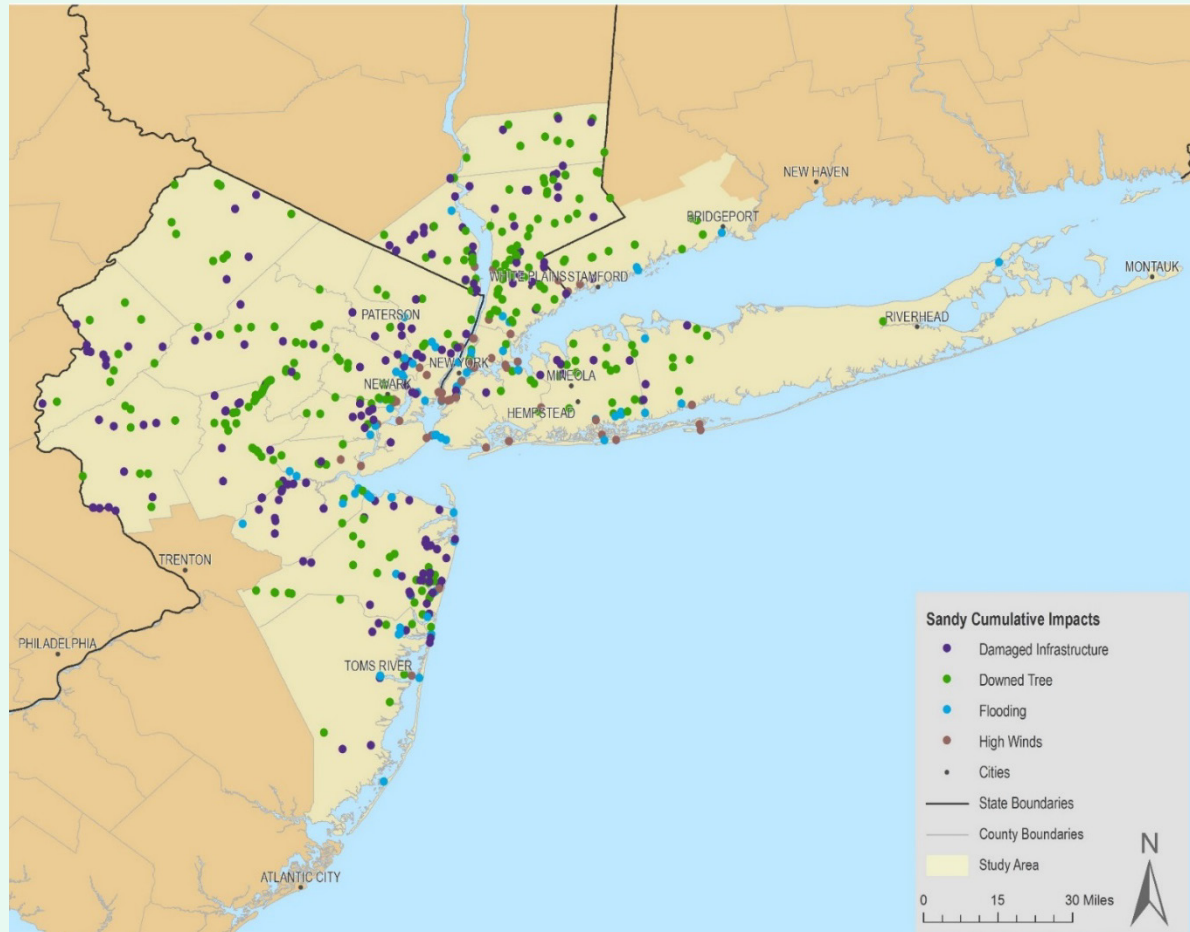


Figure 2.12. Map. Roadway system disruption reported on major regional roadways due to Hurricane Sandy.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County, Long Island, in particular, only a limited number of incidents are reported to TRANSCOM.

Hurricane Irene and Tropical Storm Lee

Hurricane Irene and Tropical Storm Lee caused a moderate level of disruption to the regional highway system in the study area. The combined rainfall from the two storms resulted in riverine flooding that destroyed significant roadway and bridge assets, particularly where culverts, bridges, and stream-adjacent roadways were vulnerable to washouts. Significant disruptions in the study area due to Hurricane Irene are shown in Figure 2.13 and included the following:

- The north (outbound) tube of the Holland Tunnel was closed due to flooding until 11 a.m. on August 28, the day after Irene passed;
- The Lower Level of George Washington Bridge was closed on August 27 due to high winds. The Palisades Interstate Parkway Entrance to the George Washington Bridge was closed until 11 a.m. on August 28;
- Flooding from the Passaic River in New Jersey closed many major arterials in Morris, Essex, and Passaic Counties. For example, U.S. 46 and portions of U.S. 202 were closed for more than 3 days following Irene, and both closed again due to flooding attributed to Lee. Near Boonton, a portion of I-287 collapsed into the Rockaway River (a tributary of the Passaic River) and was reconstructed. A portion of I-80 in Morris County washed out and needed to be reconstructed. Exit ramps from I-80 East in Parsippany-Troy Hills and Wayne closed due to flood waters, washouts, and debris. Several portions of Route 23 in Morris, Passaic and Sussex counties closed due to shoulder washouts and debris on the roadway;
- New Jersey Route 18 in Piscataway and New Brunswick closed due to flooding of the Raritan River. U.S. 206 in Somerville also closed due to flooding and debris;
- An approximately 500-foot stretch of River Vale Road in Bergen County, New Jersey was washed out by floods; and
- Rockland County Route 94 in Haverstraw, New York, was washed out.

As shown in Figure 2.14, the reported damage due to Lee in the study area was much less extensive than the damage from Irene and Sandy. Lee caused temporary flooding, downed trees, and downed power lines on roadways in northern New Jersey and in Westchester County.

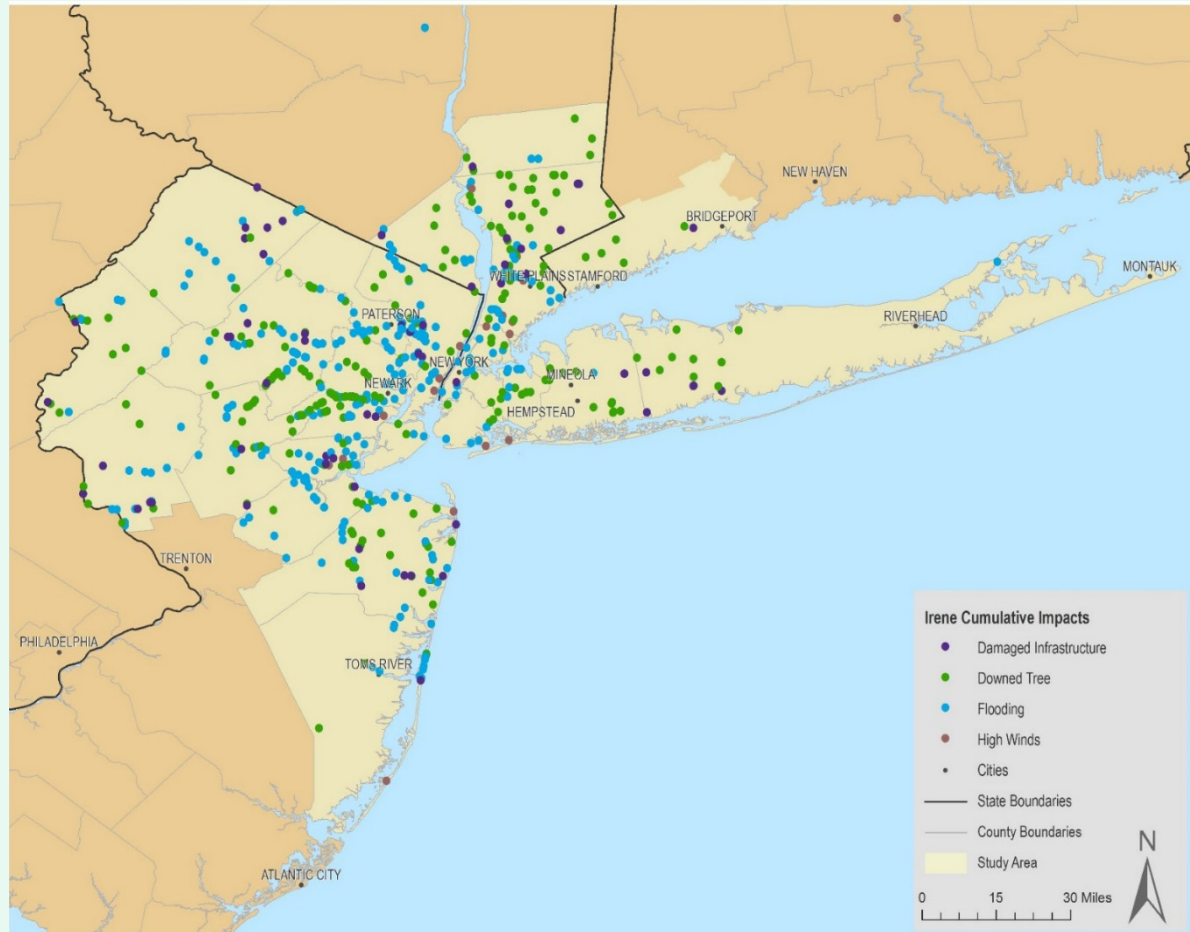


Figure 2.13. Map. Regional roadway system disruption reported on major roadways due to Hurricane Irene.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

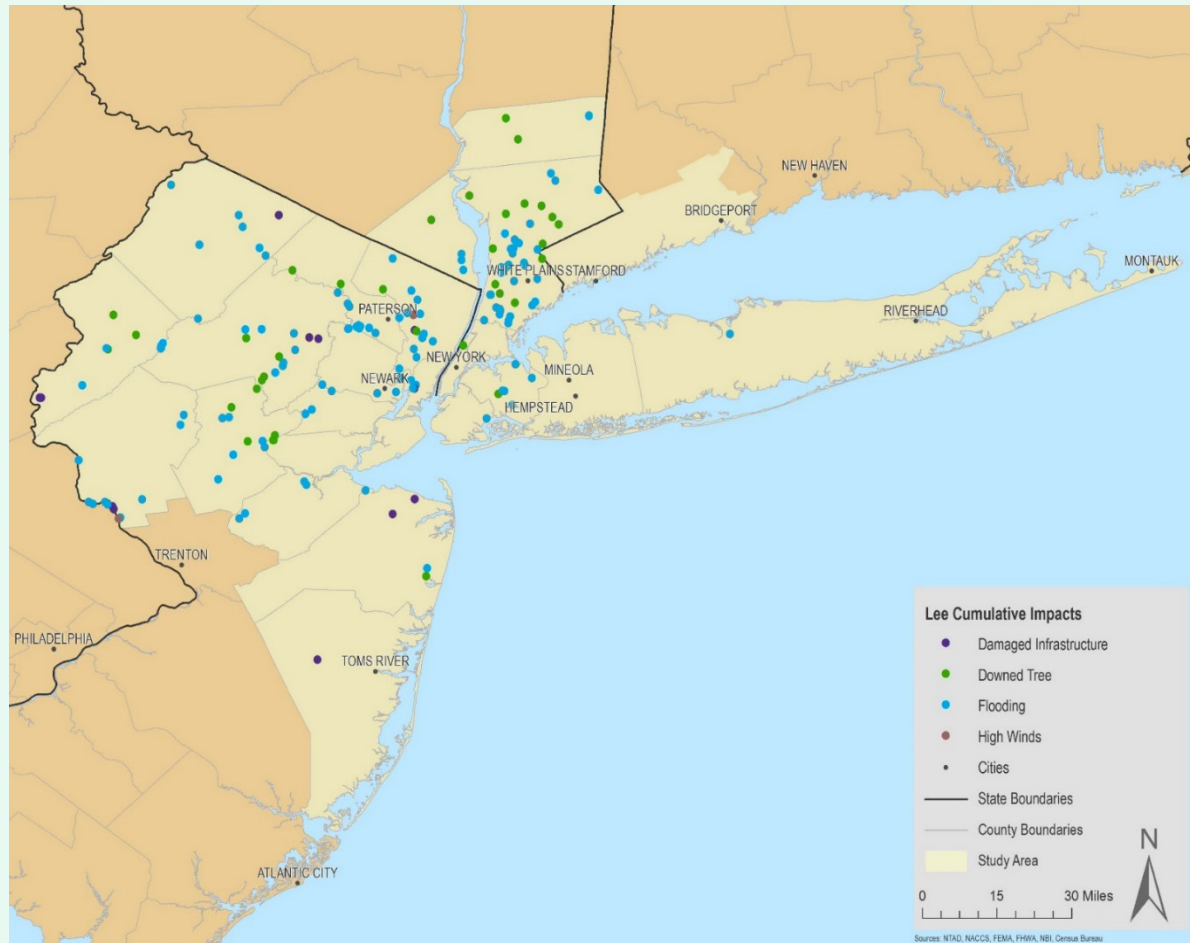


Figure 2.14. Map. Regional roadway system disruption reported on major roadways due to Tropical Storm Lee.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

Nor'easter Alfred

Disruption due to the Halloween Nor'easter of 2011 largely was due to downed trees blocking area roadways. In Westchester County, New York, and in Fairfield County, Connecticut, major roads were passable within hours of the passage of the storm. However, major disruptions to the Connecticut's power supply due to downed power lines caused some traffic signals and street lights to be dark for days after the storm.

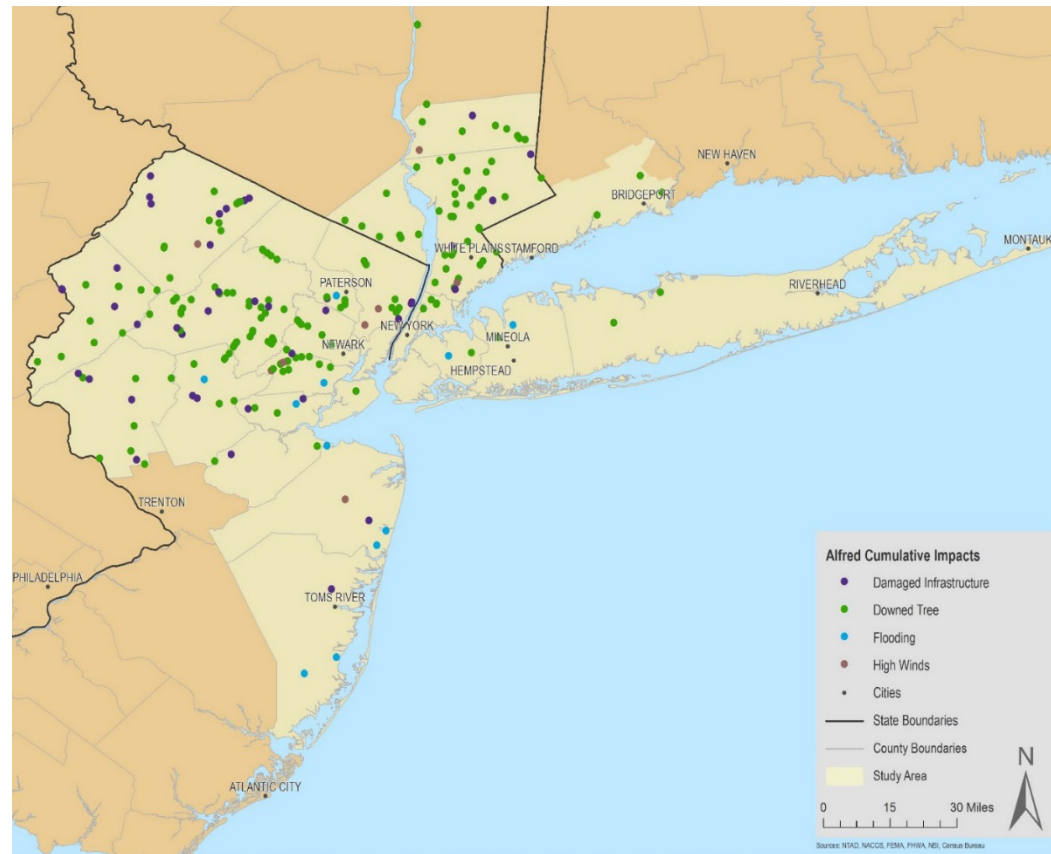


Figure 2.15. Map. Regional roadway system disruption reported on major roadways due to Alfred.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

Regional Transit System Disruption

Hurricane Sandy

Hurricane Sandy caused major disruption to the transit services of every operator in the region. Figure 2.16 shows a timeline of the disruptions and subsequent restoration of service on the MTA, New York City DOT (Staten Island Ferry), New Jersey Transit, and PANYNJ-managed transit systems, with impacts to the broader transportation system noted for reference.

Figure 2.16 focuses on the period in the immediate aftermath of Sandy. To this day, shutdowns of subway tunnels and Amtrak's East River and North (Hudson) River tunnels for short-term and long-term repairs cause significant disruption to regional travel. For example, the MTA is preparing for long-term shutdown of the L train's Canarsie Tube under the East River to repair damage from Sandy. This will affect more than 225,000 weekday L train riders between Manhattan and Brooklyn, plus additional riders on other subway and bus lines that will have to accommodate displaced L train riders.

Figure 2.16 also does not reflect the major impacts of Sandy on county-operated bus systems in the region. Long Island Bus and Westchester's Bee Line bus service were suspended for several days after Sandy, and paratransit services and other demand-responsive transportation services for the elderly, disabled, and veterans were impacted for weeks as local roadways were repaired and reopened.



Figure 2.16. Timeline. Timeline of transit disruption due to Hurricane Sandy.
(Sources: MTA, NJ TRANSIT, PANYNJ press releases; FTA report: "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report" January 2013; Testimony of Joseph J. Lhota, Chairman and CEO of the New York Metropolitan Transportation Authority, and James Weinstein, Executive Director NJ TRANSIT Corporation, to the United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.)

Hurricane Irene and Tropical Storm Lee

Prior to the arrival of Hurricane Irene, MTA New York City Transit took the unprecedented step of proactively shutting down the entire transit system so that customers would not be in harm's way, employees could safely get home, and rolling stock could be positioned in locations where they could safely weather the storm. NJ TRANSIT, the PATH subway, and local transit operators took similar measures. As a result, the region's rolling stock was largely unscathed during the coastal and riverine flooding that occurred in the days after Hurricane Irene and Tropical Storm Lee passed through the area.

A significant disruption from the one-two punch of Irene and Lee was due to the flooding of the Ramapo River in Rockland County, which severely damaged 14 miles of Metro-North Railroad's Port Jervis Line, causing three 1,000-foot washouts and one 4,000-foot washout between Suffern and Harriman, New York. The Port Jervis Line, which served 3,000 daily commuters, was out of service for nearly three months as the track and signal systems were reconstructed and repaired. Many Metro North passengers used commuter bus services to and from Orange County, straining park and ride lots beyond capacity, particularly in Harriman and Monroe.

The region's commuter rail operators and Amtrak had to clear a large amount of debris from the tracks following both Irene and Lee, but, with the exception of the Port Jervis Line, the rail system was back up and running shortly after each storm. Bus services were not heavily impacted other than temporary re-routes around debris-blocked and flooded roads. NJ TRANSIT had to relocate more than 350 buses from garages that flooded in Irene.

Additional transit system disruptions due to Irene and Lee included the following:

- Amtrak and NJ TRANSIT were affected as Northeast Corridor service was suspended from August 28 to August 31 due to flooding at the Trenton Transit Center and other storm-related damage from Irene;
- Service on the PATH was suspended from 12 PM on August 27 until 4 AM on August 29 (40 hours); and
- NJ TRANSIT's Bound Brook station was closed due to flooding from the nearby Raritan River.

Nor'easter Alfred

The Halloween Nor'easter Alfred of 2011 caused minor disruptions to MTA Metro-North Railroad service. Service was suspended on the Danbury, New Canaan, and Waterbury branches for over 24 hours due to track conditions and wind-blown debris. Local bus services in Connecticut were heavily impacted by Alfred, as were school buses that could not safely navigate local roads. Many schools were closed for at least a week during the clean up and due to power outages. Bus services began to recover throughout the week. Long-lasting power outages in Connecticut also affected traffic signals and street lights, causing a safety hazard on arterials and collector roadways.

2.4 Long-Term Damage, Disruption, and Resiliency Projects

Due to the nature of the damage associated with salt water inundation, some disruptions to the region's transportation system, and its transit system in particular, are expected to continue well into the future. For example, a sealed brake unit in an escalator in the PATH's Exchange Place station was damaged by salt water when the station was inundated by Hurricane Sandy's storm surge. This damage was not detected until a malfunction of the escalators on January 8, 2013, well over two months after the storm. Signals in Amtrak's East River Tunnels and in Long Island Rail Road's Long Beach Yard have failed repeatedly in the months after Sandy, with outages attributable to salt water corrosion of electrical and mechanical systems. As noted above, MTA New York City Transit's L Train will be closed for at least 18 months starting in 2019 to allow for extensive repairs of the Canarsie Tube under the East River. The tunnel was inundated by brackish water, which corroded steel reinforcing bar, electrical conduit, signal and communications hardware, and other metal components.

The full extent of Hurricane Sandy's damage may not become apparent for many years as the region's transit operators make necessary repairs and make the system more resilient in the face of future expected extreme weather events. As noted in Table 2.2, more than \$10 billion in resiliency-related projects have been identified to date by regional transit operators to avoid damage and disruption on the scale caused by recent major storms and other types of natural and man-made hazards.

3

Climate Data and Analysis Tools

The Post-Sandy Study team compiled climate data sets developed and/or used by governments and institutions in the three state metropolitan region and summarized their findings. The team also reviewed and made use of a range of tools to help assess exposure of transportation facilities to the impacts of climate change and extreme weather events, assess vulnerability and risk, and formulate and compare potential adaptation options. This section of the report summarizes the large amount of climate data and projections available at the time of this study and summarizes the tools used to conduct the vulnerability, risk, and adaptation assessments.

This section is organized as follows:

- Section 3.1 summarizes climate projections used in the regional, subregional, and facility-level assessments of vulnerability and risk.
- Section 3.2 provides an overview of data and analysis tools used in the assessments.
- Appendix F contains a list of resources that can be used by agencies conducting their own vulnerability and risk assessments.

3.1 Climate Projections

The project team looked at more than a dozen recent forecasts and projections of climate prepared by government agencies, research institutions, and not-for-profit organizations. This compilation presents a snapshot of available projections at the time of this study, some of which were updated and revised over the duration of the study as assumptions in global climate models were refined and downscaled based on improved science.

Table 3.1 summarizes projections from studies in existence as the Post-Sandy Study commenced, which focused mainly (but not exclusively) on temperature and precipitation averages as well as sea level rise. Tables 3.2 through 3.4 present data for average annual temperatures, average annual precipitation, and sea level rise from sources that have been used by the partners in this study:

- New York City Panel on Climate Change 2015 Report (Horton, et. al), which was used as the basis for the report “The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources and Public Health,” developed and issued by the Adaptation Subcommittee of the Governor’s Steering Committee on Climate Change;
- Responding to Climate Change in New York State, 2014 Update (also known as the “ClimAID” report; development led by the New York State Energy Research and Development Authority);
- Assessing New Jersey’s Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel, 2016; and
- “Story Map of New Jersey Temperature Trends and Projections – March 2017” published online, based on data assembled by the New Jersey Climate Adaptation Alliance.

The Post-Sandy Study region benefits from a wealth of existing data and analysis, as well as the amount of work that has been done to build consensus around the use of common sources of climate data and projections. This study makes use of data sets with regional coverage for the regional exposure analysis and draws from state and local sources for subregional and facility-level assessments of vulnerability and risk. See Section 4 for more details on how data were used in each part of the analysis.

Table 3.5 shows projections of extreme events in the New York City region. By the 2080s, the region is projected to experience 4 to 7 additional heat waves per year (three consecutive days at or above 90 degrees Fahrenheit), 4 to 14 days per year with a maximum temperature at or above 100°F (compared to an average of 0.4 days per year now), and 15 to 17 days with more than 1 inch of rainfall (compared to an average of 13 days per year today).

Table 3.1. Summary of existing climate projections for New York-New Jersey-Connecticut study area (prior to post-Sandy study).

Report Title	Year	Organization	Temperature	Precipitation	Sea Level Rise
Climate Change and a Global City: The Potential Consequences of Climate Variability and Change	2001	U.S. National Assessment and Columbia Earth Institute	2020s: 1.5°F to 3.5°F 2050s: 2.5°F to 6.5°F 2080s: 4.5°F to 10°F	2020s: 2% to 10% 2050s: -15% to 15% 2080s: -2% to 30%	2020s: 4 to 11 in. 2050s: 9 to 24 in. 2080s: 12 to 36 in.
Impacts of Sea Level Rise in the New York City Metropolitan Area	2002	Columbia University and Goddard Institute for Space Studies, Army Corps of Engineers, Wildlife Trust	N/A	N/A	2020s: 4.4 to 11.7 in. 2050s: 8.5 to 23.7 in 2080s: 14.5 to 42.5 in

Table 3.1. Summary of existing climate projections for New York-New Jersey-Connecticut study area (prior to post-Sandy study) (continuation).

Report Title	Year	Organization	Temperature	Precipitation	Sea Level Rise
Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions	2007	Union of Concerned Scientists	2020s: 1.5°F to 4.0°F 2050s: 2°F to 8°F 2080s: 3°F to 14°F	2020s: N/A 2050s: N/A 2080s: 10%	2020s: N/A 2050s: N/A 2080s: 7 to 23 in.
Climate Change Program Assessment and Action Plan	2008	New York City Department of Environment Protection	2020s: 1°F to 3°F 2050s: 3°F to 5°F 2080s: 5°F to 8.5°F	2020s: 0% to 2.5% 2050s: 2.5% to 7.5% 2080s: 7.5% to 15%	2020s: 2 to 6 in. 2050s: 6 to 12 in. 2080s: 12 to 22 in.
Climate Risk Information: New York City Panel on Climate Change	2009	NYC Office of Long-Term Planning and Sustainability	2020s: 1.5°F to 3°F 2050s: 3°F to 5°F 2080s: 4°F to 7.5°F	2020s: 0% to 5% 2050s: 0% to 10% 2080s: 5% to 10%	2020s: 2 to 5 in. 2050s: 7 to 12 in. 2080s: 12 to 23 in.
Rising Waters: Helping Hudson River Communities Adapt to Climate Change. Scenario Planning 2010-2030.	2009	The Nature Conservancy Eastern New York Chapter	2030: 2.2°F (3.3°F winter)	2030: 0.6%	2030: 2.8 in.
The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources, and Public Health	2010	Adaptation Subcommittee to the Governor's Steering Committee on Climate Change	2020s: 1.5°F to 4.0°F 2050s: 2.0°F to 8.0°F 2080s: 3.0°F to 14.0°F	2020s: 0% to 5% 2050s: 0% to 10% 2080s: 5% to 30%	2020s: 0.5 to 5 in. 2050s: 4 to 12 in. 2080s: 9.6 to 23 in.
New Jersey Climate Change Trends and Projections Summary	2011	Sustainable Jersey Climate Change Adaptation Task Force (CATF)	2020s: 1.5°F to 3°F 2050s: 3°F to 5°F 2080s: 4°F to 7.5°F	2020s: up to 5% 2050s: up to 10% 2080: 20% to 30% (winter only)	2020s: 2 to 5 in. 2050s: 7 to 12 in. 2080s: 12 to 23 in.
Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure	2012	Cambridge Systematics, Stratus Consulting	2050s: N/A 2100s: 6.5°F to 6.6°F (based on select stations)	2050s: N/A 2100s: 8.4% to 8.6%	2050s: 5.5 to 20 in. 2100s: 18 to 64 in.

Note: Climate projections shown were developed using differing underlying assumptions. See the methodology section of each report for details.

Table 3.2. Projected mean annual change in temperature, mean annual change in precipitation, and sea level rise for New York City region.

Year	Temperature Baseline (1971-2000): 54°F			Precipitation Baseline (1971-2000): 50.1 in.			Sea Level Rise Baseline (2000-2004): 0 in.		
	Low estimate (10 th percentile)	Middle range (25 th to 75 th percentile)	High estimate (90 th percentile)	Low estimate (10 th percentile)	Middle range (25 th to 75 th percentile)	High estimate (90 th percentile)	Low estimate (10 th percentile)	Middle range (25 th to 75 th percentile)	High estimate (90 th percentile)
2020s	+1.5°F	+2.0–2.9°F	+3.2°F		+1–8%	+10%	+2 in.	+4 to 8 in.	+10 in.
2050s	+3.1°F	+4.1–5.7°F	+6.6°F	+1 percent	+4–11%	+13%	+8 in.	+11 to 21 in.	+30 in.
2080s	+3.8°F	+5.3–8.8°F	+10.3°F	+2 percent	+5–13%	+19%	+13 in.	+18 to 39 in.	+58 in.
2100	+4.2°F	+5.8–10.4°F	+12.1°F			+25%	+15 in.	+22 to 50 in.	+75 in.

Source: Horton, Radley, et. al, 2015. *New York City Panel on Climate Change (NPCC) 2015 Report*.

New York State Energy Research and Development Authority (NYSERDA), 2014. "Responding to Climate Change in New York State: 2014 Update (ClimAID)," projections for Region 4 (New York City). The NYSERDA report provides separate Sea Level Rise projections for Montauk Point, which are identical to the New York City projections shown in Table 3.2 with the following exception: In 2100, the Middle range for Montauk Point is estimated at 21 to 47 in. of sea level rise, and the High estimate is 72 inches of sea level rise.

Table 3.3. Projected mean annual change in temperature for New Jersey.

Year	Temperature Baseline (1981–2010): ___ °F
2020-2039	+1.0 to 3.0°F
2040-2059	+1.2 to 6.3°F
2080-2099	+0.5 to 14.7°F

Source: *Data Visualization by Moran, Deena et. al, 2017. "Story Map of New Jersey Temperature Trends and Projections – March 2017." Notes: Average Annual Temperature Change compared to the 1981-2010 baseline in NJ Under RCP Scenarios (5th Percentile "Low Estimate", 50th Percentile Values "Central Estimate", and 95th percentile "High Estimate"). Data Source: American Climate Prospectus, D.J. Rasmussen and Dr. Robert Kopp, Rutgers University, May 2015.*

Table 3.4. Sea level rise projections for New Jersey.

Year	Central Estimate 50% probability SLR meets or exceeds...	Likely Range 67% probability SLR is between...	1-in-20 Chance 5% probability SLR meets or exceeds...	1-in-200 Chance 0.5% probability SLR meets or exceeds...	1-in-1000 Chance 0.1% probability SLR meets or exceeds...
2030	0.8 ft.	0.6-1.0 ft.	1.1 ft.	1.3 ft.	1.5 ft.
2050	1.4 ft.	1.0-1.8 ft.	2.0 ft.	2.4 ft.	2.8 ft.
2100 Low Emissions	2.3 ft.	1.7-31. ft.	3.8 ft.	5.9 ft.	8.3 ft.
2100 High Emissions	3.4 ft.	2.4-4.5 ft.	5.3 ft.	7.2 ft.	10 ft.

Source: Kopp, R.E., A. Broccoli, B. Horton, D. Kreeger, R. Leichenko, J.A. Miller, J.K. Miller, P. Orton, A. Parris, D. Robinson, C.P. Weaver, M. Campo, M. Kaplan, M. Buchanan, J. Herb, L. Auermuller and C. Andrews. 2016. *Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. Prepared for the New Jersey Climate Adaptation Alliance. New Brunswick, New Jersey.*

Table 3.5. Projections of extreme events in New York City region.

Climate Variable	Baseline (1971-2000)	Low estimate (10 th percentile)	Middle range (25 th to 75 th percentile)	High estimate (90 th percentile)	
Number of heat waves per year Heat waves are defined as three or more consecutive days with	2	2020s	3	3 to 4	4
		2050s	4	5 to 7	7
		2080s	5	6 to 9	9
Average heat wave duration (days)	4	2020s	5	5 to 5	5
		2050s	5	5 to 6	6
		2080s	5	5 to 7	8

Table 3.6. Projections of extreme events in New York City region (continuation).

Climate Variable	Baseline (1971-2000)	Low estimate (10 th percentile)	Middle range (25 th to 75 th percentile)	High estimate (90 th percentile)	
Number of days per year with...					
Maximum temperature at or above 90°F	18	2020s	24	26 to 31	33
		2050s	32	39 to 52	57
		2080s	38	44 to 76	87
Maximum temperature at or above 100°F	0.4	2020s	0.7	1 to 2	2
		2050s	2	3 to 5	7
		2080s	2	4 to 14	20
Minimum temperature at or below 32°F	71	2020s	50	52 to 58	60
		2050s	37	42 to 48	52
		2080s	25	30 to 42	49
Rainfall at or above 1 inch	13	2020s	13	14 to 15	16
		2050s	13	14 to 16	17
		2080s	14	15 to 17	18
Rainfall at or above 2 inches	3	2020s	3	3 to 4	5
		2050s	3	4 to 4	5
		2080s	3	4 to 5	5

Source: Horton, Radley, et. al, 2015. *New York City Panel on Climate Change (NPCC) 2015 Report*.
 New York State Energy Research and Development Authority (NYSERDA), 2014. "Responding to Climate Change in New York State: 2014 Update (ClimAID)," projections for Region 4 (New York City). Note, the NYSERDA report did not include number of days with maximum temperature over 100°F.

3.2 Data and Analysis Tools to Support Vulnerability and Risk Assessments

In addition to the climate projections summarized in Section 3.1, the study team benefitted from a wealth of information generated as part of other studies, and the team used a range of analysis tools to support the vulnerability and risk assessments carried out as part of this study. This section summarizes the major data sources and tools used in this study and available for agencies who would like to undertake their own assessments.

The **National Flood Hazard Layer (NFHL)** is a digital database that contains flood hazard mapping data from FEMA's National Flood Insurance Program (NFIP). The NFHL dataset represents the current effective flood risk data, and can be used to determine the extent of the 100-year and 500-year floodplains. <https://fema.maps.arcgis.com/home/item.html>.

Digital Flood Insurance Rate Maps (DFIRMS) and other resources produced by FEMA are available online from FEMA's Map Service Center: <https://msc.fema.gov/portal>.

Digital Elevation Models for the study area are available from the Connecticut Department of Energy and Environmental Protection (DEEP) and the University of Connecticut's Center for Land Use Education and Research (CLEAR), from the New Jersey Office of Information Technology (NJOIT), and from the New York State GIS Program Office via the NYS Orthos Online application at the following links:

Connecticut: <http://cteco.uconn.edu/data/lidar/index.htm>.

New Jersey: https://njgin.state.nj.us/NJ_NJGINExplorer/jviewer.jsp?pg=lidar.

New York: <https://orthos.dhSES.ny.gov/>.

There are **clearinghouses of climate change information** available from many state and local sources, such as the following:

Connecticut Environmental Conditions Online: <http://cteco.uconn.edu/index.htm>.

New Jersey Climate Adaptation Alliance: <http://njadapt.rutgers.edu/>.

New York Climate Change Science Clearinghouse: <https://www.nyclimatescience.org/>.

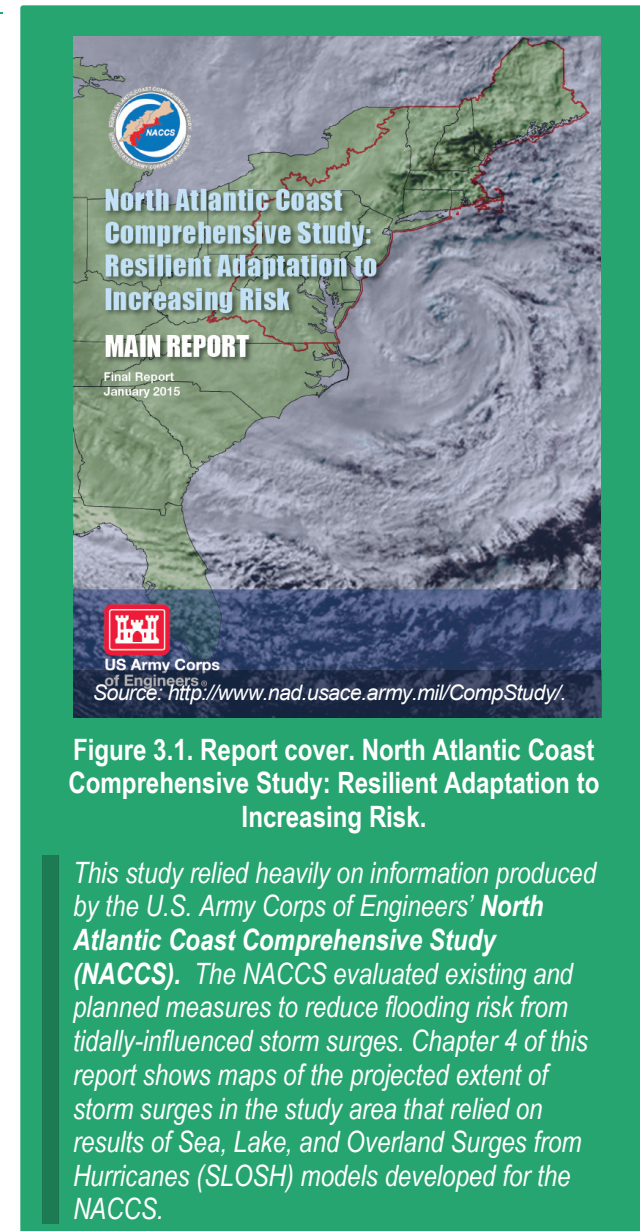


Figure 3.1. Report cover. North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk.

This study relied heavily on information produced by the U.S. Army Corps of Engineers' North Atlantic Coast Comprehensive Study (NACCS). The NACCS evaluated existing and planned measures to reduce flooding risk from tidally-influenced storm surges. Chapter 4 of this report shows maps of the projected extent of storm surges in the study area that relied on results of Sea, Lake, and Overland Surges from Hurricanes (SLOSH) models developed for the NACCS.

4

Assessing Vulnerability, Risk, and Adaptation Options in the Three State Metropolitan Region

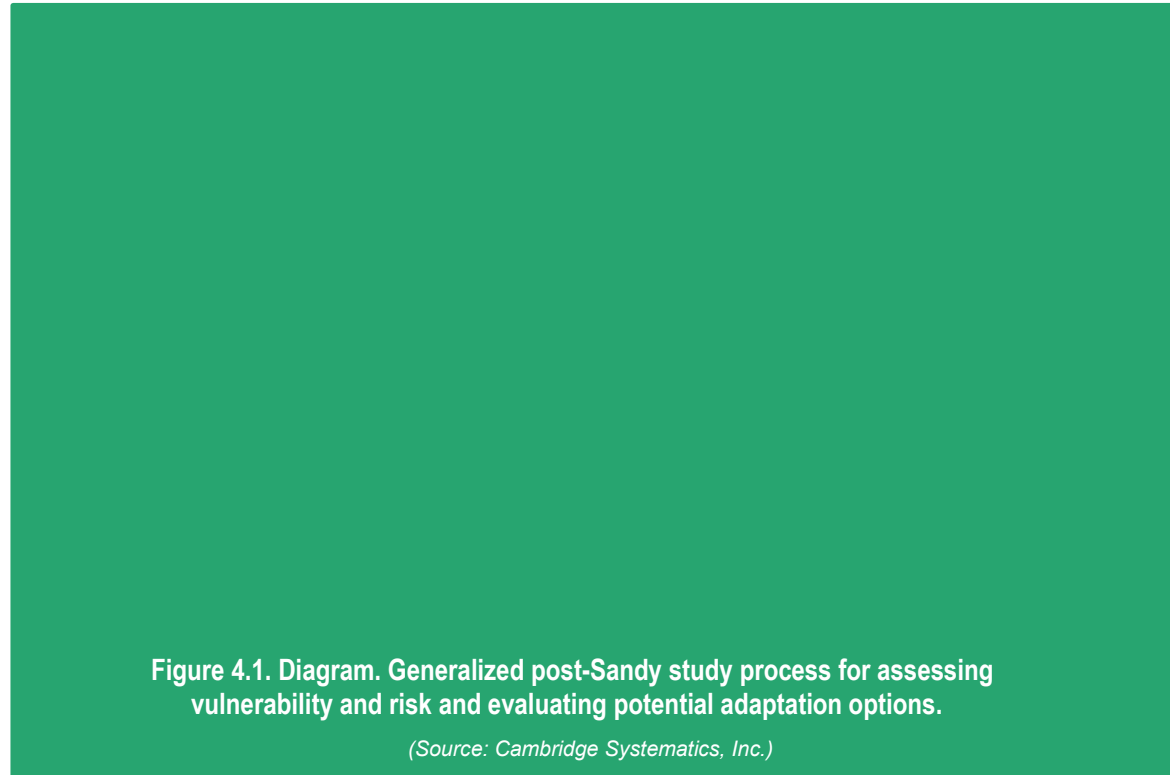
This research study provided an unprecedented opportunity to employ and refine a vulnerability and risk assessment process at three scales. This section describes how a generalized vulnerability and risk assessment process was applied at a regional scale, at the level of a corridor or small network, and for specific facilities in the region's multimodal transportation network.

- Section 4.1 introduces the process used in the Post-Sandy Study for defining and analyzing potential solutions to address climate risk and vulnerability. Appendix B contains more detailed, step-by-step methodology for addressing climate risk and vulnerability at a facility level.
- Section 4.2 discusses the exposure analysis that was conducted at a regional scale for roads and rail lines that are critical to regional connectivity. In addition to providing regional transportation agencies with data to better understand the vulnerability of the transportation system, this exposure analysis served as the primary means of identifying a set of subareas with vulnerable transportation facilities. Appendix C provides more details and maps developed as part of the regional vulnerability assessment.
- Section 4.3 summarizes more detailed assessments of vulnerability and risk that the study team conducted in three “subareas,” one in each state, after identifying and screening a short list of subareas with the Project Guidance Committee. Three full subarea vulnerability assessments are included as Appendix D to this report.
- Finally, Section 4.4 summarizes ten facility-specific assessments of vulnerability and risk that the study team conducted. Each is followed by evaluations of potential facility-specific adaptation options. The ten facility-specific assessments are included as Appendix E to this report.

4.1 Process for Assessing Vulnerability and Risk and Screening Adaptation Responses

The Post-Sandy Study team developed a process for conducting vulnerability and risk assessments and tested it at three scales, as follows (see Figure 4.1):

- A regional vulnerability assessment focused primarily on potential exposure to climate stressors.
- In three subarea analyses, the study team expanded the vulnerability assessment to look at exposure, sensitivity, and adaptive capacity at a corridor or network scale, and the team added a high-level risk assessment to help identify the highest priority assets for more detailed analysis.
- Finally, at the scale of individual facilities, the study team looked at facility- and component-specific vulnerabilities and risks over the remaining useful lives of the assets, and in one case conducted climate-risk-adjusted benefit cost analysis comparing the costs of repeated repairs and disruptions against the costs of adaptation strategies.



The remainder of Section 4 describes the process, results, and lessons learned for each of the three scales of analysis. Appendix B describes the facility-specific assessment process in more detail and includes a matrix of potential adaptation strategies. Appendix F has a list of resources and tools, including those that the project team used in conducting the regional, subregional, and facility-specific vulnerability and risk assessments for the Post-Sandy Study.

4.2 Regional Transportation System Exposure to Climate Stressors and Identification of Vulnerable Subareas

Regional Transportation System Exposure to Climate Stressors

The Post-Sandy study team conducted a regional assessment of exposure to climate stressors as a first step in identifying subareas and facilities that should be priorities for more detailed analysis. Early conversations with the project partners involved defining the scope of the transportation system to be assessed in this study, given available resources. For purposes of this study, the critical multimodal network for the three state metropolitan region was defined as follows:

- Major roadways, including the National Highway System and evacuation routes;
- Bridges on the National Highway System and major evacuation routes;
- Major freight railways, including Class 1 railroads, major rail yards, and intermodal facilities;
- All passenger rail lines; and
- Major transit and bus facilities such as bus stations and yards.

The following climate stressors and impacts were emphasized in the regional-scale exposure analysis:

- Storm surge, with and without sea level rise (which leads to inundation of transportation facilities in coastal areas); and
- Precipitation (which leads to floods in both inland and coastal areas).

Extreme heat was assumed to impact the regional uniformly and did not warrant a separate exposure analysis at the regional scale. The implications of changes in average and extreme temperatures were considered at the subarea and facility-specific levels.

The regional exposure analysis highlighted areas where there were concentrations of highway and rail assets that were potentially vulnerable to various climate stressors and therefore warranted more detailed analysis. The remainder of this section provides details about the results of the regional vulnerability assessment, including 21 vulnerable subareas.

An important step in conducting a regional vulnerability assessment is to conduct a system-level assessment of criticality to prioritize the assets and networks that are the highest priority for adaptation investments. Some regions have chosen to use an objective, data-driven approach to assigning a criticality score to each element of the transportation system, but these analyses have tended to be for a single mode (e.g., a regional highway network). Other regions have used a combination of expert input and qualitative measures to assign criticality.

To determine potential exposure of the region's key transportation facilities to storm surge and precipitation, the study team used Geographic Information Systems (GIS) to conduct an **intersection analysis**, which identified where roads, rail lines, and facilities lie within the boundaries of a 100-year or 500-year flood plain, or where they lie within the extent of storm surge predicted to be associated with a Category 1 through 4 storm. In limited parts of the study area, the team used digital elevation models to help screen out facilities that are elevated on a natural or human-made embankment and would not be exposed to adjacent flood waters.

The study team used the following primary data sources for the regional exposure analysis:

- The U.S. Army Corps of Engineers' **North Atlantic Coast Comprehensive Study** provided sea level rise and storm surge data.
 - The intersection analysis with future sea level extents was conducted for two analysis years: 2068 and 2100.
 - The intersection analysis for projected coastal storm surge zones relied on outputs of a Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model run as part of the NACCS analysis. The SLOSH model outputs depict areas of possible flooding from the maximum of maximum (MOM) event within hurricane categories 1 through 4 by estimating the potential storm surge during a landfall during different tide scenarios (i.e., high or mean tide for NY).

The SLOSH storm surge mapping is not referenced to a specific probability of occurrence nor does it include wave heights. The flooding from a worst-case Category 4 hurricane making landfall during high tide represents an extremely low probability of occurrence but high-magnitude event. The extent of the Category 4 MOM represents the maximum storm tide levels caused by extreme hurricane scenarios across the region, and, therefore, provides a reasonable approximation of the most extreme flooding extent. The intersection analysis highlights transportation assets that lie within each SLOSH zone (1 through 4).

One caveat associated with the intersection analysis is that bridges and tunnels are not represented in digital elevation models, and therefore these features have to be manually removed from maps if an analysis is performed at a level of detail at which bridges and tunnels would be discernable on maps.

Section 3.2 and Appendix F have additional sources of information and descriptions of analysis tools that may be of use in conducting vulnerability assessments.

- The Federal Emergency Management Agency (FEMA) **National Flood Hazard Layer (NFHL)** is a digital database that contains flood hazard mapping data from FEMA's National Flood Insurance Program (NFIP). The NFHL dataset represents the current effective flood risk data, and can be used to determine the extent of the 100- year and 500-year floodplains.
 - 100 Year Floodplain – A 100-year flood is a flood event that has a 1% probability of occurring in any given year. The 100-year floodplain represents the area that would be inundated during the 100 year flood, based on the 100-year flood flow rate.
 - 500 Year Floodplain – A 500-year flood is a flood event that has a 0.2% probability of occurring in any given year. The 500-year floodplain represents the area that would be inundated during the 500 year flood, based on the 500-year flood flow rate. Flooding is more extensive during the 500-year flood than the 100-year flood.

The intersection analysis highlights transportation assets that lie within these zones.

- The Federal Highway Administration's **National Bridge Inventory (NBI) Overtopping Risk ratings** are derived from Item 71 in the NBI.¹ Item 71 refers to Waterway Adequacy Appraisal Ratings. Tables 4.1 and 4.2 summarize the coding schema for waterway adequacy and overtopping risk.
 - Waterway adequacy codes can have different meanings when they are associated with different NHS functional classes; Table 4.1 shows these associations.
 - The right-hand columns of Table 4.2 list the NBI overtopping descriptions for each waterway adequacy category (a through j). The project team regrouped the codes into 6 broad categories – C0, C1, C2, C3, C4, and C5. The left-hand column of Table 4.2 shows how these broader categories correspond with the waterway adequacy categories.

Table 4.1. NBI item 71: water adequacy.

NBI Item 71 Code	Principal Arterials, Interstates, Freeways, or Expressways	Other Principal and Minor Arterials; Major Collectors	Minor Collectors; Local Roads
N	a	a	a
9	b	b	b
8	c	c	c
7			d
6	d	d	e
5		e	f
4	e	f	g
3	f	g	
2	g	h	i
1			
0	j	j	j

Note: See Table 4.2 for descriptions corresponding to each letter from a to j.
Source: Federal Highway Administration, National Bridge Inventory, Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, 1995.
<https://www.fhwa.dot.gov/bridge/mtguide.pdf>.

¹ Federal Highway Administration, National Bridge Inventory. Data available for download at <https://www.fhwa.dot.gov/bridge/nbi.cfm>.

Table 4.2. NBI codes for overtopping risk.

Overtopping Risk Code	NBI Code Description
C5	a Bridge not over a waterway.
	b Bridge deck and roadway approaches above flood water elevation (high water), chance of overtopping is remote.
C4	c Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.
	d Slight chance of overtopping bridge deck and roadway approaches.
C3	e Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.
C2	f Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.
C1	g Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.
	h Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.
	i Occasional or frequent overtopping of bridge deck and roadway approaches with severe traffic delays.
C0	j Bridge closed.

Source: Federal Highway Administration, National Bridge Inventory, Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, 1995. <https://www.fhwa.dot.gov/bridge/mtguide.pdf>.

The definitions for the frequencies of bridge overtopping as used by the NBI Coding Guide are:

- **Remote** – greater than 100 years.
- **Slight** – 11 to 100 years.
- **Occasional** – 3 to 10 years.
- **Frequent** – less than 3 years.

The definitions for the levels of impacts of bridge overtopping as used by the NBI Coding Guide are:

- **Insignificant** – Minor inconvenience. Highway passable in a matter of hours.
- **Significant** – Traffic delays of up to several days.
- **Severe** – Long term delays to traffic with resulting hardship.

Results of Regional Exposure Analysis

The regional exposure analysis revealed a high potential for the region's critical transportation facilities throughout the study area to be impacted by climate stressors. The following sections are a summary of potential exposure to climate stressors in each portion of the study area. Figures 4.2 through 4.16 show results of the intersection analyses that were conducted to support the regional-scale exposure analysis for this study. Maps depicting these results for the entire study area at the regional level are available as GIS files from FHWA.

NOTE: The transportation facilities mentioned in this section are representative examples intended to highlight the scope and scale of exposure to the impacts of extreme weather events in the study area. This is not intended to be a comprehensive, system-wide inventory of exposed roadway segments, rail segments, and other facilities.

Southwest Connecticut and Eastern Long Island

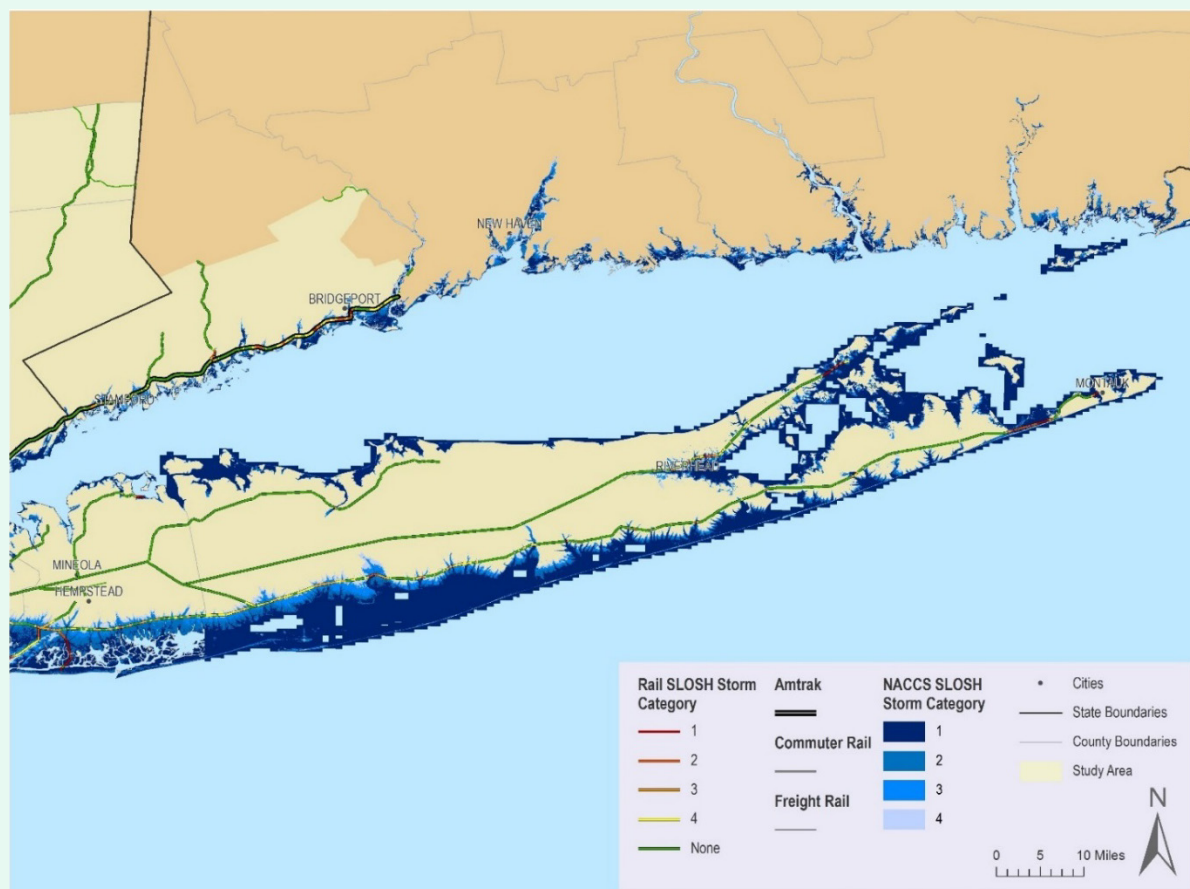


Figure 4.2. Map. Potential exposure of rail network in eastern Long Island and southwest Connecticut to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

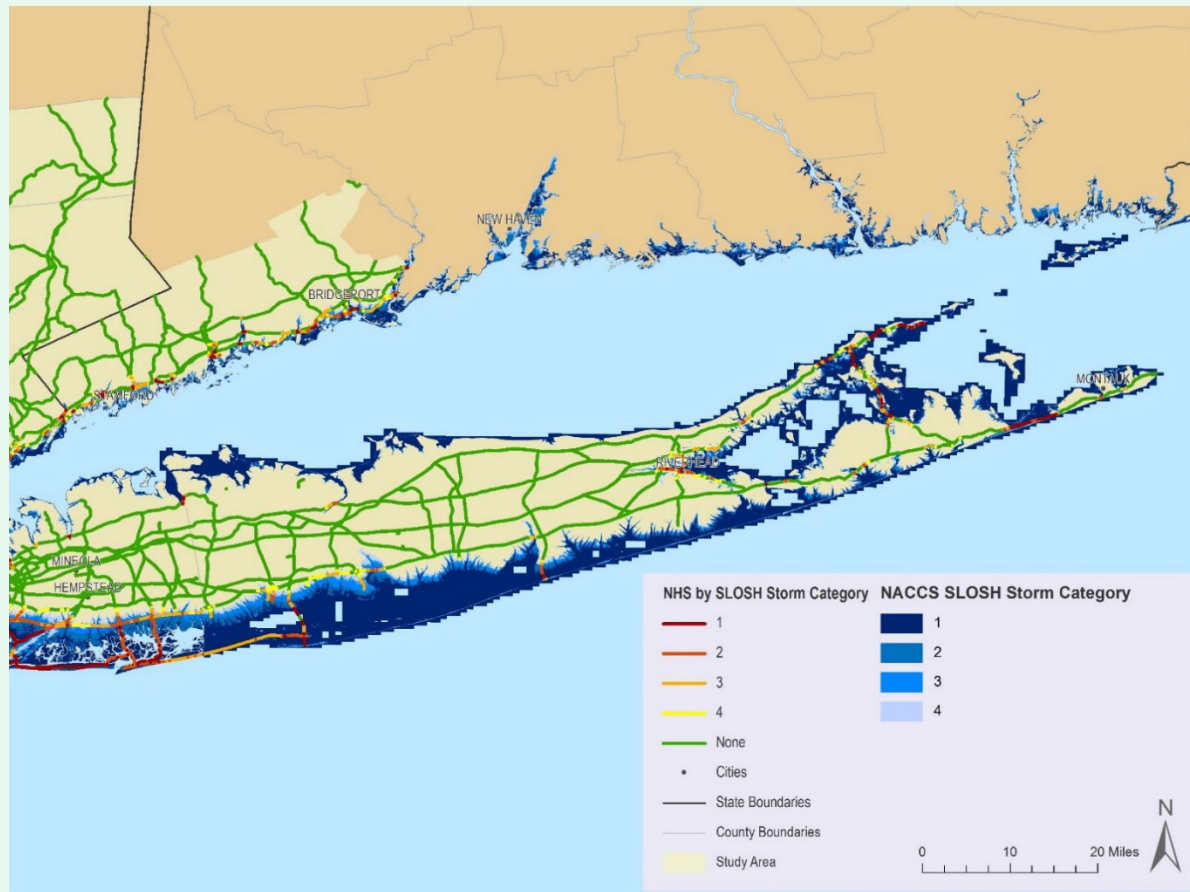


Figure 4.3. Map. Potential exposure of the National highway system in Long Island and southwest Connecticut to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

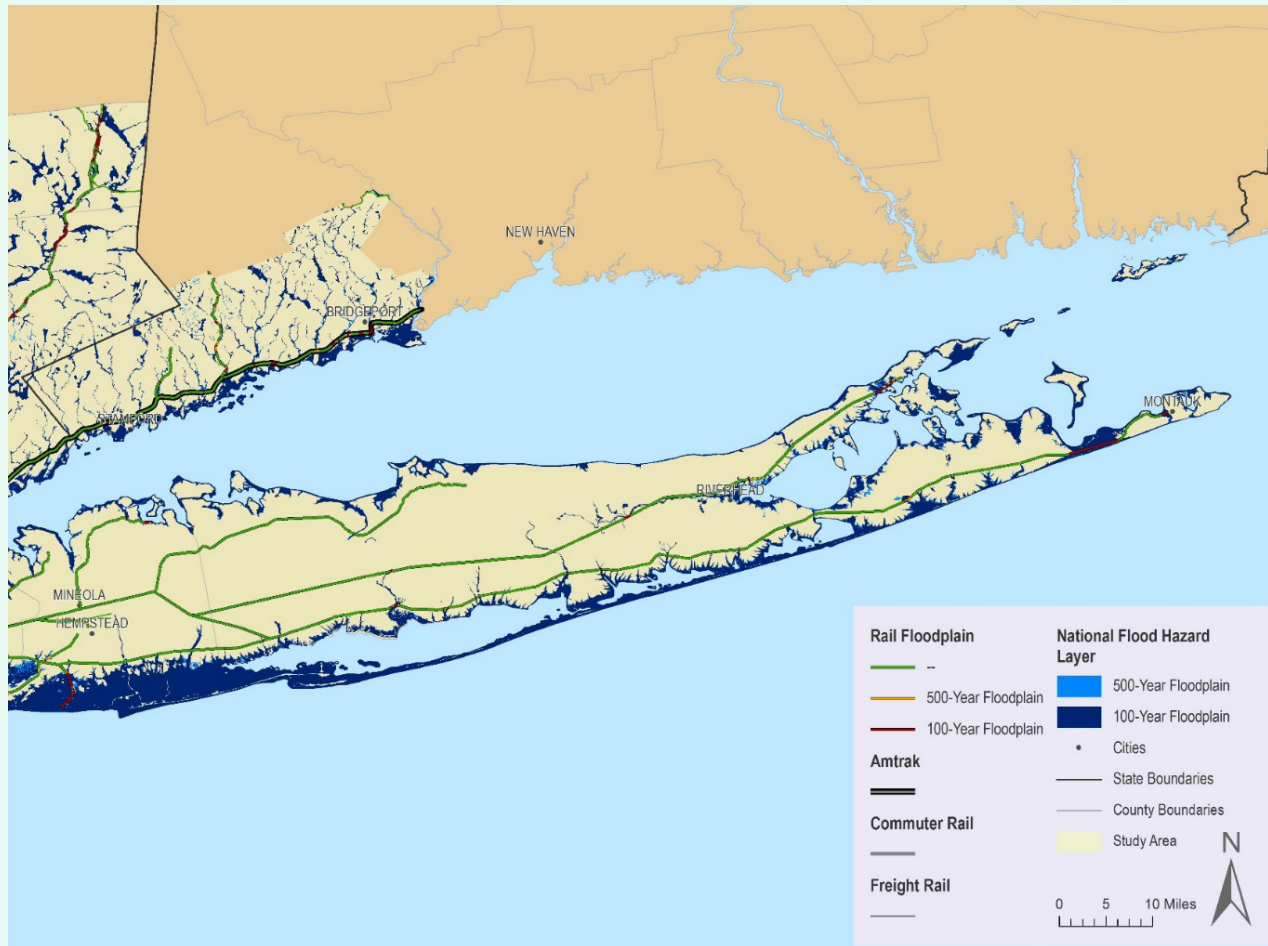


Figure 4.4. Map. Potential exposure of the rail network in Long Island and southwest Connecticut to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

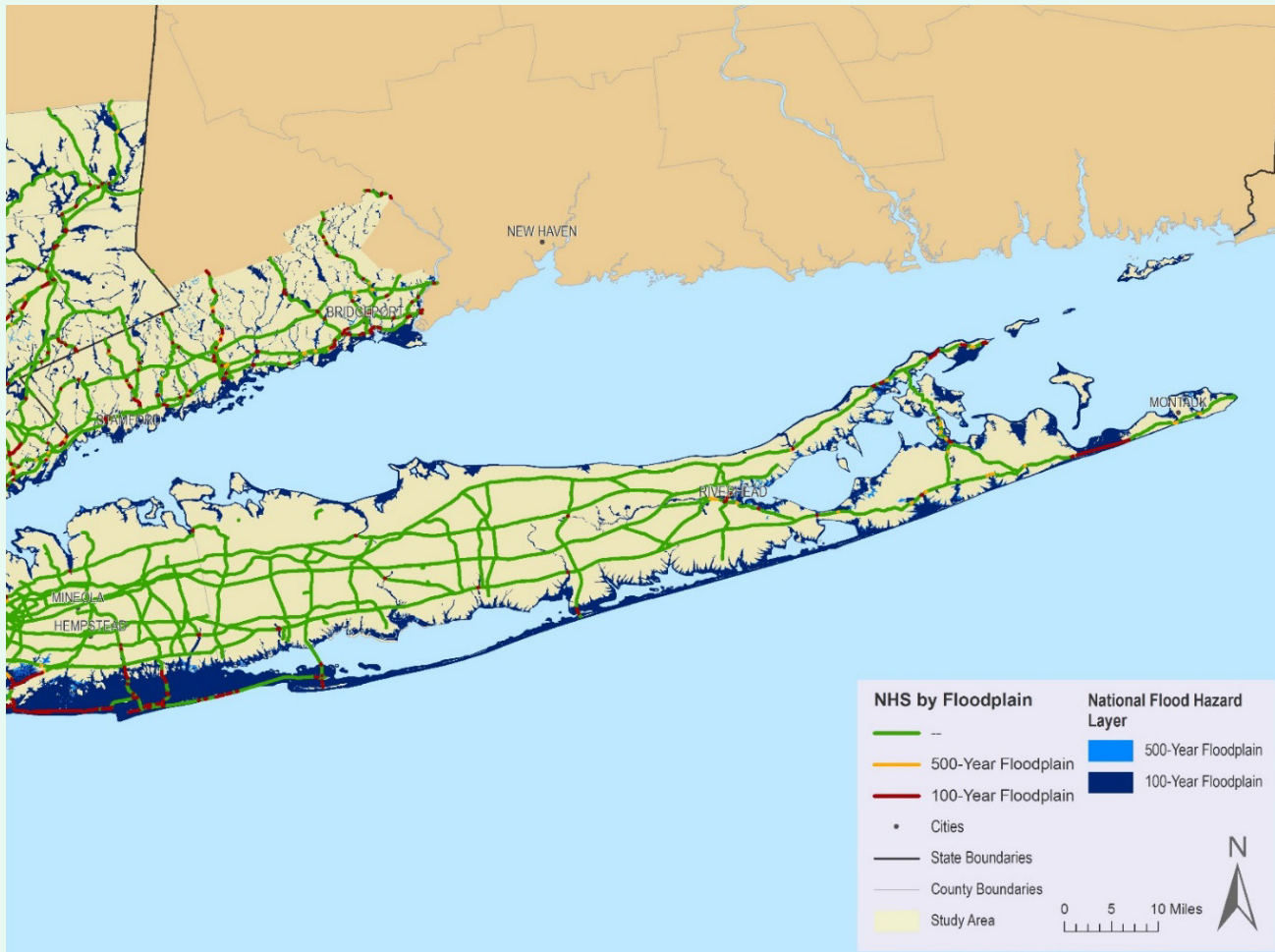


Figure 4.5. Map. Potential exposure of the National highway system in Long Island and southwest Connecticut to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

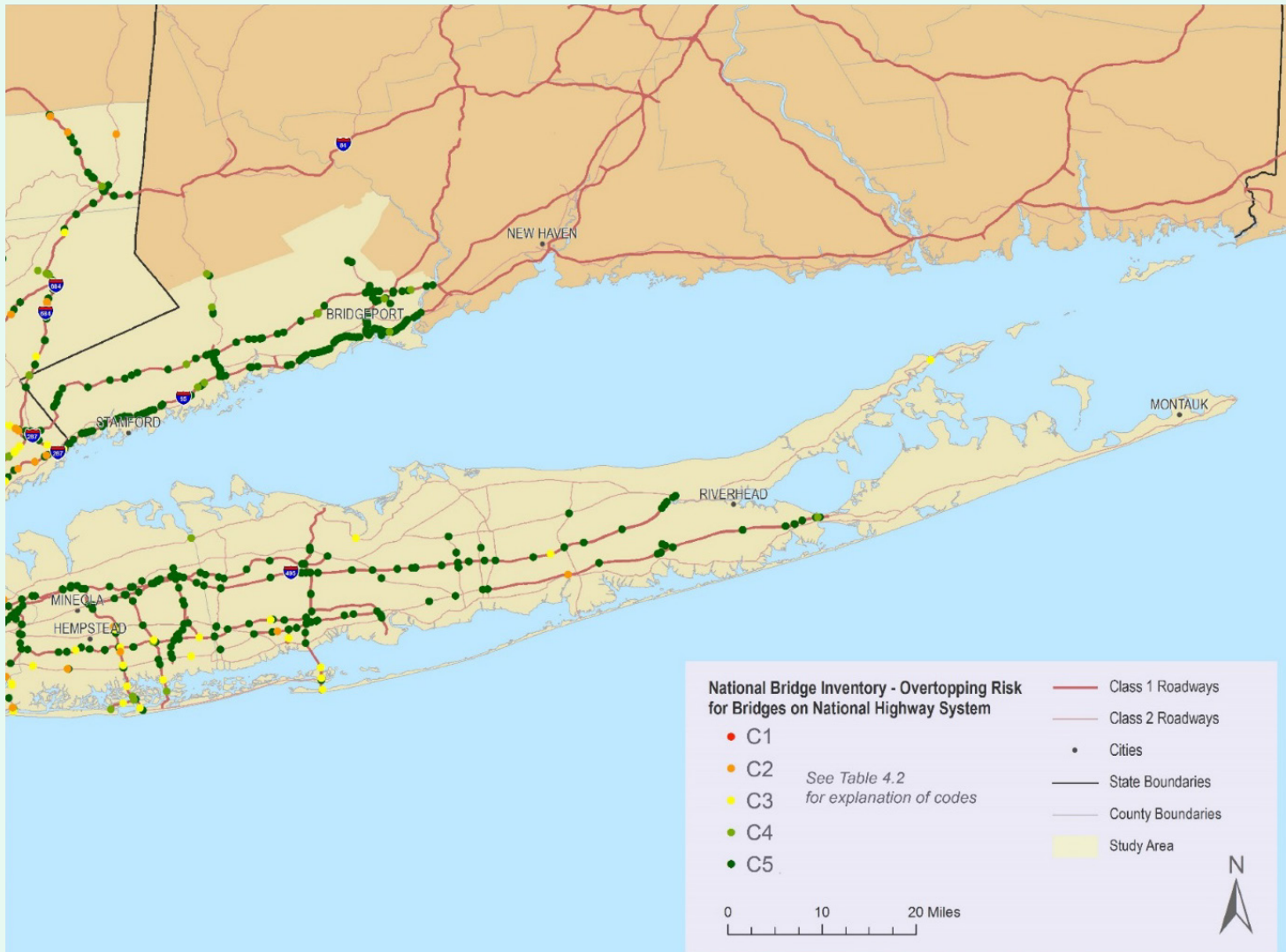


Figure 4.6. Map. National bridge inventory overtopping analysis in Long Island and southwest Connecticut.

(Source: Federal Highway Administration, National Bridge Inventory.)

Eastern Long Island

Sea level rise, storm surge, and extreme heat events are the climate stressors of primary concern in Long Island. The following areas have high potential for exposure today:

- As witnessed during Sandy, all transportation facilities on the South Shore of Long Island, roughly south of Merrick Road and west of the Connetquot River, may be exposed to inundation from storm surge during coastal storms (both summer/fall tropical storm events and winter Nor'easters) (see Figure 4.7). A Category 1 hurricane or equivalent Nor'easter—a very rare occurrence in this region today, but a more likely event by 2100—could expose all of Long Beach Island, Island Park, and Barnum Island to inundation from storm surge, plus the major north-south evacuation routes from Long Beach (most of the Nassau Expressway; large portions of Peninsula Boulevard, Austin Boulevard and Long Beach Road south of Sunrise Highway; sections of the Loop Parkway and Meadowbrook Parkway; and the Long Island Rail Road Long Beach branch). Jones Beach Island also could be exposed, with portions of Ocean Parkway and Wantagh Parkway potentially inundated. Fire Island also is vulnerable to exposure from storm surge; the southernmost portions of Robert Moses Causeway and William Floyd Parkway could be inundated, as well as the ferry terminals along both sides of Great South Bay. By 2050, projected sea level rise could mean that a Category 1 storm (or equivalent winter Nor'Easter) would cause much more widespread flooding, and storm surge from what is considered a minor coastal storm today could inundate large areas as described above.
- Elsewhere on Long Island, low-lying portions of Montauk Highway and Long Island Rail Road's Montauk Branch in the vicinity of Napeague (between East Hampton and Montauk) are particularly vulnerable to inundation from storm surge, including overwashing as water flows between the Atlantic Ocean and Napeague Bay during severe coastal storms. Similarly, at the eastern extent of the North Fork of Long Island, portions of Main Road flood between East Marion and Orient and in Orient Point (including the Orient Point Ferry terminal). The Ronkonkoma Branch of Long Island Railroad is exposed to coastal flooding between Southold and Greenport. Other National Highway System routes potentially exposed to flooding in Category 1 Hurricane (or equivalent Nor'easter) include New York State Route 114 between Sag Harbor and Shelter Island, portions of New York State Routes 24 and 25 near Riverhead, and a short segment of New York State Route 25A near Cold Spring Harbor.
- The regional and local roads serving as the sole access points to coastal communities, sewage treatment plants, and other critical infrastructure along the north and south shores of Long Island also are potentially exposed. One example is Bergen Avenue, the sole access route to the Bergen Point Wastewater Treatment Plant in East Islip. A portion of Shore Road, one of two access routes to Bayville on Long Island's North Shore, collapsed due to undermining from Sandy's storm surge.
- Major regional transportation facilities on Long Island that are more inland are less exposed to storm surge, but the impacts of sea level rise are affecting a much larger area of Long Island. The water table is so close to the surface in communities closest to the waterfront, like Freeport and Baldwin Harbor, that salt water ponding is visible on roadways at the highest tides of the month. Outfalls from drainage systems can be submerged during high tide, and further inland, the rising water table prevents ponds originally designed as detention ponds from draining between storms. As a result, during even moderate rainfall

events (particularly those that occur within four hours of high tide) rainwater backs up in drainage systems and/or overtops retention and detention ponds. The Long Island Rail Road is elevating electrical substations and other critical infrastructure along the Long Beach Branch due to inland and coastal flooding that is expected to become more frequent.

Southwestern Connecticut

Wind damage, riverine flooding, sea level rise, and inundation from coastal storm surge are the main climate stressors of concern to Southwest Connecticut. The following areas have high potential for exposure today:

- Metro-North Railroad's New Canaan Branch and Danbury Branch have high exposure to damage and disruption due to wind-blown debris. Overhead catenary and the tracks themselves can be blocked and damaged by downed trees and branches. The New Haven Line (part of Amtrak's Northeast Corridor) also is vulnerable to damage and disruption from wind-blown debris, although the wide right of way and presence of four tracks provides adaptive capacity to enable operations to resume soon after a storm passes.
- Most of the Merritt Parkway and north-south roadways on the National Highway System (including, but not limited to, the non-expressway portion of U.S. 7 north of Norwalk) also are exposed to disruption from wind-blown debris. The expressway portion of U.S. 7, Connecticut State Routes 8 and 25, and I-95 are sensitive to disruption from wind-blown debris, but these facilities are not as exposed due to the wide rights of way and high standard of maintenance for trees and signage.
- U.S. 7 and Metro-North Railroad's Danbury Branch adjacent to the Norwalk River between Norwalk and Danbury are exposed to riverine flooding. Several segments of road and rail, plus several stations, lie in the 100 year flood plain. Connecticut State Route 134 (Washington Boulevard) lies in the 100-year flood plain in Stamford, and sections of Connecticut State Route 104 (Long Ridge Road) are in the flood plain between Route 134 and the Merritt Parkway. Short stretches of many other roads in interior portions Southwest Connecticut are exposed to flooding in 100-year storm events (see Figure 4.8), and these same roads are exposed to flash floods in low-probability but high-impact rainfall events that are short but intense.
- Portions of U.S. 1 and short segments of Metro-North's New Haven Line near Bridgeport are exposed to flooding from storm surge in a Category 1 hurricane or equivalent Nor'easter. A small segment of the Danbury Branch between the New Haven Line and downtown Norwalk also is exposed to inundation from storm surge in a Category 1 storm.
- As indicated in Section 3, with more frequent extreme heat events predicted in the future, moveable bridges, electrical systems (such as those that power subways and passenger rail lines, traffic signals, lights, communications systems, and pumps) and some mechanical components will have to be replaced with more heat-tolerant components in future normal replacement cycles.

New York City and Lower Hudson Valley

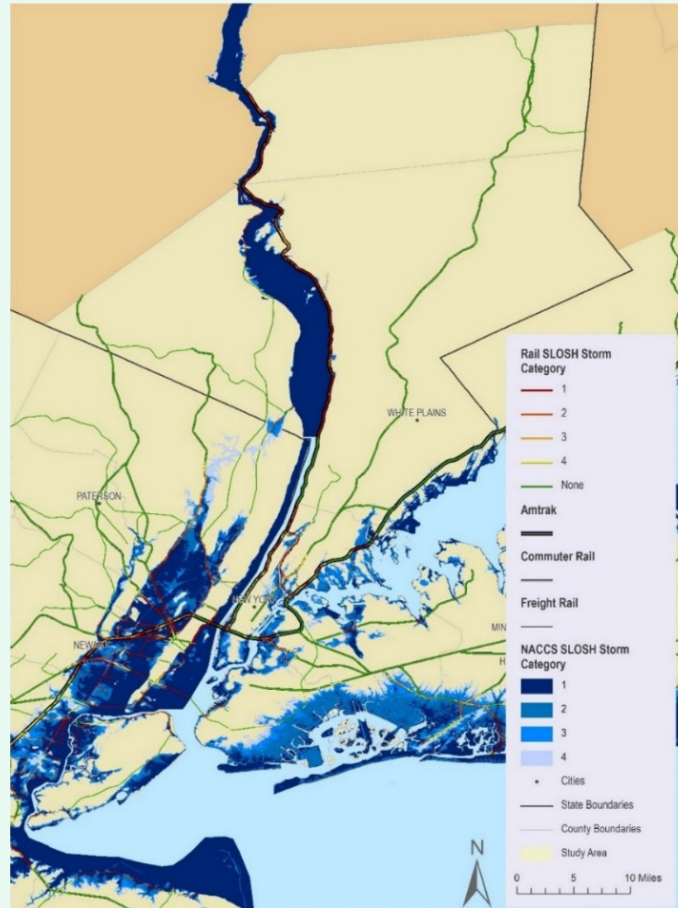


Figure 4.7. Map. Potential exposure of rail network in New York City and lower Hudson Valley to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

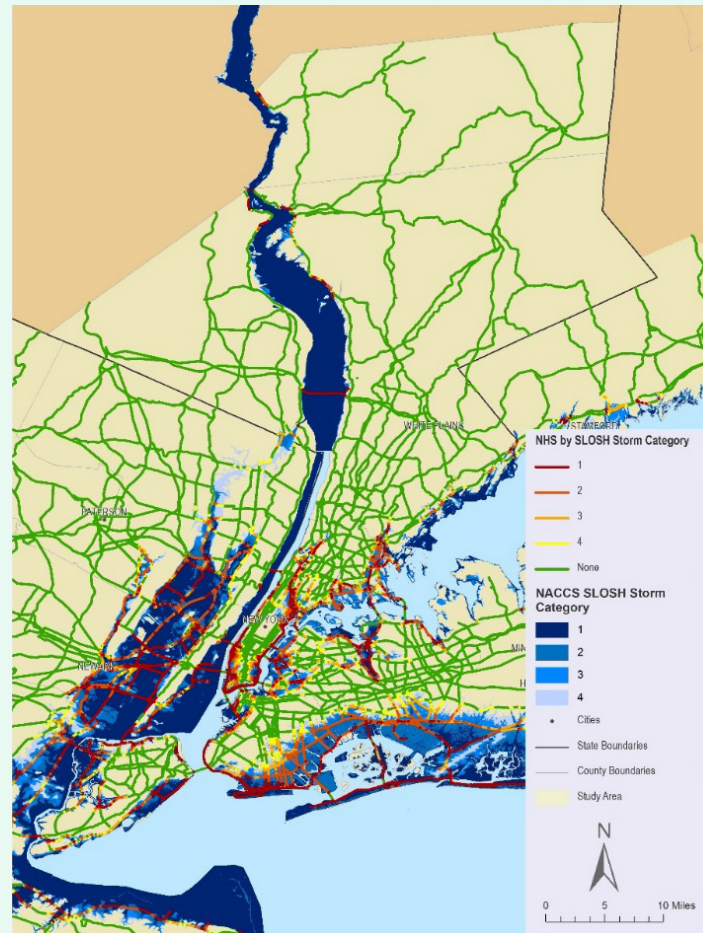


Figure 4.8. Map. Potential exposure of the National highway system in New York City and lower Hudson Valley to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed

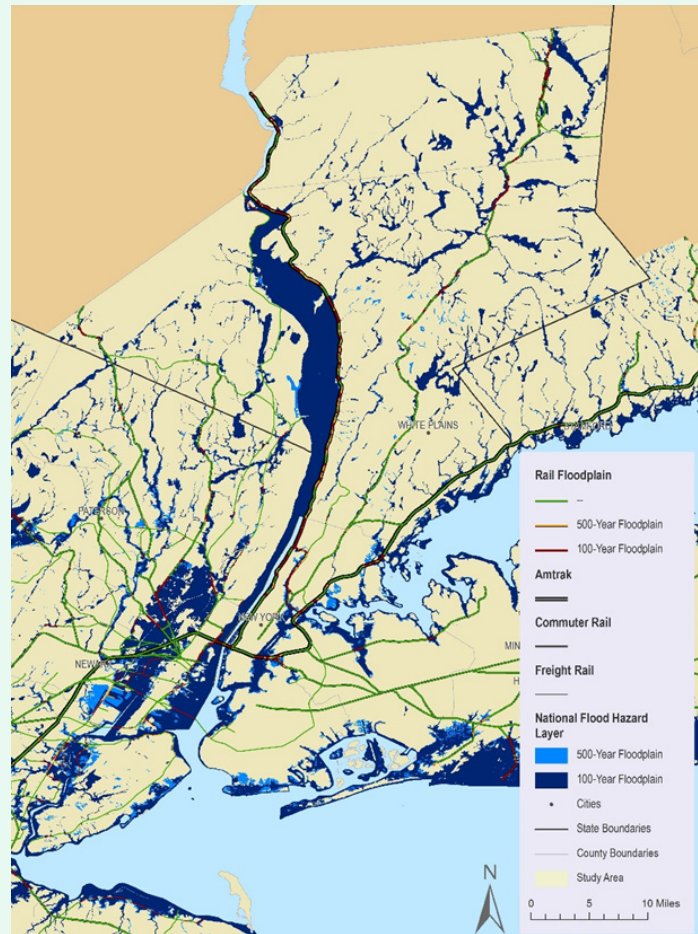


Figure 4.9. Map. Potential exposure of the rail network in New York City and lower Hudson Valley to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.



Figure 4.10. Map. Potential exposure of the National highway system in New York City and lower Hudson Valley to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

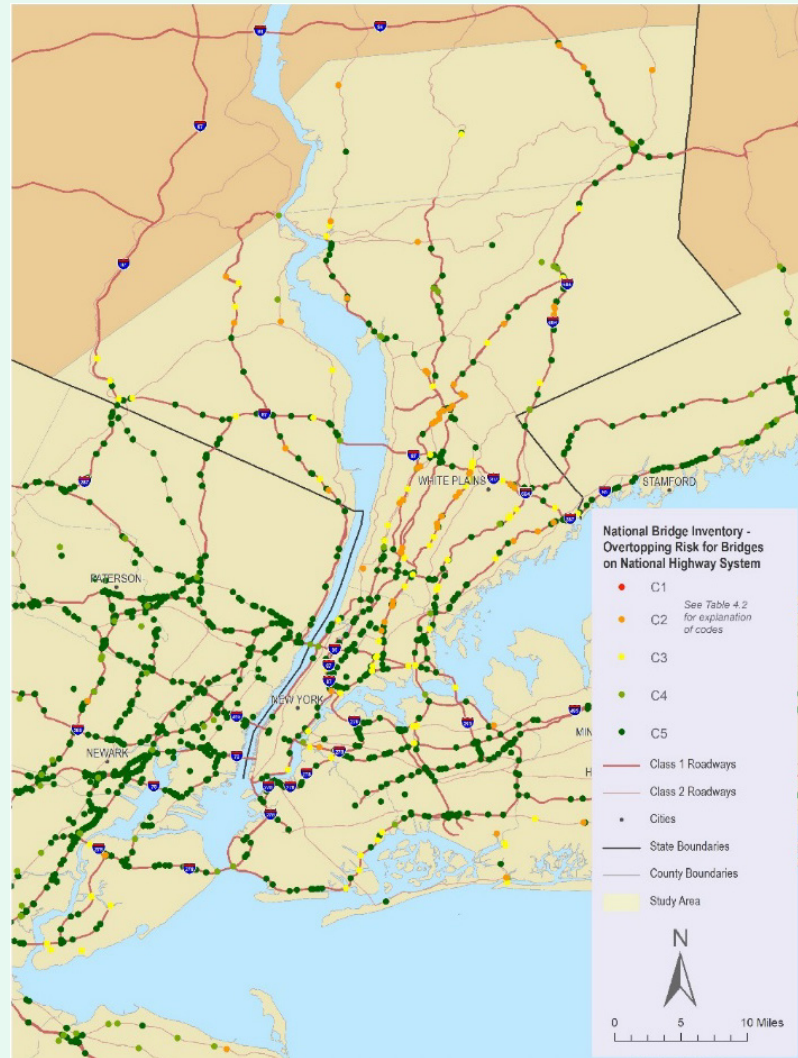


Figure 4.11. Map. National bridge inventory overtopping analysis in New York City and lower Hudson Valley.

(Source: Federal Highway Administration, National Bridge Inventory.)

New York City

The work undertaken by New York City (NYC) agencies in the wake of Hurricane Sandy represents the most thorough vulnerability and risk assessment available in the project study area. The publication of “A Stronger, More Resilient New York” in 2013 and the 2015 update of the New York City Panel on Climate Change (NPCC) report are among the most prominent examples of policy-level and analytics-based reports published to support vulnerability and risk assessment. As an example of the work that has been conducted to date, the City collected detailed exposure data in the wake of Sandy that it then compared to 100-year and 500-year floodplain maps using GIS. According to the NPCC 2015 report, “the Hurricane Sandy field-verified inundation area, a surface interpolated using field-verified high-water marks and storm-sensor data from the U.S. Geological Survey, clearly equaled and exceeded the 1983 100- and 500-year floodplains, most strikingly along the southern coasts of Brooklyn and Queens and along the eastern and southern shores of Staten Island. Northern Queens and the Bronx experienced less flooding relative to the other boroughs in part because the Long Island Sound was at low tide when Sandy made landfall.”

“A Stronger, More Resilient New York” identifies sea level rise, storm surge, and intense precipitation events as posing the greatest risks to the City’s transportation infrastructure. The report states that the 100-year flood plain encompasses “approximately 12 percent of the [City’s] roadway network, all of the major tunnel portals other than the Lincoln Tunnel, portions of both airports, a variety of commuter rail assets, all three heliports, and a number of subway entrances and vent structures, principally in Lower Manhattan...”

The report continues:

“By the 2020s, the floodplain is estimated to encompass 15 percent of the city’s roadway network, and by the 2050s, it is expected to encompass 19 percent of that network. More and more of the City’s airport infrastructure will be at risk as storm surges will move from flooding outlying runways to threatening the terminal buildings, while additional subway stations will be at risk.

More intense downpours expected with climate change also pose a major risk to the transportation system. As with storm surge, heavy downpours pose the most significant challenge to subway and vehicular tunnels throughout the city, particularly in locations where tunnel entrances are located in low-lying areas or in areas with poor subsurface drainage. Examples of infrastructure matching this flood profile include the F train on Hillside Avenue in Queens and several subway lines in Lower Manhattan. Generally, heavy downpours are expected to pose only a moderate risk to roads and bridges, which may experience more frequent temporary flooding, but not more lasting damage.

Other Risks

High winds are likely to represent a moderate risk to the above-ground portions of the city's transportation infrastructure, such as traffic signals, signs, bridges, and street lights. They also could pose challenges to the aviation system, interfering with flight operations and, in the worst cases, creating safety hazards. Although high winds can cause power outages, which have serious impacts on the transportation network as a whole, it is not believed that these impacts will be greater than those facing the city today. Heat waves, meanwhile, present a moderate threat to the city's ground transportation infrastructure, though it is not expected to become materially greater until the 2050s. Heat waves could create problems with opening and closing movable bridges and cause softening of asphalt roads. Heat waves also could become an issue for the subway system, increasing temperatures on platforms to levels that could turn what, today, is only a passenger comfort issue into a passenger safety issue. Moreover, heat waves could increase the potential for power outages, which affect transportation networks across the board.

Finally, sea level rise in and of itself is expected to pose a low risk to the city's transportation infrastructure for the next three decades. However, by the 2050s tidal flooding—already an issue for some low-lying areas—could become more widespread along the waterfront, including areas such as Southern Brooklyn and South Queens. Waterfront assets including the city's airports and ferry terminals could be placed at risk by this periodic flooding threat.”

The regional scale exposure analysis identified several clusters of vulnerable and critical transportation facilities in New York City, including the following:

- Lower Manhattan, including The Battery (Battery Park Tunnel and the north portal to the Hugh L. Carey Tunnel), Battery Park City and West Side Highway (New York State Route 9A), and FDR Drive on the Lower East Side;
- The east bank of the Hudson River and the east bank of the Harlem River, including the Metro-North Railroad Hudson Line, portions of the Empire Connection, and West Side Drive (New York State Route 9A);
- The area around Flushing Bay in The Bronx, Queens, and Manhattan, including LaGuardia Airport, the Oak Point Rail Yard, the Hunts Point Terminal Market, portions of Interstate Highway 678 in Whitestone, portions of the Grand Central Parkway and Northern Boulevard on the south shore of Flushing Bay, and the north approach to the Whitestone Bridge;
- The mouth of the Hutchinson River, including the US Route 1 (Boston Road) bascule bridge, the Hutchinson River Parkway bascule bridge, Amtrak Northeast Corridor bascule bridge, and the Pelham Parkway bascule bridge;

- The area around Jamaica Bay, including portions of the Belt Parkway, Cross Bay Boulevard, Flatbush Avenue, Neptune Avenue, and many other streets in south Brooklyn and southeast Queens that are part of the National Highway System, as well as the Long Island Rail Road Far Rockaway Branch, the New York City Transit A Train south of Howard Beach, the Rockaway bus storage facility, and JFK airport.
- The west shore of Staten Island along Arthur Kill, including portions of the West Shore Expressway (New York State Route 440), the Arthur Kill Railroad Bridge, and New York Container Terminal; and
- Numerous moveable bridges and bridge approaches that are part of the National Highway System spanning Gowanus Canal and Newtown Creek.

Lower Hudson Valley

The primary climate stressor of concern in the Lower Hudson Valley region (including Westchester, Rockland, and Putnam counties) is precipitation-based flooding. By 2100, the Lower Hudson Valley region may have between 1 and 18 percent more precipitation per year (suggesting more days with saturated soils) and between 0 and 4 additional days with more than 1 inch of rainfall. The following facilities are particularly vulnerable:

- The north-south parkways, the Harlem Line of Metro-North Railroad, and arterial roadways that run along and through river and stream valleys in Westchester County are particularly exposed and sensitive to flooding from heavy rainfall events.
 - For example, large stretches of the Saw Mill River Parkway between Dobbs Ferry and Pleasantville regularly close during heavy rainfall events, particularly those that occur when soils are already saturated and unable to soak up runoff.
 - Sections of the Bronx River Parkway from Allerton Avenue to Ardsley Road also are exposed to flooding.
- East-west roads like New York State Route 119, Virginia Road, and Harney Avenue are exposed to flooding during these events, impeding cross-county travel.

Sea level rise and storm surge also are a concern for roads and rail lines adjacent to the Hudson River and Long Island Sound:

- Portions of Metro-North's Hudson Line were inundated during Hurricanes Irene and Sandy, including the Harmon Yard in Croton-on-Hudson. At various points along the right of way, third rail, switches, snow melters, power transformers, and communications systems were inundated and destroyed by salt water, and these may be exposed to future storm surges.
- Portions of the CSX River Line north of Stony Point in Rockland County also are exposed to storm surge.
- The Haverstraw and Ossining ferry landings are vulnerable to sea level rise and storm surge.

Northern New Jersey and the North Jersey Coast

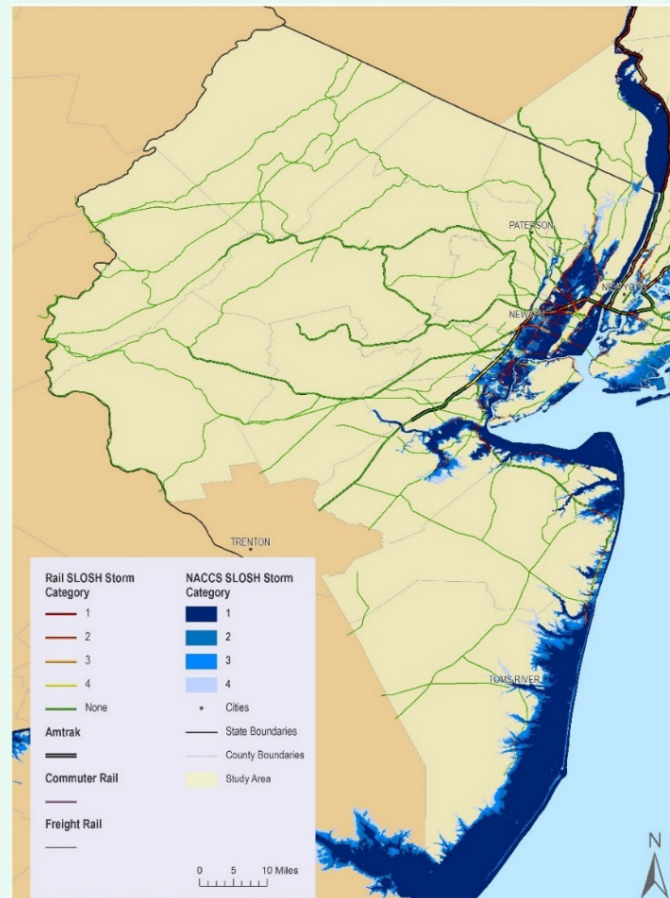


Figure 4.12. Map. Potential exposure of rail network in New Jersey to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

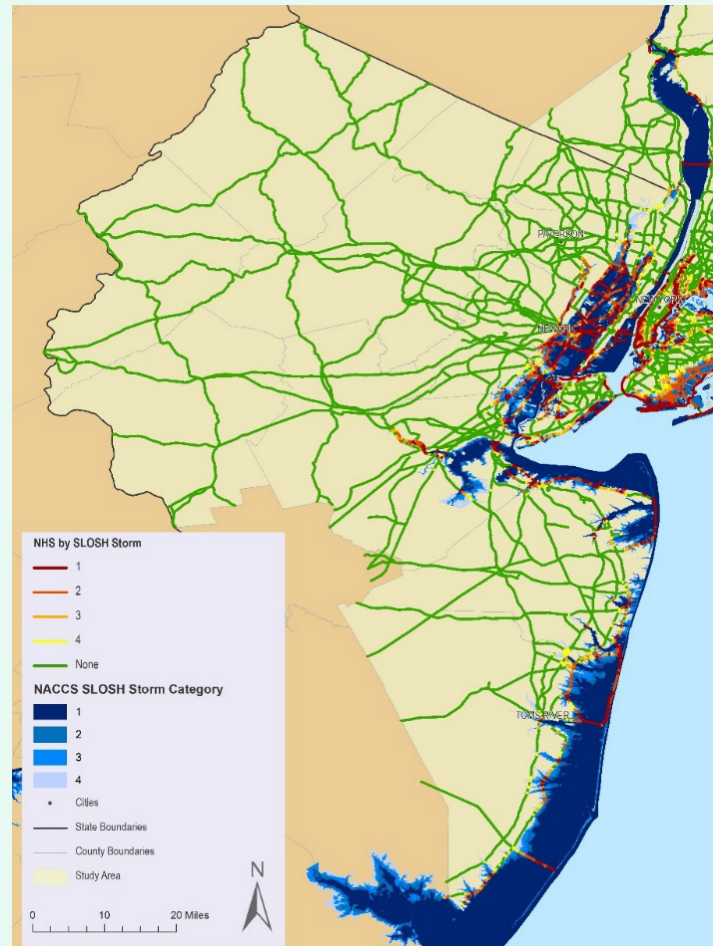


Figure 4.13. Map. Potential exposure of the National highway system in New Jersey to coastal flooding and storm surge.

(Source: Cilone, M. et al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

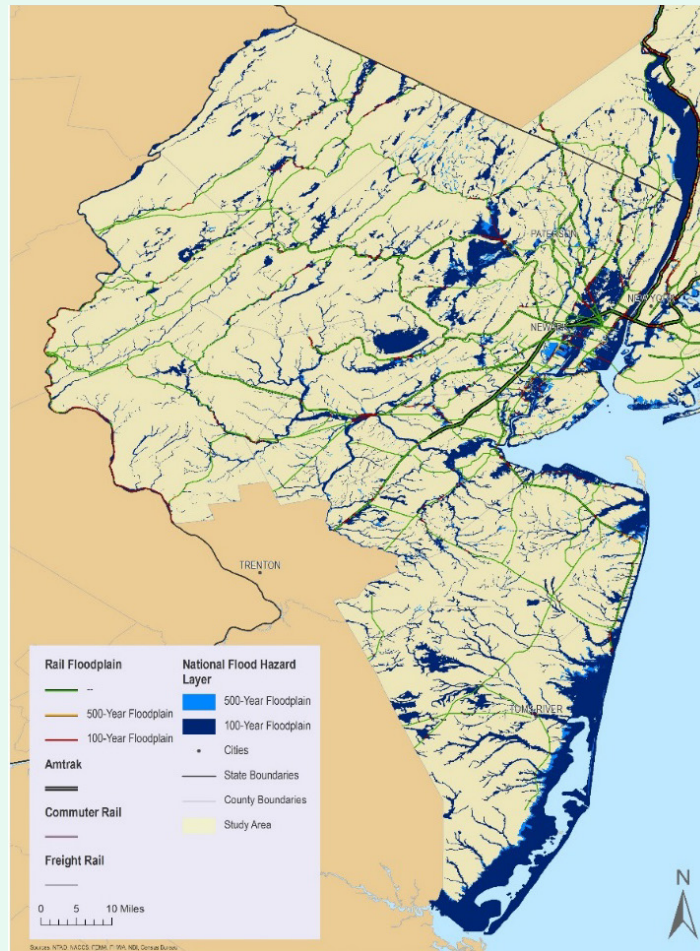


Figure 4.14. Map. Potential exposure of the rail network in New Jersey to inland flooding.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.



Figure 4.15. Map. Potential exposure of the National highway system in New Jersey to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

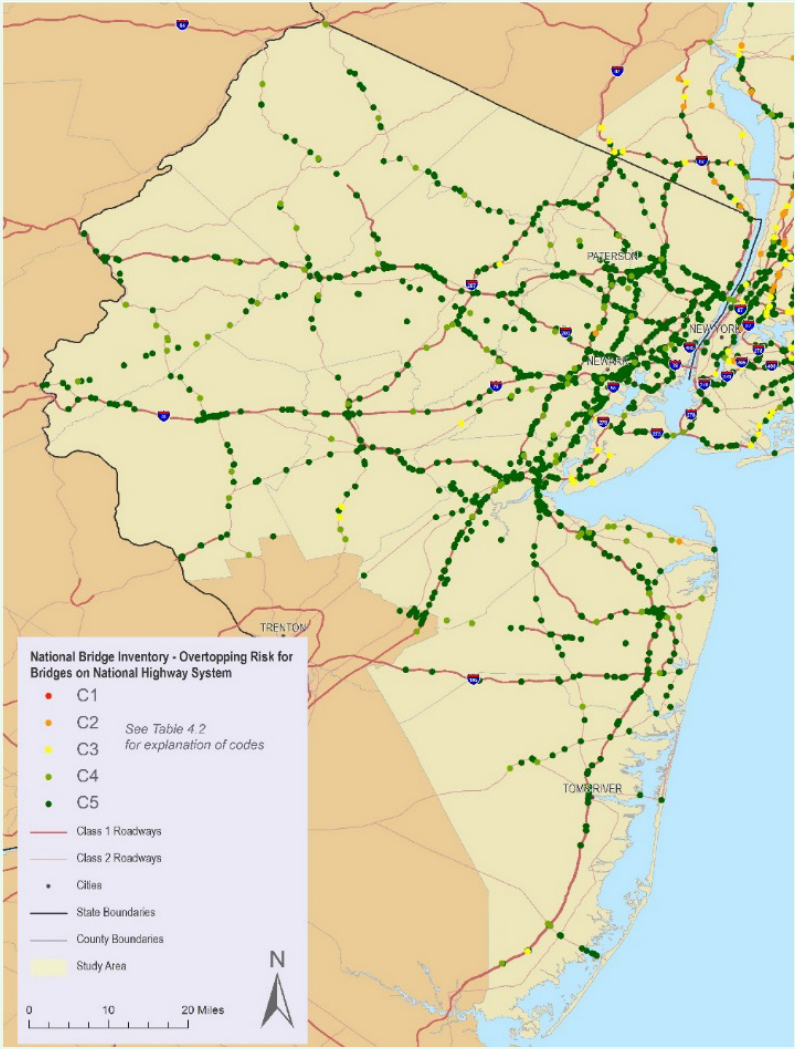


Figure 4.16. Map. National bridge inventory overtopping analysis in northern New Jersey.

(Source: Federal Highway Administration, National Bridge Inventory.)

Northern New Jersey

Sea level rise and storm surge affect coastal and tidal areas including the Meadowlands, areas bordering Newark Bay, and the River Towns from Bayonne to Fort Lee. Meanwhile, riverine flooding affects transportation facilities in the Passaic, Hackensack, and Raritan River basins. Concentrations of exposed and critical facilities include the following:

- NJ Transit's Hoboken Terminal and the surrounding areas of Hoboken are exposed to flooding at extreme high tides and during coastal storms.
- Several critical east-west commuter and evacuation routes through the Meadowlands, including New Jersey Route 7 and County Route 508, are exposed to sea level rise and storm surge. NJ TRANSIT's Meadowlands Maintenance Facility is exposed to storm surge. Large portions of the facility were inundated from Hurricane Sandy's surge. The southern side of Port Jersey and the Military Ocean Terminal in Bayonne also are exposed to sea level rise and coastal flooding due to storm surge.
- Many roads in the Passaic River basin are vulnerable to precipitation-based flooding, notably New Jersey Route 21 between Paterson and Newark, U.S. Route 46 in Wayne and Fairfield, and New Jersey Route 23 and U.S. Route 202 in Wayne, Lincoln Park, and Pequannock Township.
- Maritime facilities lining the west side of Arthur Kill are exposed to coastal flooding and sea level rise. During Hurricane Sandy, the Grover Cleveland Service Area on the New Jersey Turnpike was destroyed by flood waters from the Woodbridge River, a tributary of Arthur Kill.
- New Jersey Route 18 and River Road are exposed to flooding of the Raritan River between New Brunswick and Bound Brook.

New Jersey Coast

As detailed in the Climate Change and Vulnerability Assessment completed by North Jersey Transportation Planning Authority (NJTPA) and its partners in 2012, much of the North Jersey Coast is vulnerable to sea level rise and storm surge. The predictions of the study were borne out when areas predicted to flood in a Category 1 hurricane were inundated by Hurricane Sandy's storm surge. These included the following:

- Areas along the south shore of Raritan Bay from South Amboy through the Highlands were inundated. New Jersey Route 35 in Laurence Harbor and Keyport were closed due to flooding, and these same stretches of roadway close during severe Nor'easters as well. Low-lying portions of New Jersey Route 36 east of Keyport also are exposed to coastal floods. NJ TRANSIT's North Jersey Coast Line crossing Cheesquake Creek and Wilkson Creek also are exposed to flooding. In the future, more severe storms accompanied by sea level rise could result in more frequent closure of these critical routes for freight, local commerce, and commuting. The Garden State Parkway crossing Cheesquake Creek is not exposed to flooding today, but it could become more vulnerable to coastal flooding in the future with sea level rise. The New Jersey Route 35 and North Jersey Coast Line crossings of inlets and estuaries such as the

Navesink and Shrewsbury Rivers are exposed to storm surge. Approaches to the New Jersey Route 70 crossings of the Metedeconk and Manasquan Rivers also are exposed to storm surge.

- New Jersey Route 36 from the Highlands to Long Branch runs in close proximity to the beach and is exposed to sea level rise, storm surge, and wave action. New Jersey Route 35 from Point Pleasant to Seaside Heights has the same exposure. Both facilities were severely damaged by Hurricane Sandy's storm surge and wave action.
- All of the east-west evacuation routes from Jersey Shore beaches, including those on county roadway networks that are not part of the National Highway System, are exposed and vulnerable to storm surge. In addition, further inland, the effects of sea level rise on water tables means detention and retention ponds no longer completely drain after rainfalls, leaving adjacent roadways more vulnerable to flooding from heavy precipitation events. Stormwater outfalls are increasingly submerged as sea levels rise, further contributing to coastal flooding on these critical routes.

Identification of Vulnerable Subareas

The regional exposure analysis provided valuable information to identify the most critical and vulnerable components of the regional transportation system. The study team used a set of criteria as follows to identify 21 vulnerable subareas:

- Concentration of critical infrastructure that handles regional movement of people and freight, where critical infrastructure was defined as:
 - National Highway System and evacuation routes;
 - Major transit and rail corridors;
 - Intermodal hubs for people and freight (and access to them); and
 - Supporting infrastructure such as rail and bus storage and maintenance facilities.
- A qualitative assessment of exposure, sensitivity, adaptive capacity of the infrastructure in areas with concentrations of critical infrastructure.
 - The qualitative assessment was based in part on information on past damage and disruption collected in Task 3 of this project and judgment about future vulnerability.
 - The vulnerability assessment focuses on coastal inundation (due to a combination of sea level rise and storm surge) and inland flooding.

Figures 4.17 and 4.18 show the 21 vulnerable subareas. Tables 4.3 and 4.4 show various attributes of the 21 subareas. Appendix C contains more information about the subareas that were considered.

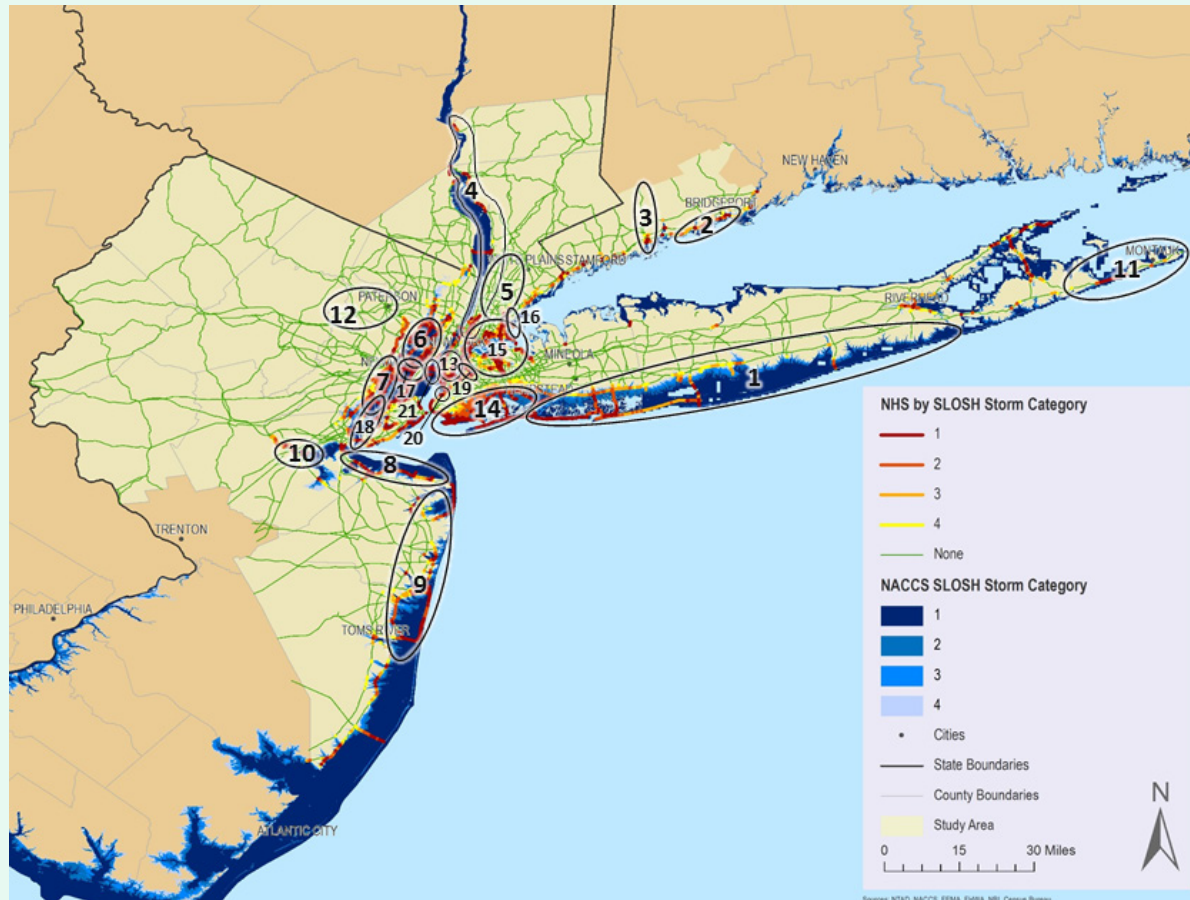


Figure 4.17. Map. Potential exposure of the National highway system to storm surge, with 21 vulnerable subareas.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to sea level rise in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

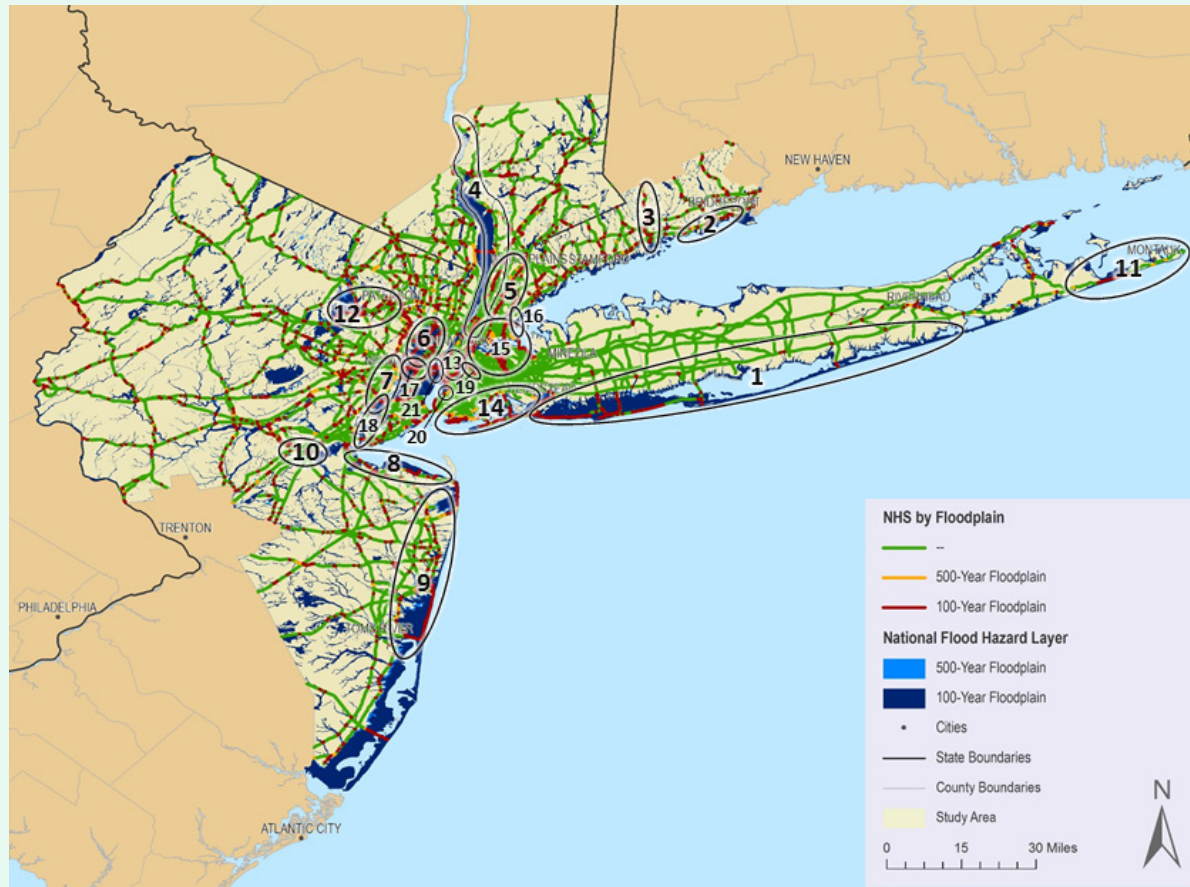


Figure 4.18. Map. Potential exposure of the National highway system to inland flooding, with 21 vulnerable subareas.

(Source: Federal Emergency Management Agency, National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

Table 4.3. Summary of climate stressors and impacts in 21 vulnerable subareas.

Map Legend (See Figures 4.4 and 4.5)	Name	Storm Surge	Sea Level Rise	Wave Action	Precipitation	Temperature
1	Long Island South Shore	●	●	●	●	●
2	Bridgeport and Fairfield Coastal Corridor	●	●	●	●	●
3	Norwalk-Danbury Corridor				●	●
4	Hudson River	●	●	●	●	●
5	Westchester County North-South Parkways/Rail				●	●
6	Lower Hackensack River, Secaucus to Hackensack	●	●		●	●
7	Newark/Elizabeth	●	●	●	●	●
8	South Shore of Raritan Bay	●	●	●	●	●
9	North Jersey Coast	●	●	●	●	●
10	New Brunswick/Raritan River area				●	
11	NY 27 and LIRR Montauk Branch	●	●	●		
12	Pompton and Passaic River Fork and Basin				●	
13	Lower Manhattan	●	●	●	●	●
14	Rockaway/Brighton Beach/Jamaica Bay	●	●	●	●	
15	Outer East River (N. Queens and SE Bronx)	●	●	●	●	
16	Lower Hutchinson River	●	●	●	●	●
17	Kearny and South Secaucus	●	●	●	●	●
18	Arthur Kill, Newark Bay to Raritan Bay	●	●		●	●
19	Newtown Creek	●	●		●	●
20	Gowanus Canal	●	●		●	●
21	Hoboken and Jersey City	●	●	●	●	

Table 4.4. Criticality assessment to inform selection of subareas for further analysis.

Map Legend (See Figures 4.4 and 4.5)	Name	National Highway System Facilities	Regional Rail Facilities	Evacuation Route(s)	Critical to Freight Movement	Critical to People Movement	Presence of Intermodal Hub
1	Long Island South Shore	●	●				
2	Bridgeport and Fairfield Coastal Corridor	●	●				
3	Norwalk-Danbury Corridor	●	●				
4	Hudson River	●	●				
5	Westchester County North-South Parkways/Rail	●	●				
6	Lower Hackensack River, Secaucus to Hackensack	●	●				
7	Newark/Elizabeth	●	●				
8	South Shore of Raritan Bay	●	●				
9	North Jersey Coast	●	●				
10	New Brunswick/Raritan River area	●					
11	NY 27 and LIRR Montauk Branch	●	●				
12	Pompton and Passaic River Fork and Basin	●					
13	Lower Manhattan	●	●				
14	Rockaway/Brighton Beach/Jamaica Bay	●	●				
15	Outer East River (N. Queens and SE Bronx)	●	●				
16	Lower Hutchinson River	●					
17	Kearny and South Secaucus	●	●				
18	Arthur Kill, Newark Bay to Raritan Bay	●	●				
19	Newtown Creek	●					
20	Gowanus Canal	●					
21	Hoboken and Jersey City	●	●				

Note: Darker shading indicates higher criticality score.

4.3 Subarea Assessments of Vulnerability, Risk, and Adaptation Options

The Post-Sandy project team narrowed down the 21 identified vulnerable subareas identified in the regional vulnerability assessment to 3 through a facilitated discussion with the Project Guidance Committee using the following guidelines:

- A diversity of geographies, climate stressors, impacts, and modes should be represented in the three subareas;
- The outcomes and results should be useful in advancing future adaptation efforts by regional stakeholders;
- The subarea assessments should avoid duplication of efforts already underway by others to assess vulnerability, evaluate adaptation options, and design and implement adaptation strategies; and
- The assessments should focus on subareas where adaptation strategies can be developed for transportation assets vs. subareas where solutions may be needed to protect a broader area including transportation and non-transportation uses.

The three selected subareas were:

- #1 Long Island South Shore,
- #3 Norwalk-Danbury Corridor, and
- #8 South Shore of Raritan Bay.

Figure 4.19 shows the locations of the three subareas and Table 4.5 summarizes the distinguishing features of each.

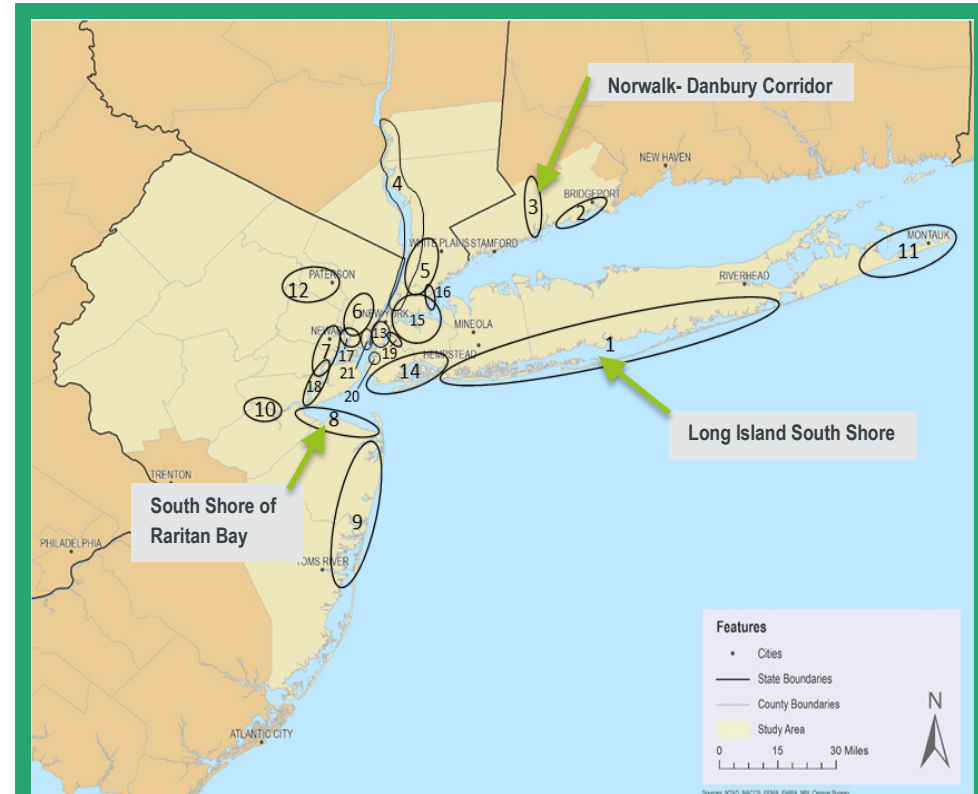


Figure 4.19. Map. Three subareas selected for assessment.

(Source: Cambridge Systematics, Inc.)

Table 4.5. Features of three selected subareas.

Feature	Long Island South Shore	Norwalk-Danbury Corridor	South Shore of Raritan Bay
County, State, Metropolitan Planning Organization.	Nassau and Suffolk counties, New York, New York Metropolitan Transportation Council.	Fairfield County, Connecticut, Western Connecticut Council of Governments.	Middlesex and Monmouth counties, New Jersey, North Jersey Transportation Planning Authority.
Transportation facilities.	Arterials, parkways, and a Long Island Railroad line linking barrier islands to Long Island.	Interregional highway and Metro-North Rail line running alongside the Norwalk River.	State highways and a NJ TRANSIT rail line running parallel to shoreline and connecting coastal communities along the bay.
Climate Stressors.	Sea level rise, storm surge, wave action, heat, wind.	Riverine flooding, heat, wind.	Sea level rise, storm surge, wave action, heat, wind.
Types of exposed and sensitive transportation assets.	Fixed bridges, and movable bridges (and their components); Causeway embankments and retaining walls; Arterial roadways and rail stations in low-lying communities.	Sections of road and rail in riverine flood plains; Road and rail bridges and culverts; Road and rail embankments and retaining walls; Rail catenary, power and communication systems, rail stations.	Sections of road and rail in coastal flood plains; Road and rail bridges and culverts; Road and rail embankments and retaining walls; Rail catenary, power and communication systems, rail stations.
Issues addressed by potential adaptation options.	Maintain availability of critical facilities used for evacuation and recovery, daily commutes, and seasonal recreation.	Address consequences of flooding in a corridor with limited adaptive capacity.	Address coastal flooding affecting mobility and accessibility in and around a mix of communities across the socioeconomic spectrum.

Application of the Assessment Process

This subarea assessment generally follows the vulnerability and risk assessment process developed for the Post-Sandy study. See Appendix B - Engineering Informed Adaptation Assessment Process This assessment begins with a summary of climate impacts. The exposure analysis, sensitivity analysis, and adaptive capacity sections of the vulnerability assessment analyze how these climate impacts could affect the transportation assets examined. The risk assessment includes information on likelihood of exposure and consequences associated with exposure to climate stressors. Then, several sets of potential adaptation options are presented for areas with relatively high risks. The three full subarea vulnerability assessments are included as Appendix D to this report.

New York: Long Island South Shore

The assessment of vulnerability and risk of the transportation network on the South Shore of Long Island yielded the following lessons learned:

- Federal, state, regional, and local agencies responsible for coastal resilience and emergency management could work together to build a comprehensive adaptation strategy that addresses vulnerability and risk in the entire South Shore. These agencies could monitor climate change over time and continue discussions about risk tolerance in the South Shore of Long Island and the thresholds for taking actions in the areas of risk mitigation, infrastructure adaptation, and strategic retreat from areas that will be inundated due to sea level rise.
- Transportation agencies could work with the U.S. Army Corps of Engineers as coastal resilience projects progress through the planning, design, and implementation process, re-run SLOSH models, and use other sources of information to determine what elements of the transportation system may remain exposed and vulnerable to the impacts of climate change after coastal protection measures are put into place. Agencies could consider improving area-wide flood prevention measures, including seawalls, groins, breakwaters, bulkheads, beach/wetlands renourishment in vulnerable areas that current resilience projects are not addressing.
- Specific to assets in this study area, New York State Department of Transportation and local transportation agencies could:
 - Develop area-wide adaptation strategies to address the vulnerability and risk of all infrastructure, including transportation assets, in populated areas of Long Beach Island, Barnum Island, Island Park, and Harbor Isle. Transportation-specific adaptation strategies will likely have limited effectiveness in these areas, aside from a few specific pieces of transportation infrastructure like rail and road bridges spanning Reynolds Chanel, Wreck Lead and Barnums Channel and traffic signal boxes and rail communications and signal components that can be raised or relocated. Some targeted investments could minimize damage when facilities do flood (e.g., waterproofing or raising electric, communications, and lighting equipment on bridges connecting the South Shore barrier islands to the mainland).
 - Continue monitoring climate conditions and impacts after the Nassau Expressway corridor projects are completed.
 - Rerun the exposure analysis for Loop Parkway, Meadowbrook Parkway, Wantagh Parkway, and Robert Moses Causeway (roads, embankments, and bridges) considering the impacts of sea level rise and storm surge once planned coastal resilience measures are in place. It is important to consider the current and future exposure, and the consequences of damage and disruption in current and future years, when planning and prioritizing adaptation measures on these parkways.
 - Review the high-level vulnerability and risk assessment presented in Appendix D, Table D.9, conduct more detailed assessments of the benefits and costs of potential adaptation strategies where needed, and identify funding for adaptation strategies that most cost-effectively address these risks.

- After conducting scour criticality and erosion assessments, take measures to prevent structural damage in event of flooding (e.g., superstructures that resist lateral flow, partially grouted riprap), prioritizing the Nassau Expressway, Meadowbrook Parkway, Loop Parkway, and Long Beach Road/Austin Boulevard corridors.
- Enhance ITS infrastructure, allowing for increased capacity on parallel roadways through integrated corridor management strategies, and maximize demand management by giving up-to-date information to travelers.
- Develop a transit contingency plan to facilitate evacuation and maintain access to the barrier islands via a bus bridge when the Long Island Rail Road Long Beach Branch is out of service due to flooding.

New Jersey: South Shore of Raritan Bay

The assessment of vulnerability and risk of the transportation network on the South Shore of Raritan Bay in New Jersey yielded the following lessons learned:

Federal, state, regional, and local agencies responsible for coastal resilience and emergency management should work together to build a comprehensive adaptation strategy that addresses vulnerability and risk along the entire south shore of Raritan Bay. They should monitor climate change over time and continue discussions about risk tolerance in northern New Jersey and the thresholds for taking actions in the areas of risk mitigation, infrastructure adaptation, and strategic retreat from areas that will be inundated due to sea level rise.

The findings of this research effort are specific to transportation and are meant to contribute to the discussion of options to help address vulnerability and assess risk for the entire south shore of Raritan Bay. The analysis was conducted for a “no-build” scenario in which there are no regional, site-specific, or asset-specific adaptation measures in place. Once potential adaptation scenarios (packages of complementary strategies) are identified, the SLOSH model should be re-run to determine before/after impacts.

Transportation agencies should work with the U.S. Army Corps of Engineers as coastal resilience projects progress through the planning, design, and implementation process, re-run SLOSH models, and use other sources of information to determine what elements of the transportation system may remain exposed and vulnerable to the impacts of climate change after coastal protection measures are put into place. Agencies should improve area-wide flood prevention measures, including seawalls, groins, breakwaters, bulkheads, beach/wetlands renourishment in vulnerable areas that current resilience projects are not addressing.

Specific to assets in this study area, New Jersey Department of Transportation, NJ TRANSIT, and local transportation agencies should consider:

- Reviewing the recommended adaptation strategies develop area-wide adaptation strategies to address the vulnerability and risk of all infrastructure, including transportation assets, in populated areas directly adjacent to the bay. Transportation-specific adaptation strategies will not be effective in these areas, aside

from things like traffic signal boxes and rail communications and signal components that can be raised or relocated. Some targeted investments could minimize damage when facilities do flood (e.g., waterproofing or raising electric, communications, and lighting equipment on bridges crossing major estuaries and creeks).

- Continue monitoring climate conditions and impacts after the Raritan River crossing projects are completed. New Jersey's investments in resilience represent a down payment that will protect those transportation assets for some time.
- Rerunning the exposure analysis for Routes 35 and 36 and the North Jersey Coast Line (roads, embankments, and bridges) considering the impacts of sea level rise and storm surge once planned coastal resilience measures are in place. It is important to consider the current and future exposure, and the consequences of damage and disruption in current and future years, when planning and prioritizing adaptation measures on these facilities.
- Enhancing ITS infrastructure, allowing for increased capacity on parallel roadways through integrated corridor management strategies, and maximize demand management by giving up-to-date information to travelers.
- Developing a transit contingency plan to facilitate evacuation and maintain access to the barrier islands via a bus bridge when the North Jersey Coast Line is out of service due to flooding.

Connecticut: Norwalk-Danbury Corridor

In a multimodal transportation corridor, a package of complementary adaptation strategies can be particularly effective at addressing vulnerability and risk. These strategies can be location-specific, they can affect multiple assets in close proximity, or they can be corridor-scale improvements.

The Norwalk-Danbury corridor is a typical case of a multimodal transportation corridor where flooding has a low likelihood of occurring in any given year, but where the consequences of flooding are high. Connecticut Department of Transportation, Metro-North Railroad, and local governments in the corridor should engage in conversations about risk tolerance and scale adaptation efforts to the level of impact that is acceptable. For example, measures could be put in place to prevent flooding from ever occurring, or infrastructure could be adapted so that it can tolerate periodic flooding without needing extensive repairs.

Overall Findings and Recommendations of Subarea Assessments

- There is a shortage of historical information on the extent, duration, and cause of transportation system disruptions, the cost of repairs, and the impacts of disruptions in service. State Departments of Transportation, Metropolitan Planning Organizations, transit operators, counties, and local governments could monitor how sea level rise, coastal and inland flooding, extreme heat, wind-blown debris, and other climate stressors are impacting the region's transportation system over time. Transportation agencies could then use this information to inform future vulnerability and risk assessments, help prioritize specific

adaptation projects, and inform planning and design work that occurs as capital projects, major rehabilitation projects and normal replacement projects advance through planning and feasibility studies and into preliminary engineering. Information on weather-related incidents that exceed a pre-determined threshold for reporting (similar to crash reporting thresholds) could be collected by first responders and recorded in incident reporting databases and transportation management systems like the INFORM (INformation FOR Motorists) system on Long Island, and aggregated regionally by TransCOM. The following information could be useful:

- More comprehensive information about the geographic extent and duration of closures and service disruptions on roads, transit lines, and waterways. Extent and duration of major disruptions are collected inconsistently and for a limited portion of the regional highway system by state and local police. Transit agencies may maintain their own historical records on rail service disruptions. There is no mechanism to collect and aggregate information at a regional scale on closures and service disruptions for arterials, local road networks, local bus services, and transportation services for communities of concern. There also are no consistently-used tags or indicators in existing reports so that disruptions due to weather events can be flagged, aggregated across all modes at a corridor or regional scale, and analyzed later.
- Primary and (if readily observable) secondary causes of road closures, transit service disruptions, drawbridge failures, and other incidents. For example, is rail service disrupted due to flooded tracks, or because water inundated a power substation and caused an electrical power failure? While detailed diagnostics and root cause analyses may take some time to complete after a major event, basic observations can be collected and reported on a standard incident reporting form by first responders (for example, a set of check boxes or drop down menus with pre-defined choices).
- Extent of damage and cost to repair or replace damaged infrastructure or components. Precise cost information may not be available until the repairs are completed, but a set of simple qualitative choices could be included on an incident reporting form (no damage/minor to moderate damage/severe damage or total destruction)
- Other pertinent information to estimate the impacts of disruption. For example, for roadways: one or more lanes closed, total roadway closure with diversions to alternate routes, total roadway closure with diversion routes also impacted. For transit: Service operating with diversions and delays in service, service limited (lines truncated or suspended at some stations/stops); service suspended on entire line/system.
- State Departments of Transportation, Metropolitan Planning Organizations, transit agencies, and local governments could use the results of anecdotal and data-based analysis to refine how climate risk is integrated into asset management practices and procedures, project formulation and design decisions, and day-to-day maintenance and operations.

4.4 Facility-Level Assessments of Adaptation Options to Address Vulnerability and Risk

A regional or subarea assessment of vulnerability and risk can be used to help identify specific facilities or assets that warrant a more detailed engineering informed adaptation assessment. However, for the Post-Sandy study, engineering-informed adaptation assessments were conducted first, because the region was still very focused on recovery from Hurricane Sandy when the project began.

The Project Guidance Committee (PGC) for this study recommended a “long list” of potential facilities for an engineering informed adaptation assessment. Through a series of group discussions and one-on-one conversations, the project team and the PGC narrowed down the list to ten facilities. Geographic diversity, diversity of climate stressors and impacts, and diversity of modes all factored into the final selection of which facilities to assess. The study team also was concerned with avoiding duplication of effort with respect to the work being undertaken by the project partners and others in the study area. Finally, given that this study was undertaken as a research effort, the budget limited the selection to ten facilities from around the region.

Figure 4.20 shows the locations of facilities that were chosen to test an engineering-informed adaptation assessment.

Table 4.6 summarizes the characteristics of the ten facilities, with an indication of sensitivity and exposure to climate stressors. Table 4.7 shows the range of potential failure modes associated with the assets.

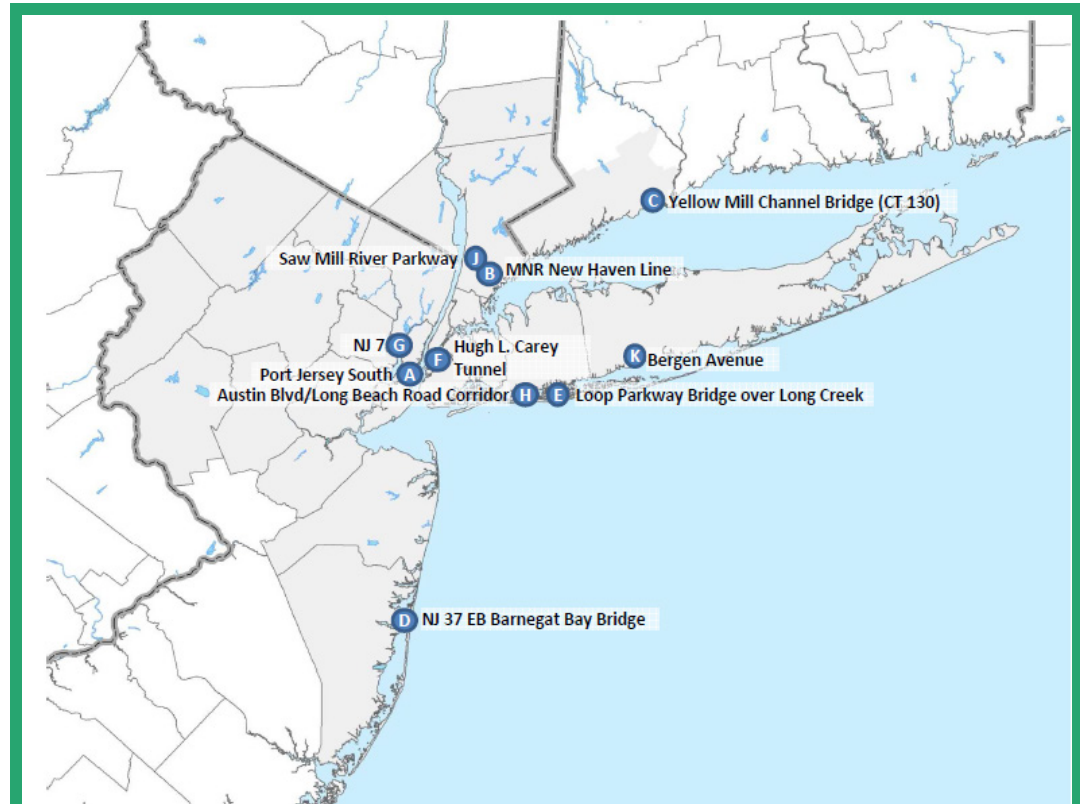


Figure 4.20. Map. Facilities selected for engineering-informed adaptation assessment.

(Source: Cambridge Systematics, Inc.)

Table 4.6. Facilities by potential climate stressor.

MAP ID	Facility Description			Potential Climate Stressor						
	Name	Location	Type/ Subtype	Sea Level Rise	Storm Surge	Extreme Precip.	Extreme Temp.	High Winds	Snow- storm	Other
A	Port Jersey South	Jersey City, NJ (Hudson)	Port	Current/ Future	Current/ Future	Current/ Future		Current/ Future		
B	MTA Metro-North Railroad New Haven Line	Pelham, NY (Westchester)	Rail Track and Power Infrastructure	Future	Future	Current/ Future	Current/ Future	Current/ Future	Current/ Future	
C	Yellow Mill Channel Bridge (CT 130)	Bridgeport, CT (Fairfield)	Draw Bridge	Future	Current/ Future					
D	NJ 37 EB over Barnegat Bay Drawbridge	Toms River, NJ (Ocean)	Draw Bridge	Future	Future	Future		Future	Future	
E	Loop Parkway Bridge over Long Creek	Town of Hempstead, NY (Nassau)	Draw Bridge	Current/ Future	Current/ Future			Current/ Future		
F	Hugh L. Carey Tunnel (I-478, formerly Brooklyn Battery Tunnel)	New York, NY (New York/Kings)	Roadway Tunnel	Current/ Future	Current/ Future	Current/ Future				Seismic Risk
G	NJ 7	Kearny, NJ (Hudson)	Roadway/ Drainage	Future	Current/ Future	Current/ Future				
H	Austin Blvd./Long Beach Road Corridor	Long Beach, NY (Nassau)	Roadway	Current/ Future	Current/ Future	Current/ Future		Current/ Future		Storm Direction
J	Saw Mill River Parkway - South of Lawrence Street	Dobbs Ferry, NY (Westchester)	Roadway			Current/ Future				
K	Bergen Avenue	West Babylon, NY (Suffolk)	Roadway	Current/ Future	Current/ Future	Current/ Future				

Table 4.7. Facilities by potential failure mode.

MAP ID	Asset Description			Potential Failure Mode								
	Name	Location	Type/ Subtype	Overtopping/ Inundation	Erosion/ Washouts	Scour	Foundation/ Structural Failure	Drainage Failure	Debris	Electrical/ Mechanical Failure	Heat Damage	Other
A	Port Jersey South	Jersey City, NJ (Hudson)	Port	Current/ Future					Current/ Future	Current/ Future		
B	MTA Metro-North Railroad New Haven Line	Pelham, NY (Westchester)	Rail Track and Power Infrastructure	Future	Future				Current/ Future	Current/ Future	Current/ Future	
C	Yellow Mill Channel Bridge (CT 130)	Bridgeport, CT (Fairfield)	Draw Bridge	Current/ Future					Current/ Future	Current/ Future		
D	NJ 37 EB over Barnegat Bay Drawbridge	Toms River, NJ (Ocean)	Draw Bridge			Future	Future			Future		Vessel Strike
E	Loop Parkway Bridge over Long Creek	Town of Hempstead, NY (Nassau)	Draw Bridge		Current/ Future	Current/ Future	Current/ Future		Current/ Future	Current/ Future		
F	Hugh L. Carey Tunnel (I-478, formerly Brooklyn Battery Tunnel)	New York, NY (New York/ Kings)	Roadway Tunnel	Current/ Future	Current/ Future		Current/ Future	Current/ Future	Current/ Future	Current/ Future	Current/ Future	
G	NJ 7	Kearny, NJ (Hudson)	Roadway/ Drainage	Current/ Future	Current/ Future		Current/ Future	Current/ Future				

Table 4.7. Facilities by potential failure mode (continuation).

MAP ID	Asset Description			Potential Failure Mode								
	Name	Location	Type/ Subtype	Overtopping/ Inundation	Erosion/ Washouts	Scour	Foundation/ Structural Failure	Drainage Failure	Debris	Electrical/ Mechanical Failure	Heat Damage	Other
H	Austin Blvd./ Long Beach Road Corridor	Island Park, NY (Nassau)	Roadway	Current/ Future	Current/ Future	Current/ Future	Current/ Future	Current/ Future	Current/ Future	Current/ Future		
J	Saw Mill River Parkway - South of Lawrence Street	Dobbs Ferry, NY (Westchester)	Roadway			Current/ Future						
K	Bergen Avenue	West Babylon, NY (Suffolk)	Roadway	Current/ Future	Current/ Future	Current/ Future						

Each of the analyses followed the process for addressing climate risk and vulnerability at a facility level described in Appendix B of this report. However, the specific study area parameters, as well as the climate information asset data used for each assessment was refined by the stakeholders in working with the study team. For example:

- Climate data was acquired from various local and national sources and may be inconsistent from assessment to assessment.
- Depending on the scale of the facility or asset, some analyses were not completed in all the assessments (e.g., regional economic and impact to disadvantaged communities).
- Stakeholder risk tolerance is critical to understanding the scenario and the adaptation measures proposed (ex. NJ7 chose a scenario that would not address hurricane level storm surge, whereas others picked scenarios that were very conservative past the expected lifespan).

The diverse set of facilities studied as part of this assessment process yielded a wealth of lessons learned that can apply to future assessments in this region and beyond. Case studies were drawn from a range of geographies, modes, climate stressor exposure, and sensitivity. In this early stage of transportation

engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

The ten facility-specific assessments are included as Appendix E to this report.

A number of lessons were drawn from the assessments:

- Agency partners have data that can be used to conduct the assessments, but information is not organized for this purpose. The “ideal” data set may not exist or may not be readily accessible (e.g., not digitized). Thus, agencies should consider:
 - Building in ample time/resources for data collection at the outset of the vulnerability and risk assessment process;
 - Prioritizing the most critical data for collection (e.g., related to key components);
 - Leveraging asset management and maintenance management systems and information (e.g., remaining useful life, repair and replacement costs) where possible; Identifying deficiencies and developing proxies early on; and
 - Setting expectations regarding the analysis process and outcomes early on based on availability of data to support the analysis and various steps.
- Agencies typically do not maintain information on failure thresholds for assets and asset components, and thus the thresholds may need to be developed specifically for this analysis.
- Over time, asset owners, with the assistance and technical support of State Departments of Transportation and Metropolitan Planning Organizations, are collecting, archiving, organizing and publishing their asset data and resilience-related information in accessible formats. However, they will need sustained, continuous support or these initial efforts to organize data, spurred by the urgency of repairing and fortifying assets in the wake of Hurricane Sandy, may fade away.
- Information on actual damage and disruption that has occurred in the past (and is occurring regularly in some coastal areas impacted by sea level rise) is critical to benefit-cost analysis and prioritization of adaptation strategies. Often, adaptation options are implemented during a major rehabilitation or normal replacement project. Thus, it is most important to have a mechanism to archive the results of the vulnerability and risk assessment so the information can be retrieved and considered in project design.

- In order to prioritize adaptation strategies and conduct benefit-cost analysis, agencies need to have discussions about acceptable levels of risk associated with assets of various types. For example, is it acceptable for an emergency evacuation route to be closed due to storm surge inundation for a few hours at the peak of the storm? Or does it need to be available at all times? What if there is a parallel alternative route that could support emergency response and recovery operations? Answers to questions like these will be crucial to selecting the appropriate adaptation response.
- Those assessments that show potential major impacts for disadvantaged communities (ex. HLCT) need to be better quantified/studied in the future so that these can be better accounted for when considering cost-benefit of adaptation strategies
- There also were several process-related observations and guidance gleaned from the assessment process:
 - Identify state or regional climate projection resources most appropriate for the agency. If a state has officially endorsed/adopted sea level rise or other climate projections, those should be strongly considered unless there are circumstances that warrant another source.
 - Climate science projections are updated regularly, so sources should be reviewed. New studies and research regularly become available, but the findings need to be vetted by experts. Adopt clear guidance on the use of climate data for agency-use, and review sources regularly for updates. Also, the level of detail available from climate scientists and reports or tools might be more than is useful for these assessments.
 - Information on failure thresholds and design thresholds related to climate stressors may not be readily available. Agencies should allow ample time to collect this information, and match expectations for the outcome of this analysis to the data that are available to support it.
 - While it is useful to have thresholds as a starting point, in some cases an agency may need to consider amending thresholds that inform application of design standards given the projected increases in the frequency, magnitude, and duration of extreme events.
 - Understand and communicate to designers and other stakeholders the distinction between exposure to a climate stressor and sensitivity to that stressor.
 - It is very difficult to assemble a comprehensive picture of damage given the multiple sources of funding for repair and the dollar threshold for reporting damage. Acute damage is much easier to quantify than longer-term deterioration due, for example, to salt water intrusion.

5

Integrating Climate Resilience in Transportation Decision-Making

Climate vulnerability and risk assessments are not intended to be standalone efforts; nor should adaptation strategies be implemented in a vacuum. This section of the report provides examples of how a climate vulnerability and risk assessment and related information—such as developed through the Post-Sandy study—can be incorporated into an agency’s policies, plans, and programs, and how the information can help deliver better projects. Section 4.1 introduces the process used in the Post-Sandy Study for defining and analyzing potential solutions to address climate risk and vulnerability. Appendix B contains more detailed, step-by-step methodology for addressing climate risk and vulnerability at a facility level.

Effective management of transportation assets is becoming an increasingly important function of transportation agencies, particularly as they transition out of an era of overseeing well-funded system expansion projects and into a future with a mature multimodal transportation system that provides opportunities for new and more efficient types of services and uses. Changing transportation technologies present unprecedented opportunities to move people and freight efficiently, but as transportation agencies use new policies, operational strategies, and targeted investments to take full advantage of these opportunities, they are increasingly aware of the risks that threaten to undermine the safety and performance of the transportation system.

Understanding and responding appropriately to vulnerabilities and risks that external factors like climate change present to transportation agencies and users of the transportation system is a critical and immediate challenge. It will require new mechanisms for coordinating across geographies, modes, and types of infrastructure.

This chapter is organized into six subsections:

- Section 5.1 provides examples of how transportation agencies in the Post-Sandy study region are currently improving the system’s resilience to climate change;
- Section 5.2 identifies barriers to adapting the system;

- Section 5.3 describes potential approaches to incorporate climate change resilience into decision-making;
- Section 5.4 focuses on agencies can address climate risk in transportation asset management;
- Section 5.5 discusses opportunities for cross-agency coordination; and
- Section 5.6 summarizes conclusions and next steps from the Post-Sandy study.

5.1 Current Transportation Adaptation Efforts in the Post-Sandy Study Region

All three state Departments of Transportation that participated in the Post-Sandy study are actively addressing climate change in their planning and project development processes. For example:

- Connecticut Department of Transportation (CTDOT) has been addressing climate change in policy and planning since the 2005 adoption of the state's Climate Change Action Plan. A refreshed Climate Preparedness Plan, adopted in 2013, calls on state agencies to integrate climate change adaptation into existing plans. CTDOT is proactively identifying assets with known vulnerabilities to climate stressors in their asset inventory and condition assessment databases (based on expert input and historical records). This information will help inform future design of normal replacement projects so that newly reconstructed bridges, culverts, roadways, rail lines, and other assets are resilient to the anticipated impacts of climate change through their next life cycle.
- New Jersey Department of Transportation has developed a new drainage management system that ranks locations based on frequency, duration, and severity of flooding. The drainage management system will be one important source of information to help the state to appropriately scale and prioritize future rehabilitation and replacement projects.
- New York State Department of Transportation has advanced resilience efforts on a number of fronts. The state's Community Risk and Resiliency Act (CRRRA), signed into law in September 2014, is intended to ensure that state monies and permits for transportation and other infrastructure projects include consideration of future physical climate risk and extreme weather events (including sea level rise and changes in storm surge and flooding). New York State Department of

Recent federal laws and regulatory actions increase the prominence of climate risk and resilience in the transportation planning and programming activities undertaken by state Department of Transportations and Metropolitan Planning Organization in the U.S. Notably:

- The Moving Ahead for Progress in the 21st Century Act (MAP-21) further institutionalizes asset management by requiring that all state Departments of Transportation develop risk-based asset management plans for National Highway System facilities.
- The Fixing America's Surface Transportation Act (or FAST Act) requires states and Metropolitan Planning Organizations to explicitly address resilience in their transportation plans and programs. Specifically, to "improve the resiliency and reliability of the transportation system and reduce or mitigate stormwater impacts of surface transportation."

Transportation has: actively participated in the development of climate forecasts and resilience-related policies through the Climate Action Council; assisted in the development of “Responding to Climate Change in New York State” (ClimAID) with climate forecasts and risk information specific to New York State; and partnered with Cornell University, Columba University, the State University of New York, and others to develop tools to assist in incorporating climate risk information into the design and operation of the state’s transportation assets and services.

Appendix F of this report has a list of research reports, tools, and other resources available from federal, state, regional, and local sources.

There are several examples of cross-sector collaborations that take into account transportation infrastructure as part of broader efforts to protect communities, such as the following:

- The New York Rising initiative, led by the New York Governor’s Office of Storm Recovery, is identifying and implementing solutions to strengthen the State’s infrastructure and critical systems in partnership with affected communities and non-governmental organizations.
- The New Jersey Climate Adaptation Alliance is focusing on climate change preparedness for built infrastructure and other key impacted sectors (public health; watersheds, rivers and coastal communities; agriculture; and natural resources).
- The New York City Panel on Climate Change (NPCC) is an independent body that advises New York City on climate risks and resiliency. The NPCC has produced regional climate forecasts that extend to 2100 and established a risk management framework to help address mitigation and resiliency across the entire metropolitan region, including consideration of climate change’s impacts on regional infrastructure and the services it provides.

Members of the four Metropolitan Planning Organizations that participated in this study, the New York Metropolitan Transportation Council (NYMTC), the North Jersey Transportation Planning Authority (NJTPA), the Greater Bridgeport and Valley Metropolitan Planning Organization (GBVMPO), and the South Western Region Metropolitan Planning Organization (SWRMPO) are active participants in initiatives inside and beyond their planning area boundaries. Through the multi-MPO Metropolitan Area Planning Forum (MAP Forum), these MPOs have fostered regional and mega-regional dialogue about adapting the transportation system to climate change.

Individual system and facility operators such as the New York Metropolitan Transportation Authority, the Port Authority of New York & New Jersey, NJ TRANSIT, and New York City Department of Transportation are national leaders in proactively planning for climate change, building more resilient transportation systems and ensuring that critical electrical and communications systems are also resilient to climate change. Finally, at the local level, counties, cities, and towns are advocating for and co-funding transportation system adaptation measures that address social equity and are consistent with locally-driven economic initiatives and community development plans.

These are just a sample of the steps transportation agencies have taken to address vulnerability and risk associated with climate change. The next section addresses obstacles that still need to be overcome.

5.2 Barriers to Effective Adaptation

Throughout this project, a number of common themes emerged that will likely present obstacles and challenges for transportation agencies that are struggling to address climate change:

- Many climate projections are available.** Although the scientific community agrees that the climate is changing, there are many projections of how much sea level will rise, how often extreme precipitation events will occur when the ground is already saturated, or how much average temperatures will increase. Almost four dozen climate models project future conditions using multiple scenarios of future levels of climate change, each in turn based on assumptions about future emissions of greenhouse gases and other variables. In addition, there are numerous techniques for downscaling output from the coarse global climate models to higher spatial resolution, as is clear in the range of climate forecasts presented in Section 3.1: Climate Data and Projections. The most statistically rigorous way to present the forecasts is in terms of probabilities (see, for example, Table 5.1). However, the probabilities can be interpreted as a lack of certainty, and that uncertainty in turn can lead to indecision and, worse, delays in implementation of adaptation measures that clearly need to be in place under any future scenario. The next section will address how to improve an agency’s decision making process in light of these uncertainties.

Table 5.1. New Jersey Climate Adaptation Alliance Projected Sea Level Rise Estimates for New Jersey (feet).

Year	Central Estimate 50% probability SLR meets or exceeds...	Likely Range 67% probability SLR is between...	1-in-20 Chance 5% probability SLR meets or exceeds...	1-in-200 Chance 0.5% probability SLR meets or exceeds...	1-in-1000 Chance 0.1% probability SLR meets or exceeds...
2030	0.8 ft.	0.6-1.0 ft.	1.1 ft.	1.3 ft.	1.5 ft.
2050	1.4 ft.	1.0-1.8 ft.	2.0 ft.	2.4 ft.	2.8 ft.
2100 Low Emissions	2.3 ft.	1.7-31. ft.	3.8 ft.	5.9 ft.	8.3 ft.
2100 High Emissions	3.4 ft.	2.4-4.5 ft.	5.3 ft.	7.2 ft.	10 ft.

Source: Kaplan, M., M. Campo, L. Auermuller, and J. Herb. 2016. Assessing New Jersey’s Exposure to Sea-Level Rise and Coastal Storms: A Companion Report to the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel Report. Prepared for the New Jersey Climate Adaptation Alliance. New Brunswick, NJ: Rutgers University. Note: Estimates are based on Kopp et al. (2014). Columns correspond to different projection probabilities. For example, the ‘Likely Range’ column corresponds to the range between the 17th and 83rd percentile; consistent with the terms used by the Intergovernmental Panel on Climate Change (Mastrandrea et al., 2010). All values are with respect to a 1991-2009 baseline. Note that these results represent a single way of estimating the probability of different levels of SLR; alternative methods may yield higher or lower estimates of the probability of high-end outcomes.

- **There is spotty historical data on the impacts of discrete weather events on transportation systems.** Transportation agencies have a limited understanding of historical impacts of weather events on the transportation system (in terms of infrastructure **damage** requiring repair and impacts like flooding that temporarily close facilities and **disrupt** the movement of people and freight). Thus, agencies have limited ability to project and quantify the impacts associated with future damage and disruption when considering the appropriate scale of an adaptation response. Without the ability to quantify the dollar amount of avoided damage and disruption, it is not possible to conduct a rigorous benefit-cost analysis of potential adaptation and mitigation strategies. The three state region's TransCOM network collects and archives data from transportation management systems (including travel speeds and incidents such as roadway closures) and in recent years has enabled analyses of event-related damage and disruption in the region. In addition, there are now numerous private sector sources of operational data on large portions of the regional transportation network.
- **Information on specific transportation facilities can be hard to find or in non-digital format.** While agencies are making great strides in advancing the collection, management, and sharing of asset-related data, there is still a gap in understanding as-built conditions relative to current design standards, the level of deterioration of transportation assets at a given point in time, the remaining useful life of an asset, projects in the development pipeline from various program areas (safety, system management, maintenance, or capacity expansion), and operational details such as historical, current, and projected demand for movement of people and freight. Individuals within one organizational "silo" may have unparalleled knowledge of one attribute, but there are not good systems and related business processes in place to share information within and between agencies.
- **Cross-agency coordination and jurisdictional issues can create delays and obstacles.** Multiple agencies may have jurisdiction over a corridor or area that is vulnerable to the impacts of climate change and extreme weather events. Similarly, there may be multiple scales of response, implemented by different entities over time that would need to work in concert to protect the transportation system (e.g., U.S. Army Corps coastal flood adaptation measures combined with a rail operator's strategy of elevating vulnerable electrical system components above projected flood elevations once the Army Corps' project is in place). Coordinating adaptation efforts over a large area, over a period of time, and for multiple infrastructure systems (transportation, power, water and sewer, communications, housing, and other structures) is an overwhelming challenge.
- **Legal and regulatory hurdles also can hinder adaptation responses.** Even when roles and responsibilities are clear, there may be legal and regulatory barriers to implementing mitigation and adaptation solutions. For example, obstacles to right of way acquisition, lawsuits from impacted landowners, or required studies of environmental and community impacts can delay or block a project. Furthermore, it is not clear if imposition of financial and other costs to anticipate climate change will withstand potential lawsuits from those who will claim they are harmed by such decisions (for example, waterfront homeowners have objected to proposals to raise elevations of sea walls and sand dunes).
- **There are limited sources of funding for transportation adaptation projects, and those that do exist are highly sought-after and competitive, or can only be accessed in the wake of a disaster.** Thus, most proactive adaptation either needs to be folded into projects in development pipeline or there needs to be a strong case to develop and implement standalone adaptation projects.

5.3 Using Climate Change Data to Inform Transportation Decision Making

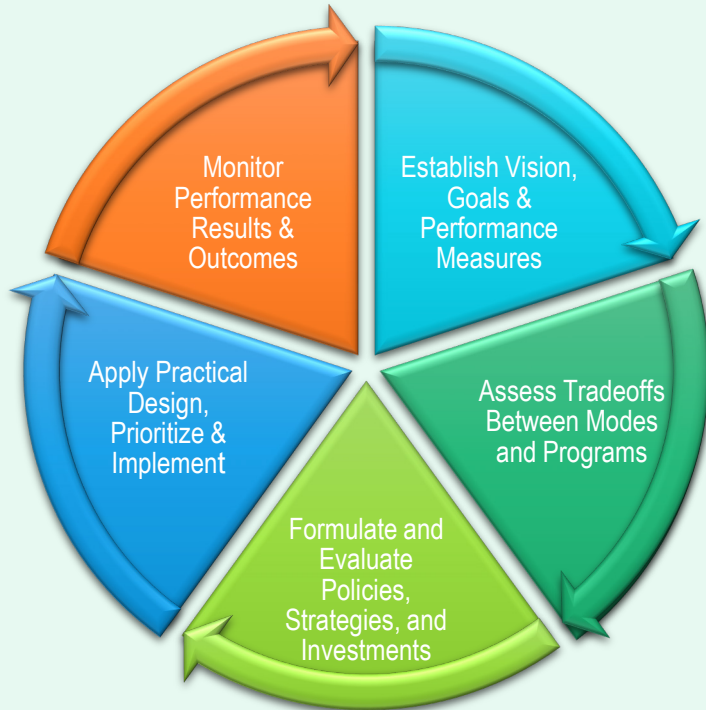


Figure 5.1. Flow chart. Generic transportation planning and programming cycle.

(Source: Cambridge Systematics, Inc.)

Transportation agencies are responsible for operating the Post-Sandy study region's transportation system day-to-day, forecasting how people and freight will use the system in the future, and making long-term investment decisions to anticipate changing future conditions, but typically based on incomplete or uncertain information. Agencies can face "analysis paralysis" due to an overwhelming amount of uncertainty and a range of variables that must be considered when considering potential options to make a system more resilient to the impacts of climate change.

Nonetheless, long term decisions on transportation systems and infrastructure are being made. Given the expected impacts of climate change, not incorporating potential risks from climate change into these decisions most likely will increase risk of premature system failure and hazard to people and personal property. Disruption due to climate change introduces risks to overall system performance.

This section discusses various ways that transportation agencies can incorporate climate change data and consider risks associated with climate change into decision making. Figure 5.1 shows a generic example of a planning and programming cycle used by transportation agencies:

- Establish clear goals, objectives, and performance measures linked to a statewide and/or regional vision;
- Conduct program-level tradeoff analysis to help select realistic and achievable performance targets;
- Determine what combinations of policies, operational strategies, and investments will minimize risk and maximize opportunity relative to targets;

- Use practical design principles in the project development process, prioritize and schedule projects for implementation based on lifecycle benefit-cost analysis; and
- Monitor performance results and outcomes over time, and feed performance information back in to other steps to continuously improve each step.

Table 5.2 shows examples of how climate vulnerability and risk data can be integrated into each step.

Table 5.2. Incorporating climate risk and vulnerability into transportation planning and programming.

Step	Opportunities to Integrate Climate Vulnerability and Risk
Establish Vision, Goals & Performance Measures	<ul style="list-style-type: none"> • Consider resilience to climate change in each element of policy framework for statewide and regional long range plans, transportation improvement programs, risk-based transportation asset management plans, and mode-specific plans. • Establish regional and statewide performance measures related to climate change, resilience, and sustainability.
Assess Tradeoffs Between Modes and Programs	<ul style="list-style-type: none"> • Include climate risk as one key element of an agency’s broader risk management framework. Include climate-related risks in agency risk register. • Test implications of various funding allocation decisions at the level of program areas and modes. How do investments in adaptation strategies vs. safety vs. pavement/bridge maintenance vs. mobility affect a state’s or region’s ability to meet short-term and long-term performance targets?
Formulate and Evaluate Policies, Strategies, and Investments	<ul style="list-style-type: none"> • Propose specific adaptation strategies based on assessment of regional, subarea, and asset-level vulnerability and risk. • Consider cost and feasibility of options. Some adaptations may be relatively expensive (perhaps requiring additional sources of revenue or outside financial support).
Apply Practical Design, Prioritize & Implement	<ul style="list-style-type: none"> • Make changes to assumptions about climate stressors, particularly for asset classes that have longer useful life and are in high-risk areas. • Conduct "bottom up" prioritization of adaptation investments to complement "top down" program-level tradeoff analysis. • Program adaptation strategies at appropriate time frames given understanding of pace of climate change (including timing of risks) and key milestones.
Monitor Performance Results & Outcomes	<ul style="list-style-type: none"> • Monitor changing climate conditions and keep abreast of latest climate projections and models to inform design and prioritization decisions. • Amass database of weather events that cause damage or disruption to the transportation system. Archive operational data and damage reports, including costs and duration of closure. • Conduct “plan vs. actual” analysis to measure effectiveness of adaptation investments in reducing or mitigating damage and disruption.

Continuous vs. Discrete Decisions

It is important to consider whether adaptation options are continuous or discrete:

- A **continuous** decision is one that in theory can be fine-tuned, such as raising height of coastal defenses or freeboard. In practice, designers often use integer increments such as raising sea walls or freeboard in one foot increments.
- A **discrete** decision is one involving changes in design (e.g., use of different materials for a roadway embankment or different designs for bridge piers) or where facility components can be ordered in increments (e.g., culvert diameters often differ by 6" increments).

The selection of adaptation can depend in part on what the selected climate scenarios show. For discrete decisions, one should consider whether the preponderance of scenarios selected implies which discrete choice is better. For example in the case of a culvert there are a range of peak flows that different diameter culverts can accommodate. The choice of the diameter for a culvert can depend in part on which size is best matched to the projected change in peak flows from the selected scenarios.

Climate vulnerability and risk can be adopted as part of a broader risk assessment and risk management process, in which multiple categories of risk are assessed and compared objectively to help set priorities for funding. Climate risk is only one category of risk considered by transportation agencies. The findings of a climate-specific vulnerability and risk assessment are not intended to stand alone, but instead should be integrated into a holistic risk management framework in order to formulate projects that make best use of limited resources and address a broad set of regional goals and desired outcomes

The approach to adaptation-related decision making portrayed in Figure 4.1 and described in more detail in Appendix B is designed to help decision makers consider risk (a combination of likelihood and consequences; the degree to which facility damage and system disruption are acceptable to an agency and its customers) and cost (to repair damage and broader economic costs associated with disruption). As noted above, the wide range of potential changes in climate can be an impediment to sound adaptation decision making.

A way forward is to focus first on the characteristics of the decision being made and then use that information to narrow the range of climate scenario choices to be considered. There are three key factors to consider initially:

1. **Tolerance for risk.** How acceptable is the potential harm from climate risks? Consider both the potential consequences of harm (e.g., severity, length and extent of disruption, and criticality of the facility) and the degree to which such harm is acceptable to decision makers and the public.
2. **Costs of adaptation and available resources.** High costs for adaptation options will make it more difficult to address higher consequence/lower probability outcomes. Low marginal costs should make it easier to address such outcomes.
3. **Feasibility.** Engineering and environmental constraints, community acceptance, operational implications, and economic considerations all can influence what strategies should be considered in an adaptation assessment. These considerations should enter the decision making process early.

The more risk aversion, the more one should focus on lower probability, high consequence climate scenarios (which, in turn, may lead to higher-cost adaptation responses across the board). If cost (due

to a lack of resources) is the driving consideration, an agency may focus only on the higher-probability climate scenarios, and accept the risk that a “black swan” event could cause widespread damage and disruption at some point. Initial discussions with stakeholders about the range of feasible or politically-acceptable adaptation options can have implications for cost later in the design process.

Climate risk and vulnerability assessments do not provide a precise recommended course of action, but rather give order of magnitude estimates of future impacts to help agencies narrow down the range of appropriate responses, and provide input on the timing of those responses. In a corresponding manner, a range of adaptation options can have order of magnitude differences in costs and potential benefits depending on when and how they are implemented.

The concept of “adaptation pathways” can be useful to guide investment decisions. Figures 5.2 and 5.3 show examples of decision trees with pathways and decision points when assumptions and climate projections can be revisited, and terminals representing courses of action that should be abandoned when changing conditions indicate that they are either too aggressive or not aggressive enough to prepare for climate change. The challenge is to select an option that can function under a wide variety of different climate (and other) conditions or can be modified as appropriate when change in climate makes the original course untenable. Here too, such consideration as risk aversion, cost, and feasibility will likely be relevant to selecting adaptation pathways.

An adaptation pathways approach is analogous to the concept of facility-specific master plans that lay out triggers (usually average daily traffic for highways or passenger enplanements for airports) for expansion projects. In a similar vein, adaptation projects can be triggered by observed data on climate-related impacts, such as elevation of Mean Higher High Water or number of hours per year that a facility is closed due to flooding. The challenge is to set these triggers such that there is sufficient lead time to plan, fund, and implement the necessary adaptation project.

Technical Experts: Implementation

At an April 2014 meeting of the Technical Experts Group established for this study, the participants discussed the following approaches to planning and designing adaptation strategies:

- Can we identify plausible extremes that merit planning for now? There are two ways to do this:
 - Look at other meteorological extremes occurring around the world and see if they could happen here. What if those kinds of events happened here?
 - Are there other kinds of events that could combine to form an extreme event?
- Agencies need to look at risk management broadly, considering climate alongside safety, asset, and performance-related risks.
- Fundamentally a decision on adaptation may boil down to deciding which type of regret is least attractive. Is it better to avoid system failure at the risk of over-adapting (e.g., building something too big) or is it better to avoid high cost or less feasible outcomes accompanied by a greater risk of system failure or diminishment of services?

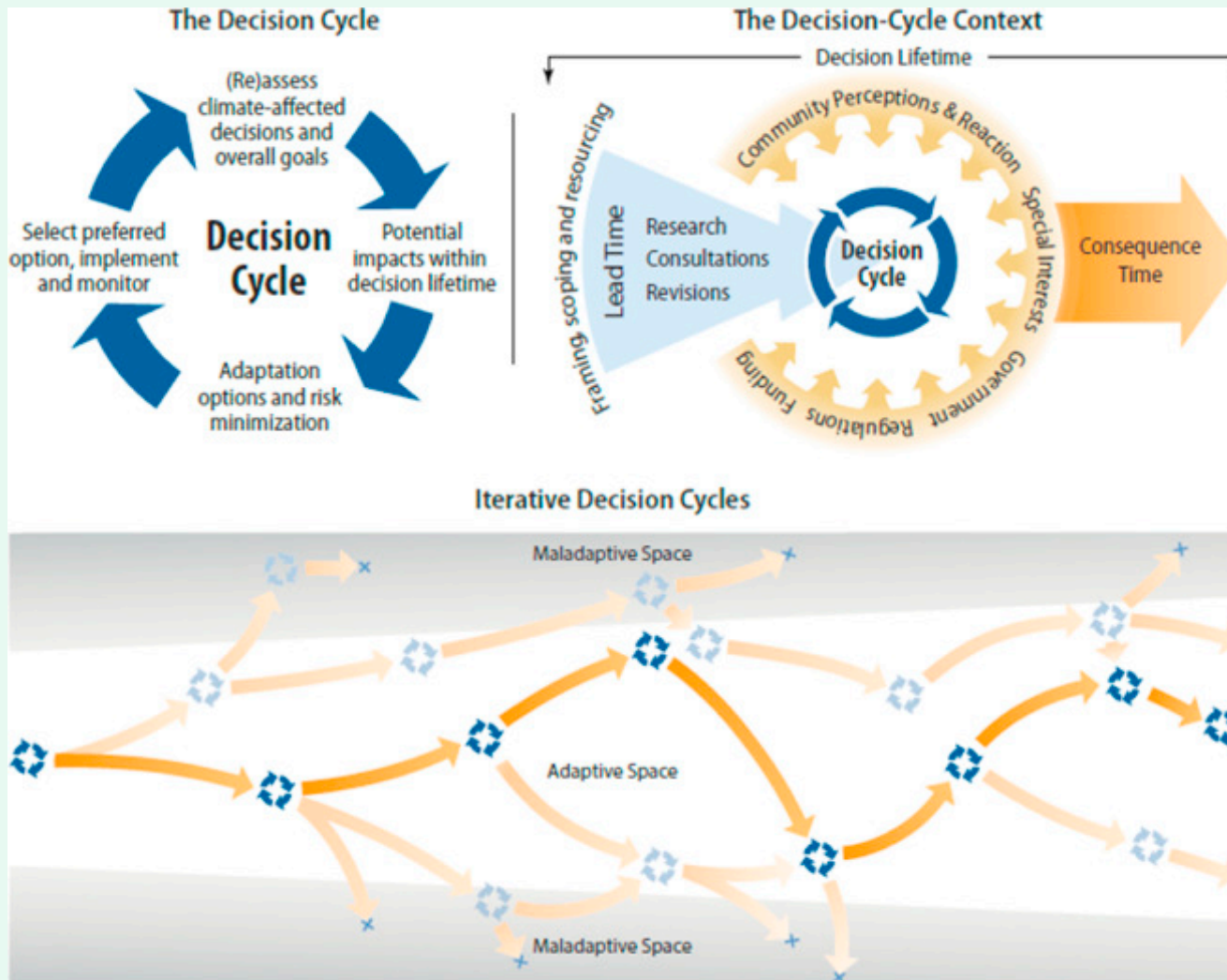


Figure 5.2. Diagram. “Adaptation Pathways” approach to decision-making.

(Source: “Reconceptualising adaptation to climate change as part of pathways of change and response.”
 Wise, R.M., et al. *Global Environmental Change*, January 2014.)

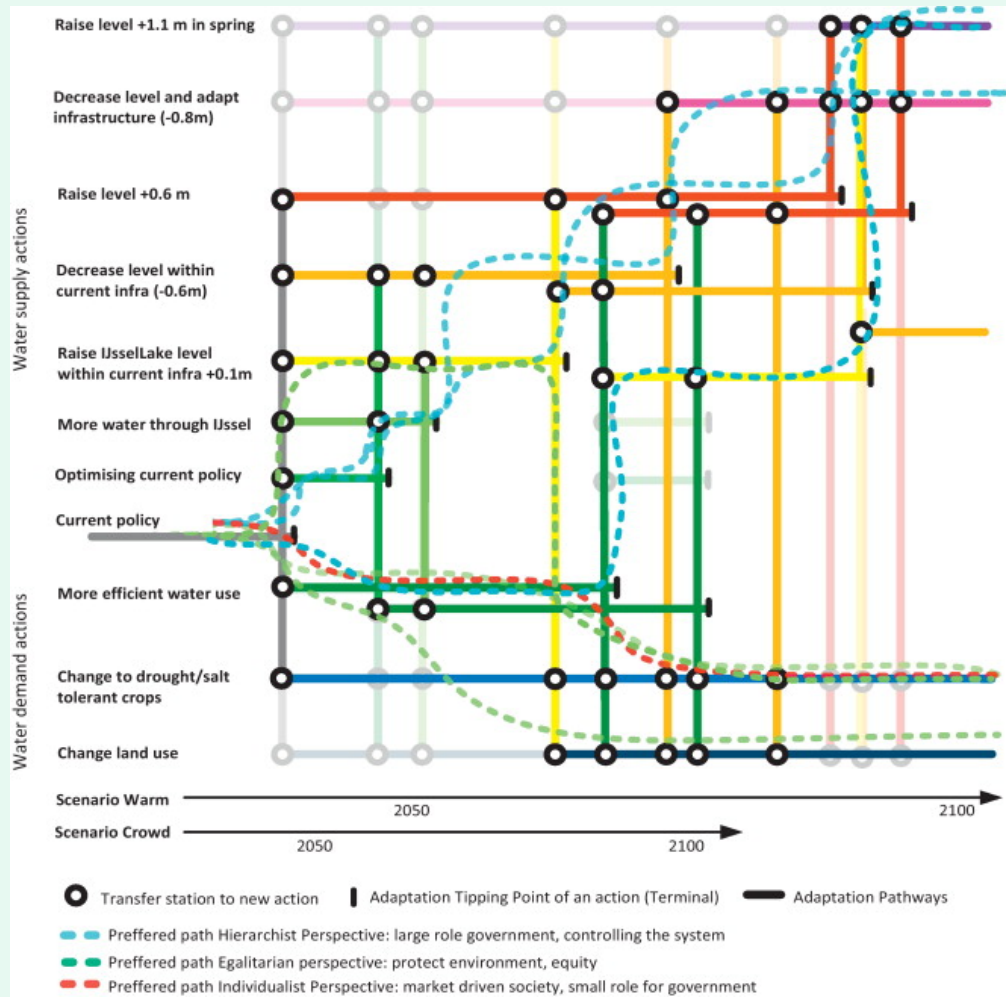


Figure 5.3. Diagram. Adaptation pathways map for water resources management, with preferred pathways for three different policy perspectives.

(Source: Haasnoot, M. et al, "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world." Global Environmental Change, Volume 23, Issue 2, April 2013, Pages 485–498.)

5.4 Addressing Climate Risk in Transportation Asset Management

In an era where the majority of a typical transportation agency's resources are directed at maintenance, operations, and normal replacement projects, many transportation agencies are moving toward risk-based asset management plans and procedures. Incorporating climate change vulnerability and risk assessments into a broader asset management process can be a natural fit. In fact, the Federal Highway Administration now requires state Departments of Transportation to specifically address climate risk in their asset management plans...

Figure 5.4 shows how an agency's risk matrix can be expanded to incorporate information from climate risk and vulnerability assessments, and how that information flows into the decision-making process.

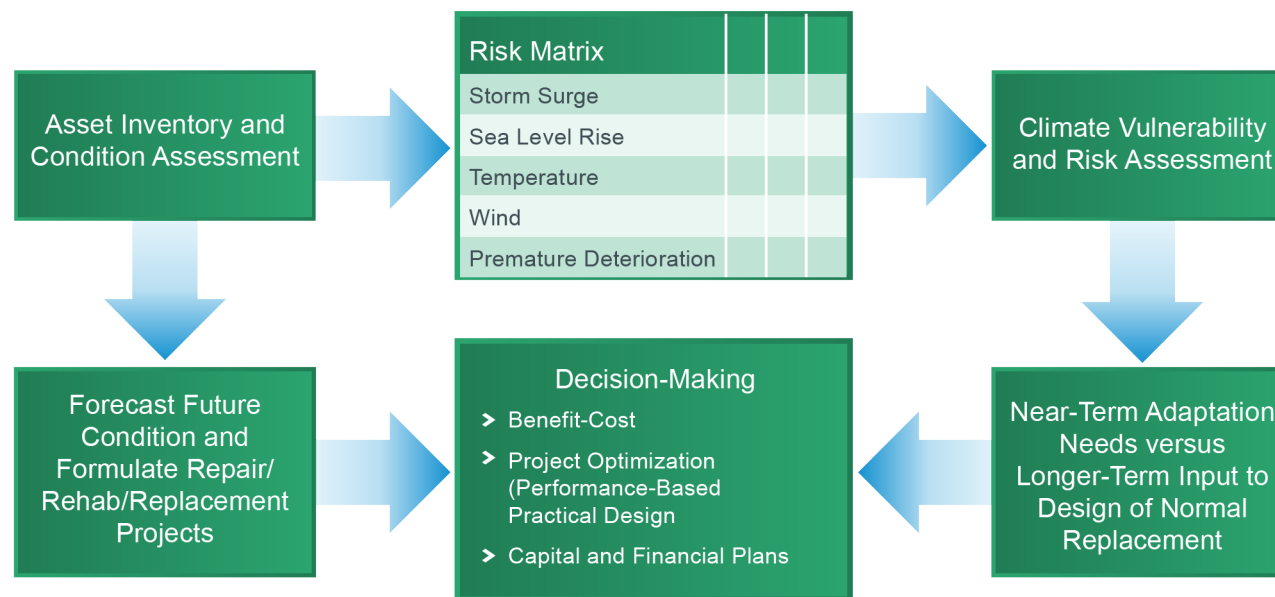


Figure 5.4. Flow chart. Integrating climate risk into transportation asset management decision processes.

(Source: Cambridge Systematics, Inc.)

5.5 Cross-Agency Coordination

Figure 5.5 shows examples of the roles that agencies at different scales can have in addressing the impacts of climate change on the transportation systems used by people and freight. Figure 5.5 (like the rest of this study) does not directly address global, national and regional-scale mitigation efforts to forestall or delay the onset of climate change-related impacts, nor does it mention national, state-level, and local-level regulations and standards that impact how infrastructure and natural systems will coexist in the future.

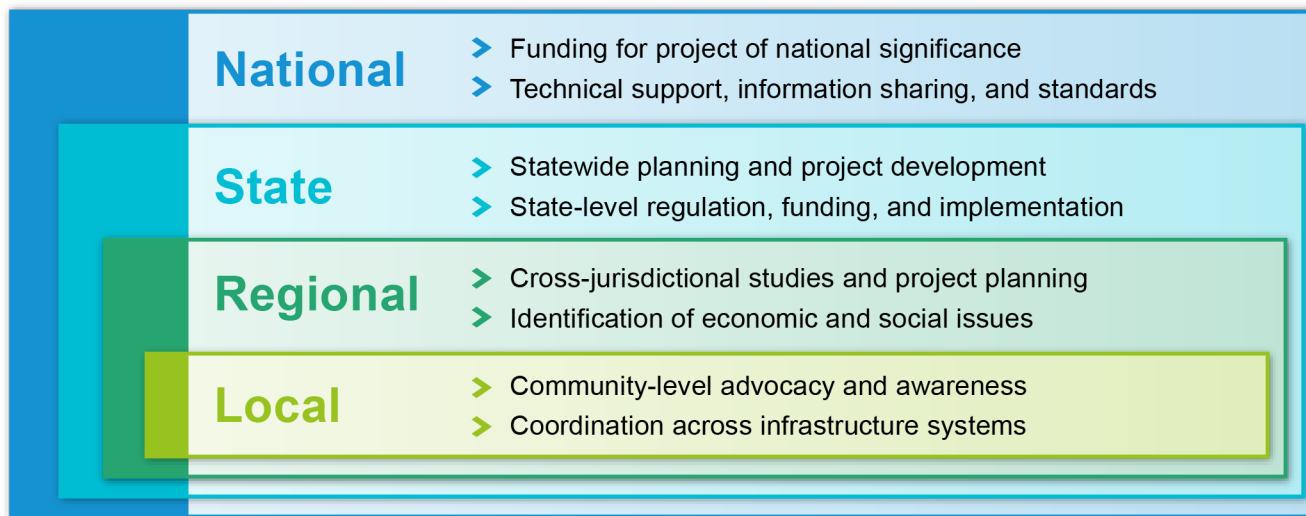


Figure 5.5. List. Addressing climate change through transportation system adaptation at various scales.

(Source: Cambridge Systematics, Inc.)

5.6 Conclusions: Mainstreaming Climate Change Resilience

- MPOs and other transportation organizations in the Post-Sandy Study region have taken impressive steps to begin addressing climate change risks.
- Nonetheless there are significant barriers because of insufficient data, uncertainty about future impacts, difficulties in coordination and insufficient funding for adaptation.
- There are decision-making techniques that can be used to identify appropriate paths for adaptation. These consider strategies appropriate for addressing uncertain risks, but also consider such factors as timing of risks and the need to avoid adverse impacts as well as costs and feasibility.
- The “state of adaptation” for the transportation sector in the New York metro region is that a lot of good work by states, regional organizations, municipalities, and MPOs has begun. There are barriers which if not overcome, could substantially limit the extent and effectiveness of adaptation efforts.

A Historical Damage and Disruption

Hurricane Sandy, Hurricane Irene, Tropical Storm Lee, and the Halloween Nor'easter of 2011 together claimed dozens of lives, caused countless injuries, and resulted in tens of billions of dollars in damage, disruption, and economic impact. This chapter summarizes how these events caused damage and disruption to the multimodal transportation system in the Post-Sandy Study area.

Hurricane Sandy, also known as "Superstorm Sandy," caused catastrophic damage to much of the study area. A storm surge that coincided with the highest tide of the month (October 2012) caused sea levels along the New Jersey coast, on Southern Long Island, and in New York Harbor to rise higher than ever before in recorded history. Many critical transportation facilities were inundated (in the case of some tunnels from floor to ceiling) and transit and roadway facilities were shut down, in some cases for weeks. The impacts of the corrosive salt water on electrical components are still being felt nearly two years later and will cause long-lasting impacts on the reliability of the region's multimodal transportation system. Major power generating stations, electrical substations, emergency backup generators, oil refineries, fuel storage facilities, and other critical components of the region's electrical and fuel distribution system also were impacted, with associated immediate and long-term impacts to the transportation system.

The one-two punch of Hurricane Irene and Tropical Storm Lee, which arrived in the region within two weeks of each other, caused extreme (primarily inland) flooding and wind-related damage in northern New Jersey and the Lower Hudson Valley. Some roadways and transit lines were damaged by floods and debris from Irene's winds and rain, then re-submerged when the same rivers and streams flooded again after Lee. In some cases, trees that survived Irene's winds were unable to withstand a second storm, as waterlogged soils were unable to support the roots of larger trees once Lee arrived.

The Halloween Nor'easter of 2011 followed close behind Irene and Lee, but this third storm followed a more southeasterly track, and therefore had its greatest impacts in Connecticut. In the portion of the study area covering Southwest Connecticut and Westchester County, New York, the Halloween Nor'easter dumped unusually large amounts of snow on trees still covered with leaves relatively early in the Fall season. The winds associated with this storm toppled large numbers of trees, blocking area roadways and train lines, and tearing down power lines that supplied electricity to Metro-North Railroad as well as traffic signals and street lights. Parts of Connecticut, primarily in the northern region (outside of the study area), were without electricity for over a week.

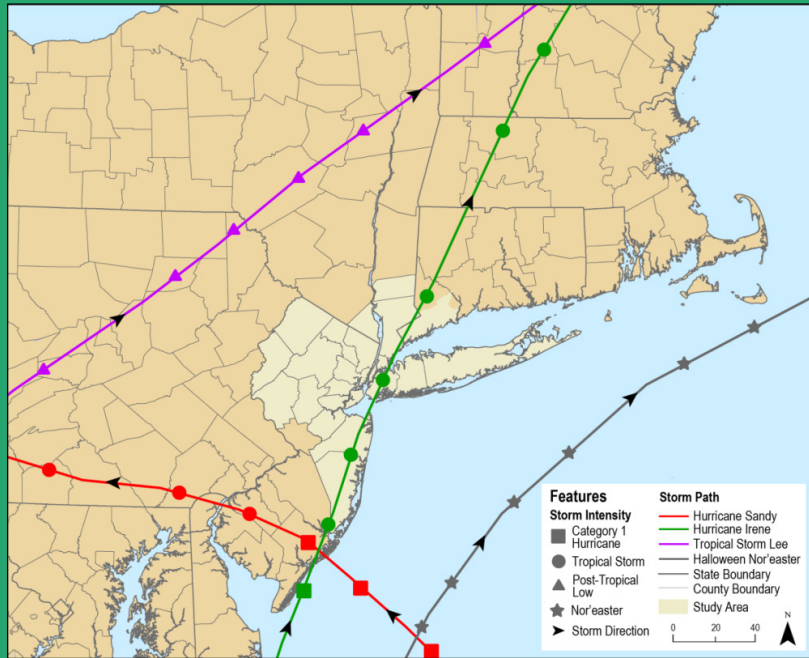


Figure A.1. Map. Path of storm centers—Sandy, Irene, Lee, and Alfred.

(Source: National Oceanic and Atmospheric Administration, Office for Coastal Management. DigitalCoast Historical Hurricane Tracks data.)

Irene, Lee, and Alfred all moved in a northeasterly direction. Sandy, however, approached from the southeast and moved west-northwest into New Jersey. Irene was the only storm whose center moved directly over the study area.

As with their paths, the strengths of these storms—measured by peak sustained wind speed—varied as well. For example, Hurricane Sandy’s intensity diminished to tropical storm strength (less than 74 mph peak sustained winds) as it made landfall in New Jersey. However, the shoreward direction of its winds caused sea water to “pile up” in the form of a storm surge along the coast. Irene—formerly hurricane strength—passed through the study area as a tropical storm, but had ample moisture associated with it. Lee was considered a post-tropical low by the time it entered the study area. Alfred was a low pressure system typically referred to as a “nor’easter.” However, both storms had enough moisture to cause significant impacts to the region. More details on the weather context of each storm can be found in the following sections.

A.1 Hurricane Sandy

This section summarizes the meteorological aspects before, during, and after Sandy’s landfall. While most of the storm’s impacts to transportation infrastructure came from the significant storm surge that deluged densely populated areas in the greater New York City region, significant winds and rainfall compounded the damage. Below is a summary of the storm surge, winds, and rainfall attributed to Hurricane Sandy.

Storm Surge (Sandy)

Sandy’s storm surge created the storm’s most significant impacts to transportation infrastructure. The storm surge caused by Sandy inundated much of the coastline in the Post-Sandy study area (see Figure A.1). This surge caused significant damage to transportation infrastructure along the coast, notably

damaging or destroying roads and bridges along the Jersey Shore and the south shore of Long Island and flooding numerous roadway and subway tunnels under the Hudson and East Rivers.

Surge extent and magnitude peaked on the evening of October 29th and early hours of October 30th as the storm made landfall and onshore winds pushed water inland. The surge was compounded by a concurrent high tide. The surge was so significant that the tide gage at Sandy Hook was destroyed by the storm (see green line in graph (G) in Figure A.2). The maximum recorded gage height was just under 15 feet at Bergen Point West Reach in Staten Island.

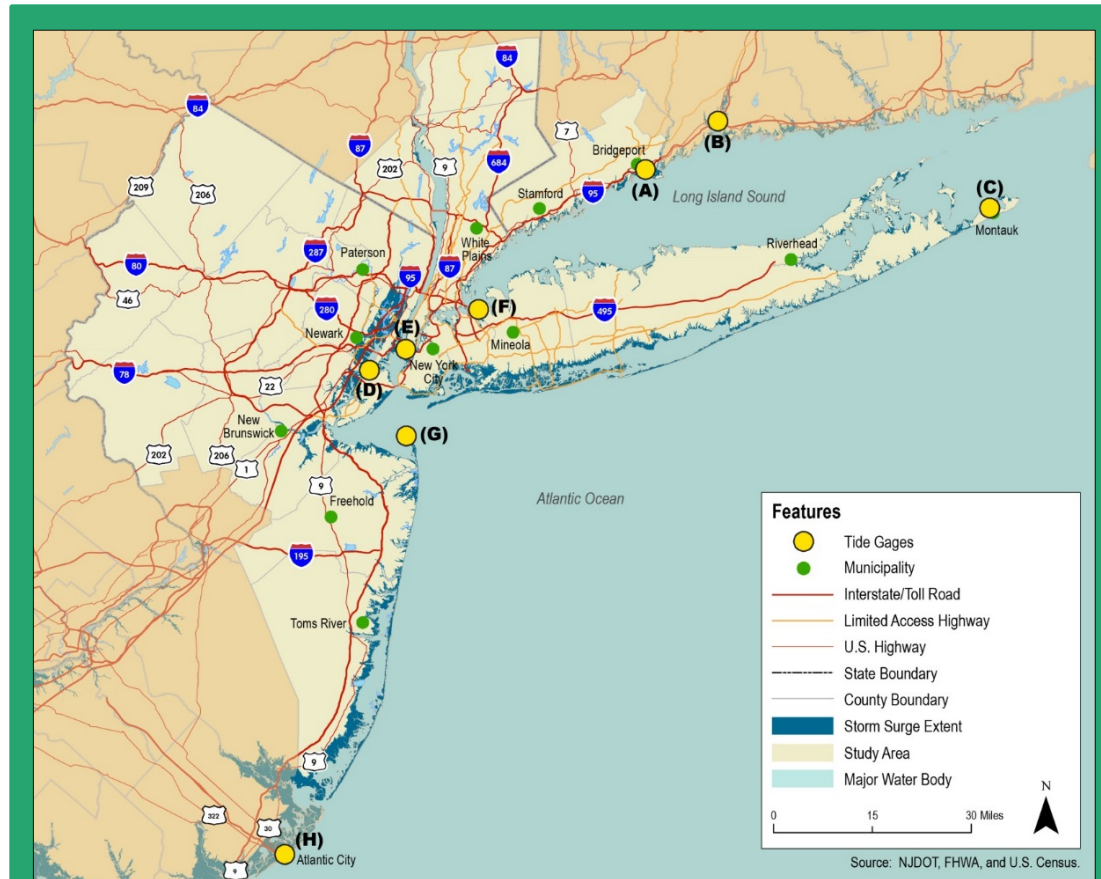


Figure A.2. Map. Tide gage locations and Sandy storm surge extent.

The storm surge extent shown is the maximum extent at any point during the storm. Source of storm surge extent data: Federal Emergency Management Agency's Modeling Task Force; 3 meter resolution.

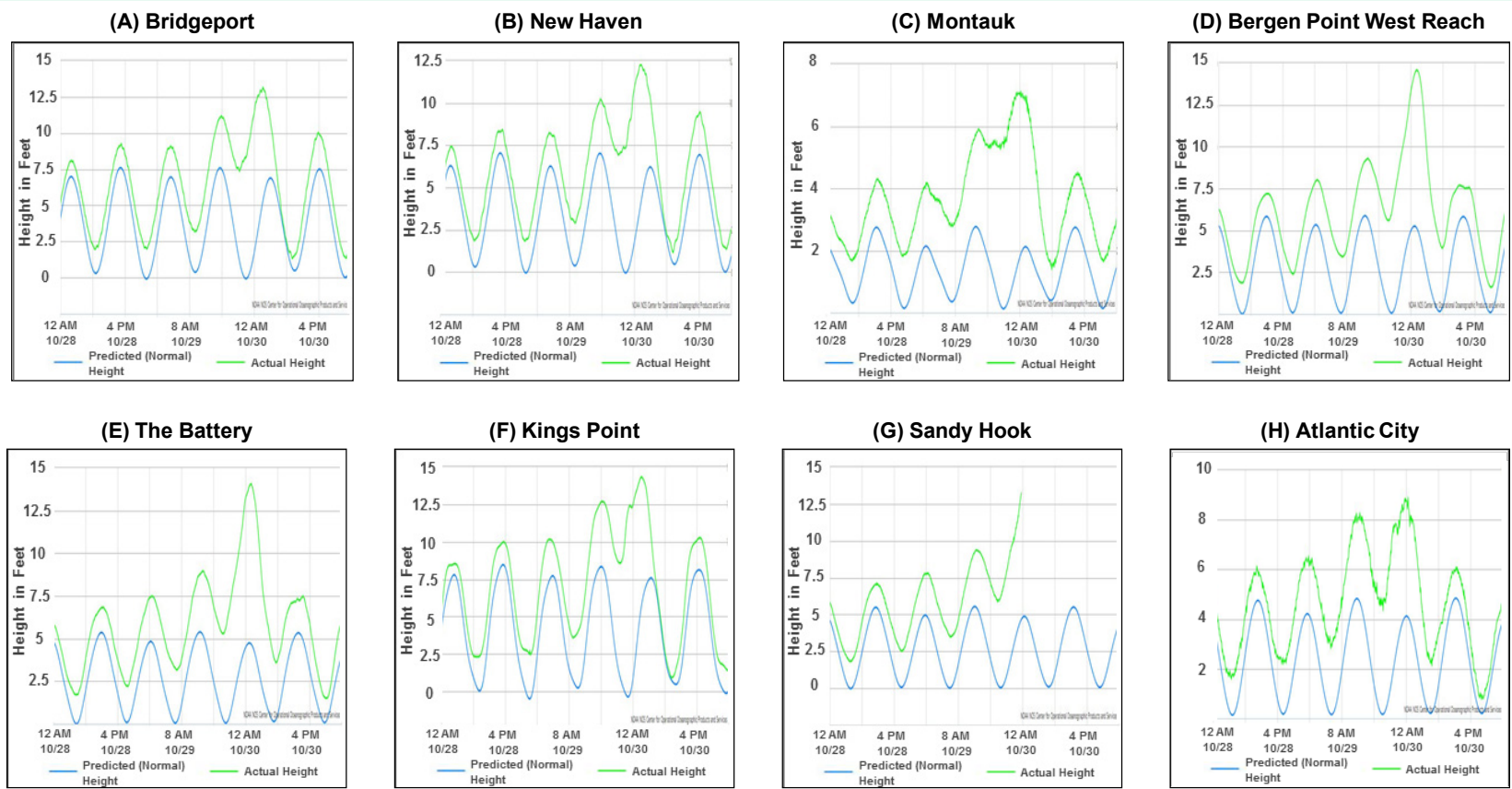


Figure A.3. Graphs. Hurricane Sandy tidal readings.

(Source: National Oceanic and Atmospheric Administration's National Ocean Service – Center for Operational Oceanographic Products and Services.)

Note: Tide gage data represent the 72-hour period from 12 AM on October 28th, 2012 through 12 AM on October 30th, 2012. Tide readings show the normal tide height in blue, and the actual reading during the storm in green. The greatest surge heights generally occurred around midnight on October 30th along the New Jersey coast and at Montauk, while peak heights were observed slightly after midnight at all other gages.

Wind (Sandy)

Although Hurricane Sandy's storm surge caused the most damage to transportation infrastructure in the study area, wind damage was also prevalent. Hurricane Sandy's maximum sustained winds fell below Hurricane levels (74 mph) as the storm came ashore. Wind gusts were significant, however, especially at Newark (78 mph), JFK (85 mph), and Long Island MacArthur (90 mph) Airports, as shown in Figure A.4, which depicts the maximum gust velocities and directions observed during the storm.

Larger symbols depict higher peak wind gusts; arrows indicate the direction of peak gusts. Peak winds were generally easterly. These high winds tended to cause damage to roadway appurtenances (signs, signals, guardrails, etc.), and were the drivers of storm surge. Wind data are from official National Weather Service weather stations.

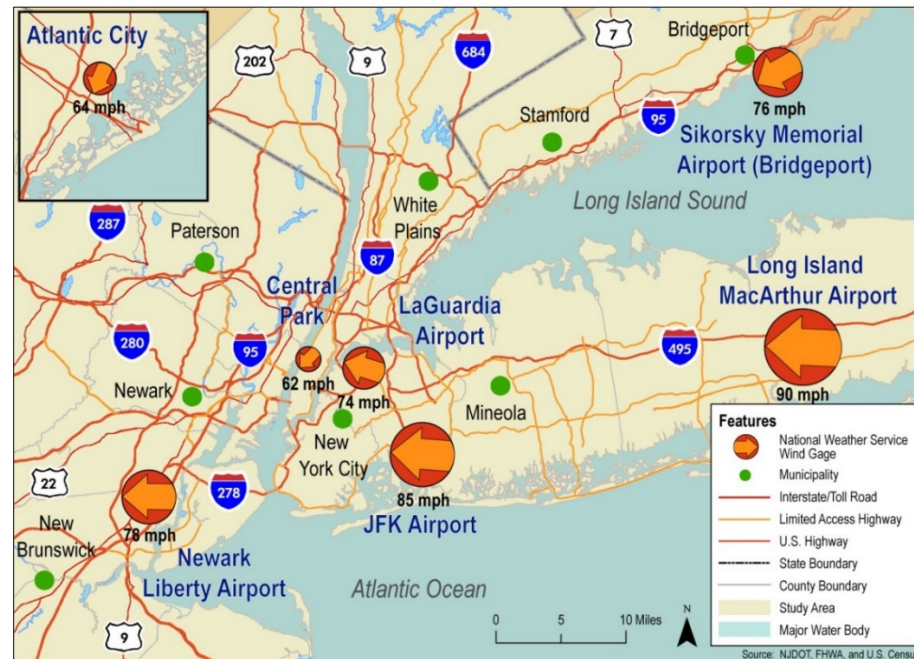


Figure A.4. Map. Hurricane Sandy peak wind gust velocities and directions.

(Source: National Weather Service.)

Rainfall (Sandy)

Compared with Sandy's storm surge, rainfall was not a significant issue on its own. However, elevated stream levels and increased discharge rates compounded flooding issues, especially for low-lying infrastructure near the coast. While rainfall totals from the storm were modest, most weather stations reported a fairly intense period of rain as the storm came ashore, especially the southern and western portions of the study area. As a result, stream gages reported significantly elevated stream and river levels and discharge rates. While the precise timing of higher stream levels varied depending upon individual basin geography and hydrology, in some cases higher stream levels corresponded with peak storm surge. This undoubtedly compounded the flooding of transportation infrastructure in many coastal areas.

Figure A.4 shows the hourly precipitation rates (gray) and cumulative precipitation (blue) during the period from 12 AM on October 28th through 12 AM on October 31st at the five official National Weather Service weather stations located within or near the study area. Atlantic City experienced both the greatest cumulative rainfall totals and the highest hourly rainfall rates among all the stations. This weather station saw six inches of total rainfall and precipitation rates peaking around 6/10ths of an inch per hour on the afternoon of October 29th. Cumulative rainfall amounts decreased dramatically to the north and east—all other weather stations saw totals between ½ and 1½ inches. Each station experienced rainfall rates of at least 1/10th of an inch per hour.

An analysis of stream gage data from the United States Geological Survey's National Water Information System shows that many area streams and rivers experienced fairly dramatic increases in discharge and height during and after Sandy's landfall. Figure A.5 and Figure A.6 depict discharge rates (maroon, cubic feet per second) for 12 representative stream gages from throughout the study area. For three of these stations, gage heights in feet (green) are also shown, giving the precise height of the river. Average (median) discharge rates for a typical day are indicated with maroon triangles, while median gage heights are given for stations where this information is available.

Each gage reported a dramatic increase in discharge during the 72-hour time frame analyzed. Due to variations in basin geography, however, the magnitude and timing of this increase varied from site to site. For example, the gages along the Toms, Manasquan, and Saddle Rivers, Bellmore Creek, and Sasco Brook all saw the greatest increases in discharge as the storm was making landfall during the late hours of October 29th and beginning of October 30th. Other locations—such as the gages on Musconetcong, Passaic, and Ramapo Rivers—saw later and more gradual increases in flow. However, the magnitude of flow increase for these sites was similar to those with earlier increases.

Increased stream and river discharge likely compounded coastal flooding in areas where peak discharge rates and heights coincided with peak storm surge levels. Notably, the timing of increased water flow from the Manasquan and Toms Rivers along the New Jersey coast likely exacerbated flooding due to storm surge as river water backed up at the rivers' outlets, inundating many transportation assets in the low-lying coastal plain.

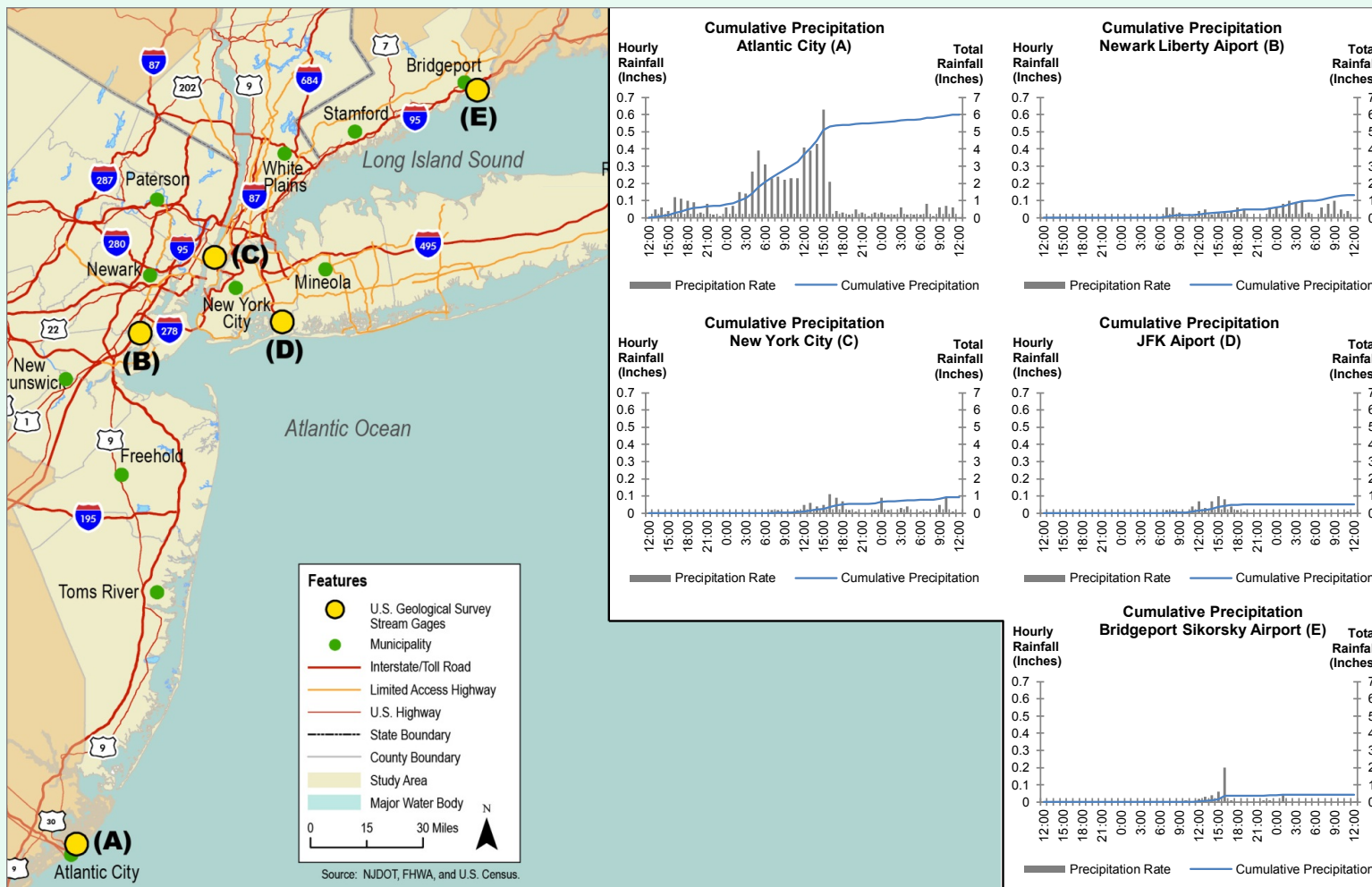


Figure A.5. Map and graphs. Hurricane Sandy rainfall observations.

(Source: U.S. Geological Survey National Water Information System (stream gage locations) and National Weather Service (cumulative precipitation).)

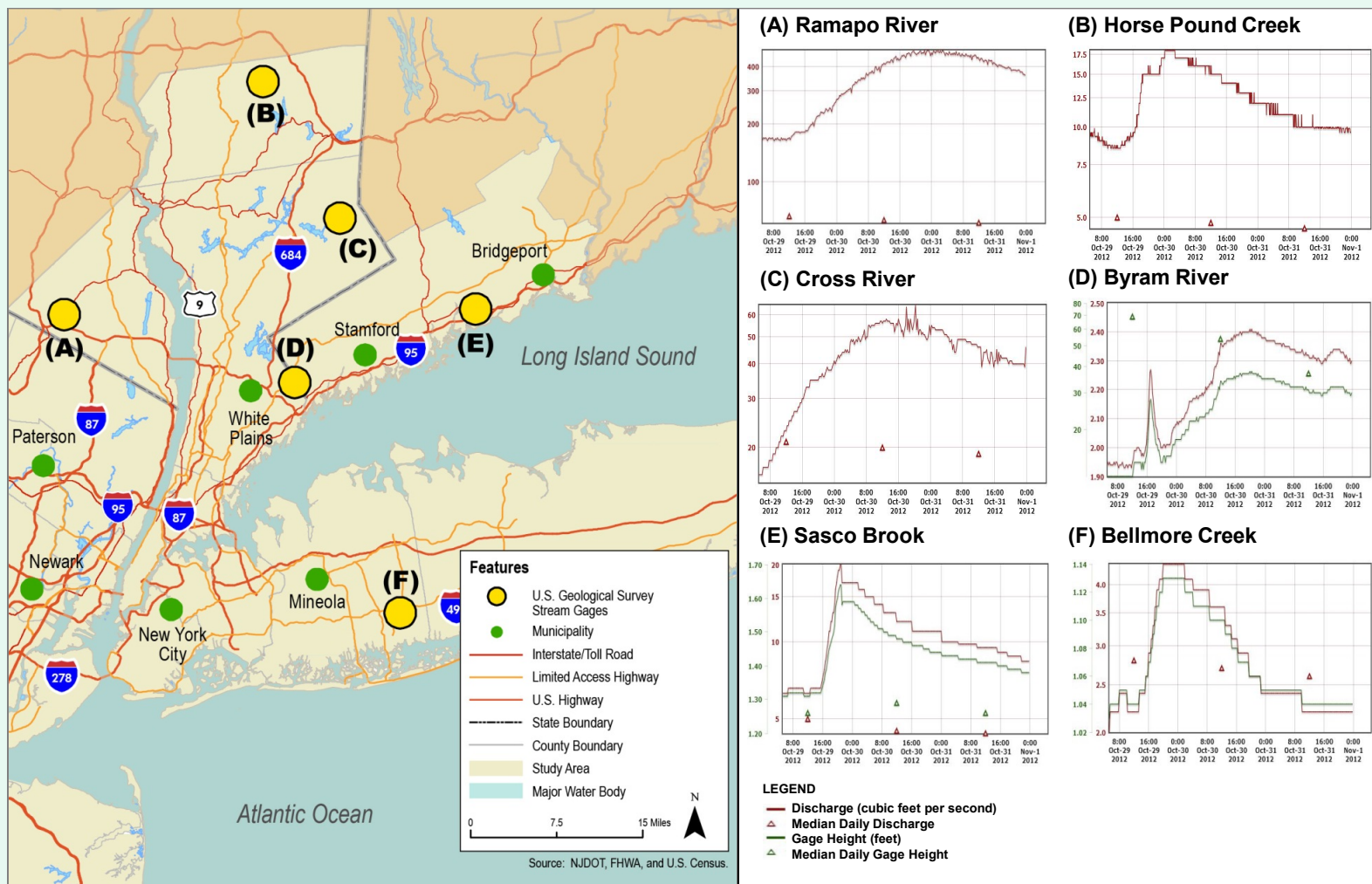


Figure A.6. Map and graphs. Hurricane Sandy stream gage observations—New York and Connecticut

(Source: U.S. Geological Survey National Water Information System.)

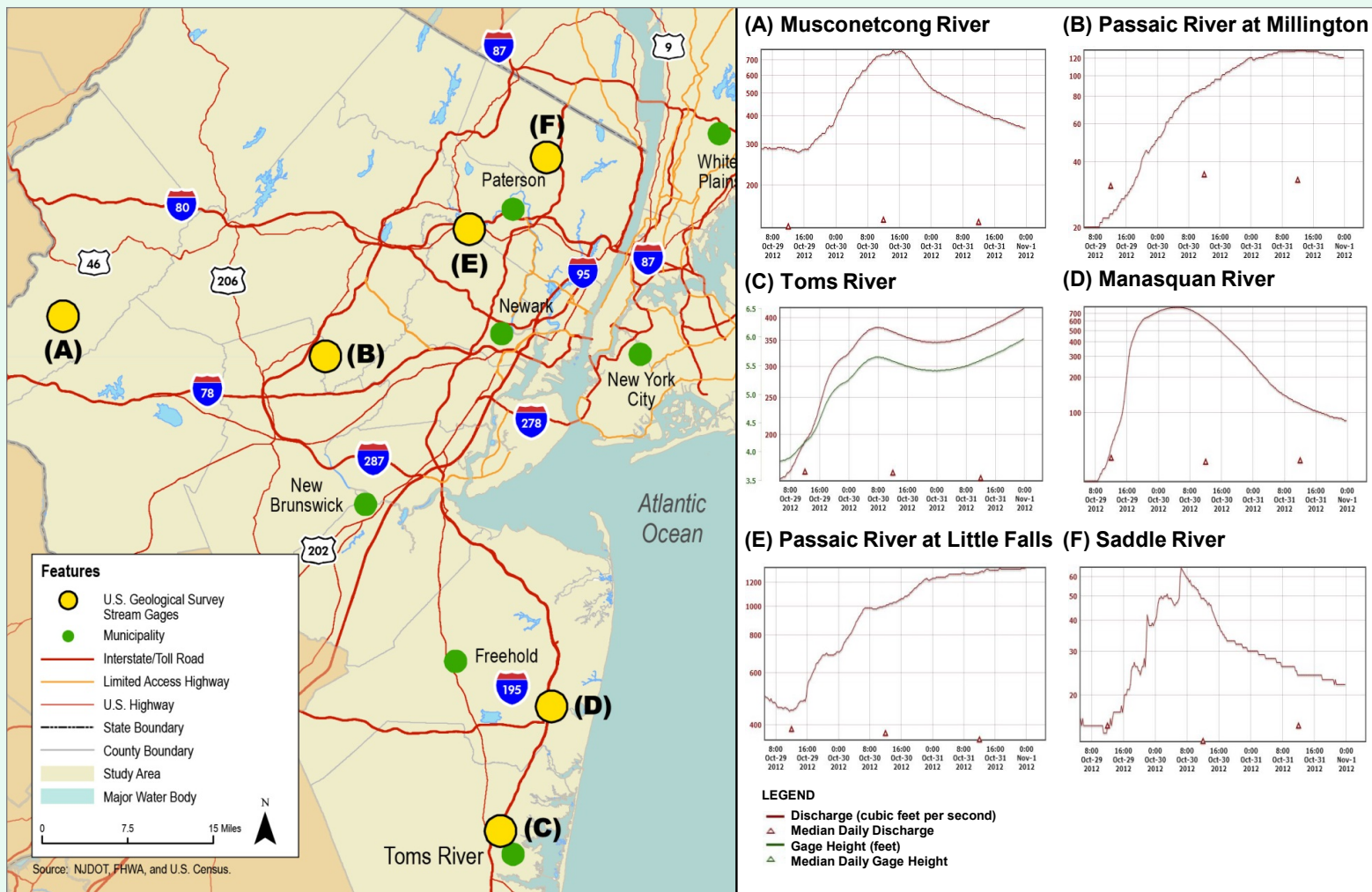


Figure A.7. Map and graphs. Hurricane Sandy stream gage observations—New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

A.2 Hurricane Irene

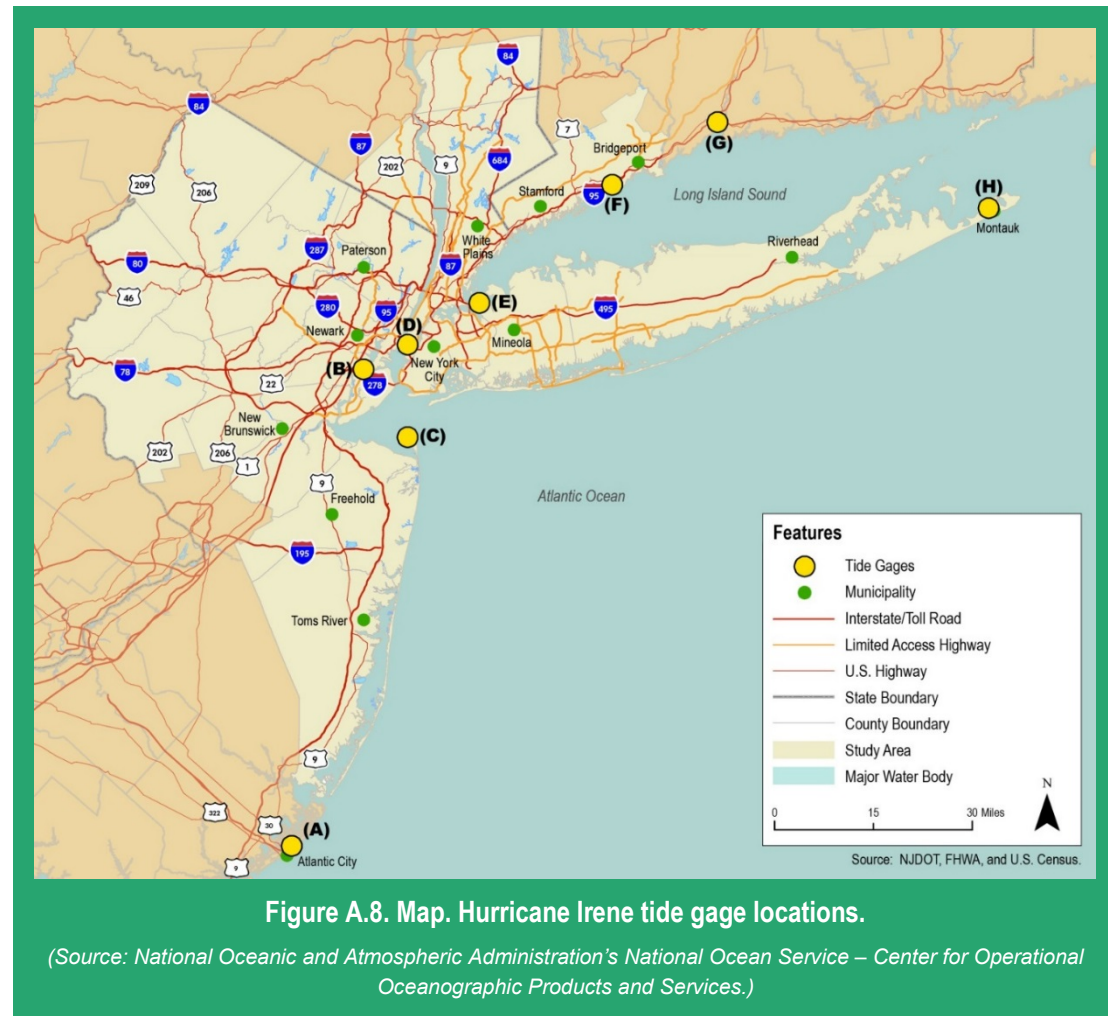
Compared with Hurricane Sandy, most of the storm's impacts to transportation infrastructure came from riverine flooding rather than storm surge. Below is a summary of the storm surge, winds, and rainfall associated with Hurricane Irene.

Storm Surge (Irene)

Although Hurricanes Irene and Sandy came ashore in New Jersey in similar locations, Hurricane Irene made its initial landfall in the continental U.S. significantly further south than Hurricane Sandy, and it approached the Jersey shore from a shallow angle on a northeasterly track, compared to Sandy's more direct impact on a northwesterly track. Therefore, Irene produced much smaller storm surges than Sandy in the study area.

Whereas Sandy caused water levels to rise to as much as 300 percent of normal tidal levels, readings taken during Irene's landfall—seen in Figure A.8 and Figure A.9—were significant, but more modest. For example, the tide gage at The Battery in Manhattan recorded a high tide that was five feet (or 100 percent) above normal as onshore winds pushed sea water inland midday on August 29th, 2011. All other tide gages in the region saw above-normal tides.

Storm surge in the region, especially along the western shore of New York Harbor and the Hudson River, likely caused rivers to back up, exacerbating the effects of riverine flooding.



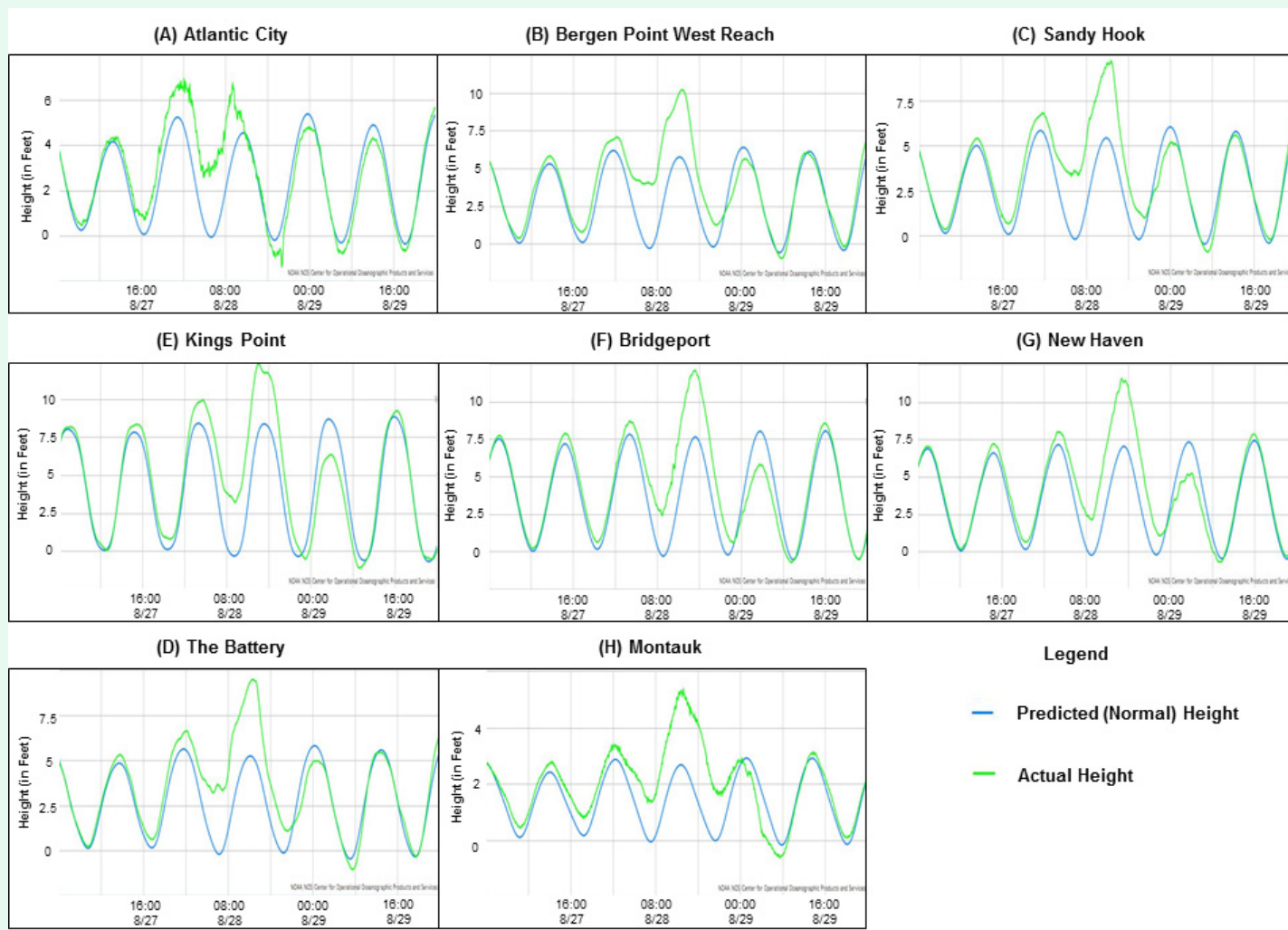


Figure A.9. Charts. Hurricane Irene tidal readings.

(Source: National Oceanic and Atmospheric Administration's National Ocean Service – Center for Operational Oceanographic Products and Services.)

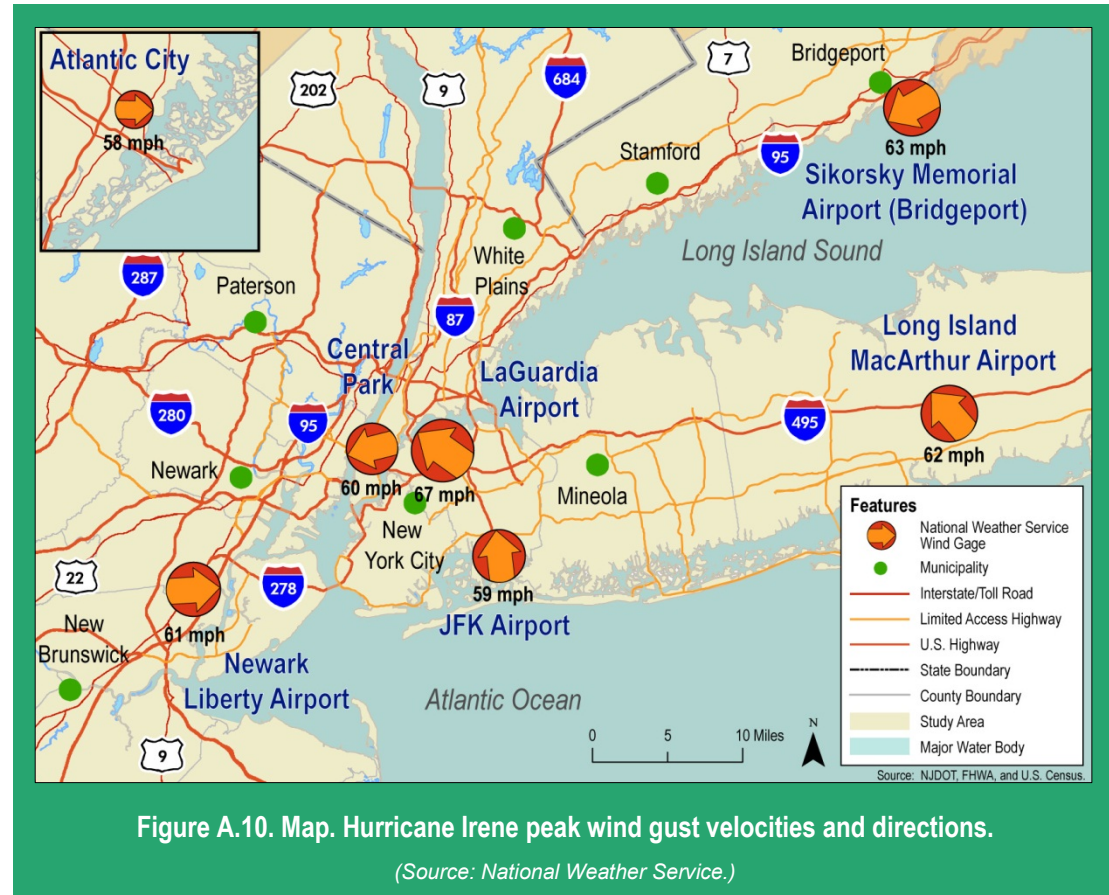
Wind (Irene)

Wind damage to transportation infrastructure in the study area was prevalent as Irene made landfall. The storm produced significant peak wind gusts, especially in and around New York City (Figure A.10). Larger symbols depict higher peak wind gusts; arrows indicate the direction of peak gusts. The highest gusts were experienced at LaGuardia Airport (67 mph), Sikorsky Memorial Airport (63 mph), and Long Island MacArthur Airport (62 mph). The direction of peak wind gusts was generally onshore and from the east or south, with Newark's peak gust (from the west) an exception.

Rainfall (Irene)

Heavy rainfall caused the bulk of damage associated with Irene. Elevated stream levels and increased discharge rates compounded flooding issues, especially for low-lying infrastructure in riverine flood plains and near estuaries. Rainfall totals from the storm were generally greater than those produced by Sandy. Additionally, most weather stations reported an intense period of rain as the storm came ashore overnight on August 27th and early August 28th, 2011.

Rainfall observations are shown in Figure A.11. Hourly precipitation rates (gray) and cumulative precipitation (blue) are shown for the period from 12 AM on August 27th through 12 AM on August 29th at the five official National Weather Service weather stations located within or near the study area. Newark Liberty Airport had the greatest observed amount of precipitation (8.92 inches, a daily precipitation amount observed roughly once every 100 years at this station), and unofficial observations showed even greater rainfall amounts to the north and west.



As runoff flowed into local streams and rivers, discharge increased and gage heights rose, as shown by official United States Geological Survey National Water Information System data in Figure A.11 and Figure A.12. Discharge rates (maroon, cubic feet per second) and gage heights in feet (green) seen during Irene were much greater than those experienced during Hurricane Sandy, causing widespread flooding damage to transportation infrastructure.

Rivers and streams in the lower Hudson Valley region of New York, and in northern New Jersey, were particularly impacted, causing flooding in many low-lying areas. The Musconetcong, Manasquan, and Saddle Rivers saw the greatest discharge rates during the storm. Every gage within the study area, however, reported a dramatic increase in discharge during the 72-hour time frame analyzed.

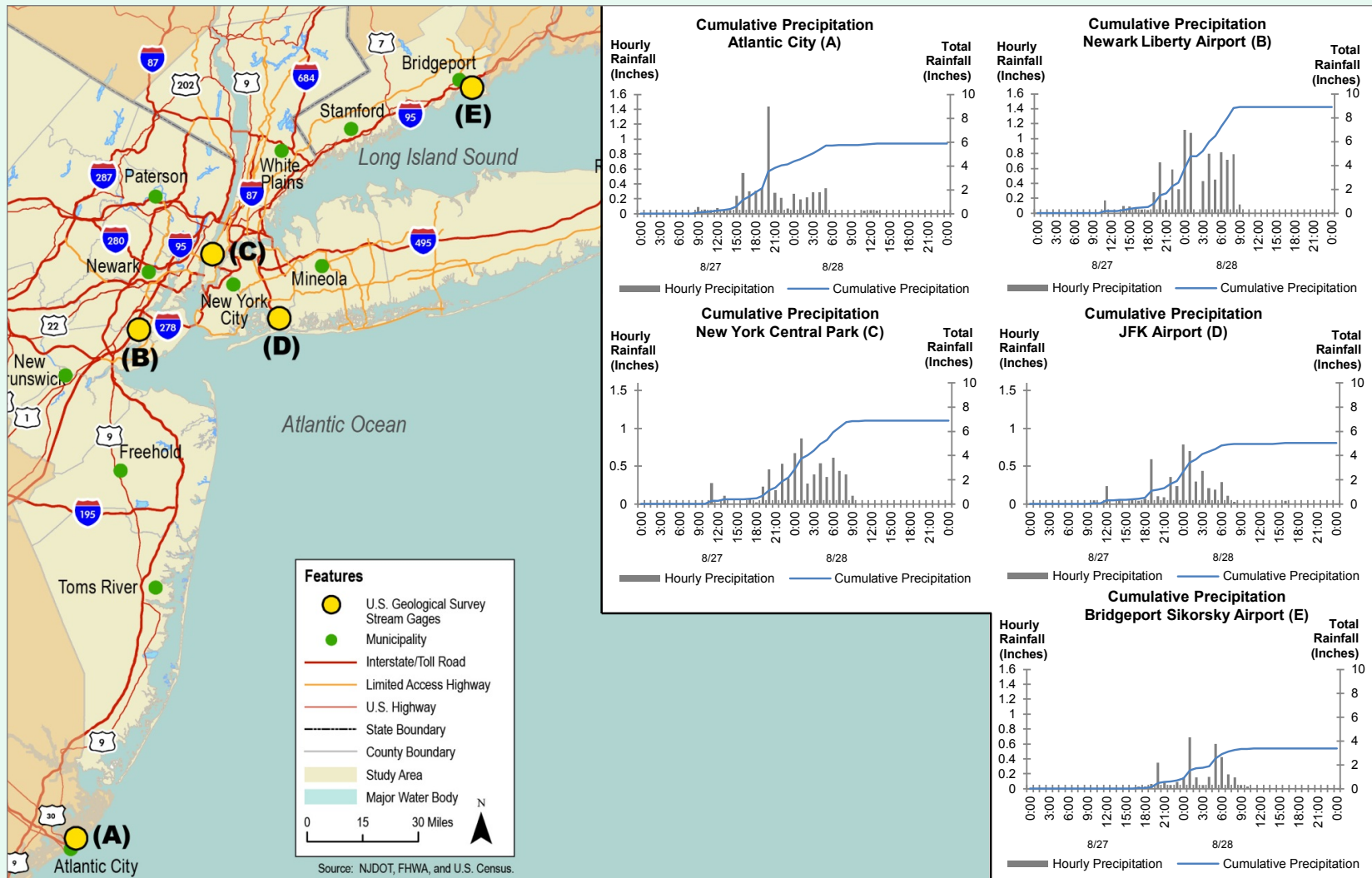


Figure A.11. Map and graphs. Hurricane Irene rainfall observations.

(Source: U.S. Geological Survey National Water Information System (stream gage locations) and National Weather Service (cumulative precipitation).)

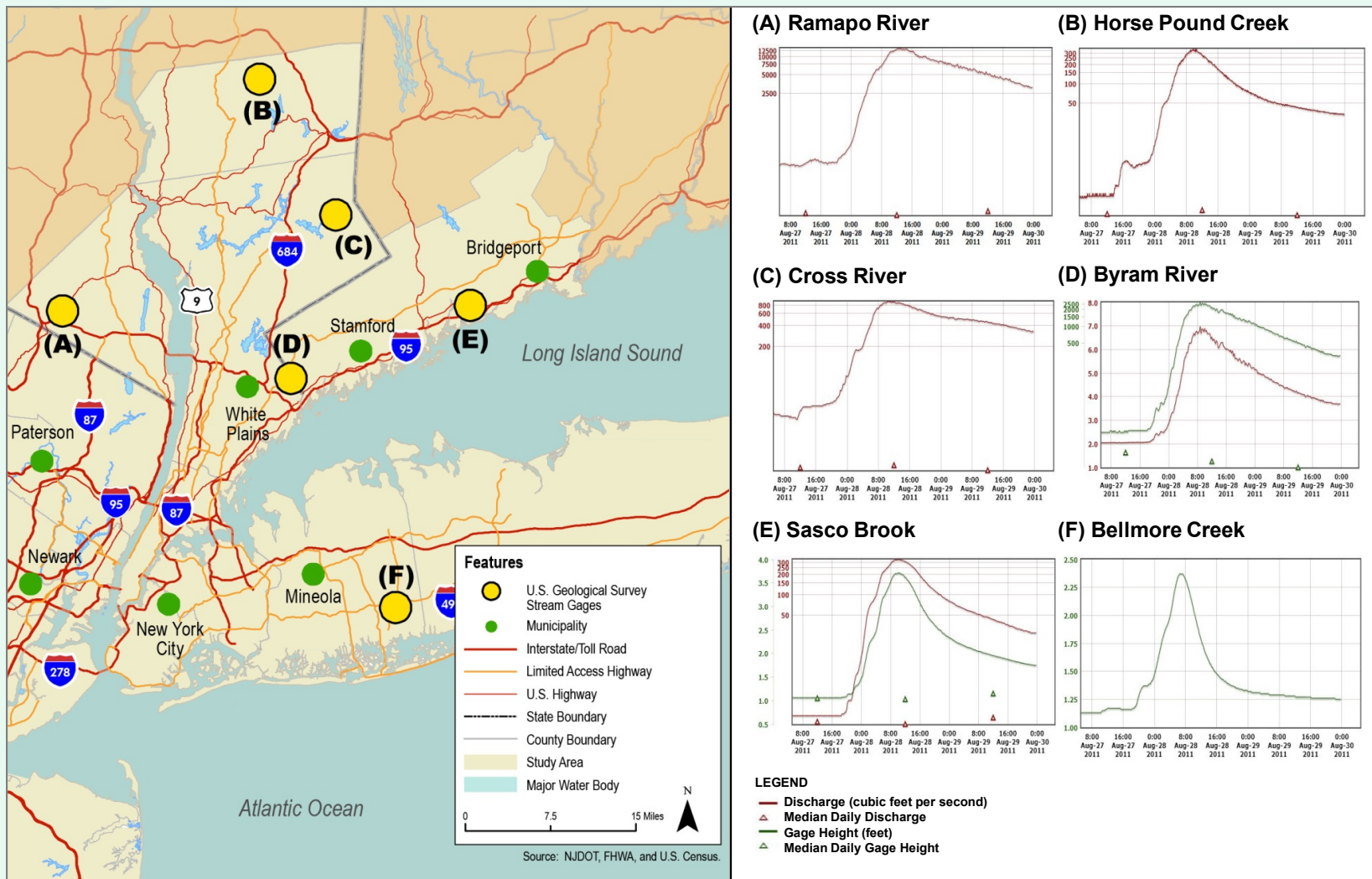


Figure A.12. Map and graphs. Hurricane Irene stream gage observations—New York and Connecticut.

(Source: U.S. Geological Survey National Water Information System.)

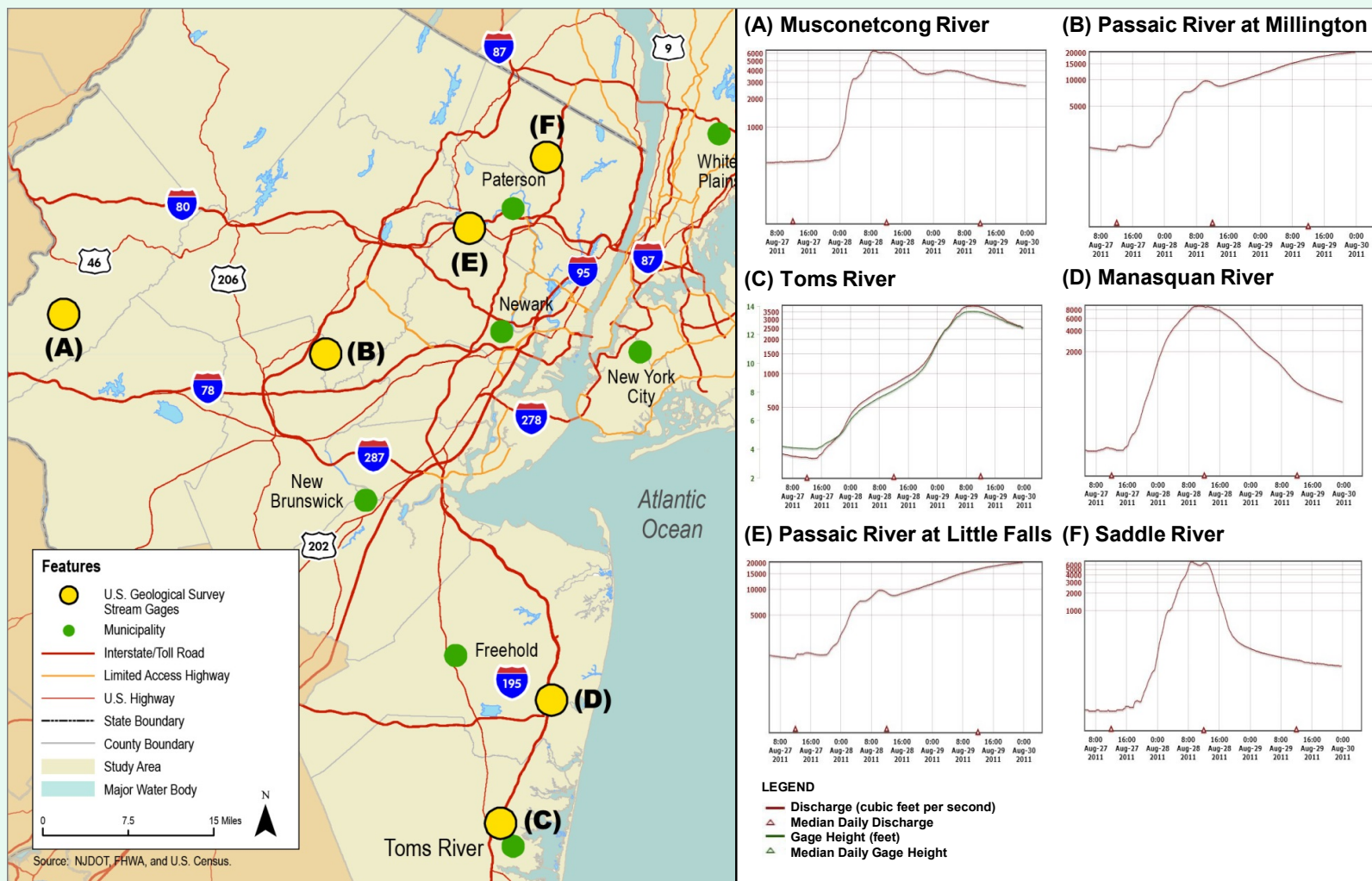


Figure A.13. Map and graphs. Hurricane Irene stream gage observations—New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

A.3 Tropical Storm Lee

Tropical Storm Lee affected the study area during the overnight hours of September 7th/8th, 2011. Lee was different from Sandy and Irene in that it approached from the southwest, rather than off the Atlantic, and no longer met tropical storm definitions when it moved into the area. Because the extra-tropical remnants of Lee could not feed off of warm ocean waters, the rainfall, wind, and storm surge associated with the storm were much less than with Sandy and Irene. However, the timing of Tropical Storm Lee—just over one week after Hurricane Irene—meant that the region was generally much more susceptible to damage, specifically with respect to flooding.

Rainfall (Lee)

The rainfall associated with Tropical Storm Lee was responsible for the storm's greatest impacts. While overall rainfall amounts were not as impressive as those during Irene, soils that were still water-laden from Irene led to drastically reduced absorption rates. Official National Weather Service weather stations at New York's Central Park and Newark Liberty Airport saw the greatest storm totals at just over 2 inches of rain, as shown in Figure A.13. Despite relatively low overall precipitation totals, rainfall rates were notably high at most weather stations around midnight September 8th, 2011. Newark Liberty Airport recorded the highest official rainfall rate of nearly 0.6 inches per hour at the event's peak, while unofficial stations to the north and west reported even higher rates.

This rainfall's effect on local rivers and streams is illustrated in Figure A.14 and Figure A.15, which show discharge rates (maroon) and stream gage heights (green) recorded by official United States Geological Survey National Water Information System gages. The stream gages at Musconetcong and Ramapo Rivers—which recorded peak discharge rates of 6,000 cubic feet per second and 3,500 cubic feet per second, respectively—reflect the greater amounts of precipitation seen in northern New Jersey and the lower Hudson River Valley during Irene and Lee. Most rivers and streams saw their discharge rates peak early on September 7th or midday September 8th, depending upon local basin geography. Swollen rivers compounded the flooding issues caused by Irene; riverine flooding caused the majorities of Lee's impacts to transportation infrastructure.

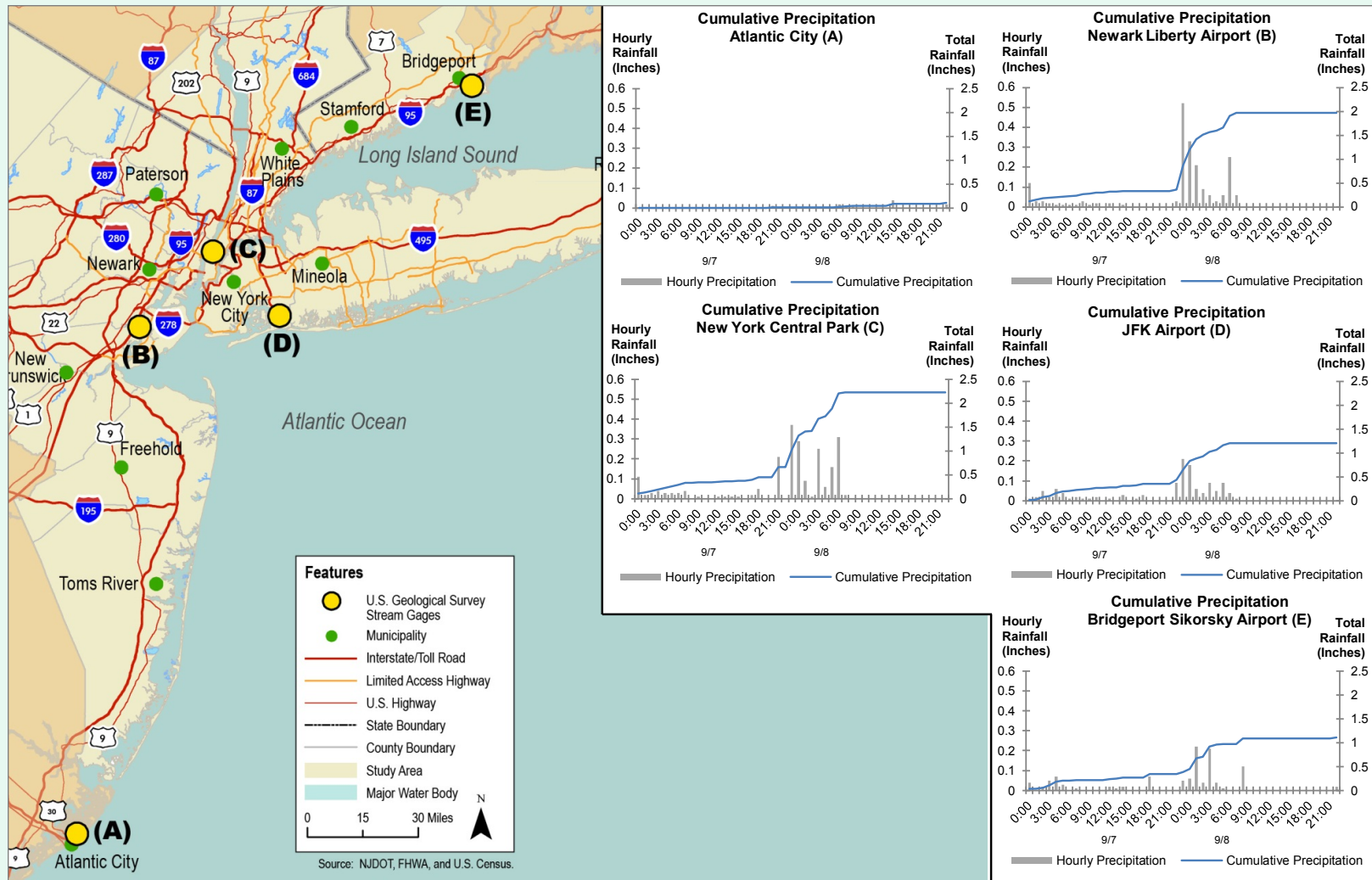


Figure A.14. Map and graphs. Tropical Storm Lee rainfall observations.
 (Source: U.S. Geological Survey National Water Information System (stream gage locations) and National Weather Service (cumulative precipitation).)

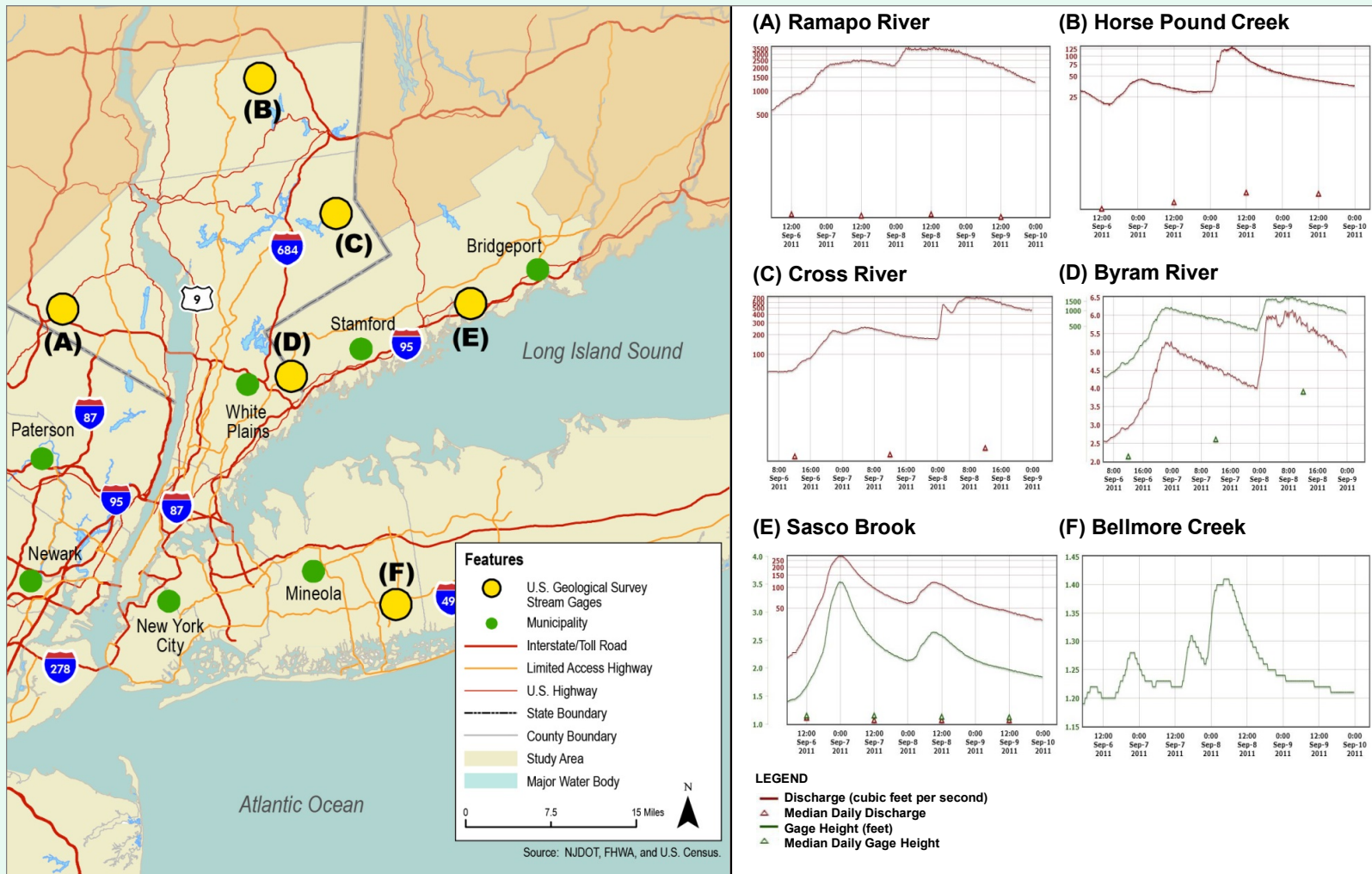


Figure A.15. Map and graphs. Tropical Storm Lee gage observations—New York and Connecticut.

(Source: U.S. Geological Survey National Water Information System.)

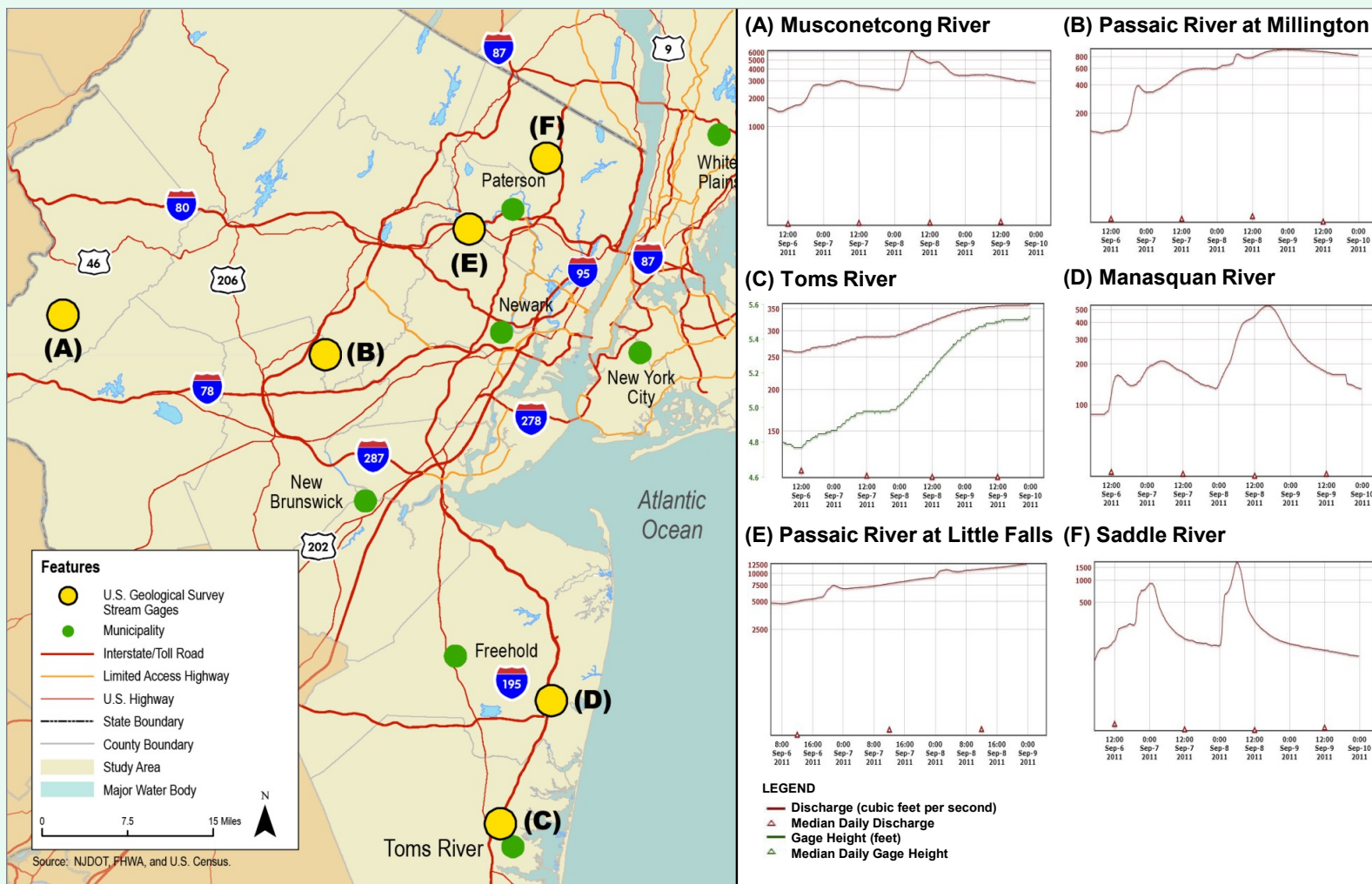


Figure A.16. Map and graphs. Tropical Storm Lee stream gage observations—New Jersey.

(Source: U.S. Geological Survey National Water Information System.)

Nor'easter Alfred

Nor'Easter Alfred affected the study area on October 28th and 29th, 2011, nearly two months after Hurricane Irene and Tropical Storm Lee, but compounded recovery efforts in a region still reeling from the two storms. Alfred was different from the preceding storms, however, in that its main impacts came not from wind, surge, or rainfall, but from snow. Snow totals were highest in areas already hard hit by Irene and Lee—northern New Jersey and the lower Hudson River Valley—as well as in southwest Connecticut. Many of these areas received nearly a foot of snow.

Snow fell on trees that were typically still in leaf and generally weakened by the previous storms. This caused many trees and branches to topple. This caused widespread damage to power lines in parts of the study area, which in turn disabled many traffic signals. Some parts of Connecticut saw power outages that lasted more than one week. Snow at some official National Weather Service weather stations broke all-time October snowfall records, including at Newark Liberty Airport (5.2 inches) and New York Central Park (2.9 inches).

The snowfall and subsequent downed trees and power lines affected rail service within the study area. Many Amtrak trains were delayed or cancelled, and New Jersey Transit suspended service on two lines until November 1st. Additionally, Metro North suspended commuter rail service on several lines due to fallen trees.

A.4 Assessment of Damage to the Three State Regional Transportation System

This section presents a summary compilation of surface transportation assets damaged as a result of four recent storms – Hurricane Irene (2011), Tropical Storm Lee (2011), the Halloween Nor'easter of 2011, also known as Storm Alfred, and Hurricane Sandy (2012). This section summarizes data on event-related damage to the regional transportation system provided by Federal Highway Administration division offices in New Jersey, New York, and Connecticut; respective Departments of Transportation in those states; the Federal Transit Administration; operators of regional transit systems in the study area; and the Federal Emergency Management Agency.

This damage assessment is not intended to be presented as a comprehensive inventory of damage to the transportation system and instead should be taken as a snapshot of information available as of October 2013 when the study team collected this information for the Post-Sandy study. Under Federal law, agencies have up to two years from the date of an event to report damages and submit claims for compensation to various Federal agencies. Even for those damage claims that have been submitted for reimbursement, reviews of eligible projects and costs associated with restoration, repair, and replacement of damaged transportation

assets are ongoing. Certain major transportation assets (for example, those that are self-funded or not part of a Federal-aid highway network or transit system) may not be eligible for Federal assistance, and thus will not appear in any inventory of Federal disaster assistance.

Federal Funding Programs for Disaster Relief

Elements of transportation systems that suffer serious damage as a result of natural disasters are eligible for disaster relief funding appropriated by Congress and administered by the U.S. Department of Transportation (U.S. DOT) and the Federal Emergency Management Agency (FEMA). The programs administered by the Federal Highway Administration (FHWA), the Federal Transit Administration (FTA), and FEMA are described below.

FHWA Emergency Relief Program

The Emergency Relief (ER) Program is intended to help States pay for unusually heavy expenses resulting from extraordinary events. In general, States can only use ER Program funding to repair damage to roads, bridges, and tunnels that are otherwise eligible for Federal aid. Normally \$100 million per year from the Highway Trust Fund is set aside to fund ER Program reimbursements for Federal Aid highways nationwide. In extraordinary circumstances, such as Hurricanes Sandy and Irene, Congress has provided additional funds for the ER Program through supplemental appropriations. For example, through the Disaster Relief Appropriations Act of 2013, Congress appropriated \$2.022 billion to the Federal Highway Administration's ER Program.

FTA Emergency Relief Program

The Public Transportation Emergency Relief Program was newly authorized in MAP-21. Unlike the ER program for Federal-aid highways, Congress funds the transit ER program entirely through supplemental appropriations. Congress appropriated \$10.4 billion to the Public Transportation Emergency Relief Program for damage to transit systems as a result of Hurricane Sandy through the Disaster Relief Appropriations Act of 2013.

Emergency Relief Programs for Other Modes

Airports are eligible for disaster relief through a similar program funded by the Airport and Airway Trust Fund, while the Federal Railroad Administration and the National Railroad Passenger Corporation (Amtrak) receive special appropriations for disaster relief on a per-event basis.

FEMA Disaster Relief Program

FEMA administers a disaster relief funding program that provides reimbursements to States, local governments, and other operators of the transportation system for damage that is not eligible for ER funding. Primarily FEMA reimburses states and local governments for costs associated with repairs to local roads and bridges.

Administration of ER and Disaster Relief Funding

Both FHWA's ER program and FEMA's disaster relief program operate on cost reimbursable bases. Grantees may submit provisional applications based on estimates of construction, repair, and cleanup costs that will be eligible for reimbursement, but both FHWA and FEMA require extensive documentation of these costs before authorizing reimbursement. The extent of damage to any given facility must be large enough to justify the administrative burden associated with submitting a grant application. In addition, reimbursements may be delayed for months or years following an event due to necessary reviews and approvals.

For the reasons stated above, the information provided by FHWA and FEMA for purposes of compiling the damage assessment for this report is a snapshot of the applications received, reviewed, and approved as of October 2013. Information on transit project cost estimates is derived from a regional damage assessment, rather than project-specific funding requests. Nevertheless, the information provides a stark picture of the extent and magnitude of damage due to Hurricanes Sandy and Irene, and, to a lesser extent, Tropical Storm Lee and the Halloween Nor'easter of 2011.

Damage to the Regional Highway System

The information presented in this section is not intended to be a comprehensive inventory of damage to the region's Federal-aid highway system. Instead, by summarizing available information on the types of damage observed from four recent storms, this report will help inform future tasks that will look at strategies to enhance the three state region's resiliency to climate change and extreme weather in the long term. The data presented in this section are limited to reported damage to highways in the study area and to the information available as of the publication of this report.

Figure A.17 and Figure A.18 compare the geographic extent of projects submitted for ER Program reimbursements for Hurricane Sandy and for the combination of Hurricane Irene and Tropical Storm Lee. Projects are shown by asset class. Maps in Figure A.19 through Figure A.22 show similar comparisons of projects by climate stressor and failure mode, respectively.

While wind-blown debris from all of the storms blocked roads and rail lines throughout the region (and caused catastrophic damage to homes, businesses, and other non-transportation infrastructure), many of the costs associated with debris clearance were not reported to FHWA as discrete events, and thus are not captured by this summary of regional damage.

These figures clearly indicate the differences in damage associated with the storms. Hurricane Sandy's storm surge caused coastal flooding, with extensive washouts and bridge damage along the Jersey Shore and the south shore of Long Island. The storm surge also led to inundation of tunnels crossing the Hudson and East Rivers, and low-lying mechanical and electrical equipment were flooded when water levels rose in coastal and near-coastal areas around the region. As water flowed into and out of major channels, bridge piers and foundations were compromised due to scouring of sediment and rocks from channel bottoms. Sandy also caused extensive wind-related damage to roadway appurtenances like signs, guardrails, fences, and lights throughout the region, either due to direct wind-related structural failure or due to damage from wind-blown trees and other debris.

The rain associated with Hurricane Irene and Tropical Storm Lee, in contrast, caused most of the reported damage, with the most severe impacts near rivers and streams away from the coast in New Jersey. Bridges and culverts spanning these streams were washed out or damaged by the flow of water or by water-carried debris, and stretches of roadways adjacent to fast-running streams or in nearby flood plains were eroded or flooded. Unlike previous heavy rainfall events that have been known to cause occasional floods and minor damage along rivers like the Passaic River, the magnitude of rainfall and subsequent floods from Hurricane Irene and Tropical Storm Lee damaged transportation assets of national significance, including Interstate Highways 80 and 287 and U.S. 46.

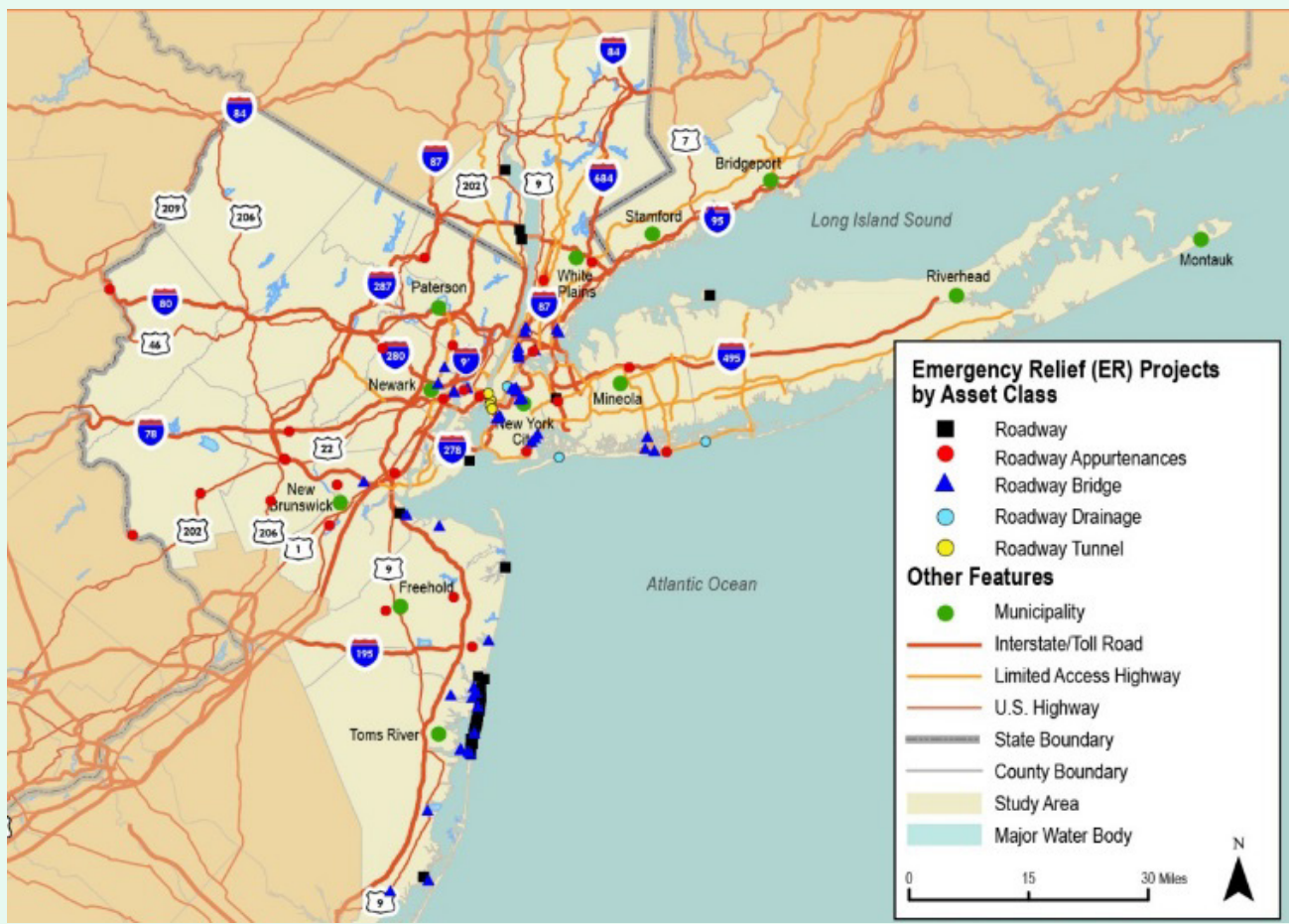


Figure A.17. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by asset class, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

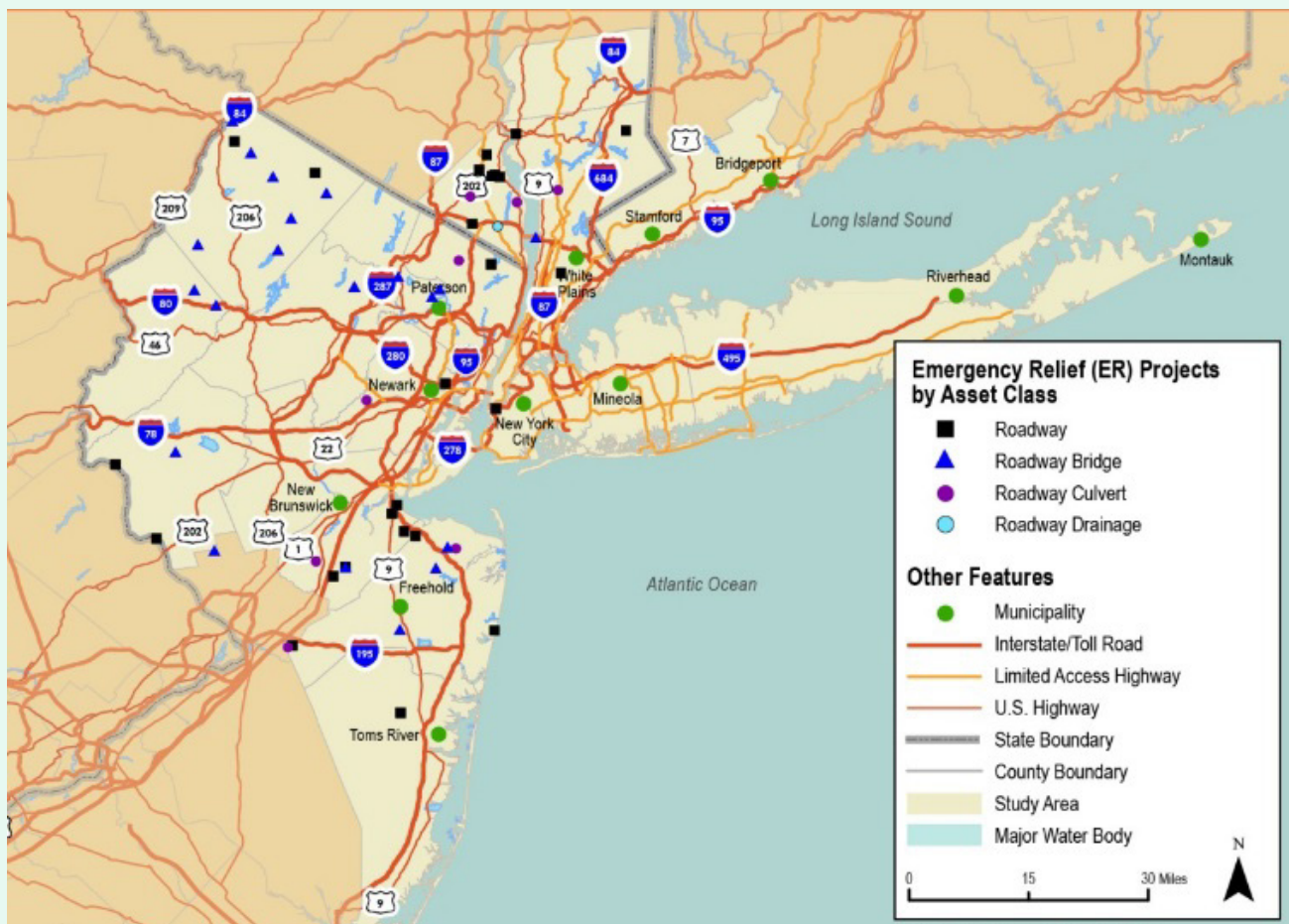


Figure A.18. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by asset class, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

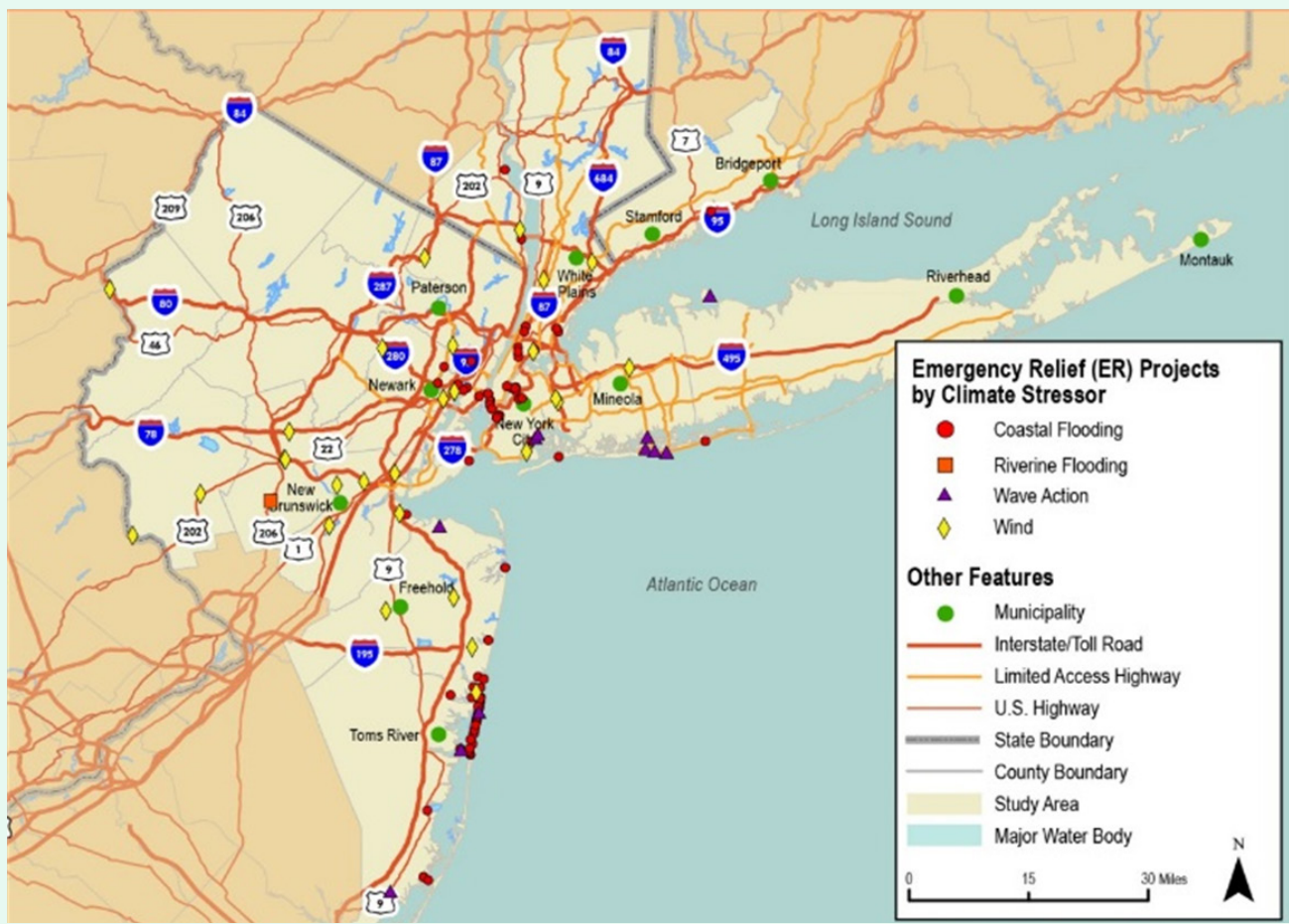


Figure A.19. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by climate stressor, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

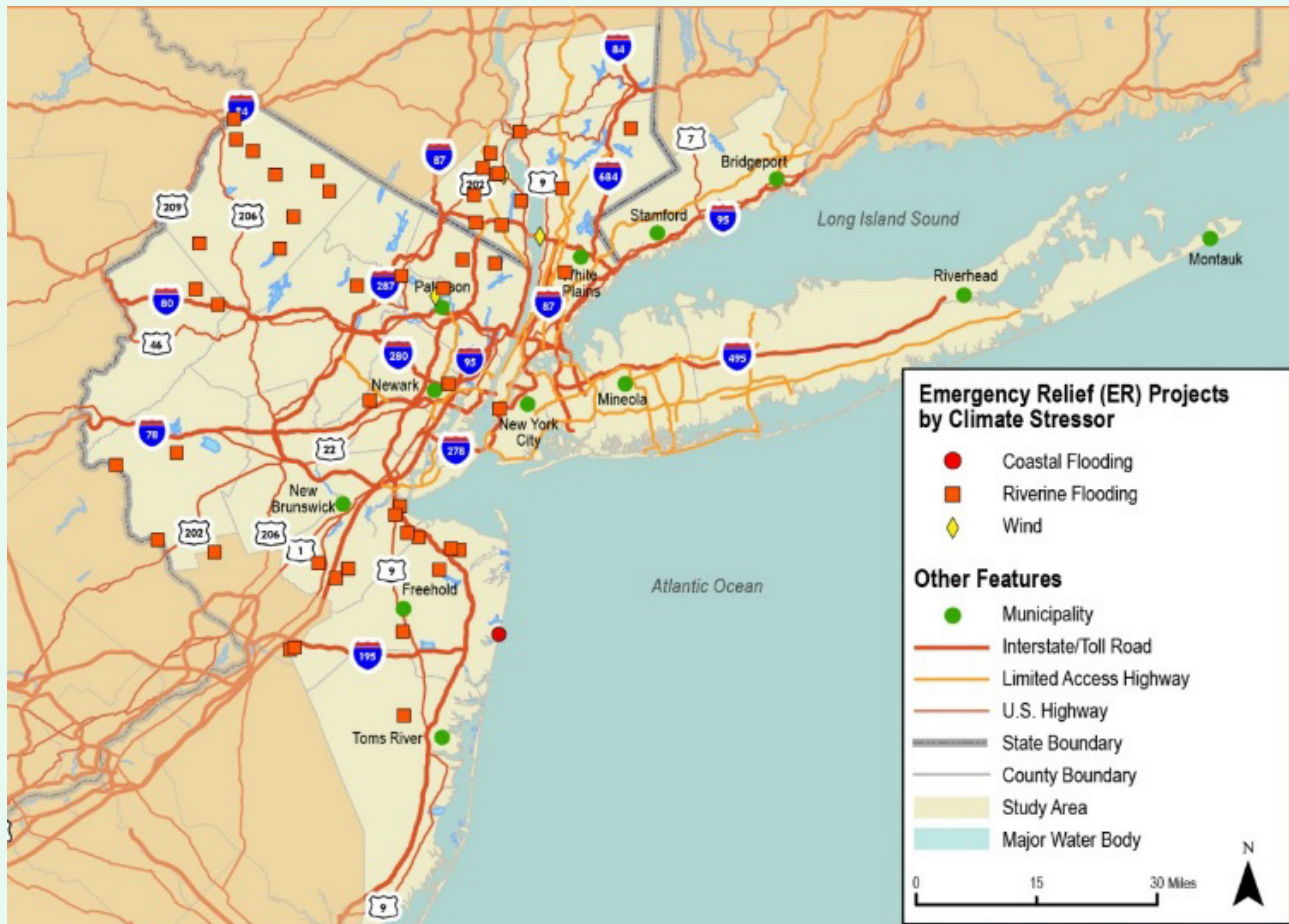


Figure A.20. Map. Projects submitted to Federal Highway Administration for Emergency Relief Funding reimbursement, by climate stressor, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

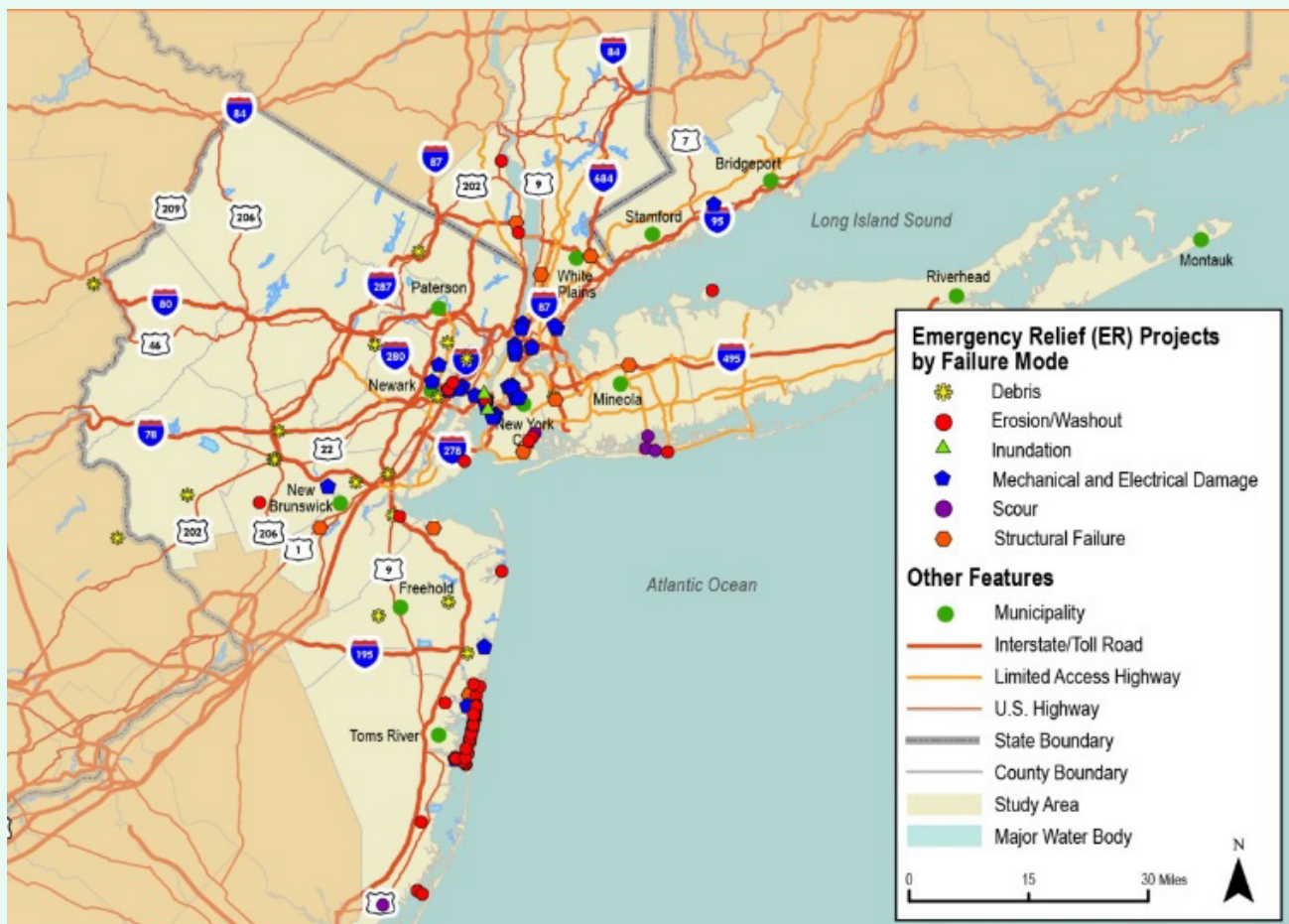


Figure A.21. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by failure mode, as of October 2013—Hurricane Sandy.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

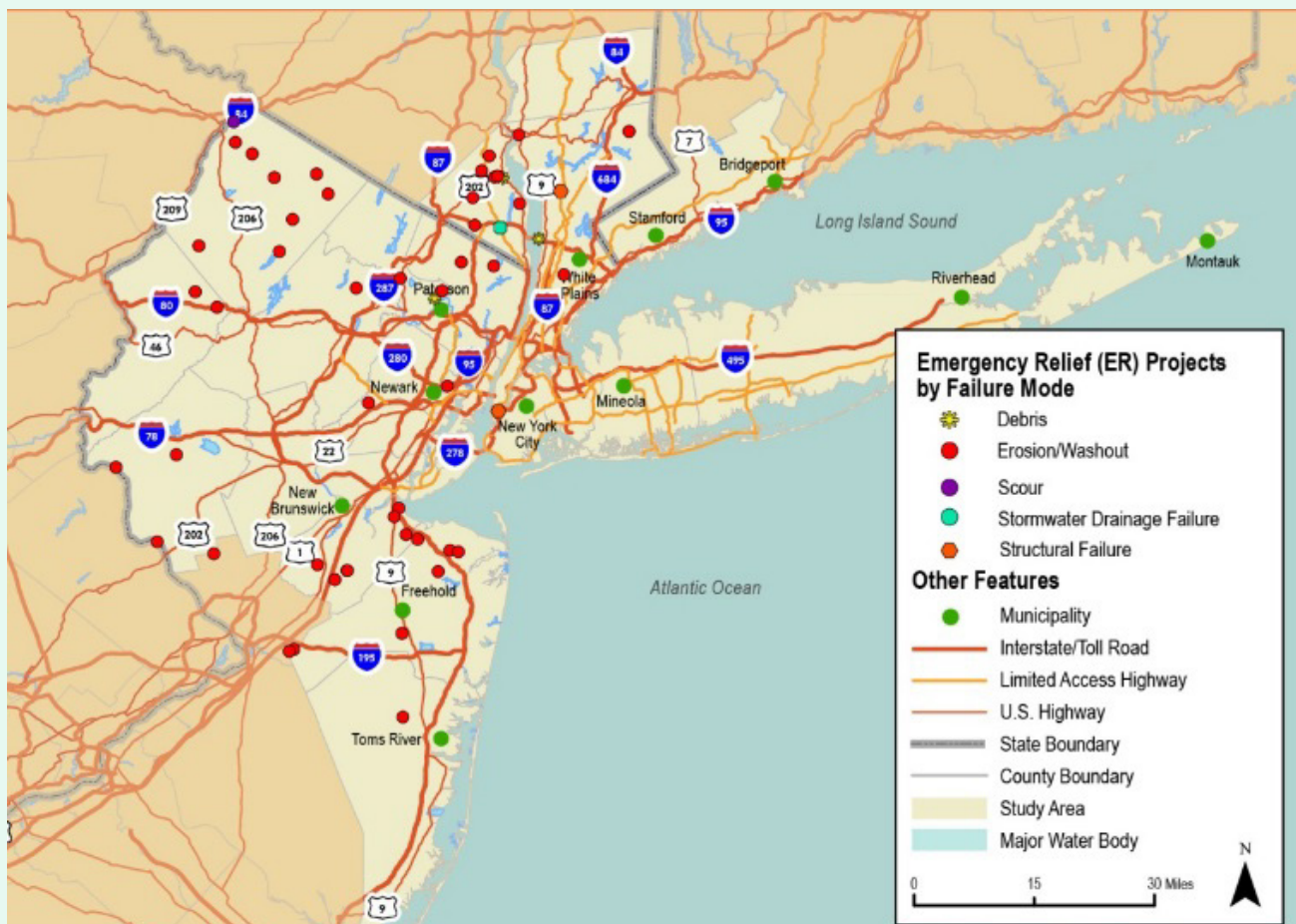


Figure A.22. Map. Projects submitted to Federal Highway Administration for Emergency Relief funding reimbursement, by failure mode, as of October 2013—Hurricane Irene and Tropical Storm Lee.

(Source: New Jersey Department of Transportation; New York State Department of Transportation; Connecticut Department of Transportation; Federal Highway Administration Headquarters and Division Offices; U.S. Census.)

Note: Map includes only projects for which Emergency Relief funding requests of more than \$50,000 have been made to FHWA as of October 2013.

As suggested by the weather context described in Section 1.0 of the full report, the patterns of damage associated with Hurricane Sandy were significantly different from the damage associated with Hurricane Irene and Tropical Storm Lee. Sandy produced damage across a much wider portion of the study area than the combination of Irene and Lee. Sandy's storm surge and wind led to concentrations of damaged roads and bridges along the Jersey Shore, on southern Long Island, and around New York Harbor and adjacent portions of the Hudson and East Rivers. Wind from Sandy damaged signs, lights, traffic signals, and other highway appurtenances further inland, either directly or indirectly (e.g., via falling trees and other wind-blown debris).

In contrast, Irene and Lee's wind and extreme rainfall led to widespread stream flooding, which damaged or washed out bridges, culverts, and roadways in interior portions of Northern New Jersey and the Lower Hudson Valley in New York. Outside the study area, flooding from Irene and Lee caused more severe and widespread damage to transportation assets in upstate New York and interior New England.

Table A.1. Top ten emergency relief program reimbursement requests by estimated repair and replacement costs, Hurricane Sandy.

Asset and Damage Description	State	County	MPO	Preliminary Estimates of Total Repair and Replacement Cost
NJ 35: Washouts and erosion due to storm surge	NJ	Ocean and Monmouth Counties	NJTPA	\$217,800,000
Ocean Parkway: Washouts and erosion due to storm surge	NY	Nassau and Suffolk Counties	NYMTC	\$39,700,000
Battery Park Underpass: Mechanical and Electrical Damage due to Storm Surge/Inundation	NY	Manhattan (New York County)	NYMTC	\$33,800,000
Federal-aid roadways in Rockaway Peninsula and Broad Channel, Queens: Washouts and mechanical/electrical damage	NY	Queens	NYMTC	\$22,800,000
Route 9A (West Street), including West Street Underpass: Damage due to wind, debris, and storm surge	NY	Manhattan (New York County)	NYMTC	\$18,300,000
Metropolitan Avenue Bridge over Newtown Creek: Mechanical and electrical damage	NY	Queens	NYMTC	\$9,300,000
Union Street Bridge over Gowanus Canal: Mechanical and electrical damage	NY	Brooklyn (Kings County)	NYMTC	\$4,600,000
Third Street Bridge over Gowanus Canal: Mechanical and electrical damage	NY	Brooklyn (Kings County)	NYMTC	\$3,300,000
207th Street University Heights Bridge: Mechanical and electrical damage	NY	Bronx and Manhattan (New York County)	NYMTC	\$3,200,000
NJ 71 Bridge over Shark River (Belmar): Mechanical and electrical damage	NJ	Monmouth County	NJTPA	\$3,000,000

Source: Federal Highway Administration, October 2013.

Note: Cost estimates are preliminary. Notable projects, such as repairs to the Hugh L. Carey Brooklyn-Battery Tunnel, the Holland Tunnel, and the Queens-Midtown Tunnel are not included in this table because preliminary estimates of repair costs had not been finalized as of the publication date.

Damage to the Regional Transit System

Rather than duplicate the extensive documentation and review of damage to the regional transit system as a result of the four storms covered by this analysis, this report presents a high-level overview of the damage associated with each storm event in an attempt to differentiate the impacts of the storms. The information presented in this section is not a comprehensive inventory of damage to the transit system in the study area. Rather, this section summarizes information available as of October 2013. The extent of damage wrought by Hurricane Sandy and the difficulty assessing long-term damage caused by the inundation of many key assets by salt water both present challenges to the region's transit service providers and to the Federal Transit Administration as they attempt to define specific restoration, repair, and replacement projects and estimate costs associated with these projects.

Hurricane Sandy

Table A.2 summarizes the costs associated with Hurricane Sandy as reported to the FTA by the region's transit operators as of January 2013. A full list of projects in each category can be found in the comprehensive report, "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report." Of the \$10.4 billion that Congress allocated to the FTA Emergency Relief program under the Sandy Supplemental funding for response, recovery, and rebuilding, \$5.7 billion (corresponding to the costs shown under the headings "Grouping 1" and "Grouping 2") has already been allocated to the agencies via formula. The remaining funding ("Grouping 3") will be allocated to projects addressing longer-term resiliency needs.

Similar to the damage caused to area roadways, the transit system was most heavily impacted by Hurricane Sandy's storm surge. Tunnels and stations flooded and above-ground tracks, rail yards, signals, and switches were inundated or washed out in a broad area covering all three states in the study area. Both New Jersey Transit and Metro-North Railroad also experienced severe wind-related damage, with trees and other debris destroying overhead catenary on rail lines west and north of New York City.

Table A.3 summarizes the most significant damage reported by each agency.

Table A.2. Summary of costs associated with Hurricane Sandy recovery, repair, and resiliency projects on the region’s transit system, as of January 2013.

Grantee/Applicant	Grouping 1: Priority Projects	Grouping 2: Other Restoration and Repair	Grouping 3: Resiliency	TOTAL
MTA NYC Transit	\$2,328,712,549 ^a	\$1,020,500,000	\$6,380,000,000	\$9,729,212,549
MTA Metro-North Railroad	\$232,397,000	\$105,400,000	\$812,000,000	\$1,149,797,000
MTA Long Island Rail Road	\$176,107,725	\$114,892,275	\$488,000,000	\$779,000,000
MTA Capital Construction	\$44,091,355			\$44,091,355
NYCDOT	\$36,792,662		\$6,100,000	\$42,892,662
PANYNJ	\$1,287,431,630		\$1,396,262,500	\$2,683,694,130
NJ Transit	\$475,741,086		\$1,055,187,500	\$1,530,928,586
Counties ^b	\$4,366,308			\$4,366,308
TOTAL	\$4,585,640,315	\$1,240,792,275	\$10,137,550,000	\$15,963,982,590

Source: FTA report: “Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report” January 2013.

^a NYC Transit identified an additional \$19,687,451 in response to the FTA’s Notice of Funding Availability which is not included in this initial damage assessment.

^b Includes costs identified by municipal transit operators in Putnam, Rockland, Westchester, and Nassau Counties, and costs submitted by New York State Department of Transportation on behalf of state-supported bus operators in FTA’s Region II.

Table A.3. Summary of damage to regional transit network from Sandy.

Transit Agency	Summary of Damage from Hurricane Sandy
MTA NYC Transit ^{a,b}	<ul style="list-style-type: none"> • Eight subway tunnels flooded, some completely from floor to ceiling. • Rockaway Line in Queens, including bridges over Jamaica Bay, completely submerged. Multiple portions washed out, and two full breaches of the embankment and causeway connecting the Rockaways to Howard Beach. • Sea Beach Line in Brooklyn, including nine above-ground stations, experienced severe flooding, resulting in damage to submerged infrastructure. • South Ferry (1) and Whitehall (R) Stations in lower Manhattan completely submerged; Rector Street (R), Rector Street (1), Broad Street (J,Z), and Bowling Green (4,5) severely flooded. • Dyckman Street (A) and 207th Street (A) Stations in Upper Manhattan and 148th Street (3) Station in Harlem severely flooded. • Coney Island Stillwell Terminal in Brooklyn severely damaged. • Switches and other equipment at rail yards and maintenance shops at Coney Island, Rockaway Park, 148th Street, and 207th Street under water and damaged. • 15 miles of damaged or destroyed signaling. • 10 escalators, three elevators, and 500 fare collection devices damaged. • Staten Island Railway (SIR) signals, switch controls, relays, and other components damaged at St. George Terminal. SIR Clifton Shop sustained structural damage, as well as damage to electrical, heating, and other systems. • MTA Bus Far Rockaway Depot flooded; equipment and office space damaged.
MTA Metro-North Railroad ^{a,d}	<ul style="list-style-type: none"> • Hudson Line flooded in numerous locations adjacent to the Hudson River. • Moderate flooding at Harmon Yard in Croton-on-Hudson impacted two locomotives, 11 passenger cars, and other equipment. • Trees down on New Canaan branch of New Haven Line damaged catenary.
MTA Long Island Rail Road ^a	<ul style="list-style-type: none"> • East River Tunnels flooded, damaging signals and communications equipment. • Mid-town Manhattan storage yard just west of Penn Station flooded. • Long Beach branch extensively damaged.

Table A.3. Summary of damage to regional transit network from Sandy (continuation).

Transit Agency	Summary of Damage from Hurricane Sandy
NJ Transit ^{a,c,d}	<ul style="list-style-type: none"> • More than 630 trees fell on rights-of-way system-wide. • More than 23 miles of catenary power and other wire damaged or destroyed. • Nine bridges, including two major draw bridges, suffered severe damage. • Nearly eight miles of track and roadbed washed out. • Key electrical substations destroyed. • Signal and communication systems and other critical systems damaged systemwide (all 12 rail lines). • Hoboken Terminal and adjacent rail yard flooded. • 71-acre Meadowlands maintenance and repair facility flooded; -261 rail cars, approximately 25 percent of NJ Transit's fleet, and 62 locomotives, approximately one third of the fleet, damaged or destroyed. • Damage to the rights of way of three light rail lines. • Minor to moderate damage at 17 bus garages statewide.
Port Authority-Trans Hudson Railroad (PATH)	<ul style="list-style-type: none"> • World Trade Center, Exchange Place, and Hoboken Stations submerged. • Several miles of track, signals, switches, and communications equipment flooded from World Trade Center to Grove Street, and near Hoboken Station. • Electrical substations flooded.
NYC Department of Transportation ^a	<ul style="list-style-type: none"> • Staten Island Ferry's St. Georges Terminal damaged by debris and flooding.

^a FTA report: "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report" January 2013.

^b Testimony of Joseph J. Lhota, Chairman and CEO of the New York Metropolitan Transportation Authority, to the United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m..

^c Testimony of Testimony of James Weinstein, Executive Director NJ TRANSIT Corporation, to United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.

^d Reuters, "New Jersey railway put trains in Sandy flood zone despite warnings," published November 17, 2012.

Hurricane Irene and Tropical Storm Lee

Hurricane Irene and Tropical Storm Lee in 2011 caused significant damage to the region's transit system as well, but the most significant damage occurred to a stretch of the Port Jervis Metro-North Railroad line in Rockland and Orange Counties, where three 1,000 foot stretches of track and one 4,000 foot stretch were washed out by flooding of the Ramapo River caused by extreme rainfall.

Irene and Lee also caused minor flooding of rail yards and maintenance areas along the Hudson River, including NJ Transit's Hoboken Terminal in Hudson County and Metro-North Railroad's Harmon maintenance facility and rail yards in Westchester County. Metro-North stations in Valhalla, Ossining and Croton-on-Hudson all experienced flooding, with minor damage. New Jersey Transit's Bound Brook station also flooded.

Nor'easter Alfred

The Halloween Nor'easter of 2011 brought snow that was trapped in leaf-covered trees early in the Fall season. Accompanying high winds caused the top-heavy trees to fall in large numbers, particularly north and east of New York City. Metro-North Railroad's New Canaan, Waterbury, and Danbury branches experienced damage from downed trees and debris.

A.5 Disruption Assessment

While damage to the transportation system as a whole has resulted in billions of dollars (and counting) in repair costs, other factors such as flooding, debris and snow-clogged roads, loss of electric power, a regional shortage of gasoline and diesel fuel, and wind also contributed to massive disruptions in service to the travelling public. Lost productivity added significantly to the overall costs of these events.

The following two sections summarize the disruptions to the highway and transit systems caused by the four storm events. As with the damage assessment above, this disruption assessment is not intended to be a comprehensive inventory, but rather to serve as an illustration of major categories of disruptions associated with the four storm events.

Regional Highway System Disruption

Hurricane Sandy

Hurricane Sandy caused extensive damage to coastal roads in New Jersey and New York, and several roadways and tunnels in lower Manhattan flooded or were extensively damaged by storm-related debris. Notable closures that caused disruption on a regional scale are shown in Figure A.23 and include the following:

- Sandy's storm surge caused major erosion or full washouts at nearly 40 locations on a 12.5-mile stretch of NJ 35. New Jersey Department of Transportation was able to reopen NJ 35 to limited traffic in January 2013, two months after the storm, but full reconstruction of the roadway was completed in a series of projects starting in 2013 and ending in 2015.
- Stretches of Ocean Parkway in Nassau and Suffolk Counties, NY, adjacent to the Atlantic Ocean also were washed out by Hurricane Sandy's wave action and storm surge. Washed out sections of Ocean Parkway reopened in April 2013.
- An estimated 86 million gallons of water flooded the Hugh L. Carey Brooklyn-Battery Tunnel between Manhattan and Brooklyn. The tunnel reopened to automobile traffic in late November 2012, nearly one month after the storm.
- The Holland and Midtown Tunnels flooded. The Holland Tunnel reopened to bus traffic on November 2 and to all traffic days later. The Midtown Tunnel was closed to all traffic until November 8.
- Although most bridges used to access barrier islands in New Jersey and New York were able to accommodate traffic within hours or days after the passage of the storm, many remained closed to all traffic except emergency vehicles and supply trucks for days or weeks to facilitate emergency response and disaster recovery in hard-hit areas.
- Prior to and during periods of sustained winds over 60 miles per hour, major bridge crossings in the region were closed to all traffic during Hurricanes Sandy. These included the George Washington Bridge, Tappan Zee Bridge, all bridges operated by MTA Bridges and Tunnels, some bridges operated by New York City DOT, and the Bear Mountain Bridge, operated by the NYS Bridge Authority. Trucks and high-profile vehicles were restricted from using these crossings when wind gusts regularly exceeded 60 miles per hour.

In addition to closures of roadway infrastructure, much of the region experienced a shortage of diesel and gasoline in the days after the storm. New York Harbor was closed to navigation by the U.S. Coast Guard for six days from October 30 to November 4. Due to storm-surge-related flooding that impacted three of the region's largest refineries and several fuel storage facilities, the region's fuel distribution system did not have capacity to transport enough fuel to the region's gas stations to meet demand. Motorists and truck drivers in New Jersey, New York City, and Long Island waited in hours-long lines attempting to refuel in the days after the storm. Often, gas stations ran out of fuel before waiting motorists could refuel. The Governors of New York and New Jersey and the Mayor of New York City imposed "even-odd" gasoline rationing at all gas stations in northern New Jersey, Long Island, and New York City. Rationing ended November 13 in New Jersey, November 17 on Long Island, and November 23 in New York City.

Power outages also caused failure of traffic signals, street lights, intelligent transportation systems infrastructure, and communications systems used to support emergency response. The Lower Manhattan street grid and major regional arterials functioned at very low levels of service with reduced capacity for days. As shown in Figure A.23, downed trees, downed power lines, and debris also blocked traffic on major regional routes for several days as state and local agencies and utilities cleared roads, sidewalks, and parking lots.

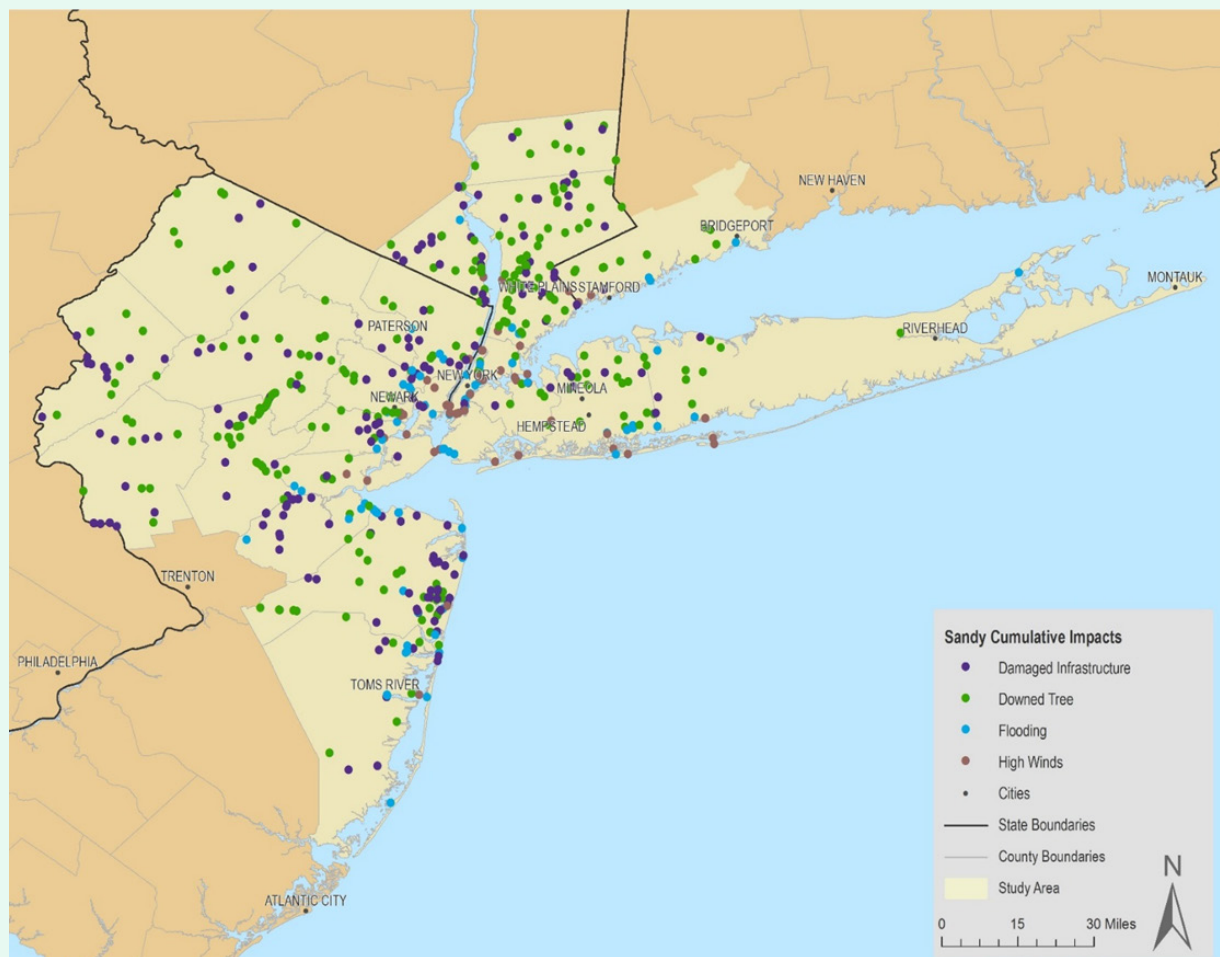


Figure A.23. Roadway system disruption reported on major regional roadways due to Sandy.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County, Long Island, in particular, only a limited number of incidents are reported to TRANSCOM.

Hurricane Irene and Tropical Storm Lee

Hurricane Irene and Tropical Storm Lee caused a moderate level of disruption to the regional highway system in the study area. The combined rainfall from the two storms resulted in riverine flooding that destroyed significant roadway and bridge assets, particularly where culverts, bridges, and stream-adjacent roadways were vulnerable to washouts. Significant disruptions in the study area due to Hurricane Irene are shown in Figure A.24 and included the following:

- The north (outbound) tube of the Holland Tunnel was closed due to flooding until 11 a.m. on August 28, the day after Irene passed;
- The Lower Level of George Washington Bridge was closed on August 27 due to high winds. The Palisades Interstate Parkway Entrance to the George Washington Bridge was closed until 11 a.m. on August 28;
- Flooding from the Passaic River in New Jersey closed many major arterials in Morris, Essex and Passaic Counties. For example, U.S. 46 and portions of U.S. 202 were closed for more than 3 days following Irene, and both closed again due to flooding attributed to Lee. Near Boonton, a portion of I-287 collapsed into the Rockaway River (a tributary of the Passaic River) and was reconstructed. A portion of I-80 in Morris County washed out and needed to be reconstructed. Exit ramps from I-80 East in Parsippany-Troy Hills and Wayne closed due to flood waters, washouts, and debris. Several portions of Route 23 in Morris, Passaic and Sussex counties closed due to shoulder washouts and debris on the roadway;
- New Jersey Route 18 in Piscataway and New Brunswick closed due to flooding of the Raritan River. U.S. 206 in Somerville also closed due to flooding and debris;
- An approximately 500-foot stretch of River Vale Road in Bergen County, New Jersey was washed out by floods; and
- Rockland County Route 94 in Haverstraw, New York, was washed out.

As shown in Figure A.25, the reported damage due to Lee in the study area was much less extensive than the damage from Irene and Sandy. Lee caused temporary flooding, downed trees, and downed power lines on roadways in northern New Jersey and in Westchester County.

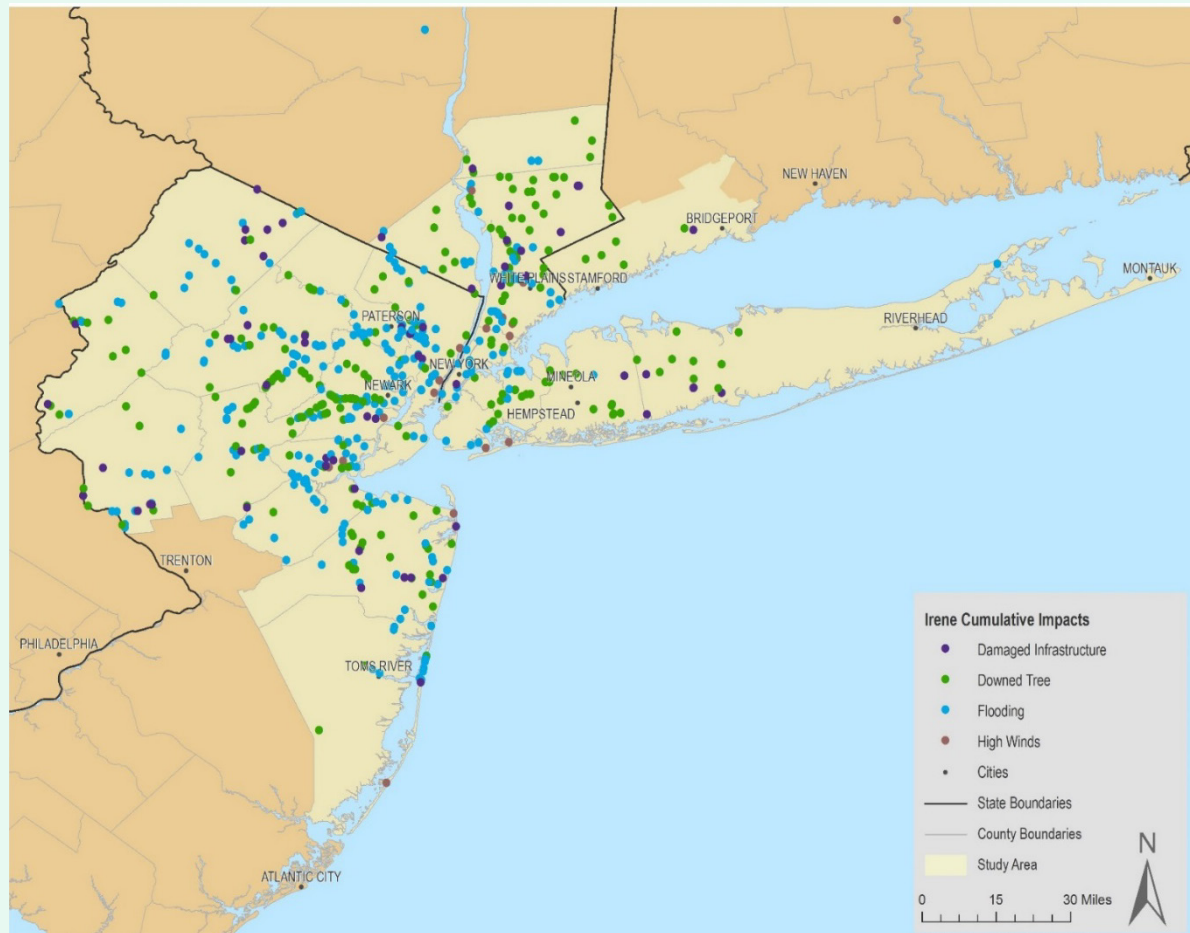


Figure A.24. Map. Regional roadway system disruption reported to TRANSCOM due to Irene.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

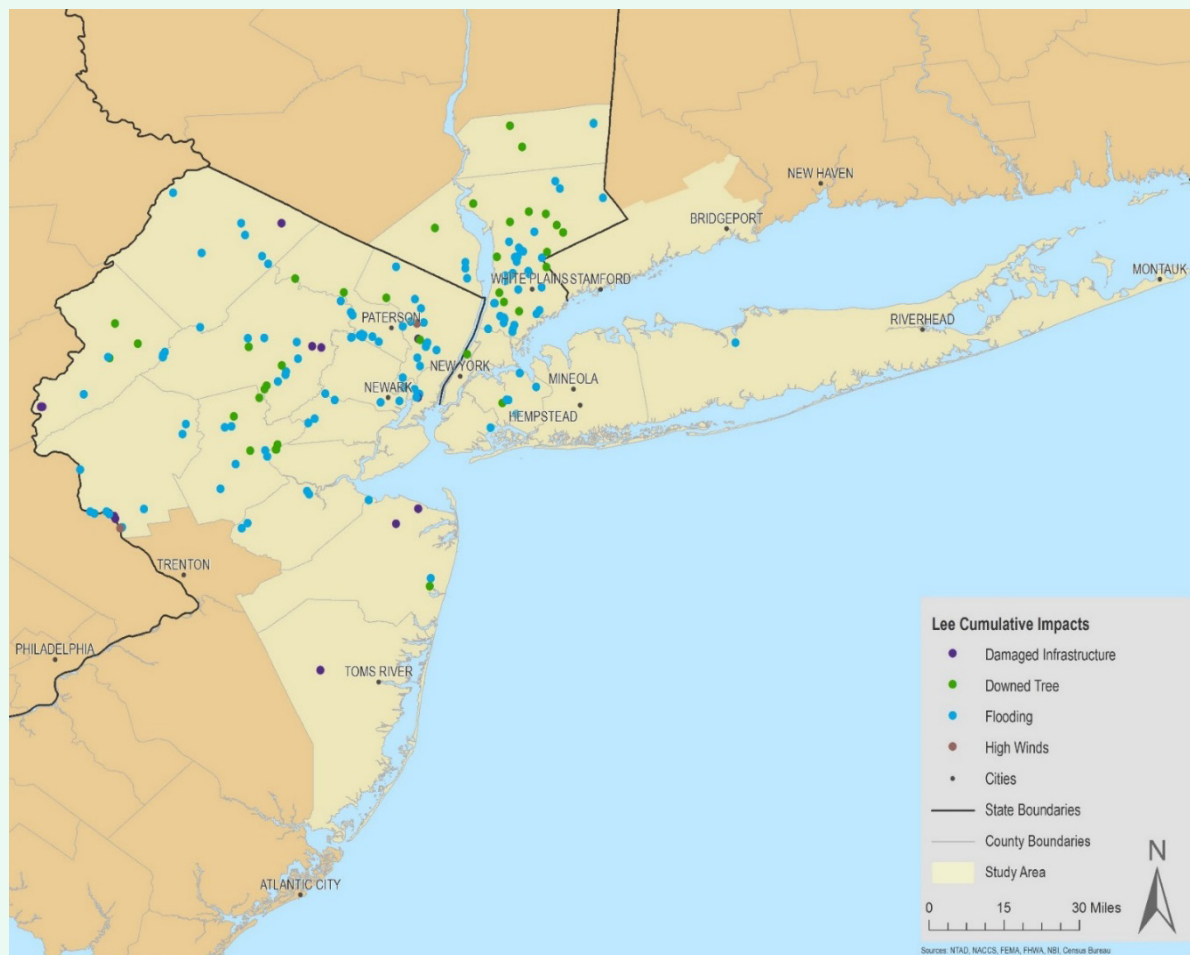


Figure A.25. Map. Regional roadway system disruption reported to TRANSCOM due to Lee.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

Nor'easter Alfred

Disruption due to the Halloween Nor'easter of 2011 largely was due to downed trees blocking area roadways. In Westchester County, New York, and in Fairfield County, Connecticut, major roads were passable within hours of the passage of the storm. However, major disruptions to the Connecticut's power supply due to downed power lines caused some traffic signals and street lights to be dark for days after the storm.

A.6 Regional Transit System Disruption

Hurricane Sandy

Hurricane Sandy caused major disruption to the transit services of every operator in the region. Figure A.26 shows a timeline of the disruptions and subsequent restoration of service on the MTA, New York City DOT (Staten Island Ferry), New Jersey Transit, and PANYNJ-managed transit systems, with impacts to the broader transportation system noted for reference.

Figure A.26 focuses on the period in the immediate aftermath of Sandy. To this day, shutdowns of subway tunnels and Amtrak's East River and North (Hudson) River tunnels for short-term and long-term repairs cause significant disruption to regional travel. For example, the MTA is preparing for long-term shutdown of the L train's Canarsie Tube under the East River to repair damage from Sandy. This will affect more than 225,000 weekday L train riders between Manhattan and Brooklyn, plus additional riders on other subway and bus lines that will have to accommodate displaced L train riders.

Figure A.26 also does not reflect the major impacts of Sandy on county-operated bus systems in the region. Long Island Bus and Westchester's Bee Line bus service were suspended for several days after Sandy, and paratransit services and other demand-responsive transportation services for the elderly, disabled, and veterans were impacted for weeks as local roadways were repaired and reopened.



Figure A.26. Timeline. Timeline of transit disruption due to Hurricane Sandy.

(Sources: MTA, NJ TRANSIT, PANYNJ press releases; FTA report: "Superstorm Sandy Public Transit Projects – Review of Cost Estimates Draft Final Report" January 2013; Testimony of Joseph J. Lhota, Chairman and CEO of the New York Metropolitan Transportation Authority, and James Weinstein, Executive Director NJ TRANSIT Corporation, to the United States Senate Committee on Commerce, Science and Transportation, Subcommittee on Surface Transportation and Merchant Marine Infrastructure, December 6, 2012, 10:30 a.m.)

Hurricane Irene and Tropical Storm Lee

Prior to the arrival of Hurricane Irene, New York City Transit took the unprecedented step of proactively shutting down the entire transit system so that customers would not be in harm's way, employees could safely get home, and rolling stock could be positioned in locations where they could safely weather the storm. New Jersey Transit, the PATH subway, and local transit operators took similar measures. As a result, the region's rolling stock was largely unscathed during the coastal and riverine flooding that occurred in the days after Hurricane Irene and Tropical Storm Lee passed through the area.

The most significant disruption from the one-two punch of Irene and Lee was due to the flooding of the Ramapo River in Rockland County, which severely damaged 14 miles of Metro-North Railroad's Port Jervis Line, causing three 1,000-foot washouts and one 4,000-foot washout between Suffern and Harriman, New York. The Port Jervis Line, which served 3,000 daily commuters, was out of service for nearly three months as the track and signal systems were reconstructed and repaired.

The region's commuter rail operators and Amtrak had to clear a large amount of debris from the tracks following both Irene and Lee, but, with the exception of the Port Jervis Line, the rail system was back up and running shortly after each storm.

Additional transit system disruptions due to Irene and Lee included the following:

- Amtrak and New Jersey Transit were affected as Northeast Corridor service was suspended from August 28 to August 31 due to flooding at the Trenton Transit Center and other storm-related damage from Irene;
- Service on the PATH was suspended from 12 PM on August 27 until 4 AM on August 29 (40 hours); and
- NJ Transit's Bound Brook station was closed due to flooding from the nearby Raritan River.

Nor'easter Alfred

The Halloween Nor'easter Alfred of 2011 caused minor disruptions to MTA Metro-North Railroad service. Service was suspended on the Danbury, New Canaan, and Waterbury branches for over 24 hours due to track conditions and wind-blown debris. Local bus services in Connecticut were heavily impacted by Alfred, as were school buses that could not safely navigate local roads. Many schools were closed for at least a week during the clean up and due to power outages. Bus services began to recover throughout the week. Long-lasting power outages in Connecticut also affected traffic signals and street lights, causing a safety hazard on arterials and collector roadways.

A.7 Long-Term Damage, Disruption, and Resiliency Projects

Due to the nature of the damage associated with salt water inundation, some disruptions to the region's transportation system, and its transit system are expected to continue well into the future. For example, a sealed brake unit in an escalator in the PATH's Exchange Place station was damaged by salt water when the station was inundated by Hurricane Sandy's storm surge. This damage was not detected until a malfunction of the escalators on January 8, 2013, well over two months after the storm. Signals in Amtrak's East River Tunnels and in Long Island Rail Road's Long Beach Yard have failed repeatedly in the months after Sandy, with outages attributable to salt water corrosion of electrical and mechanical systems.

The full extent of Hurricane Sandy's damage may not become apparent for many years as the region's transit operators make necessary repairs and make the system more resilient in the face of future expected extreme weather events. As noted in Table A.2, more than \$10 billion in resiliency-related projects have been identified to date by regional transit operators to avoid damage and disruption on the scale caused by recent major storms and other types of natural and man-made hazards.

B

Facility Level Vulnerability and Risk Assessment Process

This Appendix describes the step-by-step process used to conduct a facility-level assessment of adaptation options to address vulnerability and risk.

The process was developed as an engineering-informed adaptation assessment of specific transportation facilities as part of the Post-Hurricane Sandy study, but the steps can apply generally to transportation networks, subareas, and corridors consisting of groups of assets.

Before launching this process for a facility-specific assessment, consider the following initial actions that can help to streamline the analysis:

- Review the full assessment process and run through steps qualitatively first to determine if all steps are necessary and to set priorities;
- Conduct a system-level assessment of criticality to prioritize the facilities and networks that are the highest priority for adaptation investments. Then conduct a vulnerability and risk assessment on the most critical facilities to further screen and prioritize individual assets for the more detailed facility level analysis;
- Assemble empirical data on facility condition, the history of damage and disruption at a regional scale and for specific corridors and subareas, and facility- and component-specific thresholds for failure (damage) and disruption. Specific examples of data points include repair and replacement costs and duration of disruption.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets.

In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

- Conduct pre-screening to determine if facility level strategies are appropriate vs. area-wide or regional strategies that address multiple facilities and multiple classes of infrastructure

Pre-screening can help avoid creating “islands of adaptation” that only protect a transportation facility, ignoring the impacts of climate stressors on other adjacent transportation assets, the communities, businesses, and other origins and destinations served by the transportation system. Consider potential relationships and interactions between related projects (adjacent, upstream/downstream, etc.) up front in the analysis.

Module 1: Define Climate Impacts and Scenarios for Analysis

Step 1.1. Use sensitivity screening to identify potential climate stressors relevant to the assessment of transportation impacts.

Step 1.2. Establish current and projected scenarios for each climate stressor to be used in the vulnerability assessment (Module 2).

Inputs Needed

- Basic information on the selected system(s) or asset(s), including location and function;
- Baseline information on weather events and associated impacts (e.g., historical rainfall data and information on stream levels); and
- Projected changes in return periods of specific weather events (e.g., shifting intensity-duration-frequency curves for rainfall or change in number of days per year above 100 degrees) and changes in associated stressors and impacts (e.g., extent of 100-year and 500-year flood plain).

Step 1.1. Sensitivity screening. Use high-level, qualitative sensitivity screening to match the asset and its most critical components to relevant climate stressors and impacts, which may include the following:

- An asset or one or more of its components sustains damage and requires repair or replacement, or
- An asset is not damaged, but must temporarily be taken out of service to people and/or freight.

It is possible that a single asset could have multiple components that are vulnerable to multiple climate stressors. See Table C.1 for an example of how to apply sensitivity screening for coastal storms to various asset classes.

In Module 2, the asset will be assessed for exposure and sensitivity thresholds using a more detailed analysis. For the initial screening, it is sufficient to match the asset and its components to stressors to which they might potentially be sensitive.

This screening will rely primarily on the asset type and where it is geographically located. For example, if the asset is located inland, even if it is sensitive to flooding, sea level rise does not need to be assessed.

This initial screening is important because it will help limit the scope of data collection in Module 2.

Table B.1. Example high-level sensitivity screening matrix: coastal storms.

Climate Stressor	Storm Surge, Tidal Flooding, and Wave Action				Wind- Impacts to structural integrity; debris build-up
	Scour	Undermining/ washout	Uplift and displacement	Saltwater intrusion into electrical and mechanical equipment, Roadway overtopping and ponding of water	
Potential Applicability: Road or Rail Bridges, Culverts, and Tunnels					
Bridge superstructure			●		●
Bridge substructure	●	●	●		●
Tunnel structure					●
Tunnel ventilation and evacuation shafts and structures	●			●	●
Electrical and mechanical components			●	●	
Approaches		●		●	●
Ancillary structures (e.g., moveable bridge operator houses and equipment sheds)			●	●	●
Potential Applicability: Linear Infrastructure (Roadways and Rail Lines)					
Roadway pavement and base		●		●	●
Rail track, ballast, and base		●		●	●
Geotechnical structures and storm water management infrastructure		●		●	●
Signals, communication systems, mechanical equipment and power				●	●
Potential Applicability: Facilities					
Site		●		●	●
Building Structure			●	●	●
Electrical/Mechanical Systems				●	●
Potential Applicability: Equipment and rolling stock					
Fleet vehicles and equipment			●	●	●
Materials and supplies			●	●	●

Step 1.2. Identify current and projected climate scenarios that are appropriate for the asset, in terms of magnitude, timeframe and frequency of the weather event considering:

- The current age and the expected remaining life span of the asset. For instance, an asset that has a remaining service life of 50-75 years (such as a bridge that has been recently rehabilitated) may be reviewed using end of century projections. For an asset that has a remaining service life of less than 20-30 years (e.g., asphalt road surface, electrical components, some types of mechanical components, etc.), the use of projections for a shorter time period may be more appropriate. If an asset is very close to the end of its useful life, it may be appropriate to use the remainder of this assessment process to inform the design of the replacement project.
- The agency's tolerance for risk. An agency with a higher risk tolerance would plan for less extreme changes (e.g. a low greenhouse gas (GHG) emission scenario or climate model with low sensitivity to increasing GHG concentrations in 2050). An agency with a lower risk tolerance could be expected to plan for more extreme change (e.g. a high emission scenario and climate model with high sensitivity in 2100). See the facility-level assessments in Appendix F of this report for examples of how risk tolerance was determined on an asset-by-asset basis for purposes of this study.

Weather event return periods and recurrence intervals from current industry design standards can serve as a starting point to guide the agency towards a comfortable level of risk for current and projected scenarios. A return period or recurrence interval is an estimate of the likelihood of an event, such as a flood, to occur.

Note that a risk assessment may take into account other types of infrastructure within or near the transportation asset, such as water, sewer, electrical, or communications systems, particularly if reliant on that infrastructure for full functionality.

Lessons learned in the application of this assessment process in the Post-Hurricane Sandy study:

- Stay on top of research: climate science is continuously evolving. New studies and research regularly become available, but the findings need to be vetted by experts. Adopt clear guidance on the use of climate data, and review sources regularly for updates.
- Information on design standards related to climate stressors may not be readily available. Agencies should allow ample time to collect this information, and match expectations for the outcome of this analysis to the data that are available to support it.
- While it is useful to have standards as a starting point, in some cases and agency may need to consider amending relevant climate inputs given the projected increases in the frequency, magnitude, and duration of extreme events. For example, if today's 100-year storm is tomorrow's 50-year storm, the agency should determine risk tolerance based on the intensity and duration associated with that return period.

Module 2: Assess Vulnerability

Step 2.1. Assess the potential for **exposure** of the asset and its components to the climate stressors identified in Module 1;

Step 2.2. Perform a **sensitivity** analysis to determine to what degree the asset could be affected by future climate stressors;

Step 2.3. Evaluate the adaptive capacity of the asset and the transportation network around the asset; and

Step 2.4. Summarize the asset's vulnerability to selected climate stressor scenarios, combining the results of the exposure, sensitivity, and adaptive capacity analyses.

Inputs Needed

- List of relevant climate stressors identified in Module 1;
- Information on expected intensity, duration, and frequency of occurrence of these climate stressors today and how these variables may change in future years (from Module 1);
- Sensitivity matrix identifying potential failure thresholds for given stressors (from Module 1);
- Any available existing condition data including: as built drawings and specifications, inspection reports, load ratings, maintenance and repair records (particularly related to extreme weather events), FEMA grant applications and requests for Emergency Relief (ER) funding from FHWA or FTA (which may provide qualitative descriptions of damage, repair and replacement cost data, and other justifications for why the assets require funding);
- Prevailing codes and standards for the asset or asset components; and

Information about alternative routes and modes that serve the same origins and destinations as the asset(s) under analysis.

Exposure is an assessment of whether each climate stressor could result in:

Potential damage to or failure of an asset, or

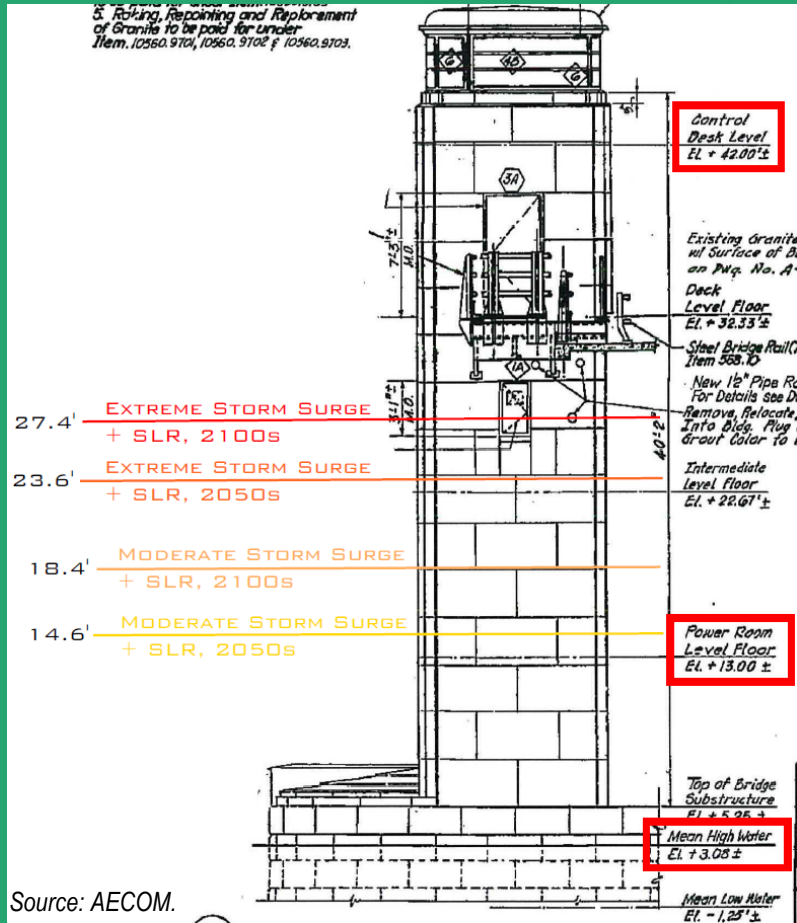
Disruption to the movement of people and goods because the asset is unavailable (for example, under water, blocked by debris, or lacking power or critical safety systems).

Step 2.1. Conduct exposure analysis for current and forecast years. Analyze whether the asset will be exposed to any or all of the climate stressors identified in Module 1. Consider changes in climate that could affect the potential for exposure to climate stressors that exceed the failure thresholds for the asset or its components over their remaining useful life:

- Sea level rise (absent storm surge);

Lessons learned in the application of this assessment process in the Post-Hurricane Sandy Study:

- Assets are not always in compliance with existing standards, or even standards that were in place when they were constructed, because of context-sensitive design practices that allow for flexibility.
- Agencies may not have easy access to as-built drawings and relevant design standards for all relevant asset components. Allow for time to assemble this information.
- Understand and communicate to stakeholders the distinction between exposure to a climate stressor and sensitivity to that stressor.



Source: AECOM.

Lessons learned in the application of this assessment process in the Post-Hurricane Sandy Study:

The figure at left shows an example of an exposure analysis applied to the control tower for a bascule bridge on Loop Parkway. The water elevations on the left are compared to the highlighted elevations of the floor containing the Control Desk and the floor containing power equipment.

- Changes in intensity, frequency, and duration of storms producing area-wide winds above the asset's failure threshold and/or coastal storm surge (including cumulative impacts of sea level rise and wind-induced waves); [note that projections of wind speeds are not readily available at this time]
- Change in frequency, intensity, and duration of precipitation (leading to flash/inland flooding in watersheds and drainage basins; localized flooding that could occur due to overloaded drainage systems; or drought and accompanying wildfires); or
- Changes in average and extreme temperatures (number of days above or below a temperature equal to an asset's failure threshold; change in freeze/thaw cycles; frequency and intensity of ice/snowfall events).

The level of effort for the exposure analysis can be tailored to the available resources for the assessment, the criticality and complexity of the asset, and the types of relevant climate stressors identified in Module 1.

- Exposure could be a simple binary analysis (e.g., a rail line is in a 100-year flood plain in the current and/or future year, or it is not).
- Alternatively, the exposure analysis could rely on more data-intensive analysis to project the magnitude of the exposure in the forecast year compared to today (e.g., a 100-year storm in 2100 will submerge the rail line in three feet of water for three consecutive high-tide cycles).

If the asset is found to be exposed to one or more climate stressors, then the vulnerability assessment continues in Steps 2.2 through 2.5. If the asset is not exposed to any climate stressor in any scenario, then the vulnerability and risk assessment for that asset/stressor combination is complete.

Step 2.2. Perform sensitivity analysis. Assess each asset or asset component identified in the previous step to determine the degree to which it may be affected by the climate stressors identified in Module 1. Depending on how sensitive an asset is to climate stressors, the asset may have a reduced level of service (e.g., a rail speed restriction imposed on a hot day), it may be temporarily taken out of service to people and freight, or the asset (or one or more of its components) may sustain damage and require repair or replacement.

Thus, there are two categories of thresholds of concern in a sensitivity analysis. Both can be presented in terms of step functions with progressively worse impacts:

- **Disruption thresholds** include the point at which an asset's level of service is reduced (this can be more than one threshold) and the point at which an asset has to be taken out of service entirely due to safety or operational concerns, and
- **Damage thresholds** (or failure thresholds) are the points at which an asset or its components require repair or replacement.

First, use engineering judgement to match the results of the exposure analysis from Step 2.1 with specific "failure modes," or reasons that an asset could be taken out of service, damaged, or destroyed. It is possible that a single asset could have multiple components that are sensitive to multiple climate stressors. Screen out the component-failure mode combinations that are not relevant.

Next, for each relevant component-failure mode combination, assemble available existing condition information and design standards. The following list provides an example:

- **As-built Construction Drawings** – As-built drawings will provide information such as elevation data, materials and components used, and any repairs that have been performed since initial construction. For bridges, information on foundation components, superstructure type, span arrangements and bearing types, and electrical or mechanical components for moveable bridges will be useful.
- **Inspection Reports** – The reports from the most recent inspection cycle will provide any previously found deficiencies and any evidence of damage due to previously experienced extreme events (such as level of scour for bridges), etc.

Sensitivity is the degree to which an asset is affected by a climate stressor. For example, a highway flooded by more than a few inches of water becomes unusable and, therefore, is highly sensitive to inundation. Signs on the roadside may not be affected by water, but could be sensitive to wind.

In this step of the assessment process, the objective is to determine the thresholds for disruption and damage and how often these thresholds are expected to be exceeded over the remaining useful life of the asset. If an asset is deemed to be highly sensitive to a particular climate stressor, the specific impacts associated with disruption and/or damage can be more finely quantified in Module 3 the Risk Assessment

Lessons learned in the application of this assessment process in the Post-Hurricane Sandy study:

- Agencies typically do not maintain information on failure thresholds for assets and asset components, and thus the thresholds may need to be developed specifically for this analysis.

- **Maintenance and Repair Records** (Including damage reports used to obtain FEMA or Emergency Response grants): If the asset has been damaged in a previous event, the extent of damage and duration of service disruption will be very useful in assessing sensitivity to future events and the consequences of future damage and disruption.
- **Prevailing Design Standards** – Only sections of the local or national codes and standards which govern design of the component will be required:
 - The information collected will allow for the comparison of the existing asset to determine if it adheres to current design standards. This will assist in the selection and prioritization of adaptation strategies in Module 4.
 - Load and Resistance Factor Design (LRFD) Bridge Design Specifications and LRFD for Movable Bridges (published by the American Association of State Highway and Transportation Officials, or AASHTO), the AASHTO Green Book, AASHTO Luminaire Specification, the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering, local bridge and roadway design manuals, railroad design criteria, etc.

For bridges, the following data may also be useful, if available:

- **Load Ratings** – The most recently performed load and inventory ratings will express structural or functional obsolescence, ability of the structure to carry its intended loading, etc.
- **Existing Hydraulic or Scour Analysis Data** – Evaluation of scour vulnerability will be based on existing scour analysis if available. of the type of information that could be collected. The specific list of information will vary according to asset and component type.

For each relevant component-failure mode combination, use data on existing conditions and design standards to determine the specific disruption thresholds and damage thresholds. Compare the as-built condition of the asset (or component) relative to the climate stresses projected to occur over its remaining useful life.

The sensitivity of an asset or component to a given climate stressor will depend on three variables:

The relationship between vulnerability and adherence to design standards is not straightforward, particularly if the standards are outdated or not relevant.

A scour analysis typically involves an assessment of the site hydrodynamic conditions (water level/tide/storm surge, current velocity and wave (if applicable) around the project site), soil conditions, and long-term channel migration records. A general scour analysis and local scour analysis can be combined to get the estimation of total scour depth. For the majority of situations, an empirical formula based on FHWA and State DOT guidance combined with engineering judgment is used to perform this kind of analysis.

Codes/guidelines from FHWA (HEC-18, HEC-20, and HEC-23 for River Scour Analysis, and HEC-25 for Scour Analysis in Coastal Environment) are usually required.

- **Intensity** of each event, (How high does the temperature get, and do these extremes exceed thresholds of concern for material specifications? What is the intensity of the rain storm? and what is the resulting height of flood waters?),
- **Duration** per occurrence (Do the high temperatures last long enough to cause damage or disruption? How long does the water remain on the roadway before draining away?),
- **Frequency** of occurrence (How many days per year will temperature exceed a threshold of concern? What is the return period of a storm that causes the roadway to flood, and how is this return period expected to change over time?).

Table B.2 shows an example of climate projections for mean annual temperature, mean annual precipitation, and sea level rise for the New York City area. Table B.3 shows projections of duration and frequency of heat waves for three periods in the future.

Finally, assign a sensitivity score to the asset. The score can be purely qualitative (high/medium/low) or a numerical ranking based on qualitative and quantitative analysis that considers an asset's criticality to the function of a corridor or network. If an asset is exposed to but not sensitive to any climate stressor, the analysis can stop here.

Lessons learned in the application of this assessment process:

Refer to the asset-level adaptation assessments in Appendix E for examples of how a sensitivity analysis can be applied at the scale of an asset.

Refer to the subarea assessments in Appendix D for examples of how a sensitivity analysis can be applied at the scale of a corridor or small network of transportation facilities.

For some impacts, antecedent conditions and time of year/day may be important as well (e.g., did the rain fall when soils were dry or when they were saturated?). Some of the climate stressors are interdependent; for example, increases in precipitation or earlier, more rapid snow melt could be drivers for changes in riverine flooding.

Accelerated deterioration of an asset may be a significant driver of costs to an agency, as assets may need rehabilitation and replacement earlier than planned. Premature deterioration is very difficult to assess, but agencies with more sophisticated asset-level and component-level deterioration models are in a good position to assess the impacts of premature deterioration. See Module 3 for more details.

Table B.2. Projected mean annual change in temperature, mean annual change in precipitation, and sea level rise for New York City region.

Year	Temperature Baseline (1971–2000): 54°F			Precipitation Baseline (1971–2000): 50.1 in.			Sea Level Rise Baseline (2000-2004): 0 in.		
	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s	+1.5°F	+2.0–2.9°F	+3.2°F		+1–8%	+10%	+2 in.	+4 to 8 in.	+10 in.
2050s	+3.1°F	+4.1–5.7°F	+6.6°F	+1 percent	+4–11%	+13%	+8 in.	+11 to 21 in.	+30 in.
2080s	+3.8°F	+5.3–8.8°F	+10.3°F	+2 percent	+5–13%	+19%	+13 in.	+18 to 39 in.	+58 in.
2100	+4.2°F	+5.8–10.4°F	+12.1°F	percent		+25%	+15 in.	+22 to 50 in.	+75 in.

Source: Horton, Radley, et. al, 2015. *New York City Panel on Climate Change (NPCC) 2015 Report*.

New York State Energy Research and Development Authority (NYSERDA), 2014. "Responding to Climate Change in New York State: 2014 Update (ClimAID)," projections for Region 4 (New York City). The NYSERDA report provides separate Sea Level Rise projections for Montauk Point, which are identical to the New York City projections shown in Table 3.2 with the following exception: In 2100, the Middle range for Montauk Point is estimated at 21 to 47 in. of sea level rise, and the High estimate is 72 inches of sea level rise.

Table B.3. Projections of heat waves in New York City region.

Climate Variable	Baseline	Climate Variable	Baseline	Climate Variable
Number of heat waves per year Heat waves are defined as three or more consecutive	2	2020s	3	3 to 4
		2050s	4	5 to 7
		2080s	5	6 to 9
Average heat wave duration (days)	4	2020s	5	5 to 5
		2050s	5	5 to 6
		2080s	5	5 to 7

Source: Horton, Radley, et. al, 2015. *New York City Panel on Climate Change (NPCC) 2015 Report*.

New York State Energy Research and Development Authority (NYSERDA), 2014. "Responding to Climate Change in New York State: 2014 Update (ClimAID)," projections for Region 4 (New York City).

Step 2.3. Assess adaptive capacity. This step will assess the adaptive capacity of the asset (and the system) – that is, the ability of the asset to return to service after a specific impact, or the system to return to service due to the availability of alternative assets. An asset that can recover quickly and is not significantly damaged, or is part of a larger system that has built-in redundancies with alternative assets is said to have high adaptive capacity. An asset that serves as the sole means of access to a community or critical facility (hospital, power plant, sewage treatment plant) and cannot recover from impacts has no adaptive capacity.

Adaptive capacity is the ability of an asset or system of assets (e.g. a roadway network, a power grid, water distribution system, etc.) to adjust to, or rebound from, an extreme weather impact by limiting the duration and/or scope of potential damages, taking advantage of network redundancy, or coping with the consequences.

For this step, consider redundancies within the asset itself (e.g., backup generators or pavement wide enough to accommodate traffic even with a partial washout of a shoulder), parallel carriageways or parallel bridge spans that could be converted to two-way traffic, and available detour routes. Depending on the climate stressor being analyzed, alternative routes may be impacted by the same climate event.

Assign a qualitative score to the asset's adaptive capacity. If the asset is exposed and sensitive to a climate stressor, but there is a large degree of adaptive capacity within the asset or in the transportation network, the agency may choose to end the assessment here.

Step 2.4. Integrate results and finalize vulnerability assessment. Describe the vulnerability of the asset qualitatively (high/medium/low) based on the combined results of the exposure analysis, sensitivity analysis, and assessment of adaptive capacity.

Module 3: Assess Risk – Likelihood and Consequence

Step 3.1. Identify the **likelihood** of damage or disruption to the asset over its remaining useful life for the selected climate scenario.

Step 3.2. Identify the potential **consequences** of asset damage or disruption.

Step 3.3. Establish the **integrated risk** of asset damage or disruption.

Inputs Needed

- Estimated changes in intensity, duration, and frequency of climate events in the selected scenario;
- Duration of disruption (time needed to repair or replace the asset);

- Direct agency costs associated with damage (primarily costs to repair or replace the asset or damaged components);
- Information used to calculate direct costs to users (additional travel time, value of time, vehicle operating costs, and safety-related costs associated with additional travel distance, along with lost wages);
- Information used to calculate broader economic impacts of disruption (direct and indirect costs to businesses); and
- Non-economic indicators used by the agency (impacts to vulnerable populations, emergency routes, access routes to critical facilities, etc.).

Likelihood is the chance that a climate stressor will impact the asset and lead to disruption or damage within the asset’s lifetime. Likelihood may be based on statistical or modeling analyses, expert views, or other qualitative or quantitative analyses.

Step 3.1. Establish likelihood that a climate stressor will disrupt or damage an asset over its remaining useful life. The work in Module 2 will establish the characteristics of an event exceeding disruption and damage thresholds. The likelihood analysis could simply consider the return period of that event, if “occurrence” is synonymous with disruption and/or damage (e.g., electrical components submerged in water often fail).

A more complex analysis might involve building probability distributions for each event that account for changes in return periods over time due to climate change. A much more complex analysis might involve establishing joint probabilities for events that are correlated (storm surge and high winds, or drought and wildfire), or considering the impacts of chronic stressors (like salt water exposure) on thresholds for disruption and failure over an asset’s remaining useful life.

Table 4.2 shows an example of a likelihood scoring scheme.

Assign a likelihood score to the asset-stressor combination. There could be separate scores for disruption and damage. All asset-stressor combinations should advance into the consequence assessment in the next step, because unlikely events with extreme consequences may be among an agency’s highest priorities for adaptation.

Step 3.2. Estimate consequences of disruption and damage. Agencies can use a range of approaches for estimating consequences based on available resources, the criticality of the asset (including its repair/replacement cost), the agency’s tolerance for risk, and other factors:

Table B.4. Example of likelihood rating scheme.

Score	Description	Occurrence of the event/impact during the asset’s lifetime
1	Almost certain	80-100%
2	Likely	60-79%
3	Possible	40-59%
4	Unlikely	20-39%
5	Remote	0-19%

- A lightweight, qualitative approach might rely on a combination of experience from past weather events and expert judgement about potential impacts in the future with climate change.
- A moderately-intensive analytical approach might involve evaluation of direct user costs due to disruption of service while the facility is repaired and estimates of direct costs to the agency to repair or replace the asset. This is the most common approach to estimating consequences of damage and disruption.
- The most rigorous evaluations might involve travel demand model runs to generate more precise estimates of travel time-related costs, combined with economic simulation models to capture indirect and induced economic impacts of the disruption on the regional economy.

Consequence refers to the outcomes (e.g., economic, ecological or social) associated with the impact of a climate stressor and can range from positive to negative. For example, one economic consequence of inundation of arterials from storm surge would be a reduction in, or higher cost of, goods movement. A social consequence would be the isolation of a low-income community from local services.

Table B.5 shows how each calculation would be performed for each of these levels of effort. Estimates of non-economic outcomes can be added to any of these approaches. For example, it may be important to know if a disruption to the system would disproportionately impact vulnerable populations, or if the disrupted facility is designated as an evacuation route, or if it is an access route to a critical facility. See Table B.6 for examples of noneconomic indicators of risk.

The “rigorous” evaluation approaches merge elements of consequence analysis and likelihood analysis into each step.

Lessons learned in the application of this assessment process:

- Repair and replacement costs may also be impacted by long-term deterioration of an asset or component due to stressors like one-time or repeated salt water exposure. The incremental repair and replacement costs can be very difficult to separate from other long-term causes of asset deterioration (e.g., freeze/thaw cycles or vibrations and stresses from overweight vehicles).

Table B.5. Alternative approaches to consequence analysis.

Estimate duration of disruption due to a given climate stressor	
Qualitative Approach	Collect information on past events that caused disruption or damage to the asset. Use expert judgement to estimate how duration of disruption could change in the future due to climate change. Estimate duration of disruption on a per-event basis in days (e.g., number of morning and/or evening commutes disrupted).
Moderately-Intensive Analytical Approach	Assemble comprehensive historical record of past events that caused disruption or damage to the asset (e.g., operational data overlaid with weather data). Use expert judgement, informed by information from climate models, to estimate how duration of disruption could change in due to climate change over the asset’s remaining useful life. Estimate average duration of disruption on a per-event basis.

Table B.5. Alternative approaches to consequence analysis (continuation).

Estimate duration of disruption due to a given climate stressor	
Rigorous Evaluation Approach	Use climate models and Monte Carlo simulations to generate probability distribution of duration of disruptions over an asset's remaining useful life.
Estimate duration of disruption due to a given climate stressor	
Qualitative Approach	Collect information on past events that caused disruption or damage to the asset. Estimate costs on a per-event basis by totaling repair and replacement costs. Multiply (a) annual probability of event requiring repair and replacement, (b) per-event repair and replacement costs, and (c) remaining years of useful life of asset.
Moderately-Intensive Analytical Approach	For each year in the remaining useful life of the asset, estimate how the annual probability of an event requiring repair and replacement will change due to climate change. Multiply (a) annual probability of event requiring repair and replacement and (b) per-event repair, replacement, and emergency management costs. Sum all the repair and replacement costs for the remaining years of useful life.
Rigorous Evaluation Approach	Based on a historical record of damage, build a depth-damage curve that relates the magnitude of an event to the cost of damage and disruption. Calculate the cumulative damage and disruption costs over the remaining useful life of the asset for all climate events (of all magnitudes) expected to occur.
Estimate costs to users due to damage and disruption	
Qualitative Approach	Estimate average detour length for vehicles and calculate additional miles traveled. Convert additional miles traveled to additional travel time. Multiply additional travel time by average value of time for users of the asset (personal value of time for individuals and commercial value of freight). Also use aggregate additional miles traveled to generate estimates of additional vehicle operating costs and costs associated with safety impacts.
Moderately-Intensive Analytical Approach	Use regional models to more precisely estimate impacts of the disruption on aggregate vehicle miles traveled and aggregate travel times for people and freight. Use these estimates to enhance calculations of travel time, vehicle operating costs, and safety-related costs associated with the disruption. Also estimate lost wages based on per capita or per-household income in the affected areas.
Rigorous Evaluation Approach	Run regional models or corridor-level simulations with dynamic traffic assignment to estimate the number of travelers in each socioeconomic group and industry who will forego trips when faced with a major system disruption, and the specific impacts of the disruption on travel patterns of those classifications of people and freight who do make the trip. Refine estimates of lost wages based on assessments of who can productively work at home or take vacation time during disruption period.
Estimate broader economic impacts of disruption	
Qualitative Approach	Qualitatively assess the impacts of disruptions in terms of lost wages
Moderately-Intensive Analytical Approach	Using estimates of the direct user costs and duration of disruption, employ a basic input-output model (e.g., Implan) to generate estimates of broader economic impacts of the disruption in one or more forecast years.
Rigorous Evaluation Approach	Use a regional economic simulation model to estimate variable impacts each year of the forecast period. Aggregate the indirect and induced economic impacts in terms of employment, per capita income, and/or regional output.

Table B.6. Examples of non-economic criteria to assess consequences of failure.

	Descriptor	A: Impact on Communities of Concern	B. Lifeline or Evacuation Route	C. Brand Impacts	D. Potential Loss of Life	E. Historical and Environmental Impacts (as appropriate)
5	Extreme	Calculate based on % of population that own a car; % of population below the poverty line that relies on the asset type. Particularly important for transit assets.	If the asset provides/is part of a designated evacuation route and there is no alternative with adequate capacity, this would be an extreme consequence.	If the agency has had a history of failures with a particular asset and has spent a lot of tax payer's money repeatedly repairing an asset to the same tolerance, then the consequence of continued failure will be higher.	Any loss of life may be considered an extreme consequence	
4	Major				N/A	
3	Moderate				N/A	
2	Minor				N/A	
1	Insignificant				N/A	

Step 3.3. Combine likelihood and consequence analysis to develop a risk rating. A risk rating can enable the agency responsible to prioritize which of its assets should be the focus of adaptation planning. A risk assessment integrates the severity or consequence of an impact with the probability or likelihood that an asset will experience a particular impact during its lifetime. The assessment applies a rating that might range from Extreme to Negligible.

Based on the likelihood of occurrence from Step 3.1 and the consequence as determined in Step 3.2, determine the overall risk rating as shown in Table 4.4. As an example, a climate impact with a likelihood of occurring of 3 (Possible) and a consequence of a 4 (Major) would result in overall risk rating of High. The resulting risk rating of Negligible, Low, Moderate, High or Extreme will be included in the Risk Profile for the asset.

Advance those assets with the highest risk rating to the next step, assessment of potential adaptation strategies.

The risk rating scale, while simplistic, is transparent and avoids false precision. Note that not all agencies will assign the same rating to each box. One agency may consider a box to be a 'low' while another considers the same box to be a 'high'. It will depend on their respective risk tolerance. Alternatively, an agency may consider it needs to deal with all risks that are classed as high or above, whereas another may consider it needs to deal with all risks that are classed as medium or above.

Table B.7. Combined risk rating.

Likelihood	Consequence				
	1 (Insignificant)	2 (Minor)	3 (Moderate)	4 (Major)	5 (Catastrophic)
1 (Remote)	Negligible	Negligible	Low	Low	Medium
2 (Unlikely)	Negligible	Low	Low	Medium	High
3 (Possible)	Low	Low	Medium	High	High
4 (Likely)	Low	Medium	High	High	Extreme
5 (Almost Certain)	Medium	High	High	Extreme	Extreme

Module 4: Formulate and Assess Potential Adaptation Strategies

Step 4.1. Develop a shortlist of technically, politically, and financially feasible adaptation strategies.

Step 4.2. Carry out a benefit cost analysis that takes into account variable climate risk over time.

Step 4.3. Identify priority adaptation strategy or package of strategies.

Inputs

- Definition of the component of the asset (extent of asset to be adapted) and its condition and vulnerability assessment (Module 2)
- Economic consequences and risk analysis (Module 3)
- Cost estimates for adaptation strategies

Step 4.1. Develop a shortlist of technically, politically, and financially feasible adaptation strategies. Consider strategies that are likely to be practical and achievable to address the vulnerability of the asset through considering the outputs of Module 2. Table B.8 provides representative examples of adaptation strategies by asset type and climate stressor. Table B.8 is not meant to be a comprehensive or exhaustive list.

Table B.8. Adaptation strategy matrix.

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Asset Specific	Bridge superstructures that can resist lateral flow and wave forces (columns and bent caps more resistant than bearings)	Bridge/culvert structural improvement or overhaul	Bridge/Culvert	Engineering	\$\$\$\$	Flood, Waves	Consequence	Longer term
Asset Specific	Add new culverts where there aren't any, add additional culverts, or widen existing culverts	Bridge/culvert structural improvement or overhaul	Bridge/Culvert	Engineering	\$\$\$	Flood	Likelihood	Mid term
Asset Specific	Replace culvert with bridge	Bridge/culvert structural improvement or overhaul	Bridge/Culvert	Engineering	\$\$\$\$	Flood	Likelihood	Longer term
Asset Specific	New bridge with foundations set below depth of scour	Bridge/culvert structural improvement or overhaul	Bridge/Culvert	Engineering	\$\$\$\$	Flood	Likelihood	Longer term
Asset Specific	Permanent floating bridge	Bridge/culvert structural improvement or overhaul	Bridge/Culvert	Engineering	\$\$\$\$	Flood, Waves,	Likelihood	Longer term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Asset Specific	Realign or reroute drainage pipes to minimum slope required to accommodate design flow and elevate discharge points above design elevation	Storm water management and capacity	Drainage	Engineering	\$\$\$	Flood	Likelihood	Mid term
Asset Specific	Regarding so that inlets/ intakes are located away from vulnerable, critical points (e.g., station entrance), or adding inlets/ intakes	Storm water management and capacity	Drainage	Engineering	\$\$\$	Flood	Likelihood	Mid term
Asset Specific	Install pumps	Storm water management and capacity	Drainage	Engineering	\$\$	Flood	Likelihood	Shorter term
Asset Specific	Elevate storage/ equipment facilities	Equipment elevation (heavy)	Equipment	Engineering	\$\$\$	Flood, Waves	Likelihood	Mid term
Asset Specific	Elevate transit stops and other multimodal transportation hubs	Equipment elevation (heavy)	Equipment	Transit	\$\$\$	Flood, Waves	Likelihood	Mid term
Asset Specific	Elevate electrical/ communications assets (related to roadway or transit systems)	Equipment elevation (light)	Equipment	Engineering	\$\$\$	Flood, Waves	Likelihood	Mid term
Asset Specific	Protect (e.g., flood proof doors) storage/ equipment facilities (can include railyards, bus storage, etc.	Equipment protection (heavy)	Equipment	Engineering	\$\$	Flood, Waves	Consequence	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Asset Specific	Protect transit stops and other multimodal transportation hubs	Equipment protection (heavy)	Equipment	Transit	\$\$	Flood, Waves	Consequence	Shorter term
Asset Specific	Cathodic protection for metal elements	Equipment protection (light)	Equipment	Engineering	\$\$	Flood	Consequence	Shorter term
Asset Specific	Replace power and communication lines using watertight conduits and fixtures.	Equipment protection (light)	Equipment	Engineering	\$\$	Flood	Consequence	Mid term
Asset Specific	Waterproof lighting fixtures	Equipment protection (light)	Equipment	Engineering	\$\$	Flood, Waves	Consequence	Mid term
Asset Specific	Backup electric power	Equipment protection (light)	Equipment	Engineering	\$\$	All	Consequence	Shorter term
Asset Specific	Heat resistant catenary and other transit equipment	Equipment protection (light)	Transit	Engineering	\$\$	Extreme Heat	Likelihood	Mid term
Asset Specific	Wind resistant signage	Equipment protection (light)	Equipment	Engineering	\$\$	Wind	Likelihood	Mid term
Asset Specific	Strengthen mooring and berthing fixtures at port facilities	Equipment protection (heavy)	Equipment	Engineering	\$\$	Wind	Likelihood	Mid term
Asset Specific	Relocate storage/ equipment facilities	Equipment relocation (heavy)	Equipment	Engineering	\$\$\$\$	Flood, Waves	Likelihood	Longer term
Asset Specific	Relocate electrical/ communications assets (related to roadway or transit systems)	Equipment relocation (light)	Equipment	Engineering	\$\$\$	Flood, Waves	Likelihood	Longer term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Asset Specific	Use more heat tolerant binders and materials; replace concrete pavements with asphalt where spalling occurs	Increase heat tolerance of existing roadway	Roadway	Engineering	\$\$	Extreme Heat	Likelihood	Mid term
Asset Specific	Concrete sealant/ surface treatment for surfaces not previously considered to be in splash zone	Increase water resilience of existing roadway	Roadway	Engineering	\$\$	Flood	Consequence	Mid term
Asset Specific	Composite reinforced concrete roadway to form water tight portion of road	Increase water resilience of existing roadway	Roadway	Engineering	\$\$\$	Flood,, Waves	Consequence	Mid term
Asset Specific	Modify roadway to more permeable material	Increase water resilience of existing roadway	Roadway	Engineering	\$\$\$	Flood, Waves	Consequence	Mid term
Asset Specific	Temporary floating bridge	Parallel capacity	Roadway	Engineering	\$\$\$	Flood, Waves	Consequence	Mid term
Asset Specific	Raise roadway/ rail/ runway elevation (can use embankment fill)	Raise asset	Roadway; Transit; Airport	Engineering	\$\$\$\$	Flood, Waves	Likelihood	Longer term
Asset Specific	Create new retaining structures to protect roadway or railway and embankment	Retaining structures	Roadway; Transit	Engineering	\$\$\$	Flood, Waves	Likelihood	Mid term
Asset Specific	For scour critical bridges or roadways and embankments parallel to streams, implement countermeasures including rock slope protection, partially grouted riprap, articulating concrete blocks	Erosion prevention - heavy	Bridge/ Culvert; Roadway	Engineering	\$\$\$	Flood,, Waves	Likelihood	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Asset Specific	Earthwork techniques (e.g., terraces, soil roughening) to control erosion and stabilize slopes	Erosion prevention - heavy	Roadway; Transit	Engineering	\$\$\$	Flood,, Waves	Likelihood	Mid term
Asset Specific	Mechanical slope stabilization (e.g., gabion baskets, concrete, rock, steel pins)	Erosion prevention - heavy	Roadway; Transit	Engineering	\$\$\$	Erosion	Likelihood	Mid term
Asset Specific	Soil bioengineering (plants as structural elements in slope protection systems), biotechnical stabilization (plants and structures)	Erosion prevention - heavy	Roadway; Transit	Natural or Nature-based	\$\$\$	Erosion	Likelihood	Shorter term
Asset Specific	Erosion control aimed at surface protection (e.g. vegetative cover, mats/ blankets)	Erosion prevention - surface	Roadway; Transit	Engineering	\$\$	Erosion	Likelihood	Shorter term
Asset Specific	Temporary gates (e.g., stop logs, inflatable plugs) for entrances to underground infrastructure, or roadway or rail underpasses	Water barriers (temporary)	Roadway; Transit	Engineering	\$\$	Flood	Consequence	Shorter term
Asset Specific	Install fender or dolphin systems to protect vulnerable piers from vessel impact, ice floes, debris	Water barriers (heavy)	Waterway Management	Engineering	\$\$	Flood, Waves, Wind	Consequence	Mid term
Asset Specific	Temporary barriers (e.g., sandbags)	Water barriers (temporary)	Roadway; Transit	Engineering	\$	Flood	Consequence	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
General	Wetland restoration	Green infrastructure flood measures	(not asset specific)	Natural or Nature-based	\$\$\$	Erosion, Waves	Likelihood	Mid term
General	Artificial/ reinforced dunes, beach nourishment, living shoreline	Green infrastructure flood measures	(not asset specific)	Natural or Nature-based	\$\$\$	Flood, Erosion, Waves	Likelihood	Mid term
General	Infill wetlands/ sloughs	Landscape management	Waterway Management	Engineering	\$\$\$	Flood	Likelihood	Longer term
General	Berms	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$	Flood	Likelihood	Longer term
General	Floodwalls/ seawalls (artificial, usually made with concrete or reinforced concrete)	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion, Waves	Likelihood	Longer term
General	Breakwaters	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion, Waves	Likelihood	Longer term
General	Bulkheads to mitigate erosion	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion, Waves	Likelihood	Longer term
General	Groins	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Erosion, Waves	Likelihood	Longer term
General	Revetments	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion, Waves	Likelihood	Longer term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
General	Storm surge barriers	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Waves	Likelihood	Longer term
General	Tidegates	Water barriers (heavy)	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion	Likelihood	Longer term
General	Levees (elongated naturally occurring ridge or artificially constructed wall, typical earthen)	Water barriers (heavy)	(not asset specific)	Natural or Nature-based	\$\$\$	Flood, Waves	Likelihood	Longer term
General	Widening/ channelization of waterways	Waterway modification	Waterway Management	Engineering	\$\$\$\$	Flood, Erosion	Likelihood	Longer term
System	Enhanced ITS Infrastructure allowing for increased capacity on alternate roadways and demand management by giving up-to-date information to travelers, coordinating access to aux lanes/ shoulders, planning/ communicating time of day restrictions/ incentives. ITS can better inform event response system.	Enhance ITS system	(not asset specific)	Operational	\$\$	All	Consequence	Shorter term
System	Increase roadway capacity on alternate/ priority routes to create redundancy	Parallel transportation capacity	(not asset specific)	Engineering	\$\$\$	All	Consequence	Mid term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
System	Improve transit capacity to compliment physical strategies	Parallel transportation capacity	(not asset specific)	Engineering	\$\$\$	All	Consequence	Mid term
System	Ferry and barge systems for movement of goods and people (could fall under "mode alternatives" in event response system)	Parallel transportation capacity	(not asset specific)	Engineering	\$\$\$	All	Consequence	Mid term
System	Enhance electricity infrastructure so that it remains functioning in extreme events and continues to power transit, traffic signals, ITS	Other infrastructure systems	(not asset specific)	Engineering	\$\$\$	All	Consequence	Shorter term
System	Enhance communications infrastructure so that it remains functioning during extreme events - for response/ recovery and for worker productivity during events (i.e., minimizing disruption by allowing workers who cannot commute during an event to telecommute)	Other infrastructure systems	(not asset specific)	Engineering	\$\$\$	All	Consequence	Shorter term
Policy/ Practice	Improved asset database with risk information	Data management	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Improved asset data collection, including recording disruption and damage	Data management	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Policy/ Practice	Improve information storage, retrieval, sharing, management systems; these can include asset management systems both general and specific to certain assets types (e.g., bridge/ culvert management system)	Data management	(not asset specific)	Policy/ Governance	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Manage future development, floodplain zoning	Development management	(not asset specific)	Policy/ Governance	\$	Flood, Waves	Consequence	Shorter term
Policy/ Practice	Review and update insurance and climate-related liabilities	Development management	(not asset specific)	Policy/ Governance	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Event-based HOV requirements (to prevent gridlock)	Enhance ITS system	(not asset specific)	Operational	\$	All	Consequence	Shorter term
Policy/ Practice	Revise rail speed guidance given effects of extreme heat on tracks	Enhanced planning	(not asset specific)	Operational	\$	Extreme Heat	Consequence	Shorter term
Policy/ Practice	Drainage study	Enhanced planning	(not asset specific)	Planning	\$	Flood	Better Risk Information	Shorter term
Policy/ Practice	Scour criticality assessment, with riverine hydraulics and sea level estimates	Enhanced planning	(not asset specific)	Planning	\$	Flood, Erosion	Better Risk Information	Shorter term
Policy/ Practice	Benefit-cost analysis at planning level and engineering level	Enhanced planning	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Policy/ Practice	Use best practices for new infrastructure projects/ updates that are already planned - work this into existing process	Enhanced planning	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Groundwater and saltwater intrusion modeling	Enhanced planning	(not asset specific)	Planning	\$	Flood	Better Risk Information	Shorter term
Policy/ Practice	Planning process and engineering standards updates to incorporate climate risks	Enhanced planning	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Probabilistic risk analysis	Enhanced planning	(not asset specific)	Planning	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Monitor existing drainage system	Monitor existing systems	(not asset specific)	Operational	\$	Flood	Better Risk Information	Shorter term
Policy/ Practice	Relocation incentives	Relocate development	(not asset specific)	Policy/ Governance	\$\$\$\$	Flood, Waves	Likelihood	Mid term
Policy/ Practice	Floodprone land acquisition	Relocate development	(not asset specific)	Policy/ Governance	\$\$\$\$	Flood, Waves	Likelihood	Mid term
Policy/ Practice	Eminent domain/ required relocation	Relocate development	(not asset specific)	Policy/ Governance	\$\$\$\$	Flood, Waves	Likelihood	Longer term
Policy/ Practice	Inter-agency coordination group for resilience and adaptation	Stakeholder coordination	(not asset specific)	Policy/ Governance	\$	All	Better Risk Information	Shorter term
Policy/ Practice	Coordinate shoreline protection efforts	Stakeholder coordination	(not asset specific)	Policy/ Governance	\$	Flood, Waves	Better Risk Information	Shorter term

Table B.8. Adaptation strategy matrix (continuation).

Strategy Scale	Strategy	Parent Strategy	Asset Type (for Asset Specific)	Type	Cost	Stressors Addressed	Primary Climate Risk Impact Type (Likelihood, Consequence, or Better Risk Information)	Timing
Policy/ Practice	Revise summer maintenance crew schedule and support as needed to address extreme heat	Update maintenance practices	(not asset specific)	Operational	\$	Extreme Heat	Consequence	Shorter term
Policy/ Practice	More frequent inspection of infrastructure vulnerable to heat (e.g., rail buckling, catenary systems).	Update maintenance practices	(not asset specific)	Operational	\$	Extreme Heat	Consequence	Shorter term
Policy/ Practice	Regular maintenance of drainage ways	Update maintenance practices	(not asset specific)	Operational	\$	Flood	Consequence	Shorter term
Policy/ Practice	Prune branches and other vegetation susceptible to wind	Update maintenance practices	(not asset specific)	Operational	\$	Wind, Flood	Consequence	Shorter term
Policy/ Practice	Update and maintain event response system. Preparation for alternate routes, suspended service, mode alternatives based on nature of event. Mutual aid agreements. Notification/ early warning system.	Upgrade/maintain event response system	(not asset specific)	Operational	\$	All	Consequence	Shorter term
Policy/ Practice	Be ready to respond to debris clearance needs	Upgrade/maintain event response system	(not asset specific)	Operational	\$	Wind, Flood	Consequence	Shorter term
Policy/ Practice	Enhance event response system to insure proper supply of food, fuel, and other goods during extreme events. Plan for parallel supply chains or extra stockpiling as necessary.	Upgrade/maintain event response system	(not asset specific)	Operational	\$\$	All	Consequence	Shorter term

If the list of adaptation strategies is extensive, use multi-criteria analysis (MCA) and / or convene stakeholder workshop to prioritize potential strategies to a short list. MCA is a comparative assessment of options, taking into account several criteria simultaneously, typically used prior to carrying out more detailed cost analysis (Step 2). MCA is very useful for outlining a clear and transparent process—conducive to stakeholder collaboration—as to why certain strategies are selected over others. MCA is also a useful screening tool, to identify options that should not be considered for further analysis, thereby helping to focus analytical resources more strategically.

Note that a package of measures may be appropriate, implemented over different time periods depending on the timing of potential impacts and the vulnerability (current, near term, long term). For example, there may be drainage improvements and basic water proofing of an asset that could be implemented in the short term, while a longer term coastal protection strategy was developed (needing more coordination and funding).

Table B.9. Example of evaluation criteria for adaptation options.

Area	Evaluation Criteria
Economic	<ul style="list-style-type: none"> ● Capital costs (rough order of magnitude cost). ● Potential change in operating and maintenance costs (rough order of magnitude cost). ● Anticipated design life of the adaptation option (quick fix / short term / long term solution). ● Functional effectiveness - level of confidence that the adaptation option will reduce vulnerability. ● Time frame for implementation of the adaptation option, potential for integration with asset renewal cycles. ● Flexibility to modify as new climate, impact and adaptation information becomes available. ● Co-benefits due to direct vulnerability reductions for other infrastructure, homes, industry, etc.
Social/Equity	<ul style="list-style-type: none"> ● Additional benefits produced (e.g. construct a levee to prevent flooding of transportation infrastructure that also provides habitat and serves as a pedestrian/bike trail). ● Community acceptability. ● Positive or negative impact to visual amenity of an area.
Environmental	<ul style="list-style-type: none"> ● Positive or negative impact to ecological value (e.g. wetland restoration as storm surge buffer). ● Positive or negative impact to ecological function (e.g. reduction of runoff in sensitive watersheds, degradation of habitat for endangered species).

Table B.9. Example of evaluation criteria for adaptation options (continuation).

Area	Evaluation Criteria
Political	<ul style="list-style-type: none"> ● Existence of, or complexity of, required Institutional arrangements or partnerships to implement the option. ● Funding availability. ● Political sensitivity. ● Benefit to multiple jurisdictions, agencies, and communities.

Step 4.2. Carry out a benefit cost analysis that is takes into account variable climate risk over time.

For the prioritized strategies which perform the best under the MCA or stakeholder review, carry out more detailed cost analysis. The benefit cost assessment of a candidate adaptation strategy compares the net incremental cost (capital and operating costs over the lifetime of the asset or a standard analysis period) to the net incremental monetary reduction in risk (i.e. potential loss) where risk is understood to depend on two factors:

- The likelihood of that consequence being realized over the analysis horizon (a function of the frequency of the climate event and the asset’s vulnerability to the climate event), and
- The magnitude of the consequence (inclusive of the value of the asset itself as well as the economic and non-economic consequences).

The economic analysis will vary depending on whether the impact anticipated is damage or deterioration. Damage evaluation is a discrete event that reduces the value of the asset. To the degree that the damage diminishes or eliminates functionality, there is also disruption. Deterioration, by contrast, is a non-discrete seemingly continuous degradation of the asset over time, which cumulatively can lead to diminished use and disruption.

For each type of impact (e.g. damage, deterioration and disruption), Table B.10 describes potential time horizons, scope of the impact and suggested estimation approach.

An important consideration in the assessment of disruption impacts is whether estimated reductions in economic activity are permanent losses or are simply shifted to a later time period when pent-up demand is released.

An example of shifting activity is retail shopping during an event that closes roads; sales are low for the day or two that roads are closed but sales are above average on the day or two following the reopening of roads as households replenish pantries.

An example of permanent loss would involve commuting financial service employees who cannot reach their jobs and their firms must suspend business until access is restored. Until the road can be repaired, telecommuting may minimize the disruption, but unlike the pent up demand for retail sales, lost business days for financial services cannot be recovered.

Table B.10. Example of evaluation criteria for adaptation options.

Type of Impact	Time Horizon	Disruption	Scope of Economic Impact	Estimation Approach
Damage	One-time per event	Correlates with severity of damage, criticality of asset, degree of use, redundancy, duration of disruption.	Factors vary with type of asset but could include: <ul style="list-style-type: none"> Increased shipping or travel costs as trips divert to a longer route (either in time or VMT); Any permanent loss of economic activity. 	Monetized value of consequence times anticipated recurrence over analysis period. An analysis period can be either standard period or useful life of asset; monetization uses standard US DOT guidance for travel time valuation or operating costs as applicable
Deterioration	Analysis period	Correlates with length of time that deterioration occurs; rate of increase may not be linear; because loss of functionality is gradual, disruption is modest up until the time that the asset suffers a critical failure. Once asset fails analysis follows outline of damage noted above.	Factors vary with type of asset but could include: <ul style="list-style-type: none"> Increased shipping or travel costs as travelers face operational restrictions as the asset gradually deteriorates—speed and weight restrictions are an example. 	Monetized value of consequence summed over analysis period

Note that a BCA could be carried out to compare two alternatives where by the asset is replaced anyway because of age/condition using existing standards, and the asset is replaced using improved standards. This would help make the decision as to whether an overall recommendation relating to code and standard updates is appropriate.

Compare results between the strategies to identify those which avoid the most risk (understood to be the magnitude of the consequence adjusted for the event likelihood) for the least cost. This is a BCA where the numerator is the incremental change in risk attributable to the strategy’s implementation relative to the baseline—because the strategy reduces the magnitude of the consequence and/or the likelihood that a candidate event will impact the asset (its vulnerability)—converted to an annual stream and adjusted to a net present value. The denominator is the incremental capital and operating cost over the useful life of the asset, adjusted to a net present value.

Finally, review details of the design of the adaptation strategy alongside current design standards (output of Module 2) and codes to see if a recommendation should be made to update those standards and codes.



Regional Exposure Analysis

As described in Section 4.0, the Post-Sandy study team conducted a regional assessment of exposure to climate stressors as a first step in identifying subareas and facilities that should be priorities for more detailed analysis. This appendix contains additional detail about the regional-level exposure analysis.

Scope of Regional Exposure Analysis

Early conversations with the project partners involved defining the scope of the transportation system to be assessed in this study, given available resources. For purposes of this study, the critical multimodal network for the three state metropolitan region was defined as follows:

- Major roadways, including the National Highway System and evacuation routes;
- Bridges on the National Highway System and major evacuation routes;
- Major freight railways, including Class 1 railroads, major rail yards, and intermodal facilities;
- All passenger rail lines; and
- Major transit and bus facilities such as bus stations and yards.

The following climate stressors and impacts were emphasized in the regional-scale exposure analysis:

- Storm surge, with and without sea level rise (which leads to inundation of transportation facilities in coastal areas); and
- Precipitation (which leads to floods in both inland and coastal areas).

An important step in conducting a regional vulnerability assessment is to conduct a system-level assessment of criticality to prioritize the assets and networks that are the highest priority for adaptation investments. Some regions have chosen to use an objective, data-driven approach to assigning a criticality score to each element of the transportation system, but these analyses have tended to be for a single mode (e.g., a regional highway network). Other regions have used a combination of expert input and qualitative measures to assign criticality.

Extreme heat was assumed to impact the regional uniformly and did not warrant a separate exposure analysis at the regional scale. The implications of changes in average and extreme temperatures were considered at the subarea and facility-specific levels.

The regional exposure analysis highlighted areas where there were concentrations of highway and rail assets that were potentially vulnerable to various climate stressors and therefore warranted more detailed analysis. The remainder of this section provides details about the results of the regional vulnerability assessment, including 21 vulnerable subareas.

Regional Exposure Analysis Methodology

To determine potential exposure of the region's key transportation facilities to storm surge and precipitation, the study team used Geographic Information Systems (GIS) to conduct an intersection analysis, which identified where roads, rail lines, and facilities lie within the boundaries of a 100-year or 500-year flood plain, or where they lie within the extent of storm surge predicted to be associated with a Category 1 through 4 storm. In limited parts of the study area, the team used digital elevation models to help screen out facilities that are elevated on a natural or human-made embankment and would not be exposed to adjacent flood waters.

One caveat associated with the intersection analysis is that bridges and tunnels are not represented in digital elevation models, and therefore these features have to be manually removed from maps if an analysis is performed at a level of detail at which bridges and tunnels would be discernable on maps.

The study team used the following primary data sources for the regional exposure analysis:

- The U.S. Army Corps of Engineers' North Atlantic Coast Comprehensive Study provided sea level rise and storm surge data.
 - The intersection analysis with future sea level extents was conducted for two analysis years: 2068 and 2100.
 - The intersection analysis for projected coastal storm surge zones relied on outputs of a Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model run as part of the NACCS analysis. The SLOSH model outputs depict areas of possible flooding from the maximum of maximum (MOM) event within hurricane categories 1 through 4 by estimating the potential storm surge during a landfall during different tide scenarios (i.e., high or mean tide for NY).

The SLOSH storm surge mapping is not referenced to a specific probability of occurrence nor does it include wave heights. The flooding from a worst-case Category 4 hurricane making landfall during high tide represents an extremely low probability of occurrence but high-magnitude event. The extent of the Category 4 MOM represents the maximum storm tide levels caused by extreme hurricane scenarios across the region, and, therefore, provides a reasonable approximation of the most extreme flooding extent. The intersection analysis highlights transportation assets that lie within each SLOSH zone (1 through 4).

- The Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) is a digital database that contains flood hazard mapping data from FEMA's National Flood Insurance Program (NFIP). The NFHL dataset represents the current effective flood risk data, and can be used to determine the extent of the 100- year and 500-year floodplains.
 - 100 Year Floodplain – A 100-year flood is a flood event that has a 1% probability of occurring in any given year. The 100-year floodplain represents the area that would be inundated during the 100 year flood, based on the 100-year flood flow rate.
 - 500 Year Floodplain – A 500-year flood is a flood event that has a 0.2% probability of occurring in any given year. The 500-year floodplain represents the area that would be inundated during the 500 year flood, based on the 500-year flood flow rate. Flooding is more extensive during the 500-year flood than the 100-year flood.

Section 3.2 and Appendix F have additional sources of information and descriptions of analysis tools that may be of use in conducting vulnerability assessments.

The intersection analysis highlights transportation assets that lie within these zones.

- The Federal Highway Administration's National Bridge Inventory (NBI) Overtopping Risk ratings are derived from Item 71 in the NBI. Item 71 refers to Waterway Adequacy Appraisal Ratings. The map legends show the alphanumeric ratings that correspond to these descriptions in the NBI database:

Table C.1. NBI codes for overtopping risk.

Overtopping Risk Code	NBI Code Description
C5	a Bridge not over a waterway.
	b Bridge deck and roadway approaches above flood water elevation (high water), chance of overtopping is remote .
C4	c Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.
	d Slight chance of overtopping bridge deck and roadway approaches.
C3	e Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.
C2	f Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.
C1	g Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.
	h Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.
	i Occasional or frequent overtopping of bridge deck and roadway approaches with severe traffic delays.
C0	j Bridge closed.

Results of Regional Exposure Analysis

The regional exposure analysis revealed a high potential for the region's critical transportation facilities throughout the study area to be impacted by climate stressors. The following sections are a summary of potential exposure to climate stressors in each portion of the study area. Figures C.1 through C.15 show results of the intersection analyses that were conducted to support the regional-scale exposure analysis for this study. Maps depicting these results for the entire study area at the regional level are available as GIS files from FHWA.

NOTE: The transportation facilities mentioned in this section are representative examples intended to highlight the scope and scale of exposure to the impacts of extreme weather events in the study area. This is not intended to be a comprehensive, system-wide inventory of exposed roadway segments, rail segments, and other facilities.

Southwest Connecticut and Eastern Long Island

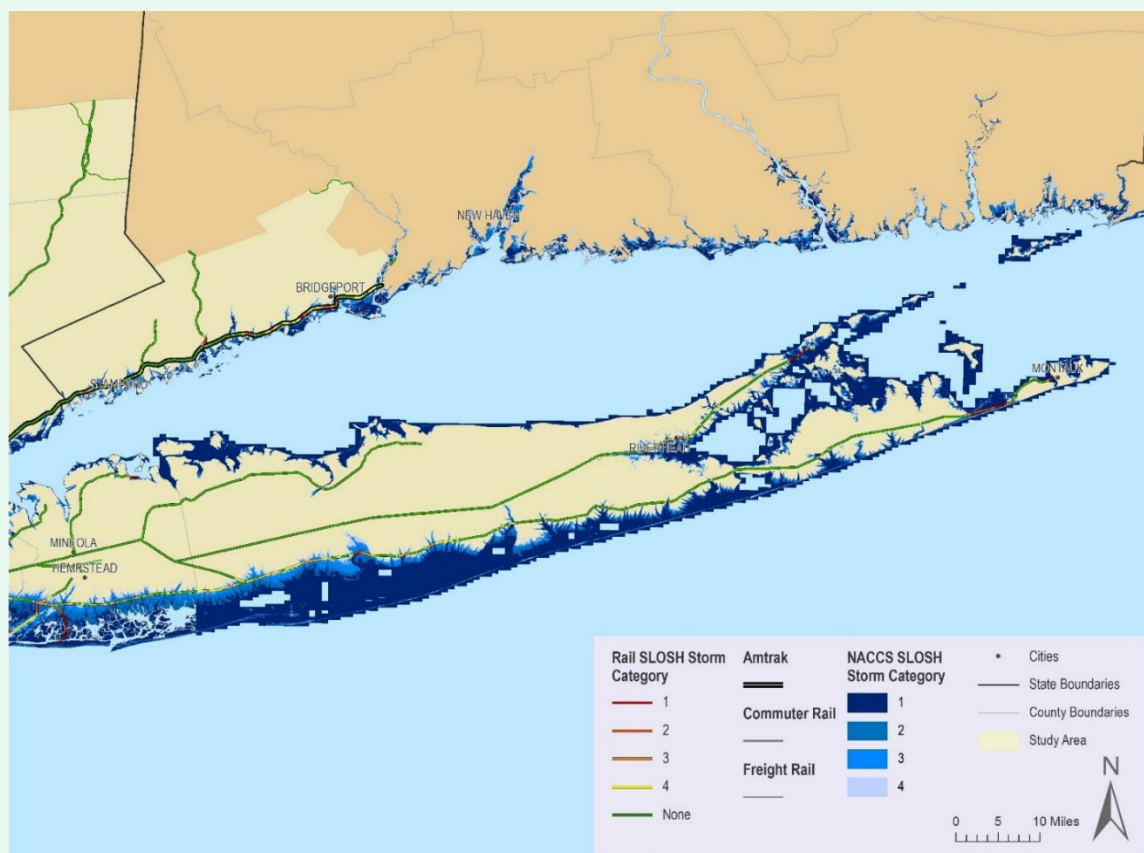


Figure C.1. Map. Potential exposure of rail network in eastern Long Island and southwest Connecticut to coastal flooding and storm surge.

(Source: Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

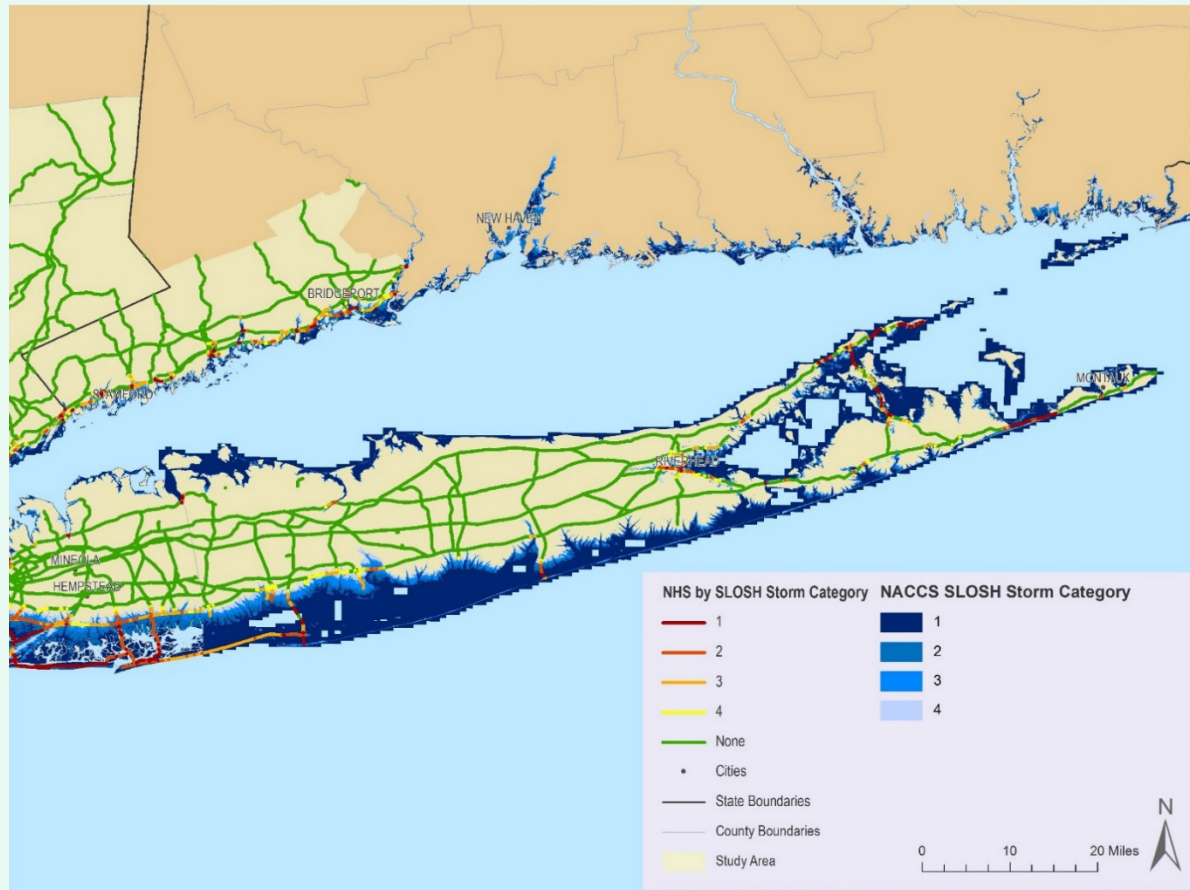


Figure C.2. Map. Potential exposure of the National highway system in Long Island and southwest Connecticut to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

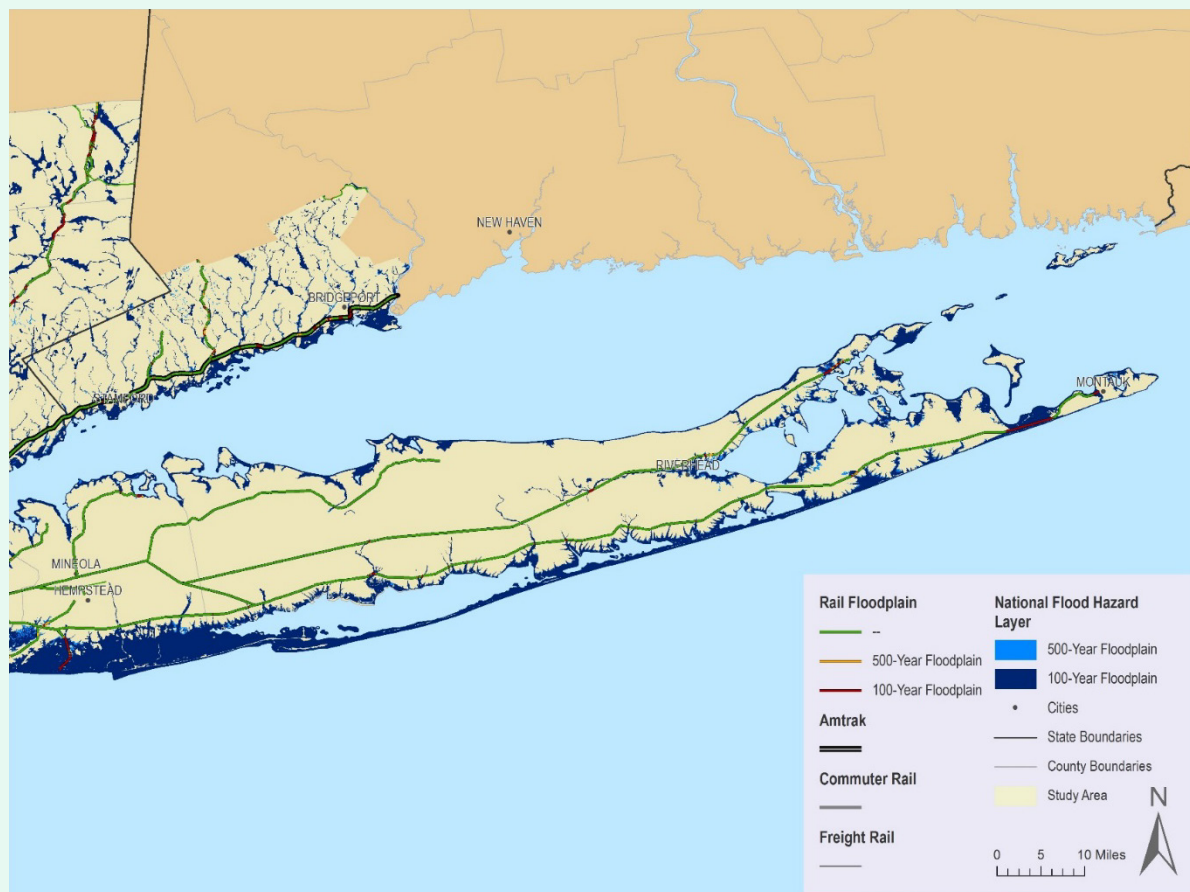


Figure C.3. Map. Potential Exposure of the rail network in Long Island and southwest Connecticut to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

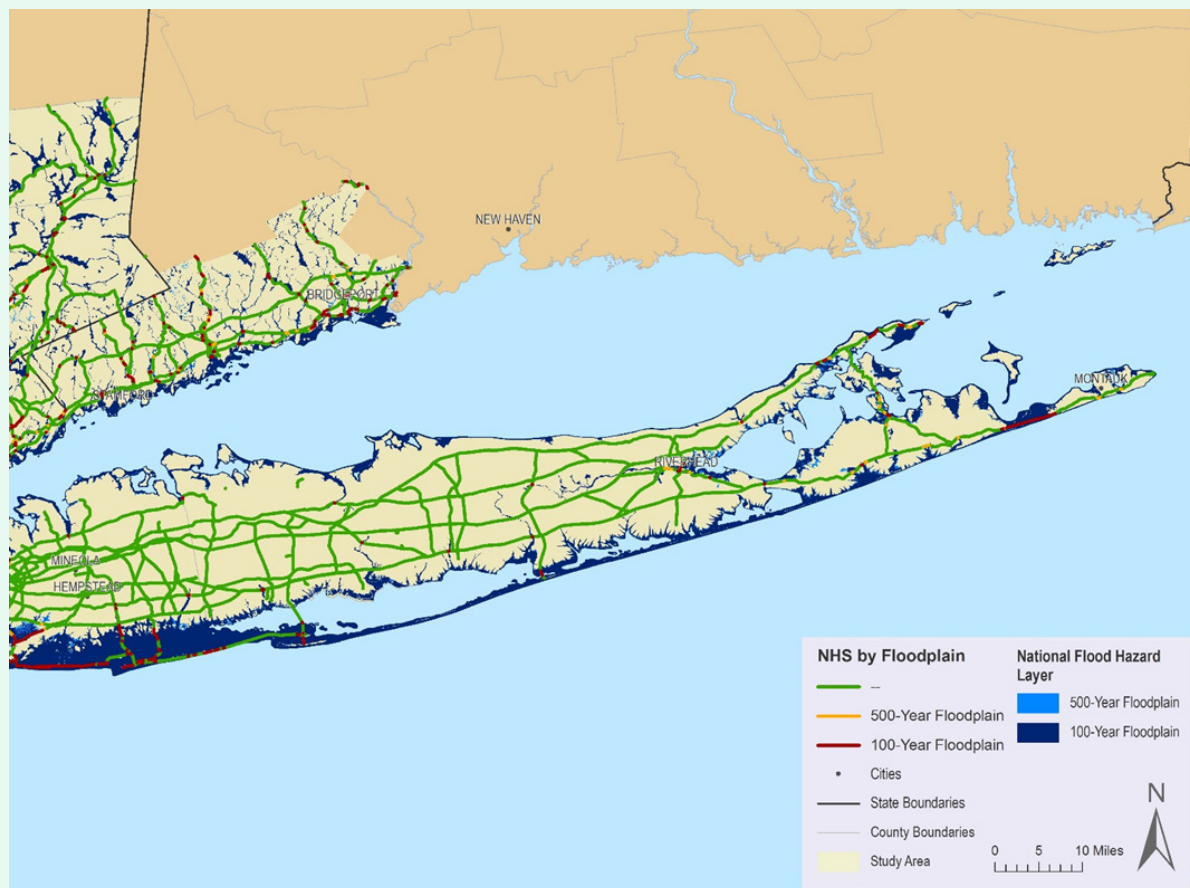


Figure C.4. Map. Potential exposure of the National highway system in Long Island and southwest Connecticut to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

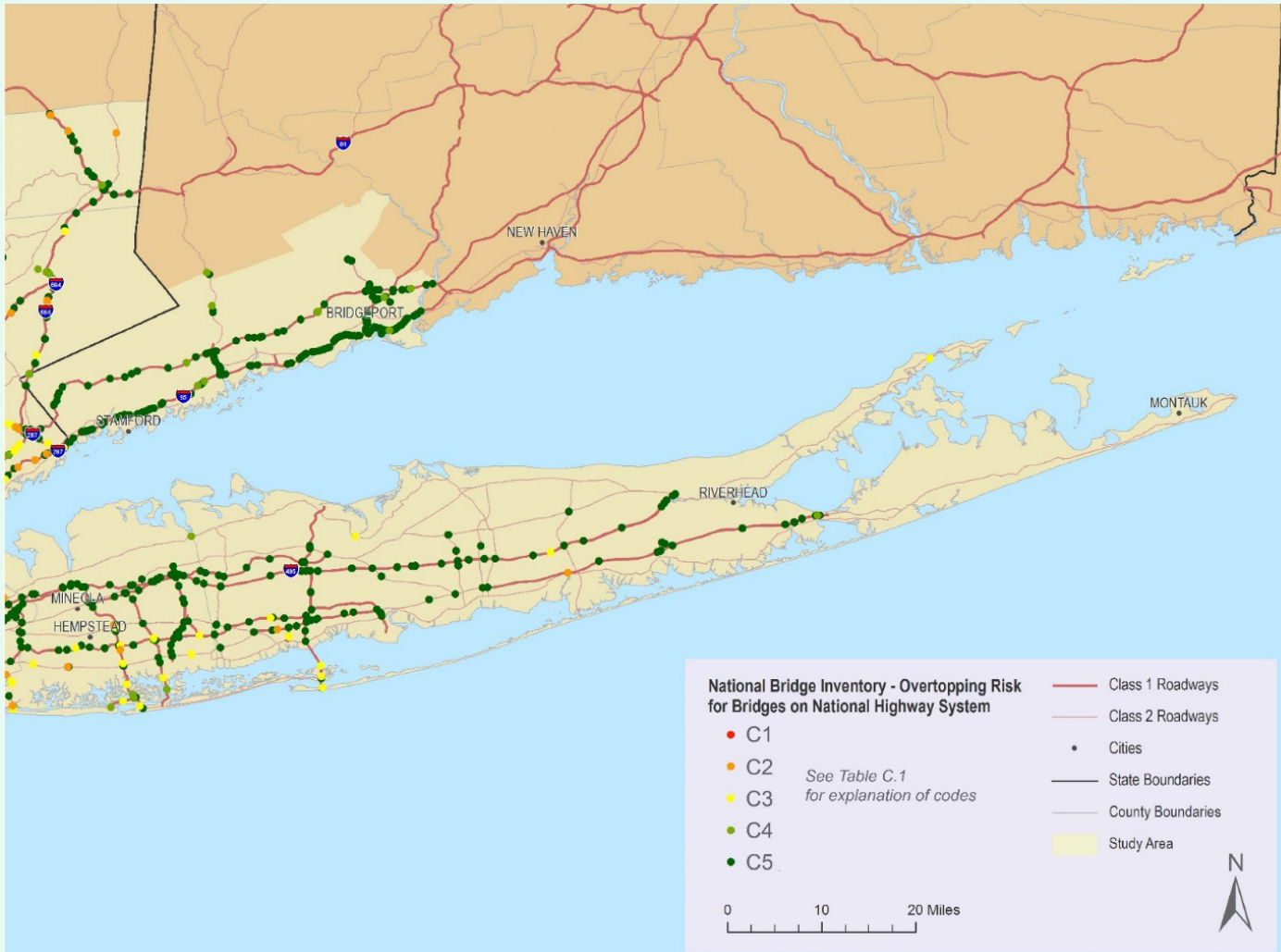


Figure C.5. Map. National bridge inventory overtopping analysis in Long Island and southwest Connecticut.

(Source: Federal Highway Administration, National Bridge Inventory.)

Eastern Long Island

Sea level rise, storm surge, and extreme heat events are the climate stressors of primary concern in Long Island. The following areas have high potential for exposure today:

- As witnessed during Sandy, all transportation facilities on the South Shore of Long Island, roughly south of Merrick Road and west of the Connetquot River, may be exposed to inundation from storm surge during coastal storms (both summer/fall tropical storm events and winter Nor'easters) (see Figures C.1 and C.2). A Category 1 hurricane or equivalent Nor'easter—a very rare occurrence in this region today, but a more likely event by 2100—could expose all of Long Beach Island, Island Park, and Barnum Island to inundation from storm surge, plus the major north-south evacuation routes from Long Beach (most of the Nassau Expressway; large portions of Peninsula Boulevard, Austin Boulevard and Long Beach Road south of Sunrise Highway; sections of the Loop Parkway and Meadowbrook Parkway; and the Long Island Rail Road Long Beach branch). Jones Beach Island also could be exposed, with portions of Ocean Parkway and Wantagh Parkway potentially inundated. Fire Island also is vulnerable to exposure from storm surge; the southernmost portions of Robert Moses Causeway and William Floyd Parkway could be inundated, as well as the ferry terminals along both sides of Great South Bay. By 2050, projected sea level rise could mean that a Category 1 storm (or equivalent winter Nor'Easter) would cause much more widespread flooding, and storm surge from what is considered a minor coastal storm today could inundate large areas as described above.
- Elsewhere on Long Island, low-lying portions of Montauk Highway and Long Island Rail Road's Montauk Branch in the vicinity of Napeague (between East Hampton and Montauk) are particularly vulnerable to inundation from storm surge, including overwashing as water flows between the Atlantic Ocean and Napeague Bay during severe coastal storms. Similarly, at the eastern extent of the North Fork of Long Island, portions of Main Road flood between East Marion and Orient and in Orient Point (including the Orient Point Ferry terminal). The Ronkonkoma Branch of Long Island Railroad is exposed to coastal flooding between Southold and Greenport. Other National Highway System routes potentially exposed to flooding in Category 1 Hurricane (or equivalent Nor'easter) include New York State Route 114 between Sag Harbor and Shelter Island, portions of New York State Routes 24 and 25 near Riverhead, and a short segment of New York State Route 25A near Cold Spring Harbor.
- The regional and local roads serving as the sole access points to coastal communities, sewage treatment plants, and other critical infrastructure along the north and south shores of Long Island also are potentially exposed. One example is Bergen Avenue, the sole access route to the Bergen Point Wastewater Treatment Plant in East Islip. A portion of Shore Road, one of two access routes to Bayville on Long Island's North Shore, collapsed due to undermining from Sandy's storm surge.
- Major regional transportation facilities on Long Island that are more inland are less exposed to storm surge, but the impacts of sea level rise are affecting a much larger area of Long Island. The water table is so close to the surface in communities closest to the waterfront, like Freeport and Baldwin Harbor, that salt water ponding is visible on roadways at the highest tides of the month. Outfalls from drainage systems can be submerged during high tide, and further inland, the rising water table prevents ponds originally designed as detention ponds from draining between storms. As a result, during even moderate rainfall

events (particularly those that occur within four hours of high tide) rainwater backs up in drainage systems and/or overtops retention and detention ponds. The Long Island Rail Road is elevating electrical substations and other critical infrastructure along the Long Beach Branch due to inland and coastal flooding that is expected to become more frequent.

Southwestern Connecticut

Wind damage, riverine flooding, sea level rise, and inundation from coastal storm surge are the main climate stressors of concern to Southwest Connecticut. The following areas have high potential for exposure today:

- Metro-North Railroad's New Canaan Branch and Danbury Branch have high exposure to damage and disruption due to wind-blown debris. Overhead catenary and the tracks themselves can be blocked and damaged by downed trees and branches. The New Haven Line (part of Amtrak's Northeast Corridor) also is vulnerable to damage and disruption from wind-blown debris, although the wide right of way and presence of four tracks provides adaptive capacity to enable operations to resume soon after a storm passes.
- Most of the Merritt Parkway and north-south roadways on the National Highway System (including, but not limited to, the non-expressway portion of U.S. 7 north of Norwalk) also are exposed to disruption from wind-blown debris. The expressway portion of U.S. 7, Connecticut State Routes 8 and 25, and I-95 are sensitive to disruption from wind-blown debris, but these facilities are not as exposed due to the wide rights of way and high standard of maintenance for trees and signage.
- U.S. 7 and Metro-North Railroad's Danbury Branch adjacent to the Norwalk River between Norwalk and Danbury are exposed to riverine flooding. Several segments of road and rail, plus several stations, lie in the 100 year flood plain. Connecticut State Route 134 (Washington Boulevard) lies in the 100-year flood plain in Stamford, and sections of Connecticut State Route 104 (Long Ridge Road) are in the flood plain between Route 134 and the Merritt Parkway. Short stretches of many other roads in interior portions Southwest Connecticut are exposed to flooding in 100-year storm events (see Figure C.3), and these same roads are exposed to flash floods in low-probability but high-impact rainfall events that are short but intense.
- Portions of U.S. 1 and short segments of Metro-North's New Haven Line near Bridgeport are exposed to flooding from storm surge in a Category 1 hurricane or equivalent Nor'easter. A small segment of the Danbury Branch between the New Haven Line and downtown Norwalk also is exposed to inundation from storm surge in a Category 1 storm.
- As indicated in Section 3, with more frequent extreme heat events predicted in the future, moveable bridges, electrical systems (such as those that power subways and passenger rail lines, traffic signals, lights, communications systems, and pumps) and some mechanical components will have to be replaced with more heat-tolerant components in future normal replacement cycles.

New York City and Lower Hudson Valley

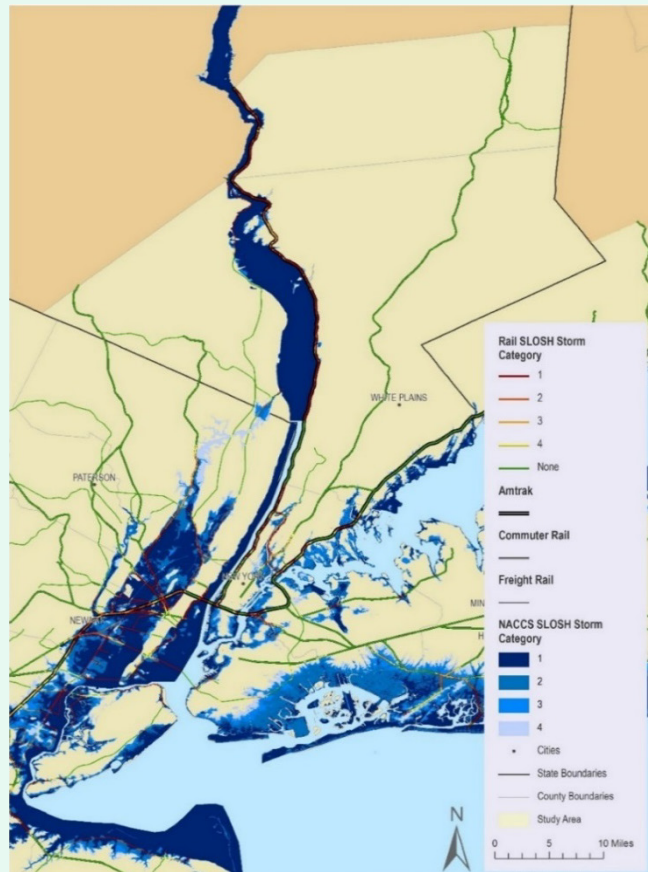


Figure C.6. Map. Potential exposure of rail network in New York City and lower Hudson Valley to coastal flooding and storm surge.

(Source: Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

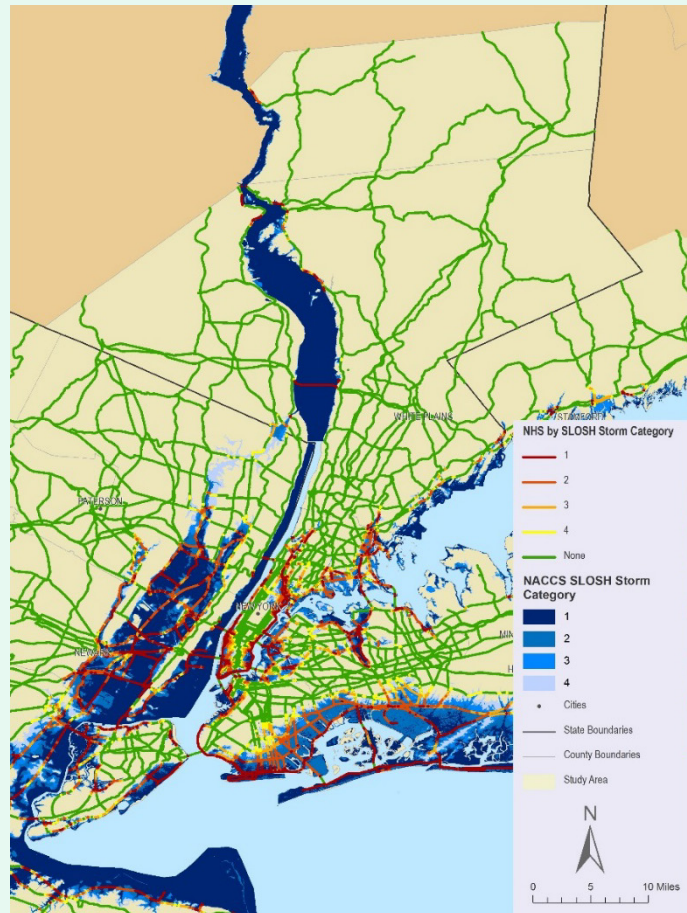


Figure C.7. Map. Potential exposure of the National highway system in New York City and lower Hudson Valley to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

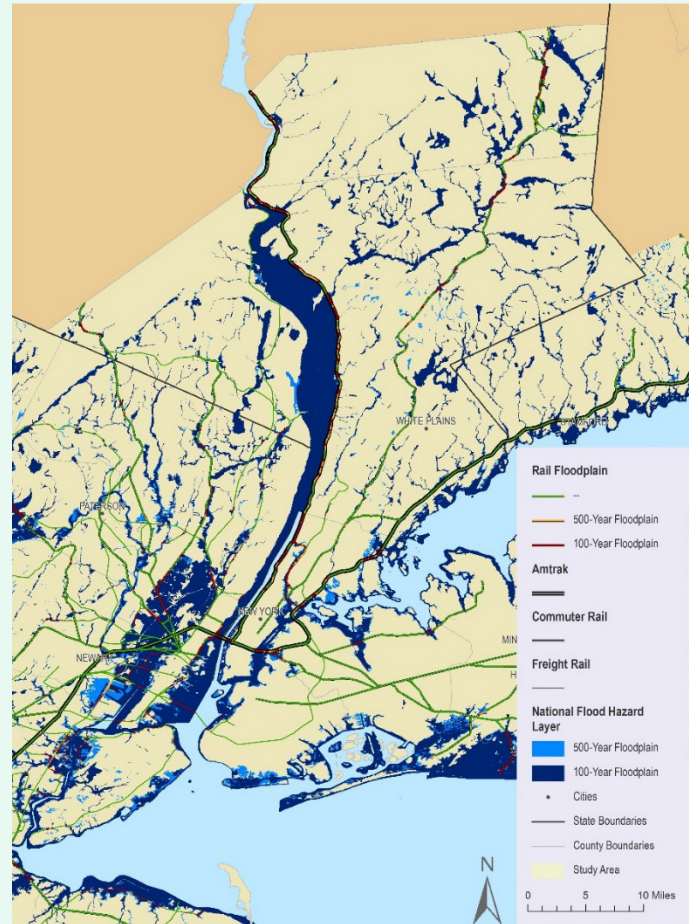


Figure C.8. Map. Potential exposure of the rail network in New York City and lower Hudson Valley to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

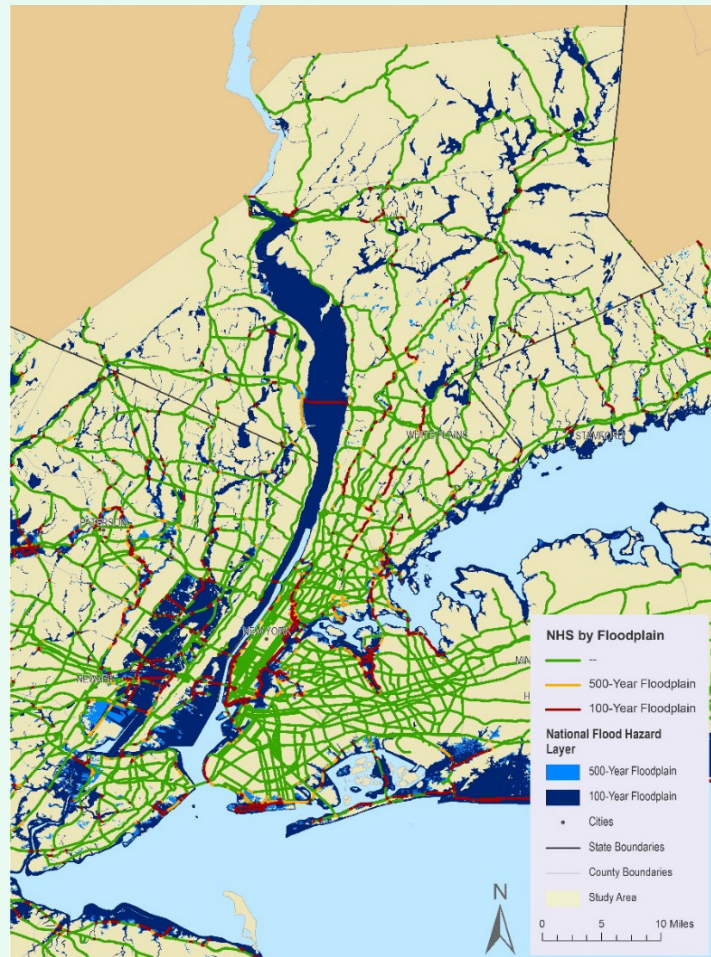


Figure C.9. Map. Potential exposure of the National highway system in New York City and lower Hudson Valley to coastal flooding and storm surge.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

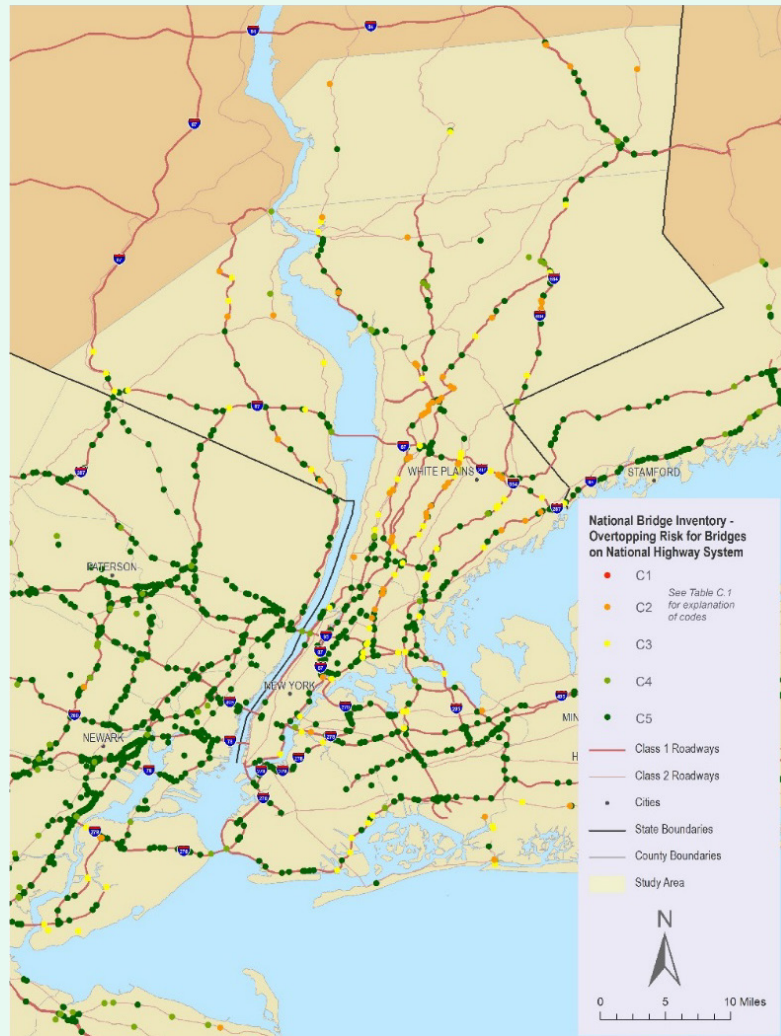


Figure C.10. Map. National bridge inventory overtopping analysis in New York City and lower Hudson Valley.

(Source: Federal Highway Administration, National Bridge Inventory.)

New York City

The work undertaken by New York City (NYC) agencies in the wake of Hurricane Sandy represents the most thorough vulnerability and risk assessment available in the project study area. The publication of “A Stronger, More Resilient New York” in 2013 and the 2015 update of the New York City Panel on Climate Change (NPCC) report are among the most prominent examples of policy-level and analytics-based reports published to support vulnerability and risk assessment. As an example of the work that has been conducted to date, the City collected detailed exposure data in the wake of Sandy that it then compared to 100-year and 500-year floodplain maps using GIS. According to the NPCC 2015 report, “the Hurricane Sandy field-verified inundation area, a surface interpolated using field-verified high-water marks and storm-sensor data from the U.S. Geological Survey, clearly equaled and exceeded the 1983 100- and 500-year floodplains, most strikingly along the southern coasts of Brooklyn and Queens and along the eastern and southern shores of Staten Island. Northern Queens and the Bronx experienced less flooding relative to the other boroughs in part because the Long Island Sound was at low tide when Sandy made landfall.”

“A Stronger, More Resilient New York” identifies sea level rise, storm surge, and intense precipitation events as posing the greatest risks to the City’s transportation infrastructure. The report states that the 100-year flood plain encompasses “approximately 12 percent of the [City’s] roadway network, all of the major tunnel portals other than the Lincoln Tunnel, portions of both airports, a variety of commuter rail assets, all three heliports, and a number of subway entrances and vent structures, principally in Lower Manhattan...”

The report continues:

“By the 2020s, the floodplain is estimated to encompass 15 percent of the city’s roadway network, and by the 2050s, it is expected to encompass 19 percent of that network. More and more of the City’s airport infrastructure will be at risk as storm surges will move from flooding outlying runways to threatening the terminal buildings, while additional subway stations will be at risk.

More intense downpours expected with climate change also pose a major risk to the transportation system. As with storm surge, heavy downpours pose the most significant challenge to subway and vehicular tunnels throughout the city, particularly in locations where tunnel entrances are located in low-lying areas or in areas with poor subsurface drainage. Examples of infrastructure matching this flood profile include the F train on Hillside Avenue in Queens and several subway lines in Lower Manhattan. Generally, heavy downpours are expected to pose only a moderate risk to roads and bridges, which may experience more frequent temporary flooding, but not more lasting damage.

Other Risks

High winds are likely to represent a moderate risk to the above-ground portions of the city's transportation infrastructure, such as traffic signals, signs, bridges, and street lights. They also could pose challenges to the aviation system, interfering with flight operations and, in the worst cases, creating safety hazards. Although high winds can cause power outages, which have serious impacts on the transportation network as a whole, it is not believed that these impacts will be greater than those facing the city today.

Heat waves, meanwhile, present a moderate threat to the city's ground transportation infrastructure, though it is not expected to become materially greater until the 2050s. Heat waves could create problems with opening and closing movable bridges and cause softening of asphalt roads. Heat waves also could become an issue for the subway system, increasing temperatures on platforms to levels that could turn what, today, is only a passenger comfort issue into a passenger safety issue. Moreover, heat waves could increase the potential for power outages, which affect transportation networks across the board.

Finally, sea level rise in and of itself is expected to pose a low risk to the city's transportation infrastructure for the next three decades. However, by the 2050s tidal flooding—already an issue for some low-lying areas—could become more widespread along the waterfront, including areas such as Southern Brooklyn and South Queens. Waterfront assets including the city's airports and ferry terminals could be placed at risk by this periodic flooding threat.”

The regional scale exposure analysis identified several clusters of vulnerable and critical transportation facilities in New York City, including the following:

- Lower Manhattan, including The Battery (Battery Park Tunnel and the north portal to the Hugh L. Carey Tunnel), Battery Park City and West Side Highway (New York State Route 9A), and FDR Drive on the Lower East Side;
- The east bank of the Hudson River and the east bank of the Harlem River, including the Metro-North Railroad Hudson Line, portions of the Empire Connection, and West Side Drive (New York State Route 9A);
- The area around Flushing Bay in The Bronx, Queens, and Manhattan, including LaGuardia Airport, the Oak Point Rail Yard, the Hunts Point Terminal Market, portions of Interstate Highway 678 in Whitestone, portions of the Grand Central Parkway and Northern Boulevard on the south shore of Flushing Bay, and the north approach to the Whitestone Bridge;
- The mouth of the Hutchinson River, including the US Route 1 (Boston Road) bascule bridge, the Hutchinson River Parkway bascule bridge, Amtrak Northeast Corridor bascule bridge, and the Pelham Parkway bascule bridge;
- The area around Jamaica Bay, including portions of the Belt Parkway, Cross Bay Boulevard, Flatbush Avenue, Neptune Avenue, and many other streets in south Brooklyn and southeast Queens that are part of the National Highway System, as well as the Long Island Rail Road Far Rockaway Branch, the New York City Transit A Train south of Howard Beach, the Rockaway bus storage facility, and JFK airport.

- The west shore of Staten Island along Arthur Kill, including portions of the West Shore Expressway (New York State Route 440), the Arthur Kill Railroad Bridge, and New York Container Terminal; and
- Numerous moveable bridges and bridge approaches that are part of the National Highway System spanning Gowanus Canal and Newtown Creek.

Lower Hudson Valley

The primary climate stressor of concern in the Lower Hudson Valley region (including Westchester, Rockland, and Putnam counties) is precipitation-based flooding. By 2100, the Lower Hudson Valley region may have between 1 and 18 percent more precipitation per year (suggesting more days with saturated soils) and between 0 and 4 additional days with more than 1 inch of rainfall. The following facilities are particularly vulnerable:

- The north-south parkways, the Harlem Line of Metro-North Railroad, and arterial roadways that run along and through river and stream valleys in Westchester County are particularly exposed and sensitive to flooding from heavy rainfall events.
 - For example, large stretches of the Saw Mill River Parkway between Dobbs Ferry and Pleasantville regularly close during heavy rainfall events, particularly those that occur when soils are already saturated and unable to soak up runoff.
 - Sections of the Bronx River Parkway from Allerton Avenue to Ardsley Road also are exposed to flooding.
- East-west roads like New York State Route 119, Virginia Road, and Harney Avenue are exposed to flooding during these events, impeding cross-county travel.

Sea level rise and storm surge also are a concern for roads and rail lines adjacent to the Hudson River and Long Island Sound:

- Portions of Metro-North's Hudson Line were inundated during Hurricanes Irene and Sandy, including the Harmon Yard in Croton-on-Hudson. At various points along the right of way, third rail, switches, snow melters, power transformers, and communications systems were inundated and destroyed by salt water, and these may be exposed to future storm surges.
- Portions of the CSX River Line north of Stony Point in Rockland County also are exposed to storm surge.
- The Haverstraw and Ossining ferry landings are vulnerable to sea level rise and storm surge.

Northern New Jersey and the North Jersey Coast

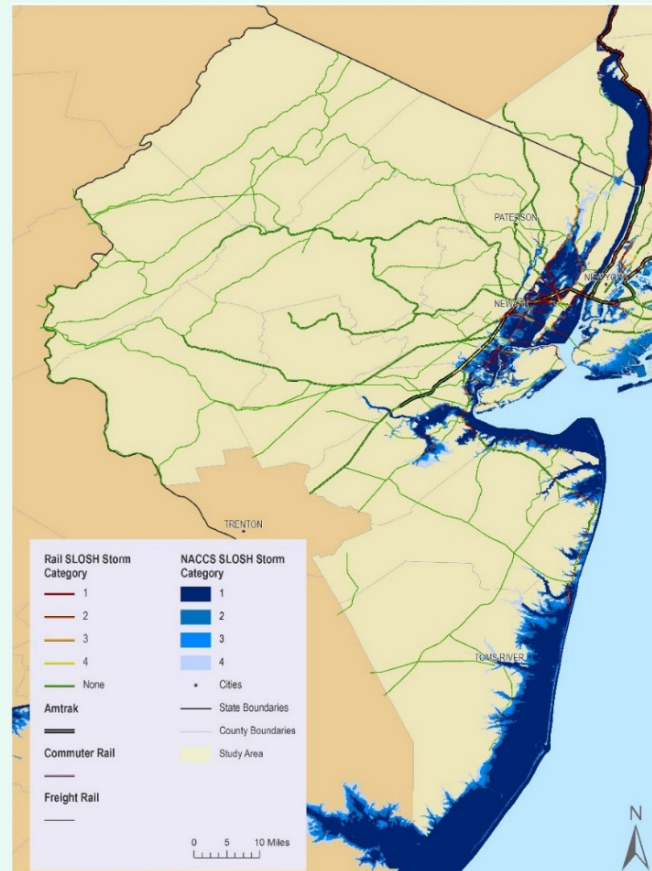


Figure C.11. Map. Potential Exposure of rail network in New Jersey to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

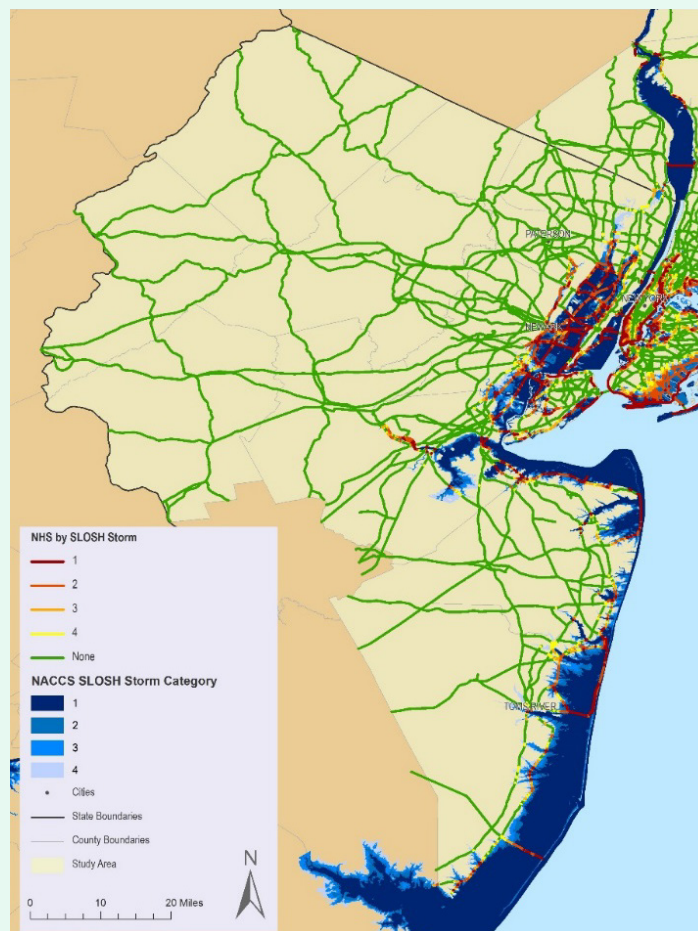


Figure C.12. Map. Potential exposure of the National highway system in New Jersey to coastal flooding and storm surge.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

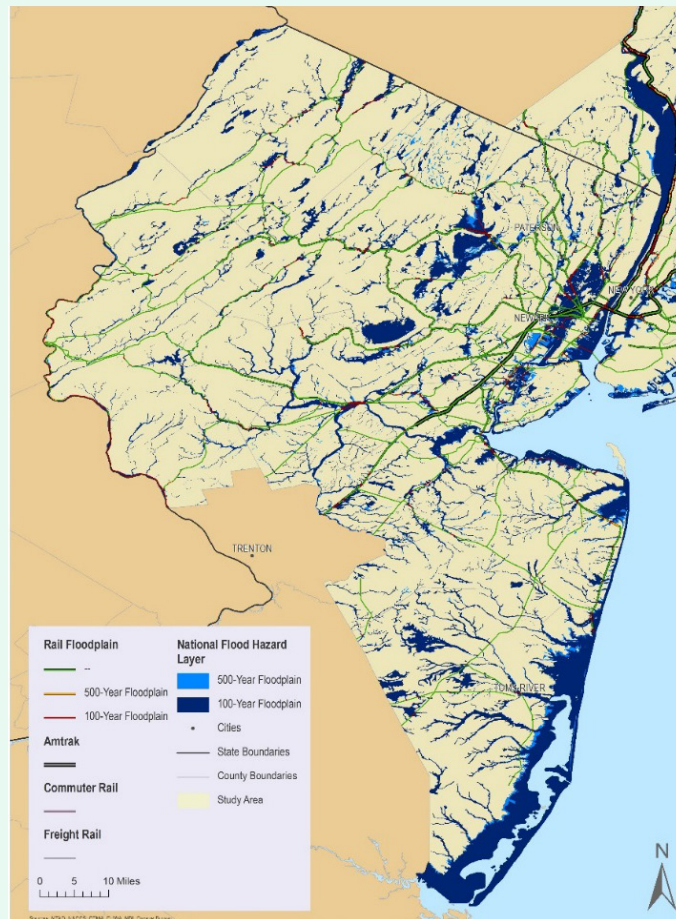


Figure C.13. Map. Potential exposure of the rail network in New Jersey to inland flooding.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves and Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.



Figure C.14. Map. Potential exposure of the National highway system in New Jersey to inland flooding.

(Source: Federal Emergency Management Agency National Flood Hazard Layer (NFHL).)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

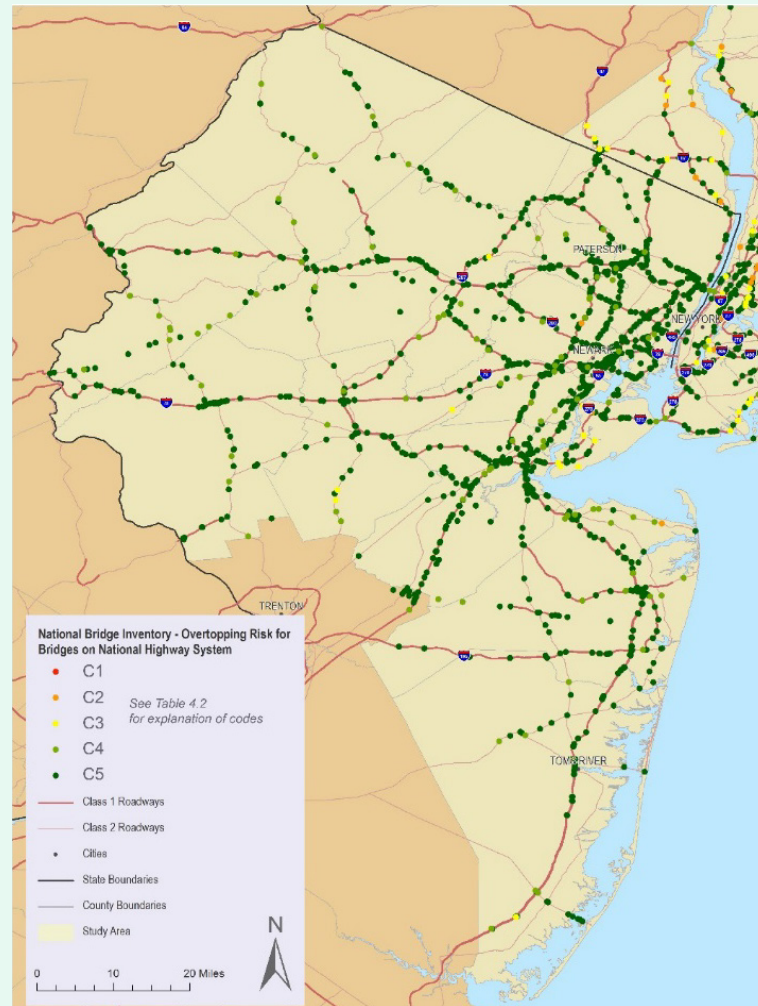


Figure C.15. Map. National bridge inventory overtopping analysis in northern New Jersey.

(Source: Federal Highway Administration, National Bridge Inventory.)

Northern New Jersey

Sea level rise and storm surge affect coastal and tidal areas including the Meadowlands, areas bordering Newark Bay, and the River Towns from Bayonne to Fort Lee. Meanwhile, riverine flooding affects transportation facilities in the Passaic, Hackensack, and Raritan River basins. Concentrations of exposed and critical facilities include the following:

- NJ Transit's Hoboken Terminal and the surrounding areas of Hoboken are exposed to flooding at extreme high tides and during coastal storms.
- Several critical east-west commuter and evacuation routes through the Meadowlands, including New Jersey Route 7 and County Route 508, are exposed to sea level rise and storm surge. NJ TRANSIT's Meadowlands Maintenance Facility is exposed to storm surge. Large portions of the facility were inundated from Hurricane Sandy's surge. The southern side of Port Jersey and the Military Ocean Terminal in Bayonne also are exposed to sea level rise and coastal flooding due to storm surge.
- Many roads in the Passaic River basin are vulnerable to precipitation-based flooding, notably New Jersey Route 21 between Paterson and Newark, U.S. Route 46 in Wayne and Fairfield, and New Jersey Route 23 and U.S. Route 202 in Wayne, Lincoln Park, and Pequannock Township.
- Maritime facilities lining the west side of Arthur Kill are exposed to coastal flooding and sea level rise. During Hurricane Sandy, the Grover Cleveland Service Area on the New Jersey Turnpike was destroyed by flood waters from the Woodbridge River, a tributary of Arthur Kill.
- New Jersey Route 18 and River Road are exposed to flooding of the Raritan River between New Brunswick and Bound Brook.

New Jersey Coast

As detailed in the Climate Change and Vulnerability Assessment completed by North Jersey Transportation Planning Authority (NJTPA) and its partners in 2012, much of the North Jersey Coast is vulnerable to sea level rise and storm surge. The predictions of the study were borne out when areas predicted to flood in a Category 1 hurricane were inundated by Hurricane Sandy's storm surge. These included the following:

- Areas along the south shore of Raritan Bay from South Amboy through the Highlands were inundated. New Jersey Route 35 in Laurence Harbor and Keyport were closed due to flooding, and these same stretches of roadway close during severe Nor'easters as well. Low-lying portions of New Jersey Route 36 east of Keyport also are exposed to coastal floods. NJ TRANSIT's North Jersey Coast Line crossing Cheesquake Creek and Wilkson Creek also are exposed to flooding. In the future, more severe storms accompanied by sea level rise could result in more frequent closure of these critical routes for freight, local commerce, and commuting. The Garden State Parkway crossing Cheesquake Creek is not exposed to flooding today, but it could become more vulnerable to coastal flooding in the future with sea level rise. The New Jersey Route 35 and North Jersey Coast Line crossings of inlets and estuaries such as the

Navesink and Shrewsbury Rivers are exposed to storm surge. Approaches to the New Jersey Route 70 crossings of the Metedeconk and Manasquan Rivers also are exposed to storm surge.

- New Jersey Route 36 from the Highlands to Long Branch runs in close proximity to the beach and is exposed to sea level rise, storm surge, and wave action. New Jersey Route 35 from Point Pleasant to Seaside Heights has the same exposure. Both facilities were severely damaged by Hurricane Sandy's storm surge and wave action.
- All of the east-west evacuation routes from Jersey Shore beaches, including those on county roadway networks that are not part of the National Highway System, are exposed and vulnerable to storm surge. In addition, further inland, the effects of sea level rise on water tables means detention and retention ponds no longer completely drain after rainfalls, leaving adjacent roadways more vulnerable to flooding from heavy precipitation events. Stormwater outfalls are increasingly submerged as sea levels rise, further contributing to coastal flooding on these critical routes.

Regional Highway System Disruptions

Hurricane Sandy

Hurricane Sandy caused extensive damage to coastal roads in New Jersey and New York, and several roadways and tunnels in lower Manhattan flooded or were extensively damaged by storm-related debris. Notable closures that caused disruption on a regional scale are shown in Figure C.20 and include the following:

- Sandy's storm surge caused major erosion or full washouts at nearly 40 locations on a 12.5-mile stretch of NJ 35. New Jersey Department of Transportation was able to reopen NJ 35 to limited traffic in January 2013, two months after the storm, but full reconstruction of the roadway was completed in a series of projects starting in 2013 and ending in 2015.
- Stretches of Ocean Parkway in Nassau and Suffolk Counties, NY, adjacent to the Atlantic Ocean also were washed out by Hurricane Sandy's wave action and storm surge. Washed out sections of Ocean Parkway reopened in April 2013.
- An estimated 86 million gallons of water flooded the Hugh L. Carey Brooklyn-Battery Tunnel between Manhattan and Brooklyn. The tunnel reopened to automobile traffic in late November 2012, nearly one month after the storm.
- The Holland and Midtown Tunnels flooded. The Holland Tunnel reopened to bus traffic on November 2 and to all traffic days later. The Midtown Tunnel was closed to all traffic until November 8.

- Although most bridges used to access barrier islands in New Jersey and New York were able to accommodate traffic within hours or days after the passage of the storm, many remained closed to all traffic except emergency vehicles and supply trucks for days or weeks to facilitate emergency response and disaster recovery in hard-hit areas.
- Prior to and during periods of sustained winds over 60 miles per hour, major bridge crossings in the region were closed to all traffic during Hurricanes Sandy. These included the George Washington Bridge, Tappan Zee Bridge, all bridges operated by MTA Bridges and Tunnels, some bridges operated by New York City DOT, and the Bear Mountain Bridge, operated by the NYS Bridge Authority. Trucks and high-profile vehicles were restricted from using these crossings when wind gusts regularly exceeded 60 miles per hour.

In addition to closures of roadway infrastructure, much of the region experienced a shortage of diesel and gasoline in the days after the storm. New York Harbor was closed to navigation by the U.S. Coast Guard for six days from October 30 to November 4. Due to storm-surge-related flooding that impacted three of the region's largest refineries and several fuel storage facilities, the region's fuel distribution system did not have capacity to transport enough fuel to the region's gas stations to meet demand. Motorists and truck drivers in New Jersey, New York City, and Long Island waited in hours-long lines attempting to refuel in the days after the storm. Often, gas stations ran out of fuel before waiting motorists could refuel. The Governors of New York and New Jersey and the Mayor of New York City imposed "even-odd" gasoline rationing at all gas stations in northern New Jersey, Long Island, and New York City. Rationing ended November 13 in New Jersey, November 17 on Long Island, and November 23 in New York City.

Power outages also caused failure of traffic signals, street lights, intelligent transportation systems infrastructure, and communications systems used to support emergency response. The Lower Manhattan street grid and major regional arterials functioned at very low levels of service with reduced capacity for days. As shown in Figure C.16, downed trees, downed power lines, and debris also blocked traffic on major regional routes for several days as state and local agencies and utilities cleared roads, sidewalks, and parking lots.

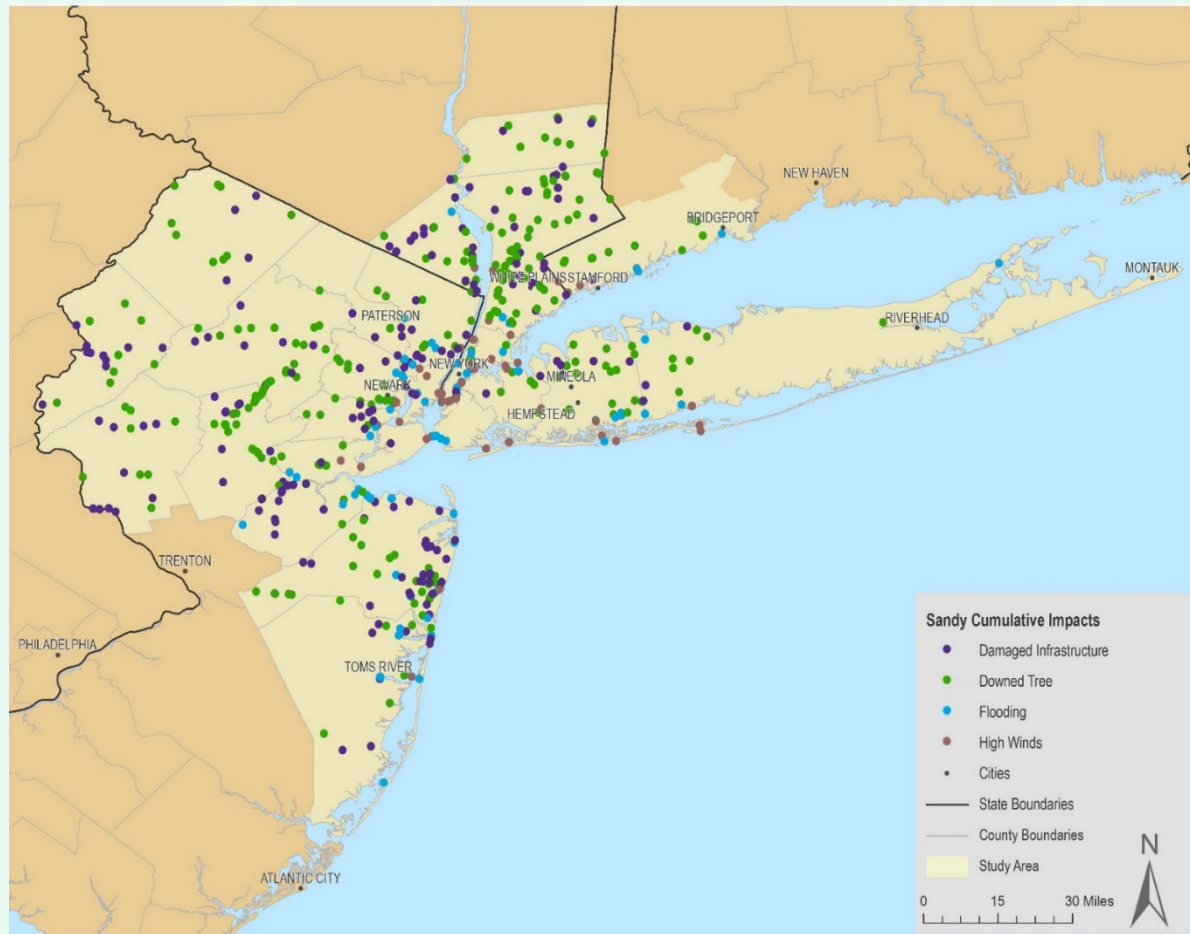


Figure C.16. Map. Regional roadway system disruption reported on major regional roadways due to Sandy.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County, Long Island, in particular, only a limited number of incidents are reported to TRANSCOM. Hurricane Irene and Tropical Storm Lee.

Hurricane Irene and Tropical Storm Lee

Hurricane Irene and Tropical Storm Lee caused a moderate level of disruption to the regional highway system in the study area. The combined rainfall from the two storms resulted in riverine flooding that destroyed significant roadway and bridge assets, particularly where culverts, bridges, and stream-adjacent roadways were vulnerable to washouts. Significant disruptions in the study area due to Hurricane Irene are shown in Figure C.17 and included the following:

- The north (outbound) tube of the Holland Tunnel was closed due to flooding until 11 a.m. on August 28, the day after Irene passed;
- The Lower Level of George Washington Bridge was closed on August 27 due to high winds. The Palisades Interstate Parkway Entrance to the George Washington Bridge was closed until 11 a.m. on August 28;
- Flooding from the Passaic River in New Jersey closed many major arterials in Morris, Essex and Passaic Counties. For example, U.S. 46 and portions of U.S. 202 were closed for more than 3 days following Irene, and both closed again due to flooding attributed to Lee. Near Boonton, a portion of I-287 collapsed into the Rockaway River (a tributary of the Passaic River) and was reconstructed. A portion of I-80 in Morris County washed out and needed to be reconstructed. Exit ramps from I-80 East in Parsippany-Troy Hills and Wayne closed due to flood waters, washouts, and debris. Several portions of Route 23 in Morris, Passaic and Sussex counties closed due to shoulder washouts and debris on the roadway;
- New Jersey Route 18 in Piscataway and New Brunswick closed due to flooding of the Raritan River. U.S. 206 in Somerville also closed due to flooding and debris;
- An approximately 500-foot stretch of River Vale Road in Bergen County, New Jersey was washed out by floods; and
- Rockland County Route 94 in Haverstraw, New York, was washed out.

As shown in Figure C.18, the reported damage due to Lee in the study area was much less extensive than the damage from Irene and Sandy. Lee caused temporary flooding, downed trees, and downed power lines on roadways in northern New Jersey and in Westchester County.

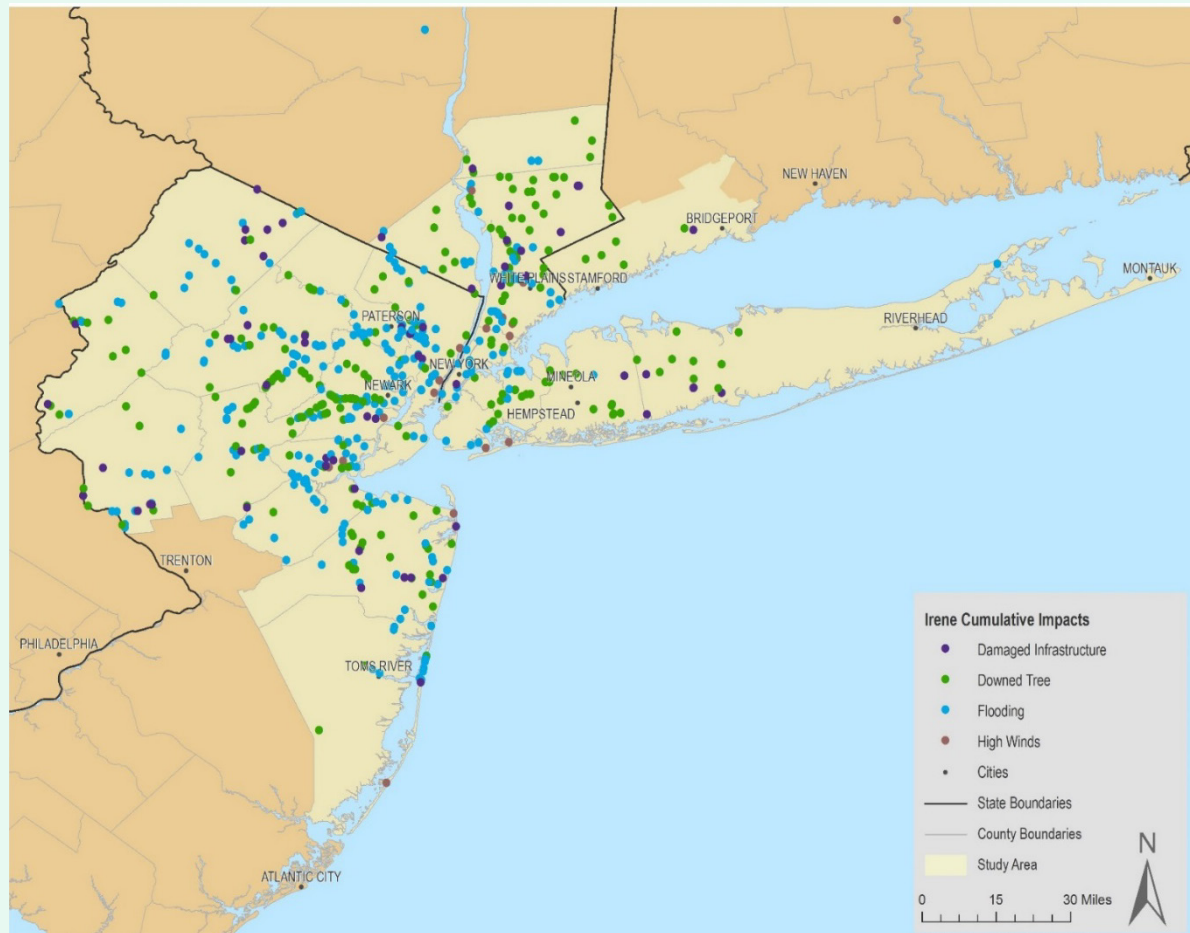


Figure C.17. Map. Regional roadway system disruption reported to TRANSCOM due to Irene.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

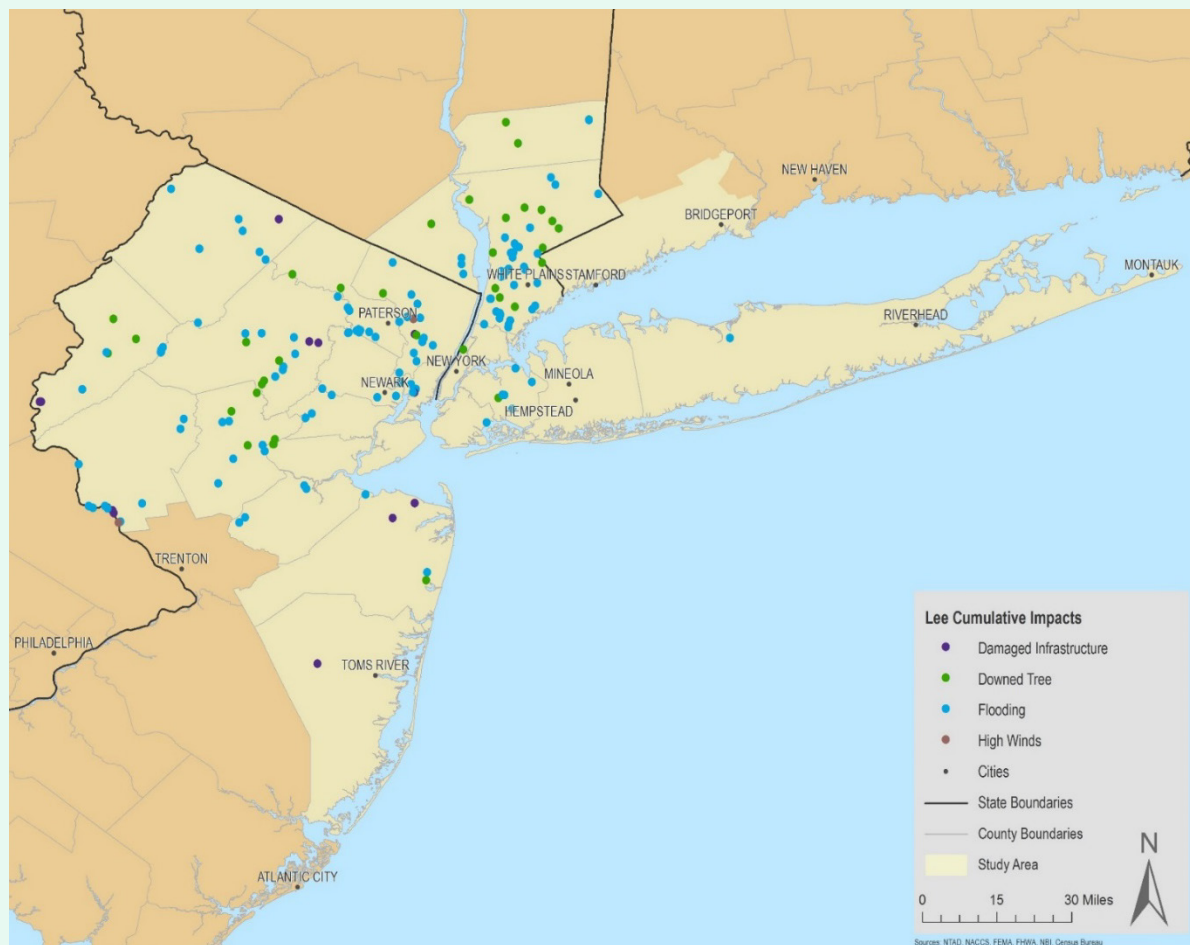


Figure C.18. Map. Regional roadway system disruption reported to TRANSCOM due to Lee.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

Nor'easter Alfred

Disruption due to the Halloween Nor'easter of 2011 largely was due to downed trees blocking area roadways. In Westchester County, New York, and in Fairfield County, Connecticut, major roads were passable within hours of the passage of the storm. However, major disruptions to the Connecticut's power supply due to downed power lines caused some traffic signals and street lights to be dark for days after the storm.

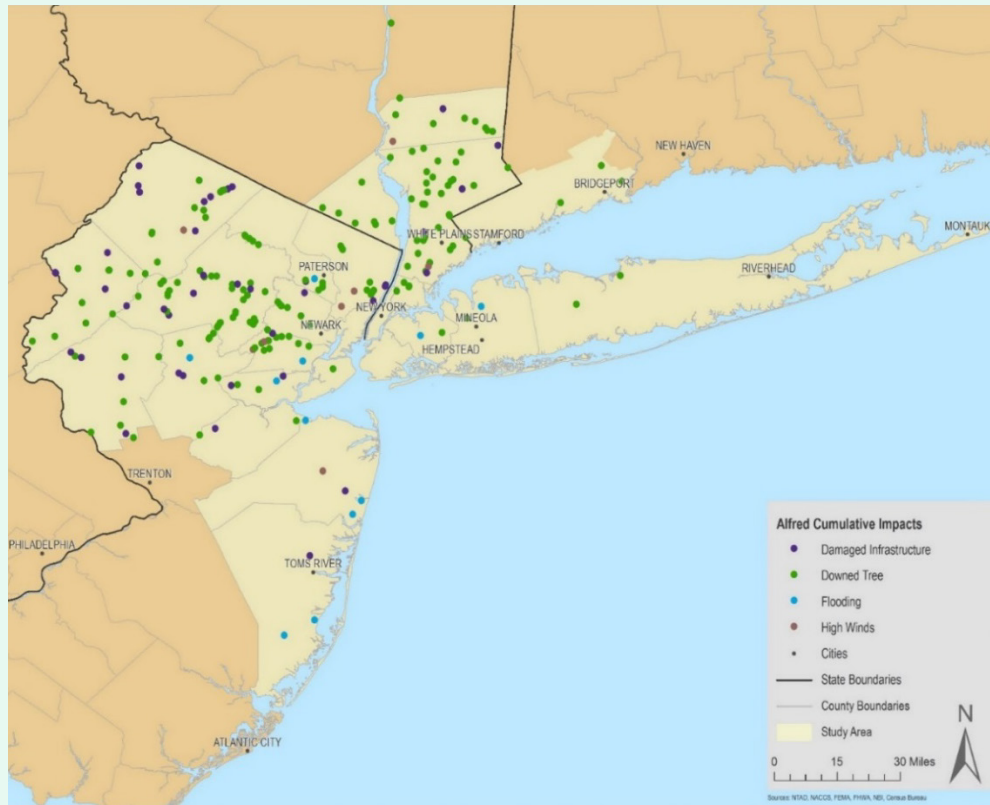


Figure C.19. Map. Regional roadway system disruption reported to TRANSCOM due to Alfred.

(Source: Transportation Operations Coordinating Committee (TRANSCOM).)

Note: This map shows only those incidents on major regional roadways reported to TRANSCOM. Disruptions to local roads are not reported to TRANSCOM. In Suffolk County in particular, only a limited number of incidents are reported to TRANSCOM.

Regional Transit System Disruption

Hurricane Sandy

Hurricane Sandy caused major disruption to the transit services of every operator in the region. Figure 2.16 shows a timeline of the disruptions and subsequent restoration of service on the MTA, New York City DOT (Staten Island Ferry), New Jersey Transit, and PANYNJ-managed transit systems, with impacts to the broader transportation system noted for reference.

Figure 2.16 focuses on the period in the immediate aftermath of Sandy. To this day, shutdowns of subway tunnels and Amtrak's East River and North (Hudson) River tunnels for short-term and long-term repairs cause significant disruption to regional travel. For example, the MTA is preparing for long-term shutdown of the L train's Canarsie Tube under the East River to repair damage from Sandy. This will affect more than 225,000 weekday L train riders between Manhattan and Brooklyn, plus additional riders on other subway and bus lines that will have to accommodate displaced L train riders.

Figure 2.16 also does not reflect the major impacts of Sandy on county-operated bus systems in the region. Long Island Bus and Westchester's Bee Line bus service were suspended for several days after Sandy, and paratransit services and other demand-responsive transportation services for the elderly, disabled, and veterans were impacted for weeks as local roadways were repaired and reopened.

Hurricane Irene and Tropical Storm Lee

Prior to the arrival of Hurricane Irene, MTA New York City Transit took the unprecedented step of proactively shutting down the entire transit system so that customers would not be in harm's way, employees could safely get home, and rolling stock could be positioned in locations where they could safely weather the storm. NJ TRANSIT, the PATH subway, and local transit operators took similar measures. As a result, the region's rolling stock was largely unscathed during the coastal and riverine flooding that occurred in the days after Hurricane Irene and Tropical Storm Lee passed through the area.

A significant disruption from the one-two punch of Irene and Lee was due to the flooding of the Ramapo River in Rockland County, which severely damaged 14 miles of Metro-North Railroad's Port Jervis Line, causing three 1,000-foot washouts and one 4,000-foot washout between Suffern and Harriman, New York. The Port Jervis Line, which served 3,000 daily commuters, was out of service for nearly three months as the track and signal systems were reconstructed and repaired. Many Metro North passengers used commuter bus services to and from Orange County, straining park and ride lots beyond capacity, particularly in Harriman and Monroe.

The region's commuter rail operators and Amtrak had to clear a large amount of debris from the tracks following both Irene and Lee, but, with the exception of the Port Jervis Line, the rail system was back up and running shortly after each storm. Bus services were not heavily impacted other than temporary re-routes around debris-blocked and flooded roads. NJ TRANSIT had to relocate more than 350 buses from garages that flooded in Irene.

Additional transit system disruptions due to Irene and Lee included the following:

- Amtrak and NJ TRANSIT were affected as Northeast Corridor service was suspended from August 28 to August 31 due to flooding at the Trenton Transit Center and other storm-related damage from Irene;
- Service on the PATH was suspended from 12 PM on August 27 until 4 AM on August 29 (40 hours); and
- NJ TRANSIT's Bound Brook station was closed due to flooding from the nearby Raritan River.

Nor'easter Alfred

The Halloween Nor'easter Alfred of 2011 caused minor disruptions to MTA Metro-North Railroad service. Service was suspended on the Danbury, New Canaan, and Waterbury branches for over 24 hours due to track conditions and wind-blown debris. Local bus services in Connecticut were heavily impacted by Alfred, as were school buses that could not safely navigate local roads. Many schools were closed for at least a week during the clean up and due to power outages. Bus services began to recover throughout the week. Long-lasting power outages in Connecticut also affected traffic signals and street lights, causing a safety hazard on arterials and collector roadways.

Long-Term Damage, Disruption, and Resiliency Projects

Due to the nature of the damage associated with salt water inundation, some disruptions to the region's transportation system, and its transit system in particular, are expected to continue well into the future. For example, a sealed brake unit in an escalator in the PATH's Exchange Place station was damaged by salt water when the station was inundated by Hurricane Sandy's storm surge. This damage was not detected until a malfunction of the escalators on January 8, 2013, well over two months after the storm. Signals in Amtrak's East River Tunnels and in Long Island Rail Road's Long Beach Yard have failed repeatedly in the months after Sandy, with outages attributable to salt water corrosion of electrical and mechanical systems.

As noted above, MTA New York City Transit's L Train will be closed for at least 18 months starting in 2019 to allow for extensive repairs of the Canarsie Tube under the East River. The tunnel was inundated by brackish water, which corroded steel reinforcing bar, electrical conduit, signal and communications hardware, and other metal components.

The full extent of Hurricane Sandy's damage may not become apparent for many years as the region's transit operators make necessary repairs and make the system more resilient in the face of future expected extreme weather events.

Identification of Vulnerable Subareas

The regional exposure analysis provided valuable information to identify the most critical and vulnerable components of the regional transportation system. The study team used a set of criteria as follows to identify 21 vulnerable subareas:

- Concentration of critical infrastructure that handles regional movement of people and freight, where critical infrastructure was defined as:
 - National Highway System and evacuation routes;
 - Major transit and rail corridors;
 - Intermodal hubs for people and freight (and access to them); and
 - Supporting infrastructure such as rail and bus storage and maintenance facilities.
- A qualitative assessment of exposure, sensitivity, adaptive capacity of the infrastructure in areas with concentrations of critical infrastructure.
 - The qualitative assessment was based in part on information on past damage and disruption and judgment about future vulnerability.
 - The vulnerability assessment focuses on coastal inundation (due to a combination of sea level rise and storm surge) and inland flooding.

Figures C.20 and C.21 show regional maps of potential exposure of the National Highway System and the regional rail network to sea level rise, with overlays of the 21 vulnerable subareas.

Figures C.22 and C.23 show regional maps of potential exposure of the National Highway System and the regional rail network to storm surge, with overlays of the 21 vulnerable subareas.

Figures C.24 and C.25 show regional maps of the potential exposure of the National Highway System and regional rail network to inland flooding, with overlays of the 21 vulnerable subareas.

Using the GIS data underlying these maps, the study team identified 21 candidate subareas based on where there were clusters of critical facilities exposed to climate stressors.

Figure C.26 shows projects funded by Emergency Relief grants after Irene, Lee, and Sandy.

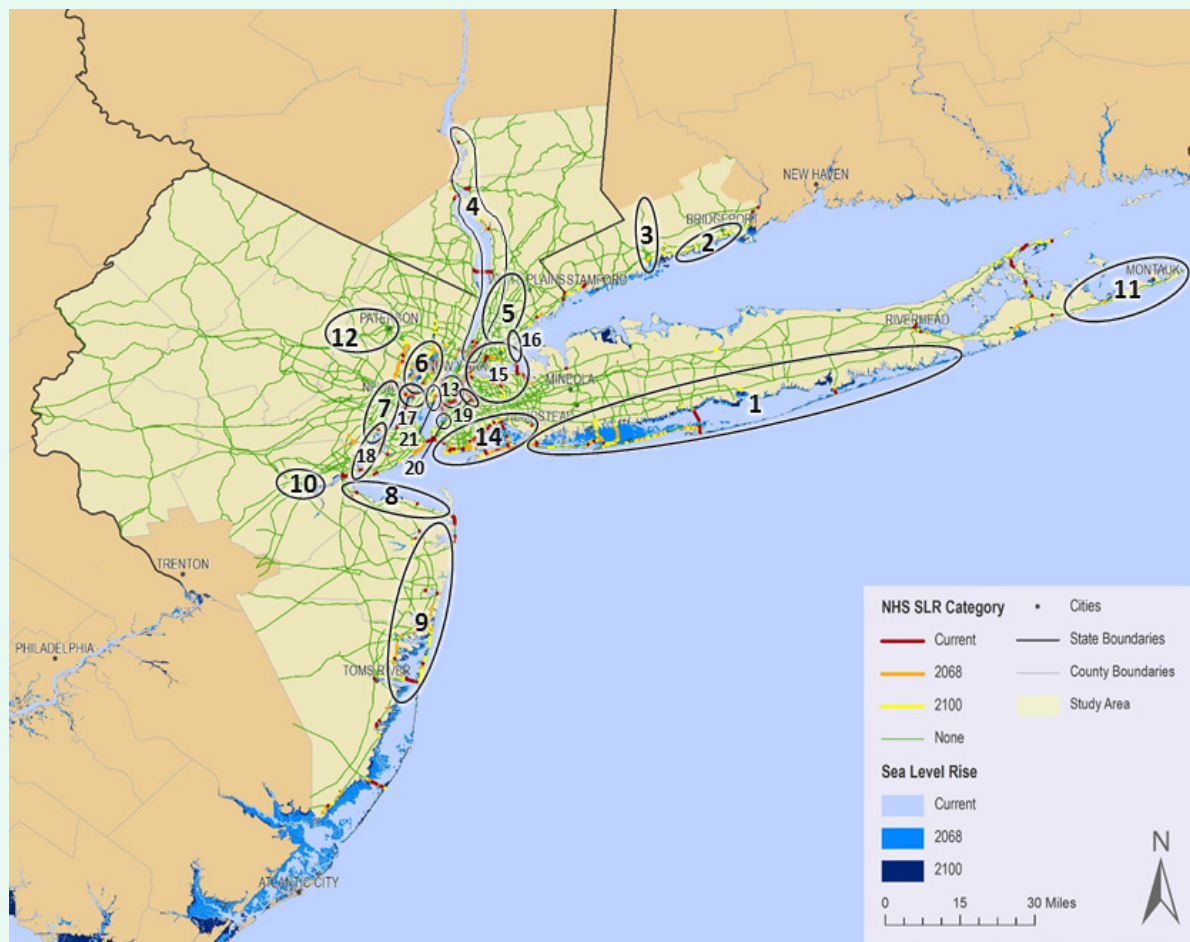


Figure C.20. Map. Potential exposure of National highway system to sea level rise, with 21 vulnerable subareas.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to sea level rise in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

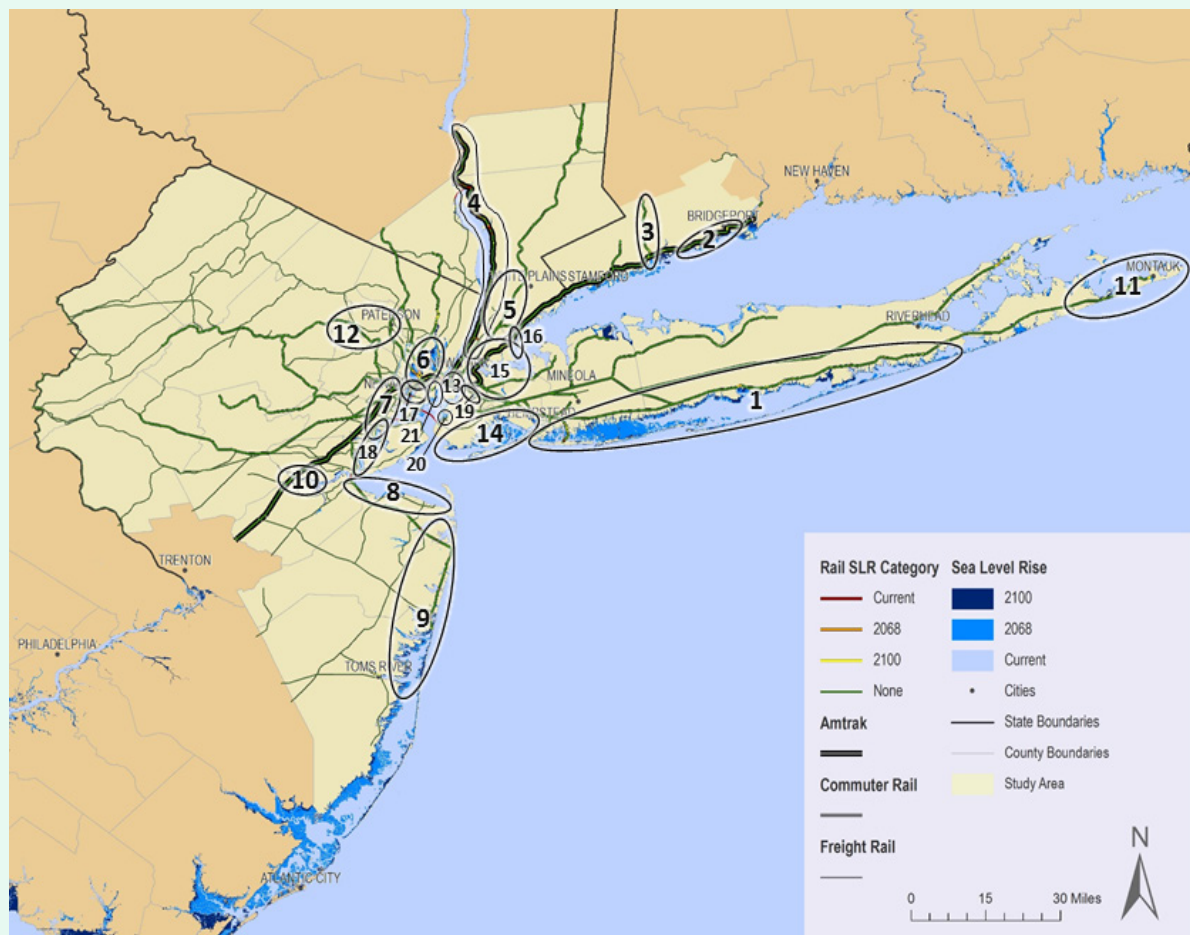


Figure C.21. Map. Potential exposure of National highway system to sea level rise, with 21 vulnerable subareas.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to sea level rise in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

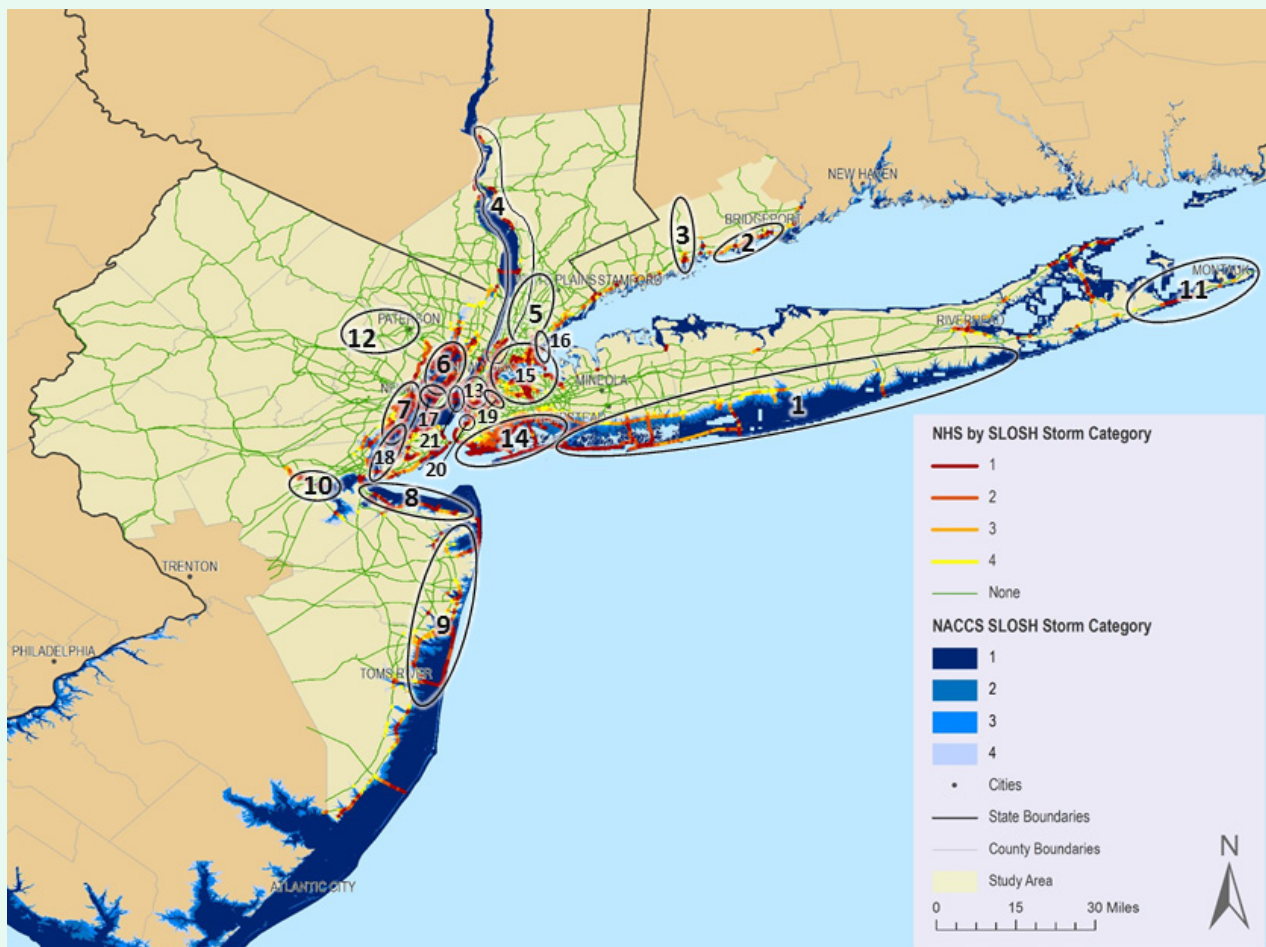


Figure C.22. Map. Potential exposure of National highway system to storm surge, with 21 vulnerable subareas.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

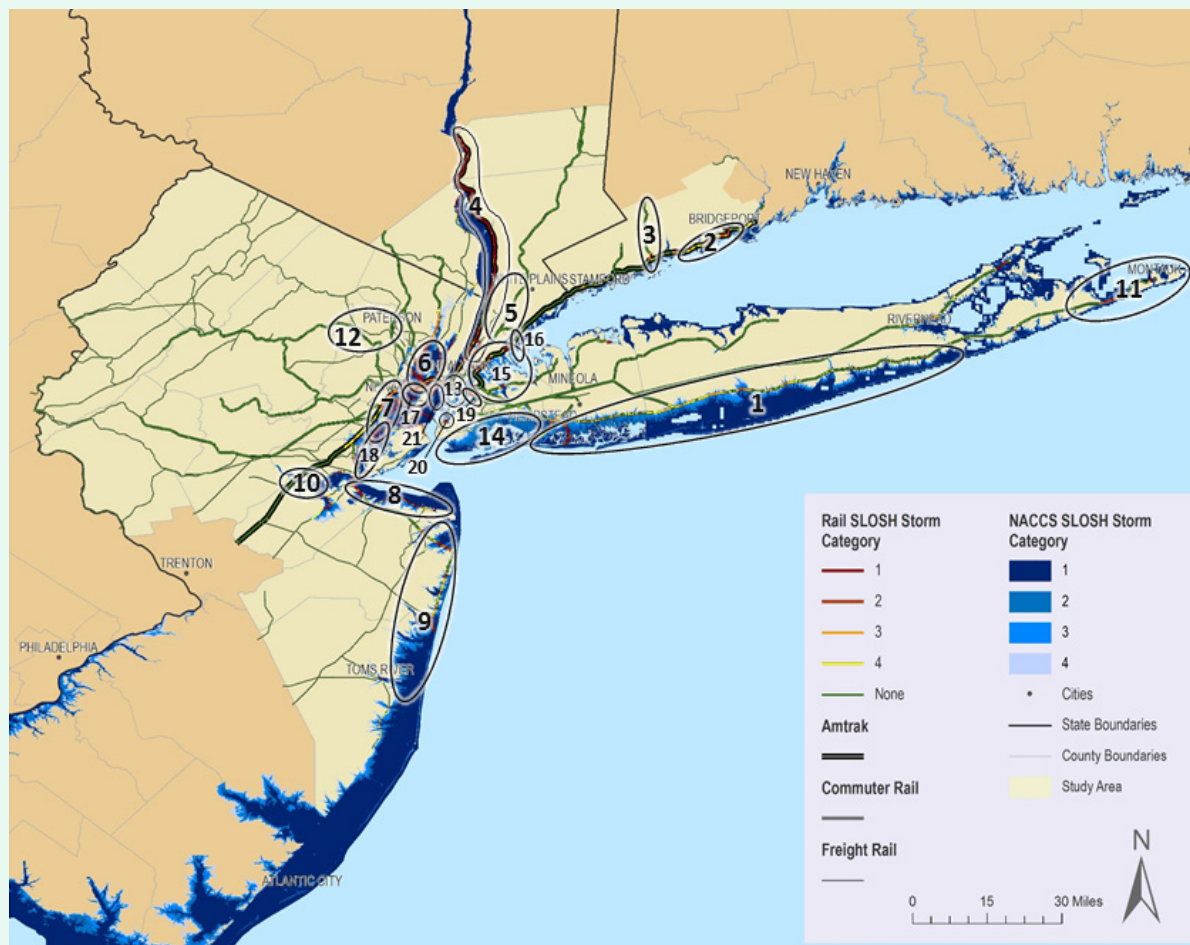


Figure C.23. Map. Potential exposure of regional rail network to storm surge, with 21 vulnerable subareas.

(Source: Cilone, M. et. al. North Atlantic Coast Comprehensive Study: Coastal Storm Model Simulations: Waves And Water Levels. U.S. Army Corps of Engineers, 2015.)

Note: The entire extents of bridges over water are shown as vulnerable to coastal flooding and storm surge in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

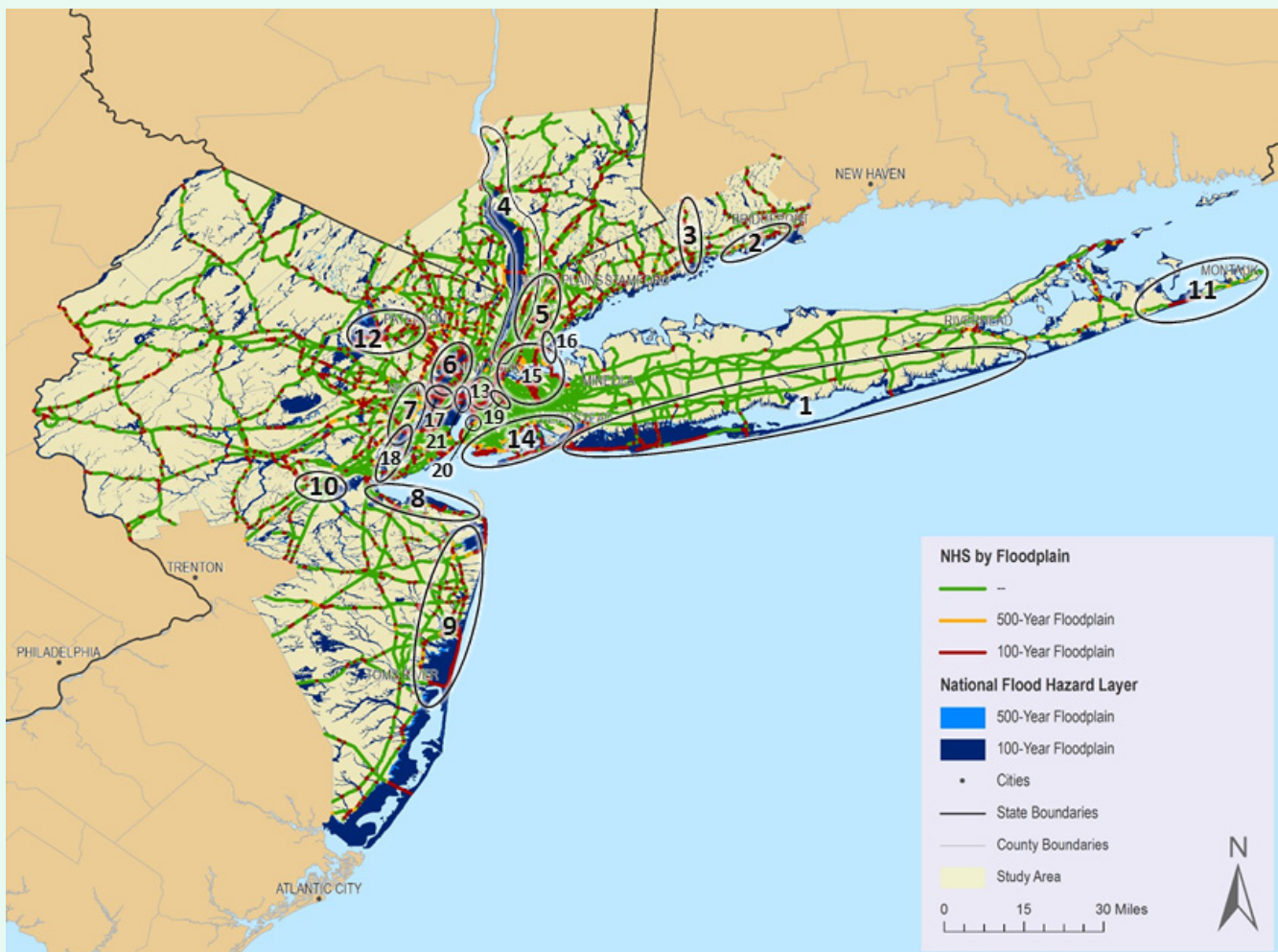


Figure C.24. Map. Potential exposure of the National highway system to inland flooding, with 21 vulnerable subareas.

(Source: Federal Emergency Management Agency, National Flood Hazard Layer.)

Note: The entire extents of bridges over water are shown as vulnerable to inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

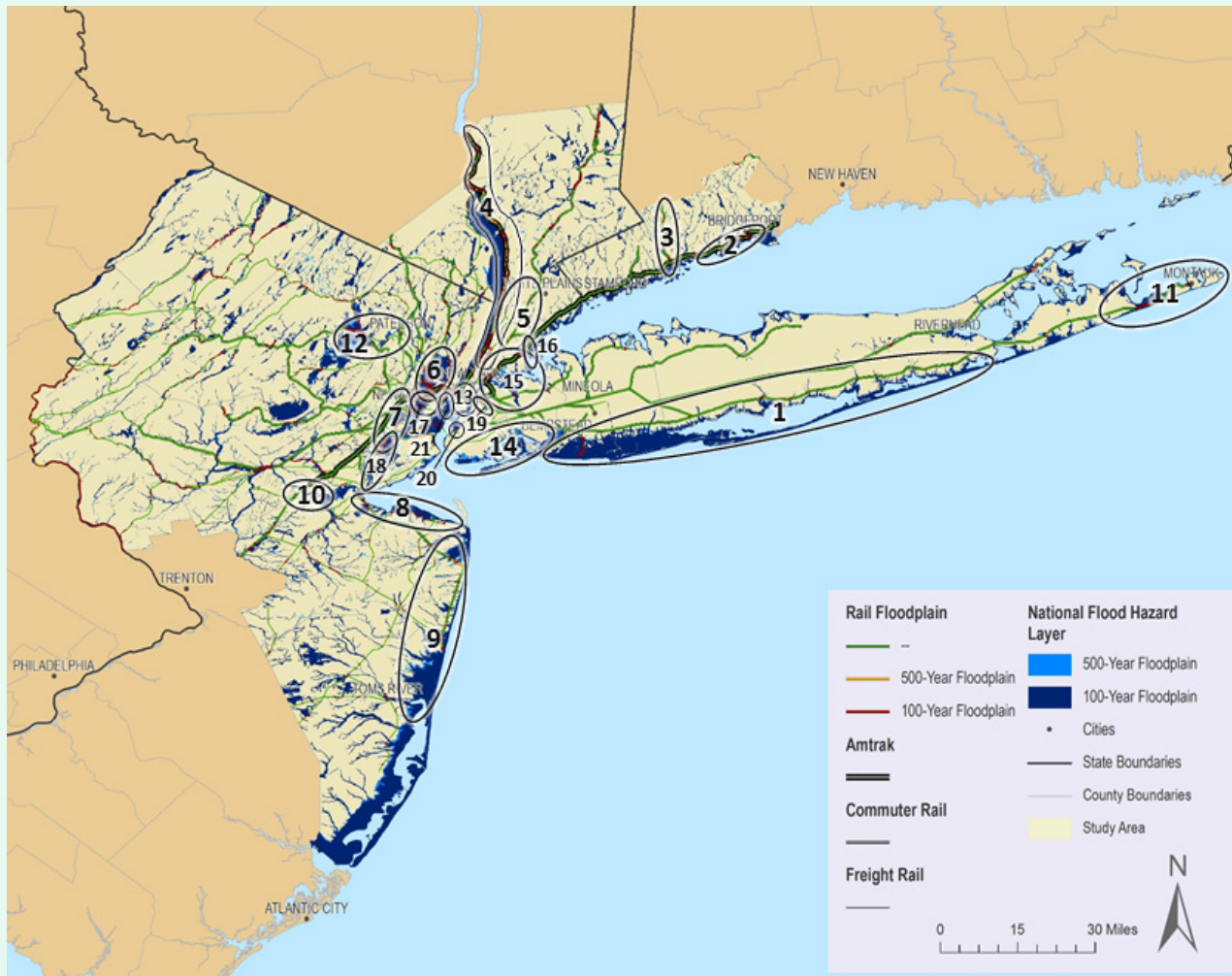


Figure C.25. Map. Potential exposure of regional rail network to inland flooding, with 21 vulnerable subareas.

(Source: Federal Emergency Management Agency, National Flood Hazard Layer.)

Note: The entire extents of bridges over water are shown as vulnerable inland flooding in this regional-scale exposure analysis. Closer examination at a facility level would be required to determine the precise components of these bridges that are potentially exposed.

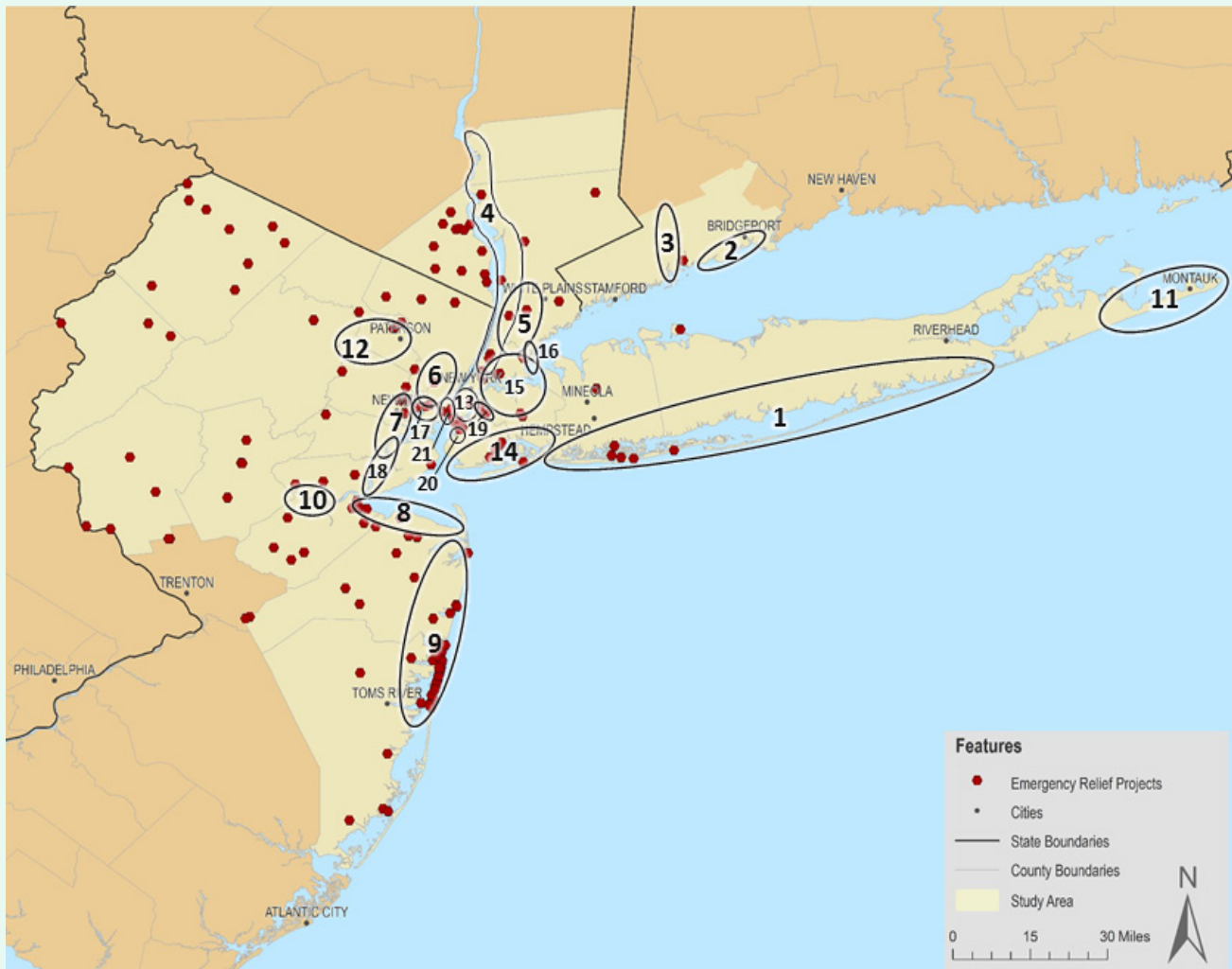


Figure C.26. Map. Locations of Federal Highway Administration Emergency relief Projects after Irene, Lee, and Sandy, with 21 vulnerable subareas.

(Source: Federal Highway Administration.)

Candidates for Subregional Assessments

The following pages show the summary-level analysis that was provided to the project stakeholders to assist them in selecting three subareas for further analysis. The stakeholders met several times to screen down the list from 21 to the 3 subareas that were chosen for a more complete analysis, as described in the next section

The Post-Sandy project team narrowed down the 21 identified vulnerable subareas identified in the regional vulnerability assessment to 3 through a facilitated discussion with the Project Guidance Committee using the following guidelines:

- A diversity of geographies, climate stressors, impacts, and modes should be represented in the three subareas (see Tables C.1 and C.2);
- The outcomes and results should be useful in advancing future adaptation efforts by regional stakeholders;
- The subarea assessments should avoid duplication of efforts already underway by others to assess vulnerability, evaluate adaptation options, and design and implement adaptation strategies (see Figure C.27); and
- The assessments should focus on subareas where adaptation strategies can be developed for transportation assets vs. subareas where solutions may be needed to protect a broader area including transportation and non-transportation uses.

Table C.2. Summary of climate stressors and impacts in 21 vulnerable subareas.

Map Legend (See Figures C.13-)	Name	Storm Surge	Sea Level Rise	Wave Action	Precipitation	Temperature
1	Long Island South Shore	●	●	●	●	●
2	Bridgeport and Fairfield Coastal Corridor	●	●	●	●	●
3	Norwalk-Danbury Corridor				●	●
4	Hudson River	●	●	●	●	●
5	Westchester County North-South Parkways/Rail				●	●
6	Lower Hackensack River, Secaucus to Hackensack	●	●		●	●
7	Newark/Elizabeth	●	●	●	●	●
8	South Shore of Raritan Bay	●	●	●	●	●

Table C.3. Summary of climate stressors and impacts in 21 vulnerable subareas (continuation).

Map Legend (See Figures C.13-)	Name	Storm Surge	Sea Level Rise	Wave Action	Precipitation	Temperature
9	North Jersey Coast	●	●	●	●	●
10	New Brunswick/Raritan River area				●	
11	NY 27 and LIRR Montauk Branch	●	●	●		
12	Pompton and Passaic River Fork and Basin				●	
13	Lower Manhattan	●	●	●	●	●
14	Rockaway/Brighton Beach/Jamaica Bay	●	●	●	●	
15	Outer East River (N. Queens and SE Bronx)	●	●	●	●	
16	Lower Hutchinson River	●	●	●	●	●
17	Kearny and South Secaucus	●	●	●	●	●
18	Arthur Kill, Newark Bay to Raritan Bay	●	●		●	●
19	Newtown Creek	●	●		●	●
20	Gowanus Canal	●	●		●	●
21	Hoboken and Jersey City	●	●	●	●	

Table C.4. Summary of climate stressors and impacts in 21 vulnerable subareas.

Map Legend (See Figures 4.4 and 4.5)	Name	National Highway System Facilities	Regional Rail Facilities	Evacuation Route(s)	Critical to Freight Movement	Critical to People Movement	Presence of Intermodal Hub
1	Long Island South Shore	●	●				
2	Bridgeport and Fairfield Coastal Corridor	●	●				
3	Norwalk-Danbury Corridor	●	●				
4	Hudson River	●	●				
5	Westchester County North-South Parkways/Rail	●	●				
6	Lower Hackensack River, Secaucus to Hackensack	●	●				
7	Newark/Elizabeth	●	●				
8	South Shore of Raritan Bay	●	●				
9	North Jersey Coast	●	●				
10	New Brunswick/Raritan River area	●					
11	NY 27 and LIRR Montauk Branch	●	●				
12	Pompton and Passaic River Fork and Basin	●					
13	Lower Manhattan	●	●				
14	Rockaway/Brighton Beach/Jamaica Bay	●	●				
15	Outer East River (N. Queens and SE Bronx)	●	●				
16	Lower Hutchinson River	●					
17	Kearny and South Secaucus	●	●				
18	Arthur Kill, Newark Bay to Raritan Bay	●	●				
19	Newtown Creek	●					
20	Gowanus Canal	●					
21	Hoboken and Jersey City	●	●				

Note: Darker shading indicates higher criticality score.

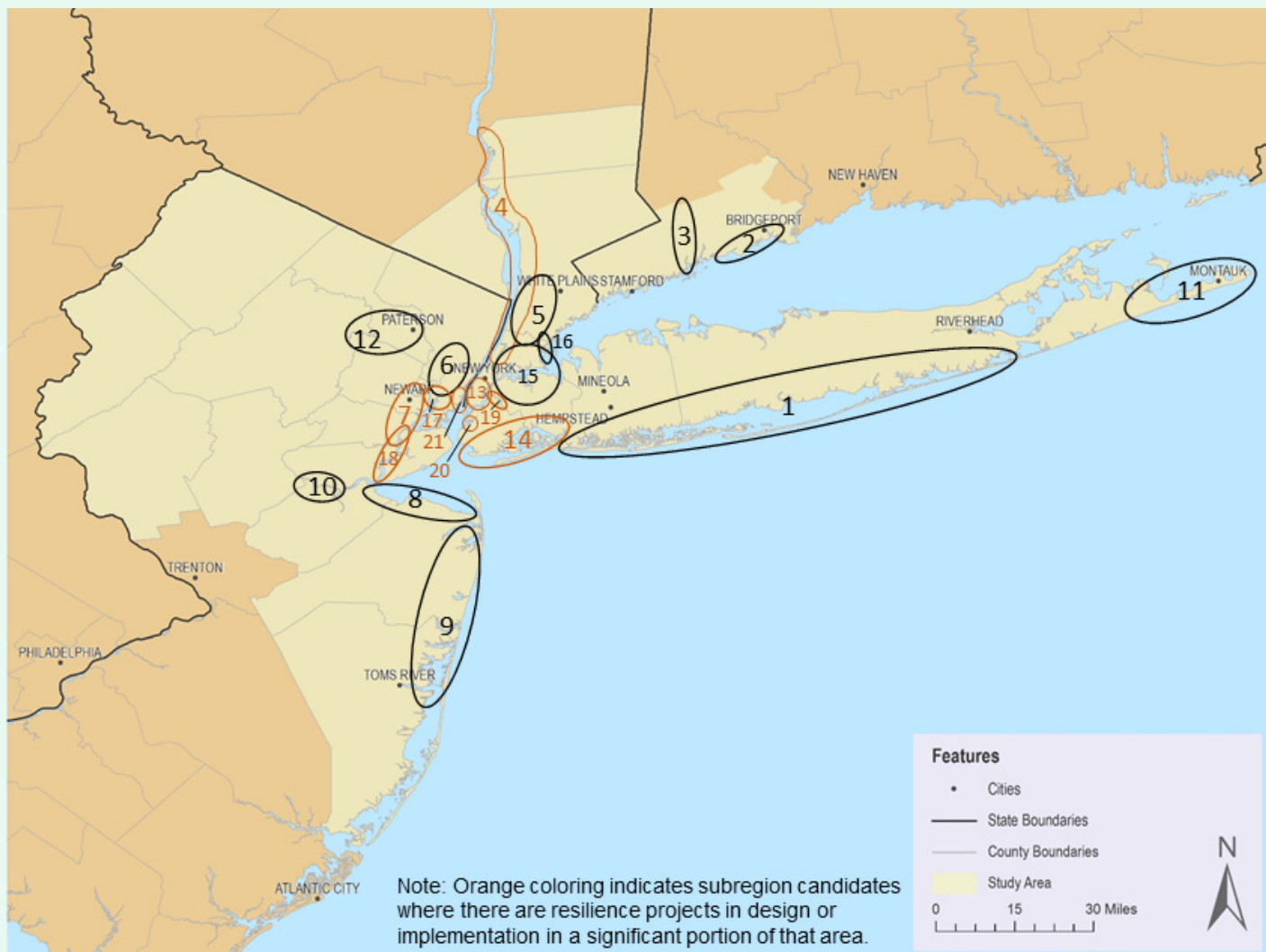


Figure C.27. Map. Locations of ongoing resilience projects.

(Source: Cambridge Systematics, Inc.)

Subareas Selected for Vulnerability Assessment

The three selected subareas were:

- #1 Long Island South Shore,
- #3 Norwalk-Danbury Corridor, and
- #8 South Shore of Raritan Bay.

Figure C.28 shows the locations of the three selected subareas, and Table C.4 summarizes the distinguishing features of each.

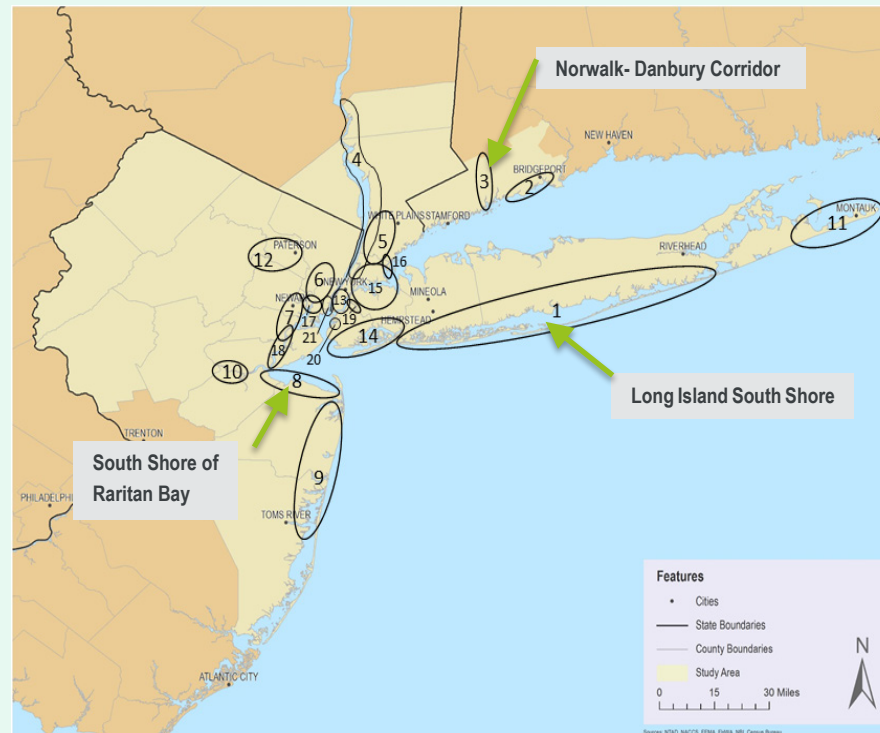


Figure C.28. Three subareas selected for assessment.

(Source: Cambridge Systematics, Inc.)

Table C.5. Features of three selected subareas.

Feature	Long Island South Shore	Norwalk-Danbury Corridor	South Shore of Raritan Bay
County, State, Metropolitan Planning Organization	Nassau and Suffolk counties, New York, New York Metropolitan Transportation Council.	Fairfield County, Connecticut, Western Connecticut Council of Governments.	Middlesex and Monmouth counties, New Jersey, North Jersey Transportation Planning Authority.
Transportation facilities	Arterials, parkways, and a Long Island Railroad line linking barrier islands to Long Island.	Interregional highway and Metro-North Rail line running alongside the Norwalk River.	State highways and a NJ TRANSIT rail line running parallel to shoreline and connecting coastal communities along the bay.
Climate Stressors	Sea level rise, storm surge, wave action, heat, wind.	Riverine flooding, heat, wind.	Sea level rise, storm surge, wave action, heat, wind.
Types of exposed and sensitive transportation assets	Fixed bridges, and movable bridges (and their components); Causeway embankments and retaining walls; Arterial roadways and rail stations in low-lying communities.	Sections of road and rail in riverine flood plains; Road and rail bridges and culverts; Road and rail embankments and retaining walls; Rail catenary, power and communication systems, rail stations.	Sections of road and rail in coastal flood plains; Road and rail bridges and culverts; Road and rail embankments and retaining walls; Rail catenary, power and communication systems, rail stations.
Issues addressed by potential adaptation options	Maintain availability of critical facilities used for evacuation and recovery, daily commutes, and seasonal recreation.	Address consequences of flooding in a corridor with limited adaptive capacity.	Address coastal flooding affecting mobility and accessibility in and around a mix of communities across the socioeconomic spectrum.

Subarea Screening

The last section of this appendix contains detailed descriptions of the 21 candidate subareas that were considered for the more detailed subarea vulnerability assessment.

1) South Shore of Long Island

State: New York

Counties: Nassau and Suffolk

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Past Disruption and Damage. Sandy: West Park Avenue in Long Beach (NHS) submerged by > 8 feet of water; most other roadways and LIRR Long Beach Branch also submerged; multiple washouts on Ocean Parkway on Jones Beach Island (~\$40 million in repairs); damage to all moveable bridges; erosion/wave action damage to multiple bridge embankments and causeways; scour-related impacts to multiple bridge structures; electrical power and communication systems destroyed. Irene: Portions of West Park Avenue in Long Beach submerged, portions of Austin Blvd/Long Beach Road submerged, and Island Park LIRR station submerged.

Overlap w/ Similar Studies. Includes Loop Parkway Bascule Bridge and Austin Blvd/Long Beach Road corridor studied in Task 4. New York Rising Community Reconstruction Plans for communities covering most of this subarea; NY Rising proposed study of Rockaway Turnpike Floodgates and Nassau Expressway Upgrades; additional work by New York State Sea Level Rise Task Force; non-transportation resilience efforts including Long Beach Bulkheading Program (bay side), Long Beach Boardwalk/Seawall/Reinforced Dune program (ocean side).

Vulnerable Assets in Subregion. NHS Routes (Nassau Expressway, Peninsula Blvd., Lido Blvd/Park Ave/Beech St, Loop Parkway, Meadowbrook Parkway, Ocean Parkway, Wantagh Parkway, Robert Moses Causeway, Sunrise Highway, William Floyd Parkway), Non-NHS Evacuation Routes (Long Beach Road/Austin Blvd corridor), and passenger rail (LIRR Long Beach Branch, including Long Beach, Island Park, and Oceanside stations; and Montauk Branch).

Notes. All access/evacuation routes exposed and sensitive to flooding. No alternative routes. History of inundation and damage (washouts and erosion) not limited to Sandy.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

2) Bridgeport and Fairfield Coastal Corridor

State: Connecticut

County: Fairfield

Towns: Bridgeport and Fairfield

MPO Planning Area: Greater Bridgeport-Valley MPO

Relative Vulnerability: Medium

Vulnerable Assets in Subregion: I-95, U.S. 1 (NHS), Metro North New Haven Line, including Amtrak NE Corridor rail service.

Past Disruption and Damage: Yellow Mill Channel Bridge damaged in Sandy storm surge; Metro-North New Haven Line disruptions due to power failure and wind-blown debris after Storm Alfred and several recent coastal storm events.

Overlap w/Similar Studies: Includes Yellow Mill Channel Bridge. Numerous CT-funded studies in Bridgeport area; State of CT analysis of Metro-North New Haven Line.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature	●	●

3) Norwalk-Danbury Corridor

State: Connecticut **County:** Fairfield **Towns:** Norwalk and Wilton **MPO Planning Area:** South Western Regional Planning Agency

Relative Vulnerability: High

Vulnerable Assets in Subregion: U.S. 7 (NHS), Metro North Railroad Danbury Branch rail line.

Past Disruption and Damage: Long-term disruption due to power failure and wind-blown debris after Alfred. This corridor has a long history of periodic flooding and damage.

Overlap w/Similar Studies: Overlap with ConnDOT Danbury Branch Electrification Study.

Climate Stressors of Concern

	Current	Future
Sea Level Rise		
Storm Surge		●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

4) Hudson River

State: New York **County:** Putnam, Westchester, the Bronx

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: Metro North Hudson Line (passenger and freight rail), stations, electrical substations, and Harmon Yard/Maintenance Facility, US 9 (NHS Principal Arterial).

Past Disruption and Damage: Many segments of Hudson Line washed out or inundated during Irene and Sandy. Harmon Shop/Yard badly damaged by Sandy storm surge. Periodic storms cause disruption to U.S. 9 and Hudson Line due to wind-blown debris.

Overlap w/Similar Studies: Extensive and detailed vulnerability and risk assessment of Hudson Line underway by MTA Metro-North Railroad.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

5) Westchester County North-South Parkways

State: New York **County:** Westchester

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: Saw Mill River Parkway from Yonkers to Elmsford and in Hawthorne; Bronx River Parkway and Metro-North Harlem Line from Gun Hill Road (The Bronx) to Valhalla; Hutchinson River Parkway from Sanford Blvd to Cross County Parkway.

Past Disruption and Damage: Moderate disruption due to roadway flooding and wind-blown debris during Irene and Sandy; all three corridors are subject to regular flooding due to heavy precipitation.

Overlap w/Similar Studies: Includes Saw Mill River Parkway segment studied in Task 4. Numerous NYSDOT analyses of flood protection and mitigation measures along Westchester parkways.

Climate Stressors of Concern

	Current	Future
Sea Level Rise		
Storm Surge		
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

6) Lower Hackensack River, Secaucus to Hackensack

State: New Jersey

County: Hudson, Essex, and Bergen

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: Rail (Frank Lautenberg Secaucus Junction Station; Amtrak Northeast Corridor; New Jersey Transit; CSX River Line; North Bergen Yard; Little Ferry Yard), NHS (NJ 17, NJ 120, Washington Ave/River Street, I-95/NJ Turnpike Eastern and Western Spurs, NJ 3, US 46, I-80, NJ 4; many NHS Principal Arterials). High vulnerability for some assets

Past Disruption and Damage: Rail lines and yards inundated during Sandy, impacted during Irene; Washington Avenue/River Street corridor has history of flooding

Overlap w/Similar Studies: NJ Meadowlands Commission/MERI analyses and NJDEP study of Hackensack River flood mitigation measures

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

7) Newark/Elizabeth

State: New Jersey

County: Essex and Union

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: Northeast Corridor (passengers) and Chemical Coast (freight) lines, numerous rail yards; Newark Liberty International Airport; Port Newark and Elizabeth; many private seaport terminals; I-95/NJ Turnpike, US 1-9, I-78, NJ 21, many other NHS principal arterials. High vulnerability for some assets.

Past Disruption and Damage: Damage to port equipment (cranes and stackers), flooded wharves, extensive damage and disruption to rail and highway routes serving Port Newark and Elizabeth.

Overlap w/Similar Studies: Overlap with Port Authority (Port Newark-Elizabeth, Newark Liberty Airport, PATH).

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

8) South Shore of Raritan Bay

State: New Jersey

County: Middlesex and Monmouth

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: Garden State Parkway, NJ 35, NJ 36, NJ Transit North Jersey Coast Line, Natural Gas terminal. High vulnerability.

Past Disruption and Damage: Sandy storm surge caused barges and tugboats to dislodge from moorings, causing damage to fenders and piers of NJ 35 and NJ Transit North Jersey Coast Line bridges over Cheesequake Creek; boats came to rest on NJ Transit Cheesequake Bridge; NJ Transit bridge over Raritan River also impacted by barges and large boats.

Overlap w/Similar Studies: NJ Transit Raritan River drawbridge resilience project.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

9) North Jersey Coast

State: New Jersey

County: Monmouth

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: Garden State Parkway, NJ 18, NJ 33, NJ 34, NJ 35, NJ 36, NJ 37, NJ 66, NJ 70, NJ 71, NJ 88, numerous east-west evacuation routes on county system; NJ Transit North Jersey Coast Line.

Past Disruption and Damage: Extensive damage during Sandy (more than \$200 million in ER funding for NJ 35 repairs alone); frequent moderate disruption due to inundation at moon tides and due to surge from moderate coastal storms.

Overlap w/Similar Studies: Includes NJ 37 Mathis Bridge studied in Task 4. Numerous efforts underway to address resilience of North Jersey Coast.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

10) Raritan River – New Brunswick

State: New Jersey

County: Middlesex

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: Medium

Vulnerable Assets in Subregion: NJ 18, River Rd, major crossings (US 1, NJ Turnpike, NE Corridor rail).

Past Disruption and Damage: NJ 18 inundated during Irene and Sandy.

Overlap w/Similar Studies: none known.

Climate Stressors of Concern

	Current	Future
Sea Level Rise		
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

11) Montauk Point

State: New York

County: Suffolk

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: NY 27 and LIRR Montauk Branch.

Past Disruption and Damage: History of damage to NY 27 in Montauk and near Napeague Harbor due to wave action; LIRR Montauk station in FEMA zone AE (flooded during 2010 Hurricane Earl).

Overlap w/Similar Studies: Town of Easthampton Coastal Assessment and Resiliency Plan.

Notes: Highly vulnerable and highly critical for a smaller population, though this population swells during summer.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

12) Pompton Passaic

State: New Jersey

County: Passaic

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: Medium

Vulnerable Assets in Subregion: Rail (Montclair-Boonton Line from Mtn View Wayne to Towaco; freight line), NHS (I-80, US46, NJ 23, etc.).

Past Disruption and Damage: Rail (Montclair-Boonton Line from Mtn View Wayne to Towaco; freight line), NHS (I-80, US46, NJ 23, etc.).

Overlap w/Similar Studies: Forthcoming NJTPA Passaic River Basin study.

Climate Stressors of Concern

	Current	Future
Sea Level Rise		
Storm Surge		
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

13) Lower Manhattan

State: New York

County: New York (Manhattan)

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: NHS (West Side Highway, FDR Drive, many others), MTA subway and bus, ferry terminals.

Past Disruption and Damage: Billions of dollars in damages and weeks-long disruption to transportation across modes. Battery Park Underpass completely flooded from floor to ceiling during Sandy storm surge; West Side Highway and FDR Drive impacted; all New York City Transit subways inundated, including extensive damage to South Ferry Station; salt water damaged electrical systems, signals, and communication systems in East River tunnels; electricity disrupted in all of Lower Manhattan below 34th Street for a week after the storm.

Overlap w/Similar Studies: Includes Hugh L Carey Tunnel. Numerous NYC-led efforts to address resilience of Lower Manhattan, including ongoing Battery Park reconstruction and East Side Coastal Resilience project.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

14) Jamaica Bay (including The Rockaways and Brighton Beach)

State: New York

County: Kings (Brooklyn) and Queens

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: NHS (Belt Parkway, Cross Bay Blvd, Flatbush Ave, Neptune Ave, many others), Rail (LIRR Far Rockaway branch), MTA subway and bus, JFK airport.

Past Disruption and Damage: Sandy Damage: A Train causeway across Jamaica Bay devastated by wave action and storm surge, requiring complete reconstruction; extensive damage to Cross Bay Blvd and Flatbush Avenue. Surface streets in the Rockaways were completely flooded. Wave action and storm surge from moderate coastal storms cause flooding in low-lying areas of the Rockaways.

Overlap w/Similar Studies: CUNY Science And Resilience Institute study of Jamaica Bay resilience; also NYC, Port Authority, and MTA activities to address resilience of JFK Airport, New York City Transit, and other transportation facilities surrounding Jamaica Bay.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

15) Outer East River

State: New York

County: Bronx, Kings (Brooklyn) and Queens

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: Bruckner Expressway (I-278) and Bruckner Blvd, eastern Cross Bronx Expressway and Throgs Neck Bridge (I-295), Bronx-Whitestone Bridge and Whitestone Expressway (I-678), Grand Central Parkway; Northern Blvd, Astoria Blvd, and numerous other NHS Principal Arterials; Amtrak Northeast Corridor Hells Gate line; LaGuardia Airport; Hunts Point Market.

Past Disruption and Damage: Sandy damage: LaGuardia Airport runways, taxiways, and aprons flooded from Flushing Bay to terminals; damage from wave action to south approach to Whitestone Bridge; Bruckner Blvd flooded in Port Morris; damage to Oak Point rail yard.

Overlap w/Similar Studies: Overlap with NYC, Port Authority activities.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

16) Lower Hutchinson River

State: New York

County: Bronx

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: US 1 Boston Road bascule bridge, Hutchinson River Parkway bascule bridge, Amtrak Northeast Corridor bascule bridge, Pelham Parkway bascule bridge.

Past Disruption and Damage: Electrical and mechanical equipment on bascule bridges serving Hutchinson River Parkway, Amtrak Northeast Corridor, and Pelham Parkway all damaged due to Irene-related flooding.

Overlap w/Similar Studies: None known.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

17) Kearny and South Secaucus

State: New Jersey

County: Hudson, Bergen and Essex

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: NJ 7, NJ Turnpike Eastern Spur, US 1-9; NJ Transit Meadowlands Maintenance and Storage Facility; CSX Kearny Intermodal Facility; NS Croxton Intermodal Terminal; Secaucus station; Portal Bridge; NE Corridor; Hoboken lines; many freight rail lines and spurs.

Past Disruption and Damage: Extreme damage to NJ Transit Meadowlands maintenance and storage facility, plus operations center; inundation of NJ 7 and Truck US 1/9; inundation of CSX intermodal Croxton Intermodal Terminal; damage to Portal Bridge.

Overlap w/Similar Studies: Includes stretch of NJ 7 studied in Task 4. NJ Transit Grid project to improve electrical system resilience; Delco Yard project to increase rail car storage outside vulnerable areas; Portal Bridge replacement project.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

18) Arthur Kill (NJ)

State: New Jersey

County: Union

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: NJ Turnpike (including interchanges 13 and 12, plus Grover Cleveland and Thomas Edison Service Areas), I-278 (Goethals Bridge), Outerbridge Crossing; Chemical Coast rail line; numerous private port facilities; Bayway oil refinery.

Past Disruption and Damage: Storm surge caused damage to Bayway Oil Refinery, causing disruption to regional supply of gasoline for weeks following Sandy. Numerous private marine terminals and oil/chemical storage facilities damaged. Thomas Edison Service Plaza on NJ Turnpike damaged.

Overlap w/Similar Studies: New Jersey Department of Environmental Protection study of Arthur Kill flood mitigation.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action	●	●
Precip.-based Flooding	●	●
Temperature		●

19) Newtown Creek

State: New York

County: Kings (Brooklyn), Queens

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: High

Vulnerable Assets in Subregion: Numerous movable bridges.

Past Disruption and Damage: Metropolitan Avenue Bridge: \$9.3 million in repairs due to Sandy damage.

Overlap w/Similar Studies: Various NYC-led resilience efforts underway.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

20) Gowanus Canal

State: New York

County: Kings (Brooklyn)

MPO Planning Area: New York Metropolitan Transportation Council

Relative Vulnerability: Medium

Vulnerable Assets in Subregion: Numerous movable bridges.

Past Disruption and Damage: Union Street Bridge and Third Street Bridge: \$8 million in damage due to Sandy.

Overlap w/Similar Studies: Various NYC-led resilience efforts underway.

Climate Stressors of Concern

	Current	Future
Sea Level Rise	●	●
Storm Surge	●	●
Wave Action		
Precip.-based Flooding	●	●
Temperature		●

21) Hoboken and Jersey City

State: New Jersey

County: Hudson

MPO Planning Area: North Jersey Transportation Planning Authority

Relative Vulnerability: High

Vulnerable Assets in Subregion: NJ Transit Hoboken Terminal and ferry terminal; PATH; Hudson-Bergen Light Rail; Holland Tunnel and approaches; north-south routes

Past Disruption and Damage: Extensive and long-lasting disruption to Hoboken Terminal; damage to Holland Tunnel and approaches; inundation of PATH that led to long-term service disruption on Newark-WTC route.

Overlap w/Similar Studies: New Jersey Department of Environmental Protection Study of Hudson River flood mitigation; Rebuild by Design competition produced strategies to protect entire area from future inundation; not limited to transportation. NJ Transit undertaking resilience projects in area of Hoboken Terminal and Long Slip. Port Authority of New York & New Jersey efforts to build resilience into PATH system, including electrical system upgrades and flood protection measures.

D

Subarea Assessments of Multimodal Corridors and Networks: New York

D.1 New York: Long Island South Shore

Introduction

The regional transportation system vulnerability assessment conducted as part of the Federal Highway Administration's Post-Hurricane Sandy Transportation Resilience Study (Post-Sandy Study) identified 21 potential subarea candidates for a “meso-scope” assessment of vulnerability and risk as an interim step between regional and asset-specific vulnerability and risk assessments. Stakeholders representing federal, state, regional, and local transportation agencies narrowed down the list to three subareas:

- Communities on barrier islands and lining interior bays along the South Shore of Long Island;
- The communities on the southern edge of Raritan Bay in New Jersey; and
- The Norwalk-Danbury corridor (U.S. 7 and Metro-North Railroad's Danbury Branch) along the Norwalk River in Connecticut.

The regional vulnerability assessment identified communities on barrier islands and lining interior bays along the South Shore of Long Island as a particularly vulnerable subarea of the regional transportation network. This subarea analysis focuses on the transportation system on the South Shore of Long Island that has long been affected by coastal storms.

This subarea assessment seeks to determine which portions of the transportation network in the South Shore of Long Island warrant a closer examination over the next 50 years due to the increased risks of damage and disruption associated with climate change, and what adaptation strategies could be appropriate given the magnitude of damage and disruption that could be expected before and after these strategies are implemented.

The scope of analysis of the subarea on the South Shore of Long Island was refined to focus on north-south connections between Long Island South Shore barrier islands and the mainland of Long Island. As shown in Figure D.1, the major regional transportation assets examined include:

- Long Beach Road/Austin Boulevard Corridor between Long Beach Island and NY 27;
- Loop Parkway between Lido Beach and the Meadowbrook Parkway;
- Meadowbrook Parkway between Ocean Parkway and NY 27;
- Wantagh Parkway between Ocean Parkway and NY 27;
- Robert Moses Causeway between Fire Island and NY 27; and
- The Long Island Rail Road Long Beach Branch between Long Beach and Lynbrook; including stations at Long Beach, Island Park, Oceanside, East Rockaway, Centre Avenue, and Lynbrook; the Long Beach rail yard; and four power substations.

The transportation system in the South Shore of Long Island has long been affected by year-round coastal storms. Hurricane Sandy caused widespread devastation, and impacts continue to this day as communities continue to rebuild and add resilience to infrastructure and community services. Before and after Sandy, coastal storms (including summer tropical systems and winter Nor'easters) have caused moderate to major coastal flooding in the same communities that were impacted by Sandy, damaging transportation assets and causing closures that disrupted the movement of people and freight.

This assessment seeks to determine which portions of the north-south evacuation routes warrant a closer examination over the next 50 years due to the increased risks of damage and disruption associated with climate change. The research conducted as part of this assessment is intended to contribute to (rather than supersede or substitute for) a broader regional conversation about vulnerability and risk. Although this assessment presents a representative list of transportation-specific adaptation strategies that could be appropriate given the magnitude of damage and disruption that could be experienced through 2050 and 2100, it is entirely possible that regional adaptation and mitigation measures being studied by others in parallel with this effort could reduce or eliminate the vulnerabilities and risks identified in the sections that follow...This subarea assessment generally follows the vulnerability and risk assessment process developed for the Post-Sandy study. See Appendix B - Engineering Informed Adaptation Assessment Process This assessment begins with a summary of climate impacts. The exposure analysis, sensitivity analysis, and adaptive capacity sections of the vulnerability assessment analyze how these climate impacts could affect the transportation assets examined. The risk assessment includes information on likelihood of exposure and consequences associated with exposure to climate stressors. Then, several sets of potential adaptation options are presented for areas with relatively high risks.

Additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through this assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.



Figure D.1. Map. Study area: Long Island south shore.

(Source: ESRI, HERE, DeLorme, US Geological Survey, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, OpenStreetMap contributors, GIS User Community.)

Source for Bridge Data: Federal Highway Administration, National Bridge Inventory.)

At the west end of the study area, two additional transportation corridors running through are undergoing thorough resilience and adaptation efforts already. These two corridors are not included in the subarea analysis for this project:

- Nassau Expressway/Peninsula Boulevard corridor in Nassau County between Long Beach Island and NY 27; and
- The Long Island Rail Road Far Rockaway Branch between Far Rockaway and Valley Stream; includes the Far Rockaway rail yard; Far Rockaway, Inwood, Lawrence, Cedarhurst, Woodmere, Hewlett, Gibson, and Valley Stream Stations.

Finally, in the immediate aftermath of Hurricane Sandy, the reconstruction of Ocean Parkway and the dunes protecting Ocean Parkway along the length of Jones Beach Island resulted in improvements that were designed to withstand a high impact coastal storm event. Thus, Ocean Parkway also is not included in this analysis.

This subarea assessment generally follows the vulnerability and risk assessment process developed for the Post-Sandy study. See Appendix B - Engineering Informed Adaptation Assessment Process This assessment begins with a summary of climate impacts. The exposure analysis, sensitivity analysis, and adaptive capacity sections of the vulnerability assessment analyze how these climate impacts could affect the transportation assets examined. The risk assessment includes information on likelihood of exposure and consequences associated with exposure to climate stressors. Then, several sets of potential adaptation options are presented for areas with relatively high risks. Finally, examples of hypothetical benefit-cost analyses for adaptation options are discussed.

Sensitivity Screening and Climate Impacts

Hurricane Sandy in October 2012 caused widespread disruption and damage to the Long Island Subarea. Before and after Sandy, coastal storms (including summer tropical systems and winter Nor'easters) have caused flooding in some of the same communities that were impacted by Sandy. This analysis focuses primarily on sea level rise and storm surge impacts on transportation assets in low lying coastal areas, but other climate stressors are shown in Table D.2 for information purposes.

Table D.1. Transportation system sensitivity to climate stressors in the Long Island subarea.

Climate Stressor	Impacts	Relevant Transportation Facilities and Facility Components
Storm surge, magnified by sea level rise over time	Inundation and overtopping	<ul style="list-style-type: none"> • Low-lying segments of highways and rail track. • Stations and park and ride lots. • Maintenance, storage, and other facilities. • Electric power infrastructure.
	Long-term corrosion and reduced useful life due to salt water intrusion	<ul style="list-style-type: none"> • Electrical and mechanical equipment on moveable bridges. • Signals, communications equipment, and power systems for rail. • Power supply and controllers for roadway signals and lighting. • Intelligent Transportation Systems infrastructure.
	Bridge scour due to velocity of water in inlets/outlets	<ul style="list-style-type: none"> • Bridges, particularly those over channels directly exposed to storm surge entering inlets from the Atlantic Ocean.
	Transport of marine vessels, causing damage to and blockage of bridges, rail tracks, and roadways	<ul style="list-style-type: none"> • Bridges, bridge approaches, and roads and rail lines in low-lying areas adjacent to marinas and navigable waterways.
Sea level rise, absent storm surge	Inundation and overtopping during high tides; reduced effectiveness of drainage systems during heavy precipitation events	<ul style="list-style-type: none"> • Roadways, rail lines, and related assets in low-lying and/or poorly-drained areas. • Reduced water infiltration capacity for stormwater management facilities.
Wave action	Erosion of bridge approaches and causeway embankments	<ul style="list-style-type: none"> • Sections of roadway and rail on causeways in open waters
Wind	Road and rail closures due to wind-blown debris Wind damage	<ul style="list-style-type: none"> • Roads and rail lines; bridges, culverts, and drainage structures. • Signs and buildings (particularly roofs and other components sensitive to wind).
Temperature	Expansion of metal movable bridge spans and rail track during extreme heat events	<ul style="list-style-type: none"> • Rail lines, including tracks, moveable bridges, and electrical systems. • Moveable bridges on roadways.

Current and Projected Climate Scenarios

Coastal Flooding due to Sea Level Rise and Storm Surge

The transportation assets that are the focus of this subarea assessment serve as vital emergency evacuation and recovery routes before, during, and after major coastal storms. Therefore, the study team used the higher end of the ranges of published projections of sea level rise, still water elevations, and wave heights for the exposure analysis. For county and local roads and less critical transportation assets, it may be appropriate to use mid-range or lower estimates, based on the risk tolerance of the agency conducting the analysis.

The project team obtained sea level rise projections and future floodplain GIS layers from the New York State Energy Research and Development Authority (NYSERDA). The analysis used projections from NYSEDA’s 2014 update to the report “Responding to Climate Change in New York State” (commonly known as “ClimAID”). Consistent with NYSDOT’s low risk-tolerance approach to this assessment, high-end (90th percentile) sea level rise projections are examined for mid- and end-of-century time horizons. These two scenarios are summarized in Table D.2.

Future floodplains were obtained from the NYSEDA study, Analysis of Future Floodplains in New York State.² That study developed 10-, 50-, 100-, and 500-year future coastal floodplains for a number of SLR elevations. This analysis used the two sets of floodplains that corresponded the closest to the 90th percentile SLR elevations in the ClimAID report. These included 24 inch SLR (roughly corresponding with the 2050s 90th percentile SLR) and 72 inch SLR (roughly corresponding with the 2100s 90th percentile SLR) for 10-, 50-, 100-, and 500-year coastal floodplains.

Table D.2. 90th percentile sea level rise scenarios.

Year	Project Sea Level Rise
2050	2.5 feet
2100	6.3 feet

Source: New York State Energy Research and Development Authority, 2014: Update to the report “Responding to Climate Change in New York State.”

Table D.3. Projected mean average changes in baseline temperature of 54.6 °F.

Year	Low Estimate (10 th Percentile)	Middle Range (25 th to 75 th Percentile)	High Estimate (90 th Percentile)
2050	+ 3.1 °F	+ 4.1 to 5.7 °F	+ 6.6 °F
2100	+ 4.2 °F	+ 5.8 to 10.4 °F	+ 12.1 °F

Source: New York State Energy Research and Development Authority, 2014: Update to the report “Responding to Climate Change in New York State.”

² New York State Energy Research and Development Authority, 2016. Report 16-18: “Analysis of Future Flood Plains for New York State.” Available for download at <https://www.nyseda.ny.gov/-/media/Files/Publications/Research/Environmental/16-18-Analysis-Future-Floodplains-NYS.pdf>.

Temperature

The 2014 ClimAID report projected that average temperatures for the New York City region could increase from 3.1 to 6.6 degrees Fahrenheit in 2050 and between 4.2 and 12.1 degrees Fahrenheit in 2100 (see Table D.3). Today there are 18 days with temperatures above 90 degrees Fahrenheit; in 2050 there could be between 32 and 57 days per year above 90 degrees (see Table D.4).

Table D.4. Changes in extreme events: 2050.

	Baseline	Low Estimate (10 th Percentile)	Middle Range (25 th to 75 th Percentile)	High Estimate (90 th Percentile)
Days over 90 °F	18 days	32 days	39 to 52 days	57 days
# of heat waves	2	4	5 to 7	7
Duration of Heat Waves	4 days	5 days	5 to 6 days	6 days
Days below 32 °F	71 days	37 days	42 to 48 days	52 days
Days over 1" rainfall	13 days	13 days	14 to 16 days	17 days
Days over 2" rainfall	3 days	3 days	4 to 4 days	5 days

Source: New York State Energy Research and Development Authority, 2014: Update to the report "Responding to Climate Change in New York State".

Extreme Events

Table D.5 shows the projected changes in extreme weather events in 2050. The "baseline" column shows the average annual occurrence of each event today. The number of days with temperatures above 90 degrees Fahrenheit is expected to increase, while the number of freeze-thaw cycles is expected to decrease significantly in the study area.

Vulnerability Assessment: Exposure Analysis

The exposure analysis in this section focuses on storm surge, taking into account the amplification of storm surge impacts due to sea level rise over time; sea level rise absent storm surge, and wave action. **It is important to note that the exposure analysis should be interpreted as a “no-build” scenario: it does not take into account efforts currently underway to improve resilience of major portions of this study area that could change an area’s exposure to a particular flood event.** Also note that the exposure to wind and temperature is assumed to be uniform across the study area.

Exposure Analysis: Storm Surge

For highway and rail, NHS and LIRR GIS layers were overlaid onto the floodplain layers to identify the exposed assets.³

For bridges, the attribute information in the National Bridge Inventory (NBI) was used to assess exposure.⁴ NBI Item 71 – Waterway Adequacy – identifies overtopping risks of bridges/culverts. Tables D.6 and D.7 summarize the coding schema for waterway adequacy and overtopping risk. Waterway adequacy codes can have different meanings when they are associated with different NHS functional classes; Table D.5 shows these associations.

The right-hand columns of Table D.6 list the NBI overtopping descriptions for each waterway adequacy category (a through j). The project team regrouped the codes into 6 broad categories – C0, C1, C2, C3, C4, and C5. The left-hand

Table D.5. NBI Item 71: Water adequacy.

NBI Item 71 Code	Principal Arterials, Interstates, Freeways, or Expressways	Other Principal and Minor Arterials; Major Collectors	Minor Collectors; Local Roads
N	a	a	a
9	b	b	b
8	c	c	c
7			d
6	d	d	e
5		e	f
4	e	f	g
3	f	g	
2	g, h, i	h, i	i
1			
0	j	j	j

Source: Federal Highway Administration, National Bridge Inventory, Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges, 1995. <https://www.fhwa.dot.gov/bridge/mtguide.pdf>.

Note: See Table D.6 for descriptions corresponding to each letter from a to j.

³ In ArcGIS, the floodplains of Nassau and Suffolk Counties with the same attributes in terms of coastal flood return periods and SLR projections were merged, resulting in 8 floodplain layers. Then, the Intersect tool was used to identify the assets or stretches of assets that are exposed.

⁴ Federal Highway Administration, National Bridge Inventory. Data available for download at <https://www.fhwa.dot.gov/bridge/nbi.cfm>.

column of Table D.6 shows how these broader categories correspond with the waterway adequacy categories. Figures D.2, D.3, and D.4 show coastal flood plains for current, 2050s and 2100s timeframes.

Table D.6. NBI Codes for Overtopping risk.

Overtopping Risk Code	NBI Code Description
C5	a Bridge not over a waterway.
	b Bridge deck and roadway approaches above flood water elevation (high water), chance of overtopping is remote .
C4	c Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.
	d Slight chance of overtopping bridge deck and roadway approaches.
C3	e Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.
C2	f Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.
C1	g Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.
	h Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.
	i Occasional or frequent overtopping of bridge deck and roadway approaches with severe traffic delays.
C0	j Bridge closed.

The definitions for the frequencies of bridge overtopping as used by the NBI Coding Guide are:

- **Remote** – greater than 100 years
- **Slight** – 11 to 100 years
- **Occasional** – 3 to 10 years
- **Frequent** – less than 3 years

The definitions for the levels of impacts of bridge overtopping as used by the NBI Coding Guide are:

- **Insignificant** – Minor inconvenience. Highway passable in a matter of hours.
- **Significant** – Traffic delays of up to several days.
- **Severe** – Long term delays to traffic with resulting hardship.

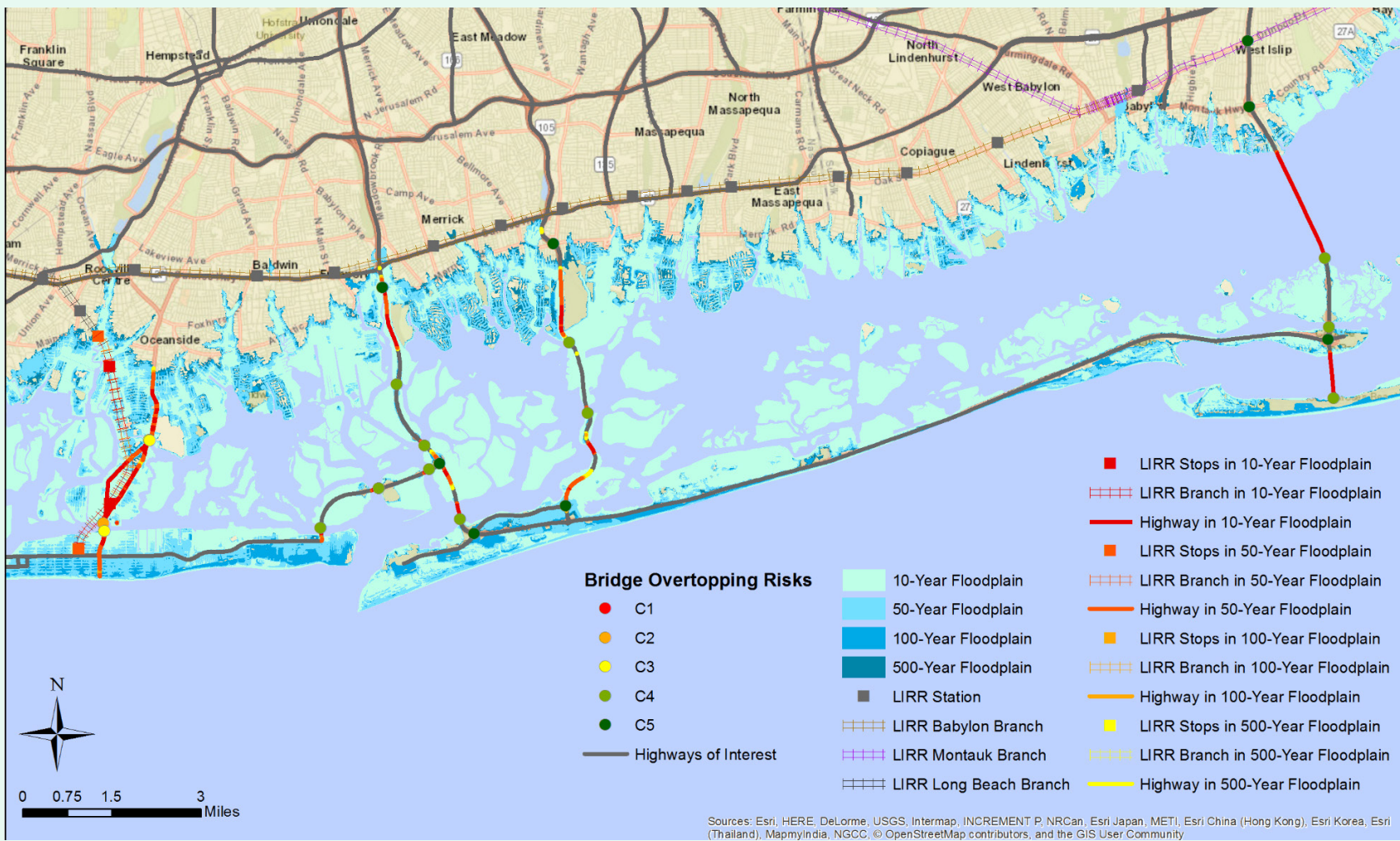


Figure D.2. Map. Coastal flood plains: current.

(Source: New York State Energy Research and Development Authority, 2016. Report 16-18: "Analysis of Future Flood Plains for New York State.")

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place on barrier islands and inland communities in the study area.

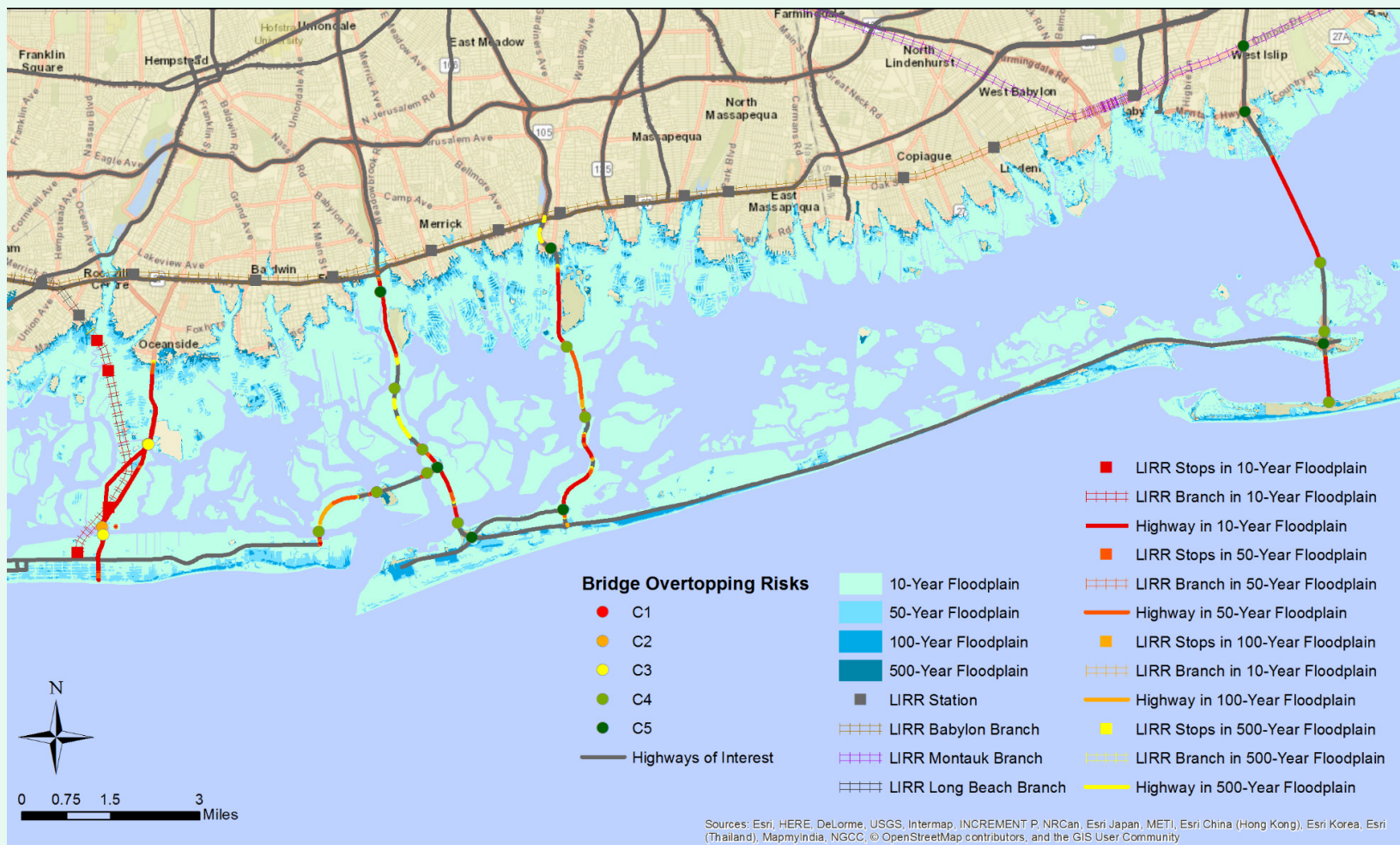


Figure D.3. Map. Coastal flood plains—2050s sea level rise (24 inches; ~90th percentile).

(Source: New York State Energy Research and Development Authority, 2016. Report 16-18: “Analysis of Future Flood Plains for New York State.”)

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place on barrier islands and inland communities in the study area.

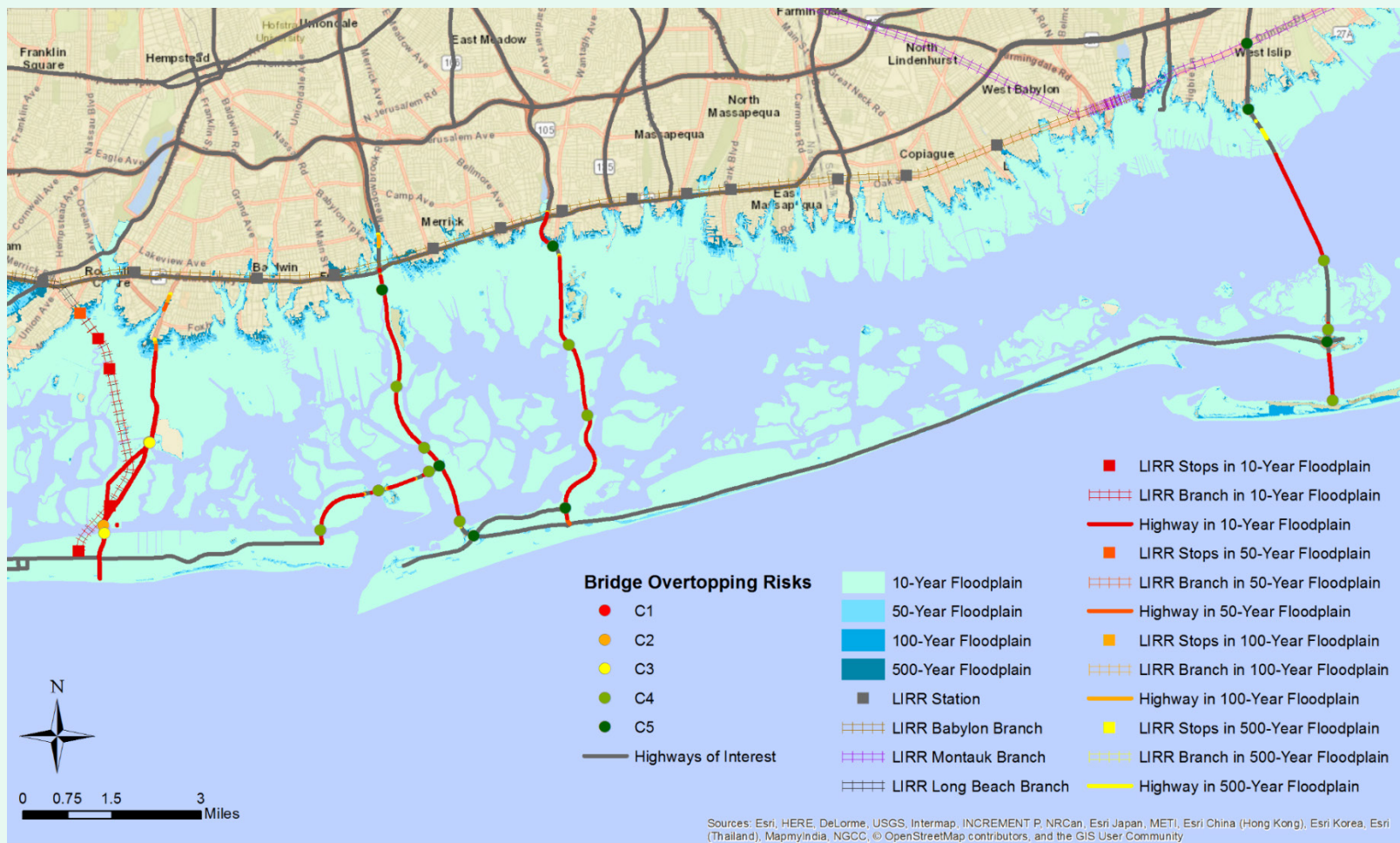


Figure D.4. Map. Coastal flood plains – 2100s sea level rise (72 inches; ~90th percentile).

(Source: New York State Energy Research and Development Authority, 2016. Report 16-18: "Analysis of Future Flood Plains for New York State.")

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place on barrier islands and inland communities in the study area.

Past Damage and Disruption

During Hurricane Sandy, west Park Avenue in Long Beach (a National Highway System facility) was submerged in more than 8 feet of water; most other roadways and LIRR Long Beach Branch also were submerged. There were multiple washouts on Ocean Parkway on Jones Beach Island where wave action destroyed dunes adjacent to the Parkway.

All of the moveable bridges in the area sustained damage to electrical components and failed in the closed position, blocking marine traffic. Wave action in the bays and waterways between the barrier islands and the mainland damaged multiple bridge embankments and causeway embankments along the Loop, Meadowbrook, and Wantagh parkways. The advancing and retreating water from Sandy's storm surge led to scour-related impacts to multiple bridge structures.

Throughout the area, the storm surge inundated electrical power and communication systems, causing almost complete loss of power for weeks after the storm. Power substations and signal systems on the Long Island Rail Road Long Beach Branch were destroyed, and stations along the branch were completely submerged.

Portions of the study area also were impacted by the storm surge from Hurricane Irene. Portions of west Park Avenue in Long Beach were submerged, as were low-lying portions of the Austin Blvd/Long Beach Road corridor. The Island Park Long Island Rail Road station also was submerged.

Portions of the study area experience blue sky flooding at peak high tides, with water ponding on local roadways. Moderate to heavy rainfall events that coincide with high tide produce flooding throughout the study area because the outfalls for storm water drainage systems can be submerged by high tides. This problem is particularly acute along Long Beach Road and Austin Boulevard in Island Park and on local roads.

Exposure Analysis: Sea Level Rise

The impacts of sea level rise absent storm surge can be observed at extreme high tide events, where water pools in low-lying areas and emerges from manhole covers and catch basins due to backed up storm sewers. When heavy rainfalls coincide with high tides, the outlet points of drainage systems can be below the water line, reducing the capacity of the drainage system and causing localized flooding. In addition, where roadways cross low-lying areas on embankments, the embankments can act as dikes that impede drainage from flood plains, particularly when culverts and drainage pipes through the embankments are undersized.

As reported by Nassau County, partial flooding occurs on the segment of Long Beach Road north of the bridge over Hudson Channel during storms with 3 to 5 inches of precipitation, particularly those that coincide with high tide. Nor'easters that produce a combination of high northeasterly winds and heavy rainfall commonly cause flooding. The inadequacy of the existing drainage system was identified as a contributor to the flooding. Similar flooding occurs on Long Beach Road and Austin Boulevard in Island Park.

Exposure Analysis: Wave Action

FEMA Flood Insurance Rate Maps indicate that large portions of the corridors that are the focus of this subarea analysis are in or are immediately adjacent to areas exposed to moderate wave action. Portions of the Long Beach Road/Austin Boulevard corridor are exposed to moderate wave action today during storm events with more than a 1 percent chance of occurring in a given year.

While many of the Parkway roadway surfaces are above the level of a 100-year flood elevation today, the causeway embankments supporting the roadways are vulnerable to wave action during moderate coastal storms. If sea levels rise as projected, wave action will become a severe problem, potentially compromising the integrity of the causeways or requiring extreme measure to harden them, including constructing sea walls. Bridge abutments are exposed to wave action as well, and as sea level rises, there is increasing potential for exposure of the underside of bridges to wave action, which could result in displacement of the bridge deck or other impacts to bridges' structural integrities.

Exposure Analysis: Temperature and Wind

Both temperature and wind are assumed to impact the study area uniformly. See the sensitivity analyses in the next section for a more detailed assessment of the potential impacts associated with these climate stressors.

Vulnerability Assessment: Sensitivity Analysis

The sensitivity of an asset or component to a given climate stressor depends on three variables:

- Intensity of each event;
- Duration per occurrence; and
- Frequency of occurrence.

The time between two successive events also can affect how severe the impacts of the second event will be. A moderately intense rainfall event that saturates soils can set up conditions where a less severe rainfall event can lead to more severe flooding than would be expected from an isolated storm. The inability of the soil to absorb water leads to higher runoff that would be predicted if a storm were analyzed as an isolated event.

The exposure analysis in the previous section showed representative outcomes associated with a 100-year storm in 2016, 2050, and 2100. Most of the assets included in the study area are sensitive to inundation from either coastal flooding due to storm surge, inland precipitation-based flooding, or nuisance flooding that is exacerbated over time by sea level rise. Roads and rail lines must be closed to traffic when they flood, and power substations and other electrical components

can fail when exposed to any water. Salt water exposure can have immediate impacts and also longer-term impacts because the corrosive properties of salt water accelerates deterioration of cement in concrete, reinforcing bars in concrete road beds and structures, metal wires in electrical systems (including those powering lights and traffic signals), pipes and drainage system elements, and other metal components, reducing their remaining useful lives.

There is not a complete record of the extent or cost of damage in past events, and the duration of inundation in past events (and thus the ability to forecast duration of inundation in future events) is also not well-understood. Sandy inflicted massive damages on many communities in or near the study area. Long Beach Island experienced roughly \$250 million in damage from Sandy.⁵ Jones Beach Island also suffered significant damages.⁶

The sensitivity screening matrix in Table C.1 shows several other climate variables to consider. Extreme heat can warp steel rail tracks, with speed restrictions imposed on curved sections of track when temperatures reach 95 degrees and on straight sections of track when temperatures reach 105 degrees. Heat also can cause moveable rail and roadway bridges with metal components to get stuck closed, and they can fail to reseal themselves in the proper position when closing if the metal expands on hot days, particularly during extended heat waves.

For both inundation and temperature, the sensitivity analysis in this section is binary: either an asset is “wet” or it is not, and either the temperature exceeds a threshold or it does not.

Vulnerability Assessment: Adaptive Capacity and Consequence Analysis

Adaptive capacity is a measure of how well a transportation system can accommodate a closure of one segment of rail line or roadway. This section summarizes the adaptive capacity of the transportation network in the study area. It also briefly addresses consequences associated with disrupting or damaging the network.

Four evacuation routes serve densely-populated Long Beach Island:

- The **Atlantic Beach Bridge and the Nassau Expressway/Peninsula Boulevard corridor** on the west end. The Nassau Expressway corridor provides the most direct access to the regional highway network for commercial vehicles, but it is also the most vulnerable to flooding due to its elevation, its proximity to Jamaica Bay, and fact that it crosses two major drainage channels (Motts Creek and Valley Stream) that channel rainwater from a broad area of the “Five Towns” of the south shore of Long Island into Jamaica Bay.

⁵ <http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487486/fact-sheet-jones-inlet-to-east-rockaway-inlet-long-beach/>.

⁶ <http://newyork.cbslocal.com/2012/11/15/jones-beach-in-ruins-but-parks-officials-vow-to-have-it-ready-for-memorial-day/>.

- **Long Beach Road/Austin Boulevard** at the center of the island. Long Beach Road/Austin Boulevard and Peninsula Boulevard are designated evacuation routes that connect Long Beach Island to emergency shelters and other vital government services provided by the Town of Hempstead, Nassau County, and New York State that are located in offices in Hempstead and Mineola.
- The **Long Island Rail Road Long Beach Branch** via the Wreck Lead Bridge. There is only one rail line with a single track crossing the Long Island Rail Road's Wreck Lead Bridge.
- **Loop Parkway and Meadowbrook Parkway** on the east end. While the Loop Parkway and Meadowbrook Parkway are higher-capacity, controlled access facilities, trucks and buses are generally prohibited from these routes, and low bridge clearances limit this route's use by some emergency vehicles necessary for response and recovery activities during and after a storm.

Jones Beach Island in Nassau County is home to Jones Beach State Park, one of the state's premier recreation areas and a major tourist destination. The park is important to the quality of life of Long Island residents and to the region's tourism economy. The park's beaches, hiking and biking trails, and the Nikon Theater (a major concert venue) together draw six million visitors per year. During the annual Bethpage Air Show on Memorial Day weekend alone, the island has attracted more than two hundred thousand visitors.

In Suffolk County, Jones Beach Island has a mix of municipal parks and residential areas. There are about 200 full-time residents and many more part-year residents or renters in the summer months.

Three routes connect Jones Beach Island to the mainland of Long Island:

- The **Meadowbrook Parkway**, about 2.5 miles from the west end. The portion of the Meadowbrook Parkway north of its junction with the Loop Parkway serves as a critical evacuation route for Long Beach Island and thus is strategically important from an evacuation and life safety perspective.
- The **Wantagh Parkway**, about 2 miles east of the Meadowbrook. Although the Wantagh Parkway appears somewhat redundant with the Robert Moses Causeway and Meadowbrook Parkway, any event that would cause closure of the Wantagh also would likely flood Ocean Parkway and cut off access to the alternative evacuation routes

Table D.7. Traffic volumes for studied corridors.

Corridor	AADT at Highest Volume Segment in Study Area	Highest Volume Segment	
		From	To
NY 878 – Nassau Expressway ^a	22,493	Seagirt Blvd. Bridge	Toll Booth Atlantic Beach Bridge
Long Beach Rd./Austin Blvd.	40,240	--	Daly Blvd.
Loop Pkwy.	29,283	Lido Blvd.	Meadowbrook Pkwy.
Meadowbrook Pkwy.	36,111	Village of Freeport	Merrick Dr.
Wantagh Pkwy.	10,446	--	Merrick Dr.
Robert Moses Causeway	15,394	Ocean Parkway	--

- The **Robert Moses Causeway**, on the east end of the island about 13 miles east of the Wantagh Parkway. Robert Moses Causeway was built to comparatively higher elevations and is not projected to be exposed to sea level rise or storm surge through the end of the century.

^a North-south corridor outside study area shown for reference.

Table D.7 shows traffic volumes for the north-south corridors in the study area, according to NYSDOT 2014 Highway Inventory data.⁷ The Long Beach Road/Austin Boulevard had the highest volume among the corridors and is probably the highest consequence corridor. While NY-878 and the Loop Parkway could provide some adaptive capacity, they only do so in the event they and their connecting roadway along Long Beach Island (e.g., Lido Boulevard) remain unflooded.

The Jones Beach Island corridors carry fewer people. While the Meadowbrook Parkway volume is relatively high, much of this volume comes from Long Beach Island via the Loop Parkway. Closure of the Meadowbrook Parkway results in greater consequences given that Loop Parkway feeds into it. Robert Moses Causeway is more isolated from the Meadowbrook and Wantagh Parkways; a coastal storm event flooding one of the corridors could easily impact Ocean Parkway, the road that connects them, at some point. Its volume is lower than Meadowbrook Parkway. In terms of traffic volume, the relative consequence of the examined corridors, from highest to lowest, is estimated to be: (1) Long Beach Road/Austin Boulevard, (2) Meadowbrook Parkway, (3) Loop Parkway, (4) Robert Moses Causeway, and (5) Wantagh Parkway.

LIRR Long Beach Branch daily ridership was just over 20,000 trips for both directions in 2012.⁸ Station-specific ridership was only available for earlier years. Table D.8 shows weekday station passenger counts for both directions in 2006. Long Beach had the highest passenger count and a markedly higher count than any other station in study area (East Rockaway, Oceanside, Island Park). The Long Beach yard is critical to operations of the entire branch, and thus the relative consequences of a disruption at any point are similar.

When railroad service is disrupted, buses can usually provide substitute service. However, the levels of service and travel times can be substantially different, and this substitution can disproportionately impact transit-dependent populations with lower incomes.

Table D.8. LIRR Long Beach branch 24-hour passenger counts by station (2006 data).

Station	Bi-directional Weekday Passenger Count
Lynbrook	5,476
Centre Ave.	958
East Rockaway	1,401
Oceanside	2,786
Island Park	2,220
Long Beach	8,721

Source: Long Island Rail Road, 2012 Ridership Book. (Most recent available).

⁷ <https://www.dot.ny.gov/divisions/engineering/technical-services/highway-data-services/inventory-listing>.

⁸ Long Island Rail Road, 2012 Ridership Book.

Risk Assessment

Risk is a function of likelihood and consequence. Overall, climate risks are high in Long Island's South Shore area. In the current timeframe, the corridors already face sizeable risks, which will grow with future sea level rise.

Given available information about past damage and disruption, exposure, and climate impacts, the likelihood of experiencing flooding is relatively high in the corridors studied. The majority of the examined portions of the Long Beach Branch and Long Beach Road/Austin Boulevard corridor has a greater than 10 percent annual chance of flooding in the current timeframe. Considerable stretches of Meadowbrook Parkway, and Wantagh Parkway have a greater than 10 percent chance of annual flooding in the current timeframe, with the former two experiencing more inundation from Sandy. The Loop Parkway bridges also have a greater than 10 percent annual chance of flooding in the current timeframe. With 24 inches of sea level rise by 2050, likelihoods would increase, and almost all of the Wantagh Parkway would experience a greater than 10 percent annual chance of flooding. With an additional 48 inches of sea level rise by the 2100s (or 72 inches more than today), almost all of the examined sections of the corridors, except for Robert Moses Causeway, would have a greater than 10 percent annual chance of flooding. The areas served by these roadways would also be inundated absent an area-wide adaptation effort such as construction of seawalls, levees, and pumps.

The Long Beach Road/Austin Boulevard corridor is estimated to be at the highest risk of the corridors examined, given that it has the highest likelihood of flooding and the highest consequence when inundation does occur. The Long Beach Branch is also at high risk due to its sensitivity to flooding; the substations and electrical, signal, and communications equipment are highly likely to be inundated, and past storms have shown they can incur significant damages as a result.

The Meadowbrook Parkway is also one of the higher risk corridors examined. With its roadway volume, Loop Parkway is the corridor with the second-highest level of risk, followed by Robert Moses Causeway, and then Wantagh Parkway.

Table D.9 summarizes the risk assessment for the corridors in the study area. Following the table is a summary of the types of adaptation and resilience efforts underway in and near the study area that could reduce the likelihood and/or consequences of exposure to the climate stressors identified in this assessment.

Table D.9. Summary of climate vulnerability and risk assessment (no-build scenario).

Assets of Interest	Current Year	2050s	2100s
Long Beach Rd/ Austin Blvd Corridor between Long Beach Island and NY 27	<p>Large portions of the corridor are in the 10-year floodplain.</p> <p>Ponding and nuisance flooding occurs during extreme high tide events and during minor coastal storms and Nor'Easters because water levels block drainage outfalls and cause sea water to back up in storm sewers.</p>	<p>Most segments of the corridor south of Atlantic Avenue in Oceanside are projected to be exposed to coastal floods during minor storms.</p> <p>Nuisance flooding is projected to become more common, causing longer periods of ponding around drains and coverage of travel lanes, short-term road closures at extreme high tides, and longer-term road closures during coastal storms.</p>	<p>All segments south of Atlantic Avenue are projected to be inundated at normal high tides.</p> <p>Some portions between Atlantic Avenue and NY 27 exposed to 50-, 100-, or 500-year floods.</p>
Loop Parkway between Lido Beach and the Meadowbrook Parkway	<p>Scour of bridge foundations during storm surge, particularly Long Creek Bridge.</p> <p>Damage to causeway embankments and bridge foundations due to wave action during major coastal storm events.</p> <p>Risk of occasional inundation of electrical and mechanical components of Long Creek bascule bridge.</p>	<p>The western portion of the Parkway is more likely to be exposed to flooding and embankment erosion from wave action.</p> <p>More severe scour of Long Creek Bridge foundations and potential for impacts to substructures of all bridges due to wave action during storm surge.</p>	<p>Almost the entire Parkway is projected to be exposed to 10-year floods.</p> <p>Bridge structures and abutments are all projected to be impacted by wave action.</p>
Meadowbrook Parkway between Ocean Parkway and NY 27	<p>Northern portions of corridor closer to mainland in 10-year or 50-year floodplains. Portion close to interchange with Loop Parkway also exposed.</p> <p>Risk of occasional overtopping of bridge approaches and erosion of bridge abutments due to wave action.</p>	<p>The northern stretch of the Parkway near NY 27 and the southern stretch of the Parkway near Ocean Parkway are exposed to 10-year floods. Northern stretch is also projected to experience flooding during moderate precipitation events due to inability to drain water from area as drainage outfalls are submerged.</p>	<p>Almost the entire Parkway is projected to be exposed to 10-year floods.</p> <p>Bridge structures and abutments are all projected to be impacted by wave action.</p>

Table D.9. Summary of climate vulnerability and risk assessment (no-build scenario) (continuation).

Assets of Interest	Current Year	2050s	2100s
Wantagh Parkway between Ocean Parkway and NY 27	<p>Northern portions of corridor closer to mainland lie in 10-year or 50-year floodplains. Some other portions are exposed, including southern end of the parkway before it crosses onto Jones Beach Island.</p> <p>Occasional overtopping of approaches to bridges over Island Creek and Goose Creek. Potential erosion of bridge abutments due to wave action.</p>	<p>Most segments south of Merrick Road are exposed to coastal floods. The middle portions of the Parkway are exposed to 50-year floods, whereas the rest are likely to be exposed to 10-year floods.</p> <p>Northern segments of Parkway are projected to experience flooding during moderate precipitation events due to inability to drain water from area as drainage outfalls are submerged.</p>	<p>Almost the entire Parkway is exposed to 10-year floods. Bridge structures and abutments are all projected to be impacted by wave action.</p>
Robert Moses Causeway between Fire Island and NY 27	<p>No exposure to flooding. Scour of bridge piers during moderate to severe storm surges.</p>	<p>Risk of occasional overtopping of bridge approaches due to wave action. Due to sea level rise, wave action could impact bridge abutments and areas immediately adjacent to the water.</p>	<p>Increased risk of overtopping of bridge approaches. A small portion of the roadway south of Montauk Highway leading to the open water portion of the Causeway is projected to be exposed to 500-year floods.</p>
The Long Island Rail Road Long Beach Branch between Long Beach and Lynbrook	<p>Most portions of railroad right of way in 10- or 50-year floodplains, including the Long Beach rail yard and one electrical substation. Oceanside and Island Park stations are in 10-year floodplain. East Rockaway and Long Beach stations are in 50-year floodplain.</p> <p>The abutments to the bridges over Wreck Lead Channel and Hudson Channel are in zones potentially exposed to moderate wave action according to current FEMA Flood Insurance Rate Maps.</p>	<p>The portion of the railroad right of way south of East Rockaway station is projected to be exposed to 10-year floods.</p> <p>East Rockaway, Oceanside, Island Park, and Long Beach stations are projected to be exposed to 10-year floods.</p> <p>The moveable bridge over Wreck Lead Channel is projected to be susceptible to inundation and damage to mechanical and electrical equipment.</p> <p>Electrical components at ground level are projected to be exposed to inundation from salt water during 100-year events. Elevated components may be susceptible to exposure due to wave action when surrounding areas are completely inundated.</p>	<p>The entire stretch of the railroad south of Centre Avenue station is projected to be exposed to 10-year floods. Centre Ave. station is projected to be exposed to 50-year floods. East Rockaway, Oceanside, Island Park, and Long Beach stations are projected to be exposed to 10-year floods.</p>

Note: The risk assessment conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place on barrier islands and inland communities in the study area. See next section for summary of planned and proposed projects.

Adaptation Strategies

Adaptation strategies should consider how to address not only climate risk and its components but also the wider range of risks that agencies face and the broader planning context and goals. Practitioners must address adaptation collaboratively with other agencies studies, projects, and stakeholders. Choosing the right adaptation strategy or strategies for a particular location or system often depends on what strategies are planned or implemented in nearby locations and systems.

Along the Long Island South Shore, there are a number of relevant studies and projects. Previous sections discussed some of these. Directly relevant studies and projects include:

- Long Island Rail Road Long Beach Branch restoration project, an approximately \$120 million effort that involves.⁹
 - Replacing three of the four electrical substations (Oceanside, Oil City, Long Beach) on raised platforms
 - Replacing and raising signal, communications, and electrical systems well above the floodplain
 - Wreck Lead Bridge (between Island Park and Long Beach) systems restoration: replace underwater cable, bridge electrical system, and emergency generator
- NYSDOT Nassau Expressway (NY 878) Operational Improvement, an approximately \$110 million project that includes drainage improvements and options for raising the expressway by two or four feet.¹⁰
- Ocean Parkway restoration, an approximately \$32 million project replacing destroyed roadway and sand dunes and replenishing native vegetation.¹¹

⁹ <http://www.mta.info/news/2014/04/12/major-long-beach-branch-restoration-project-begins>.

¹⁰ <https://www.dot.ny.gov/regional-offices/region10/projects/ny878-nassau-expy>.

¹¹ <https://www.governor.ny.gov/news/governor-cuomo-announces-start-pavement-reconstruction-long-islands-ocean-parkway>.

- Atlantic Coast of Long Island, Jones Inlet to East Rockaway Inlet, Long Beach Island, NY, an approximately \$230 million project, which plans adding or improving beachfill, berms, dunes, groins, etc. to Long Beach island.¹²
- Rockaway East – NY Rising Community Reconstruction Program, which proposes drainage, bayside coastal protection, bus circulator service, and other projects.¹³
- Five Towns – NY Rising Community Reconstruction Program, which proposes a Rockaway Turnpike/Nassau Expressway Resilience Corridor flood protection study and enhancements, a South Shoreline improvement program, extensive stormwater infrastructure upgrades, etc.¹⁴
- Village of Atlantic Beach/Atlantic Beach Estates/East Atlantic Beach – NY Rising Community Reconstruction Program, which proposes installing solar-powered street lights, backflow preventers, and a microgrid power system; conducting a perimeter dune system feasibility study; and implementing other measures.¹⁵
- Long Beach – NY Rising Community Reconstruction Program, which proposes bulkhead improvements, drainage improvements, canal gates, critical facility resiliency (e.g., including parking garage for emergency vehicles, elevation of electrical, IT systems for emergency responders, etc.), etc.¹⁶ The program also includes the Beech Street/Park Street Complete Streets and Drainage Improvement Project, which will integrate flood mitigation strategies into traffic calming and safety improvements along a coastal evacuation route at the west end of the Long Beach barrier island.
- Barnum Island/Oceanside/the Village of Island Park/Harbor Isle – NY Rising Community Reconstruction Program, which proposes emergency transportation lifeline safety plans and staging areas, critical facility resiliency measures, drainage improvements, flooding safeguards, beach restoration, etc.¹⁷

¹² http://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/ny/coast/LongBeach/Long%20Beach_Presentation_Draft_Falt_June29_2016_PMupdate.pdf?ver=2016-07-11-102925-180.

¹³ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/rockawayeast_nyrcr_plan_17mb.pdf.

¹⁴ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/fivetowns_nyrcr_plan.pdf.

¹⁵ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/atlanticbeach_atlanticbeachestates_eastatlanticbeach_nyrcr_plan.pdf.

¹⁶ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/long_beach_nyrcr_plan.pdf.

¹⁷ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/bi-o-vip-hi_final-20140701opt.pdf.

The program also proposes to analyze the inter-municipal stormwater drainage system and make recommendations to address flooding from astronomical high tides, severe rainfall events and rising sea level. Segments of Long Beach Road, and the entirety of Austin Boulevard will be analyzed and flood mitigation strategies will be designed.

- Village of Island Park – A Hazard Mitigation Grant Program project proposes to analyze the inter-municipal stormwater drainage system and make recommendations to address flooding from astronomical high tides, severe rainfall events and rising sea level.
- Hamlet of Oceanside – A project under the NY Rising Community Reconstruction Program proposes to analyze the inter-municipal stormwater drainage system and make recommendations to address flooding from astronomical high tides, severe rainfall events and rising sea level.
- Lido Boulevard/Point Lookout – NY Rising Community Reconstruction Program, which proposes rock revetment and dune repairs, stormwater drainage improvements, critical facility resilience, etc.¹⁸
- Freeport – NY Rising Community Reconstruction Program, which proposes stormwater drainage improvements, including along the Meadowbrook Corridor, Merrick Road resiliency measures, solar-powered streetlights, bulkhead repairs, etc.¹⁹
- Bellmore/Merrick – NY Rising Community Reconstruction Program, which proposes drainage improvements (including the Meadowbrook Corridor), streetscape resiliency, road raising, etc.²⁰
- Seaford/Wantagh – NY Rising Community Reconstruction Program, which proposes drainage improvements, bulkhead replacements/upgrades, infrastructure improvements along critical roads to maintain access during storm events, local road raising.²¹

¹⁸ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/lidobeach-pointlookout_nyrcr_20140430.pdf.

¹⁹ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/freeport_nyrcr_plan.pdf.

²⁰ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/bellmore-merrick_nyrcr_plan.pdf.

²¹ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/seaford-wantagh_nyrcr_plan.pdf.

- West Gilgo to Captree – NY Rising Community Reconstruction Program, which proposes communications and operations improvements between entities during emergency management and evacuation, back-up power enhancement, public safety improvements (fire protection, potable water, 911 GPS data and signage), shoreline stabilization, dune and wetlands enhancements.²²
- Fire Island – NY Rising Community Reconstruction Program, which proposes communications system enhancements, enhancing the emergency access route, etc.²³

For the Long Island South Shore study area, the Post-Sandy study team created an Adaptation Toolbox to list examples of potential strategies that could be considered along the corridor. The matrix in Table D.10 shows these strategies organized by whether they are more suited for (1) higher risk tolerance and lower investment level versus lower risk tolerance and higher investment levels; and (2) shorter term versus longer term. The matrix is not meant to be a rigid structure; some strategies might appear in multiple quadrants, and some of the quadrants might blend together in some instances. Instead, the matrix is intended to illustrate the range of possible strategies for addressing climate vulnerabilities along the corridor with respect to risk tolerance and timeframe.

Strategies in the upper left quadrant (near term, higher risk tolerance) cater more toward managing rather than preventing disruptive events. In the upper right (longer term, higher risk tolerance), strategies are still focused more on adaptive capacity and consequence reduction but also consider issues with physical infrastructure as climate risks increase. Strategies in the bottom left (near term, lower risk tolerance) also manage disruption but consider more aggressive approaches and potential infrastructure damages that might arise in the future. In the bottom right (longer term, lower risk tolerance), there are some heavier damage and disruption prevention measures, including those that address the coastline and coastline property generally, rather from solely a transportation perspective.

<p style="text-align: center;">Near Term Higher Risk Tolerance/ Lower Investment <i>e.g., Communications, coordination, ongoing maintenance</i></p>	<p style="text-align: center;">Long Term Higher Risk Tolerance/ Lower Investment <i>e.g., raising elevation vulnerable components as part of normal replacement projects</i></p>
<p style="text-align: center;">Near Term Lower Risk Tolerance Higher Investment <i>e.g., incorporate sea level rise projections into projects currently in development and design process; areawide flood prevention measures</i></p>	<p style="text-align: center;">Long Term Lower Risk Tolerance Higher Investment <i>e.g., consider higher-end sea level rise projections in future infrastructure designs and area- wide flood prevention measures; relocation assistance</i></p>

²² https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/west_gilgo_to_captree_nyrcr_plan.pdf.

²³ https://stormrecovery.ny.gov/sites/default/files/crp/community/documents/fire_island_nyrcr_plan_0.pdf.

Table D.10. Examples of potential adaptation strategies for south shore of Long Island.

	Near Term	Longer Term
Higher Risk Tolerance/ Lower Investment	<ul style="list-style-type: none"> • Assume corridors will flood and target investments that minimize damage when they do (e.g., waterproofing or raising electric, communications, lighting equipment). • Communication/Coordination: Update and maintain event notification and response system for roadways, including evacuation routes. • Communication/Coordination: Transit coordination and contingency plan for flooding and high-wind events on Long Beach Branch. Leverage bus lines. • Communication/Coordination: Regularly coordinate with other stakeholders to ensure complementary adaptation strategies and identify gaps. • Communication/Coordination: Better tracking of disruption and damage information to inform planning. • Prune branches and other vegetation susceptible to wind 	<ul style="list-style-type: none"> • Concrete sealant/surface treatment for surfaces not previously inundated. • Cathodic protection for metal elements. • Continue to raise or relocate vulnerable electrical/communications assets (related to roadway or transit systems). • Erosion control aimed at surface protection (e.g. vegetative cover, mats/blankets) for areas that flood regularly. • More frequent inspection of infrastructure vulnerable to heat (e.g., rail buckling, catenary systems). • Increase regular maintenance of drainage ways. • Enhance resiliency of emergency services and electricity infrastructure (e.g., microgrids, solar-powered lights). • Review and update insurance and climate-related liabilities. • Coordinate with stakeholders to add general coastal protection measures in vulnerable areas that have do not already have them. • Identify any roadways where flooding is considered intolerable and examine roadway elevation levels that would prevent flooding going forward...
Lower Risk Tolerance/ Aggressive Investment	<ul style="list-style-type: none"> • Use resilience best practices and incorporate SLR projections for new infrastructure projects/ updates that are already planned (e.g., Long Beach Branch raising substations and equipment and NY 878 raising road above future rather than current 100-year floodplains); this is important given the amount of funded resilience activities already occurring on LI. • Implement flood prevention measures (e.g., watertight barriers on roadside), prioritizing most vulnerable corridors (i.e., top priority would be Long Beach Rd./Austin Blvd.). • After conducting scour criticality and erosion assessments, take measures to prevent structural damage in event of flooding (e.g., superstructures that resist lateral flow, partially grouted riprap), prioritizing most vulnerable corridors. • Enhanced ITS Infrastructure allowing for increased capacity on alternate roadways and demand management by giving up-to-date information to travelers. ITS can better inform event response system. • Improve area-wide flood prevention measures, including seawalls, groins, breakwaters, bulkheads, beach/wetlands renourishment in vulnerable areas that current resilience projects are not addressing. 	<ul style="list-style-type: none"> • Implement flood prevention measures (e.g., watertight barriers on roadside) for most vulnerable corridors. • Raise roadway elevations where flooding is intolerable. • More aggressive erosion control strategies. • Improve bus transit capacity. • Strengthen mooring/berthing fixtures at docks. • Fender or dolphin systems to protect vulnerable piers and other infrastructure from vessel and debris impact. • Flood-prone land acquisition / incentivized relocation.

Lessons Learned

The examples illustrate important lessons for cost-effective resilience planning. Key implications and lessons include:

- Transportation infrastructure can be designed to withstand a temporary flood provided that individuals are safe and disruption costs are relatively low (e.g., people and freight are able to travel within a short period of time). Under this and other strategies, practitioners could investigate how to minimize or eliminate recurring damage.
- When individuals are cut off from their homes for substantial periods due to transportation infrastructure failure alone, larger projects that prevent this disruption can be more feasible. Economic performance depends heavily on a number of variables, including roadway volume, project cost, closure length, disruption cost per day (including productivity losses and detour time), build and no build failure thresholds, and recurring damage costs.
- In cases where larger construction projects have favorable benefit-cost ratios, but construction impacts are substantial, it might be more cost-effective to begin construction soon after a storm event, while the asset is closed (assuming an adaptation project is already designed and approvals can be expedited) or soon after the event, assuming a temporary restoration of service can be installed and can provide mobility until the larger project can begin.
- Early notification, effective evacuation, and enhancing productivity of evacuees (i.e., making telecommuting more viable) can help reduce the larger disruption costs and allow practitioners to delay or forego massive disruption prevention projects such as raised roadways.
- Parallel adaptation efforts can affect the economics of a particular project substantially; coordination is key.
- Likewise, the status of non-transportation assets (e.g., households, workplaces, electrical infrastructure, water infrastructure, power infrastructure) is important to consider. A north-south corridor flood prevention project in this study area will tend to be less cost effective if the homes and infrastructure on the barrier islands are going to be damaged or disrupted anyway; individuals living on the barrier islands face disruption costs regardless of the transportation corridor's status. The transportation network's benefits rely on the value of the origins and destinations that it connects.
- Practitioners should consider conducting sensitivity testing and ground truthing when conducting BCA and related analyses.

Potential Next Steps

Federal, state, regional, and local agencies responsible for coastal resilience and emergency management would do well to work together to build a comprehensive adaptation strategy that addresses vulnerability and risk in the entire South Shore. These agencies could monitor climate change over time and continue discussions about risk tolerance in the South Shore of Long Island and the thresholds for taking actions in the areas of risk mitigation, infrastructure adaptation, and strategic retreat from areas that will be inundated due to sea level rise.

The findings of this research study are specific to transportation and are meant to contribute to the discussion of options to help address vulnerability and assess risk for the entire South Shore of Long Island. The analysis was conducted for a “no-build” scenario in which there are no regional, site-specific, or asset-specific adaptation measures in place. Once potential adaptation scenarios (packages of complementary strategies) are identified, the SLOSH model could be re-run to determine before/after impacts.

Transportation agencies should consider working with the U.S. Army Corps of Engineers as coastal resilience projects progress through the planning, design, and implementation process, re-run SLOSH models, and use other sources of information to determine what elements of the transportation system may remain exposed and vulnerable to the impacts of climate change after coastal protection measures are put into place. Agencies could improve area-wide flood prevention measures, including seawalls, groins, breakwaters, bulkheads, beach/wetlands renourishment in vulnerable areas that current resilience projects are not addressing.

Specific to assets in this study area, New York State Department of Transportation and local transportation agencies should consider the following actions:

- Develop area-wide adaptation strategies to address the vulnerability and risk of all infrastructure, including transportation assets, in populated areas of Long Beach Island, Barnum Island, Island Park, and Harbor Isle. Transportation-specific adaptation strategies may not be as effective in these areas, aside from a few specific pieces of transportation infrastructure like rail and road bridges spanning Reynolds Chanel, Wreck Lead and Barnums Channel and things like traffic signal boxes and rail communications and signal components that can be raised or relocated. Some targeted investments could minimize damage when facilities do flood (e.g., waterproofing or raising electric, communications, and lighting equipment on bridges connecting the South Shore barrier islands to the mainland).
- Continue monitoring climate conditions and impacts after the Nassau Expressway corridor projects are completed. New York State’s investments in resilience on the Nassau Expressway corridor and in the “Five Towns” area represent a down payment that will protect that area for some time.
- Rerun the exposure analysis for Loop Parkway, Meadowbrook Parkway, Wantagh Parkway, and Robert Moses Causeway (roads, embankments, and bridges) considering the impacts of sea level rise and storm surge once planned coastal resilience measures are in place. It is important to consider the current and future exposure, and the consequences of damage and disruption in current and future years, when planning and prioritizing adaptation measures on these parkways.
- Review the high-level vulnerability and risk assessment presented in Appendix B, Table B.10, conduct more detailed assessments of the benefits and costs of potential adaptation strategies where needed, and identify funding for adaptation strategies that most cost-effectively address these risks.

- After conducting scour criticality and erosion assessments, take measures to prevent structural damage in event of flooding (e.g., superstructures that resist lateral flow, partially grouted riprap), prioritizing the Nassau Expressway, Meadowbrook Parkway, Loop Parkway, and Long Beach Road/Austin Boulevard corridors.
- Enhance ITS infrastructure, allowing for increased capacity on parallel roadways through integrated corridor management strategies, and maximize demand management by giving up-to-date information to travelers.
- Develop a transit contingency plan to facilitate evacuation and maintain access to the barrier islands via a bus bridge when the Long Island Rail Road Long Beach Branch is out of service due to flooding.

There is a shortage of historical information on the extent, duration, and cause of transportation system disruptions, the cost of repairs, and the impacts of disruptions in service. New York State Department of Transportation, the Long Island Rail Road, local transit operators, counties, and local governments could monitor how sea level rise, coastal and inland flooding, extreme heat, wind-blown debris, and other climate stressors are impacting the transportation system in the South Shore of Long Island over time. These agencies could use this information to inform future vulnerability and risk assessments, help prioritize specific adaptation projects, and inform planning and design work that occurs as capital projects, major rehabilitation projects and normal replacement projects advance through planning and feasibility studies and into preliminary engineering. Information on weather-related incidents that exceed a pre-determined threshold for reporting (similar to crash reporting thresholds) could be collected by first responders and recorded in incident reporting databases and transportation management systems like the INFORM (INformation FOR Motorists) system on Long Island, and aggregated regionally by TransCOM. The following information would be useful:

- More comprehensive information about the geographic extent and duration of closures and service disruptions on roads, transit lines, and waterways. Extent and duration of major disruptions are collected inconsistently and for a limited portion of the regional highway system by state and local police. Long Island Rail Road maintains its own historical records on rail service disruptions. There is no mechanism to collect and aggregate information at a regional scale on closures and service disruptions for arterials, local road networks, local bus services, and transportation services for communities of concern. There also are no consistently-used tags or indicators in existing reports so that disruptions due to weather events can be flagged, aggregated across all modes at a corridor or regional scale, and analyzed later.
- Primary and (if readily observable) secondary causes of road closures, transit service disruptions, drawbridge failures, and other incidents. For example, is rail service disrupted due to flooded tracks, or because water inundated a power substation and caused an electrical power failure? While detailed diagnostics and root cause analyses may take some time to complete after a major event, basic observations can be collected and reported on a standard incident reporting form by first responders (for example, a set of check boxes or drop down menus with pre-defined choices).

- Extent of damage and cost to repair or replace damaged infrastructure or components. Precise cost information may not be available until the repairs are completed, but again a set of simple qualitative choices could be included on an incident reporting form (no damage/minor to moderate damage/severe damage or total destruction)
- Other pertinent information to estimate the impacts of disruption. For example, for roadways: one or more lanes closed, total roadway closure with diversions to alternate routes, total roadway closure with diversion routes also impacted. For transit: Service operating with diversions and delays in service, service limited (lines truncated or suspended at some stations/stops); service suspended on entire line/system.

New York State Department of Transportation, the Long Island Rail Road, and local governments could use the results of anecdotal and data-based analysis to refine how climate risk is integrated into asset management practices and procedures, project formulation and design decisions, and day-to-day maintenance and operations.

D.2 New Jersey: South Shore of Raritan Bay

Introduction

The regional transportation system vulnerability assessment conducted as part of the Federal Highway Administration's Post-Hurricane Sandy Transportation Resilience Study (Post-Sandy Study) identified 21 potential subarea candidates for a "meso-scope" assessment of vulnerability and risk as an interim step between regional and asset-specific vulnerability and risk assessments. Stakeholders representing federal, state, regional, and local transportation agencies narrowed down the list to three subareas:

- Communities on barrier islands and lining interior bays along the South Shore of Long Island;
- The communities on the southern edge of Raritan Bay in New Jersey; and
- The Norwalk-Danbury corridor (U.S. 7 and Metro-North Railroad's Danbury Branch) along the Norwalk River in Connecticut.

The regional vulnerability assessment identified the area bordering Raritan Bay in New Jersey as a particularly vulnerable subarea of the regional transportation network. This subarea analysis focuses on the transportation system along the south shore of Raritan Bay that has long been affected by coastal storms.

The study area includes major roadways and rail lines running parallel to the shoreline in Middlesex and Monmouth counties from the Raritan River to the Navesink River. As shown in Figure D.10, the major regional transportation assets examined include:

- NJ TRANSIT North Jersey Coast Line from the south end of Raritan River Bridge to the Hazlet/Middletown border, including South Amboy, Aberdeen-Matawan, and Hazlet stations;
- NJ 35 from the south end of the Raritan River Bridge to NJ 36 in Keyport;
- NJ 36 from Garden State Parkway Exit 117 to the Highlands-Sea Bright Bridge over the Shrewsbury River (also known as the Captain Joseph Azzolina Memorial Bridge);
- US 9 from the south end of the Raritan River Bridge to the Garden State Parkway; and
- The Garden State Parkway from the south end of the Raritan River Bridge to Exit 117.

This assessment seeks to determine which portions of the transportation network in the south shore of Raritan Bay warrant a closer examination over the next 50 years due to the increased risks of damage and disruption associated with climate change, and what adaptation strategies could be appropriate given the magnitude of damage and disruption that could be expected before and after these strategies are implemented. The research conducted as part of this assessment is intended to contribute to (rather than supersede or substitute for) a broader regional conversation about vulnerability and risk. Although this assessment presents a representative list of transportation-specific adaptation strategies that could be appropriate given the magnitude of damage and disruption that could be experienced through 2050 and 2100, it is entirely possible that regional adaptation and mitigation measures being studied by others in parallel with this effort could reduce or eliminate the vulnerabilities and risks identified in the sections that follow.

This subarea assessment generally follows the vulnerability and risk assessment process developed for the Post-Sandy study. See Appendix B - Engineering Informed Adaptation Assessment Process This assessment begins with a summary of climate impacts. The exposure analysis, sensitivity analysis, and adaptive capacity sections of the vulnerability assessment analyze how these climate impacts could affect the transportation assets examined. The risk assessment includes information on likelihood of exposure and consequences associated with exposure to climate stressors. Then, several sets of potential adaptation options are presented for areas with relatively high risks.

Additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through this assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

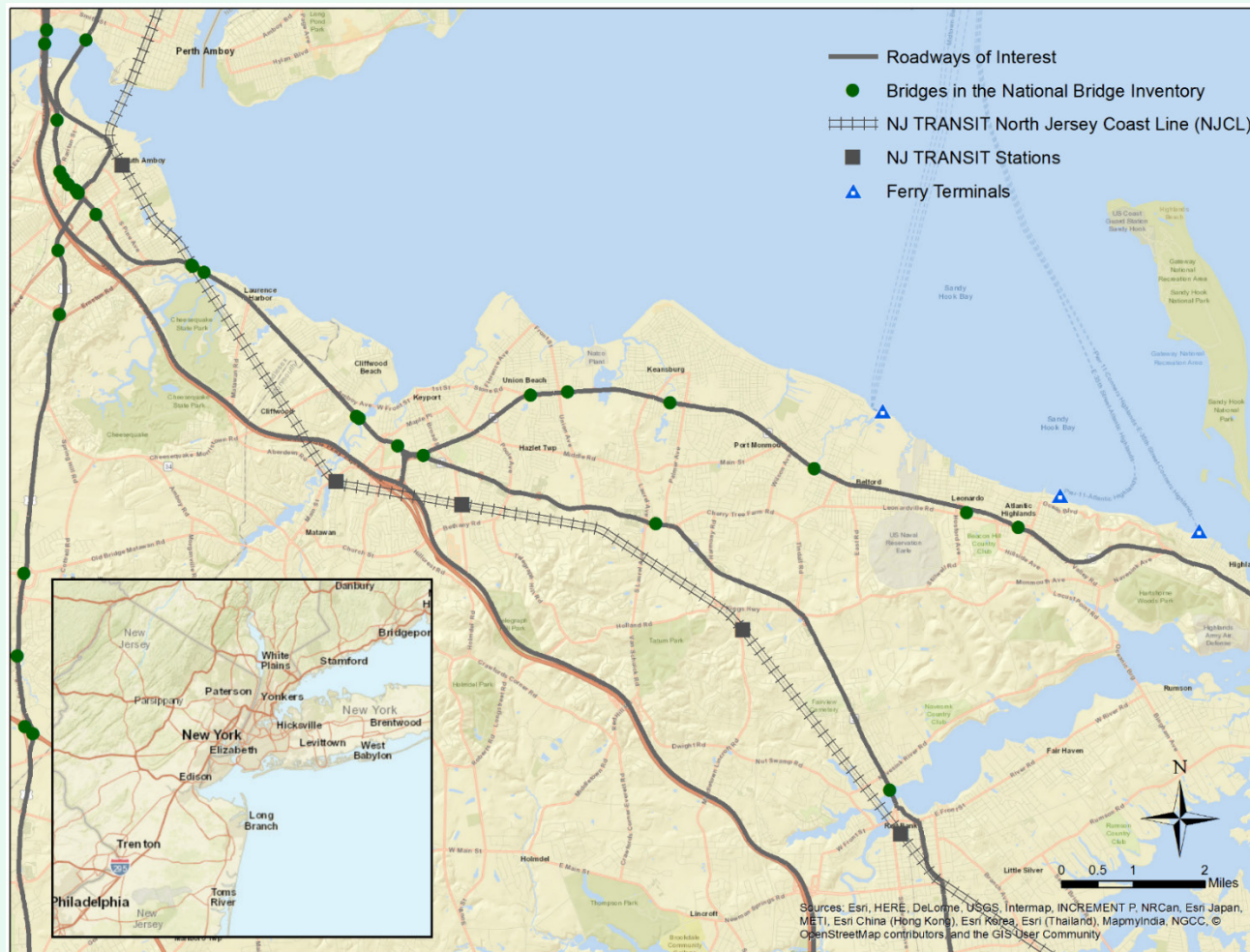


Figure D.5. Map. Study area: South Shore of Raritan Bay.

(Sources: Esri, HERE, DeLorme, USG, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, NGCC, OpenStreetMap contributors, and the GIS User Community.)

Source for Bridge Data: Federal Highway Administration, National Bridge Inventory.)

Sensitivity Screening and Climate Impacts

Hurricane Sandy in October 2012 caused widespread disruption and damage in the Raritan Bay Subarea. Before and after Sandy, coastal storms (including summer tropical systems and winter Nor'easters) have caused flooding in some of the same communities that were impacted by Sandy. This analysis focuses primarily on sea level rise and storm surge impacts on transportation assets in low lying coastal areas, but also lists other climate stressors shown in Table D.11.

Table D.11. Transportation system sensitivity to climate stressors in the Raritan Bay subarea.

Assets of Interest	Current Year	2050s
Storm surge, magnified by sea level rise over time	Inundation and overtopping	<ul style="list-style-type: none"> • Low-lying segments of highways and rail track. • Stations and park and ride lots. • Maintenance, storage, and other facilities. • Electric power infrastructure.
	Long-term corrosion and reduced useful life due to salt water intrusion	<ul style="list-style-type: none"> • Electrical and mechanical equipment on moveable bridges. • Signals, communications equipment, and power systems for rail. • Power supply and controllers for roadway signals and lighting. • Intelligent Transportation Systems infrastructure.
	Bridge scour due to velocity of water in inlets/outlets	<ul style="list-style-type: none"> • Bridges, particularly those over channels directly exposed to storm surge from Raritan Bay.
	Unmooring and transport of marine vessels, which then cause damage to and blockage of bridges, rail tracks, and roadways	<ul style="list-style-type: none"> • Bridges, bridge approaches, and roads and rail lines in low-lying areas adjacent to marinas and navigable waterways.
Sea level rise, absent storm surge	Inundation and overtopping during high tides; reduced effectiveness of drainage systems during heavy precipitation events	<ul style="list-style-type: none"> • Roadways, rail lines, and related assets in low-lying and/or poorly-drained areas.
Wave action	Erosion of shoreline roads and rail lines Erosion of bridge approaches and causeway embankments	<ul style="list-style-type: none"> • Sections of roadway and rail adjacent to Raritan Bay. • Bridges and causeways across major inlets from Raritan Bay.
Temperature	Expansion of metal (e.g., rail track, moveable bridges, and catenary wires) during extreme heat events Power outages	<ul style="list-style-type: none"> • Rail lines, including tracks, moveable bridges, catenary, and electrical systems. • Moveable bridges on roadways.

Current and Projected Climate Scenarios

Sea Level Rise and Storm Surge

The transportation assets that are the focus of this mesoscopic analysis are major regional commuter routes, and they also serve as vital emergency evacuation and recovery routes before, during, and after major coastal storms. Therefore, the project team used the higher end of the ranges of published projections of sea level rise, still water elevations, and wave heights for the exposure analysis. For county and local roads and less critical transportation assets, it may be appropriate to use mid-range or lower estimates, based on the risk tolerance of the agency conducting the analysis

For sea level rise and storm surge, water levels were identified for sea level rise projections for three time frames – current, 2050, and 2100 – and for two surge scenarios –still water elevation during a 100-year storm event and still water elevation plus wave action during a 100-year storm event. Six scenarios are shown in Table D.12.

Sea level rise (SLR): The project team used the “High” scenario for sea level rise at Sandy Hook produced by the National Oceanic and Atmospheric Administration (NOAA) and published in the U.S. Army Corps of Engineers’ North Atlantic Coast Comprehensive Study (NACCS).²⁴ All elevations are expressed in terms of the North American Vertical Datum of 1988 (NAVD88).

- Current: **0.00 feet**
- Year 2050: **+2.22 feet**
- Year 2100: **+7.10 feet**

Note that a “100-year storm event” could arrive as a tropical storm or hurricane in summer and fall or a Nor’Easter during the winter and spring.

Storm Surge elevations: The project team explored transects in the project study area from the FEMA Flood Insurance Studies for Monmouth County and Middlesex County. Still water elevations without wave action are more relevant for the inland portions of the study area, where many of the key transportation assets in this analysis are located. Wave action should be taken into account for transportation assets adjacent to the coast.

²⁴ U.S. Army Corps of Engineers, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, January 2015. Report, appendices, and geodatabase available for download at: <http://www.nad.usace.army.mil/CompStudy/>

- 100-year event still water elevation: **13 feet**. This elevation is at the higher end of the range of still water elevations associated with a 100-year storm event for transects in this project’s study area. Transect still water elevations range from 11.1 feet to 13.3 feet.
- 100-year event wave height: **6.8 feet**. Again, this is the high end range for 100-year event wave heights among the transects in our study area.

Temperature

There are no formally adopted temperature projections specific to the study area in New Jersey. The New York State Energy Research and Development Authority’s 2014 update to the report “Responding to Climate Change in New York State” (commonly known as “ClimAID”) projected that average temperatures for the New York City region could increase from 3.1 to 6.6 degrees Fahrenheit in 2050 and between 4.2 and 12.1 degrees Fahrenheit in 2100 (see Table D.13).

Table D.12. Water levels for six climate scenarios.

		Surge Elevation	
		100-Year Storm	100-Year Storm plus 6.8 feet of Wave Action
Sea Level Rise	Baseline (0.00 feet)	13.00 feet	19.80 feet
	2050 (+2.22 feet)	15.22 feet	22.02 feet
	2100 (+7.10 feet)	20.10 feet	26.90 feet

Source: NOAA High Scenario for Sandy Hook and FEMA Flood Insurance Studies in Monmouth and Middlesex counties.

Table D.13. Projected mean average changes in baseline temperature of 54.6°F.

Year	Low Estimate (10 th Percentile)	Middle Range (25 th to 75 th Percentile)	High Estimate (90 th Percentile)
2050	+ 3.1 °F	+ 4.1 to 5.7 °F	+ 6.6 °F
2100	+ 4.2 °F	+ 5.8 to 10.4 °F	+ 12.1 °F

Source: New York State Energy Research and Development Authority, 2014: Update to the report “Responding to Climate Change in New York State”.

Extreme Events

Table D.14 shows the projected changes in extreme weather events in 2050. The “baseline” column shows the average annual occurrence of each event today. Today there are 18 days with temperatures above 90 degrees Fahrenheit; in 2050 there could be between 32 and 57 days per year above 90 degrees. The number of freeze-thaw cycles is expected to decrease significantly in the study area.

Table D.14. Changes in extreme events: 2050.

	Baseline	Low Estimate (10 th Percentile)	Middle Range (25 th to 75 th Percentile)	High Estimate (90 th Percentile)
Days over 90 °F	18 days	32 days	39 to 52 days	57 days
# of heat waves	2	4	5 to 7	7
Duration of heat waves	4 days	5 days	5 to 6 days	6 days
Days below 32 °F	71 days	37 days	42 to 48 days	52 days
Days over 1” rainfall	13 days	13 days	14 to 16 days	17 days
Days over 2” rainfall	3 days	3 days	4 to 4 days	5 days

Vulnerability Assessment: Exposure Analysis

The exposure analysis in this section focuses on storm surge, taking into account the amplification of storm surge impacts due to sea level rise over time; sea level rise absent storm surge, and wave action. The impacts of wind and temperature are assumed to be uniform across the study area.

Exposure Analysis: Storm Surge

Bridges: Overtopping Risk

For bridges, the attribute information in the National Bridge Inventory (NBI) was used to assess exposure.²⁵ NBI Item 71 – Waterway Adequacy – identifies overtopping risks of bridges/culverts. Tables D.16 and D.17 summarize the coding schema for waterway adequacy and overtopping risk. Waterway adequacy codes can have different meanings when they are associated with different NHS functional classes; Table D.16 shows these associations.

²⁵ Federal Highway Administration, National Bridge Inventory. Data available for download at <https://www.fhwa.dot.gov/bridge/nbi.cfm>.

The right-hand columns of Table D.16 list the NBI overtopping descriptions for each waterway adequacy category (a through j). The project team regrouped the codes into 6 broad categories – C0, C1, C2, C3, C4, and C5. The left-hand column of Table D.15 shows how these broader categories correspond with the waterway adequacy categories.

Table D.15. NBI codes for overtopping risk.

Overtopping Risk Code	NBI Code Description
C5	a Bridge not over a waterway.
	b Bridge deck and roadway approaches above flood water elevation (high water), chance of overtopping is remote .
C4	c Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.
	d Slight chance of overtopping bridge deck and roadway approaches.
C3	e Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.
C2	f Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.
C1	g Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.
	h Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.
	i Occasional or frequent overtopping of bridge deck and roadway approaches with severe traffic delays.
C0	j Bridge closed.

Table D.16. NBI item 71: water adequacy.

NBI Item 71 Code	Principal Arterials, Interstates, Freeways, or Expressways	Other Principal and Minor Arterials; Major Collectors	Minor Collectors; Local Roads
N	a	a	a
9	b	b	b
8	c	c	c
7			d
6	d	d	e
5		e	f
4	e	f	g
3	f	g	
2	g, h, i	h, i	i
1			
0	j	j	j

The definitions for the frequencies of bridge overtopping as used by the NBI Coding Guide are:

- **Remote** – greater than 100 years
- **Slight** – 11 to 100 years
- **Occasional** – 3 to 10 years
- **Frequent** – less than 3 years

The definitions for the levels of impacts of bridge overtopping as used by the NBI Coding Guide are:

- **Insignificant** – Minor inconvenience. Highway passable in a matter of hours.
- **Significant** – Traffic delays of up to several days.
- **Severe** – Long term delays to traffic with resulting hardship.

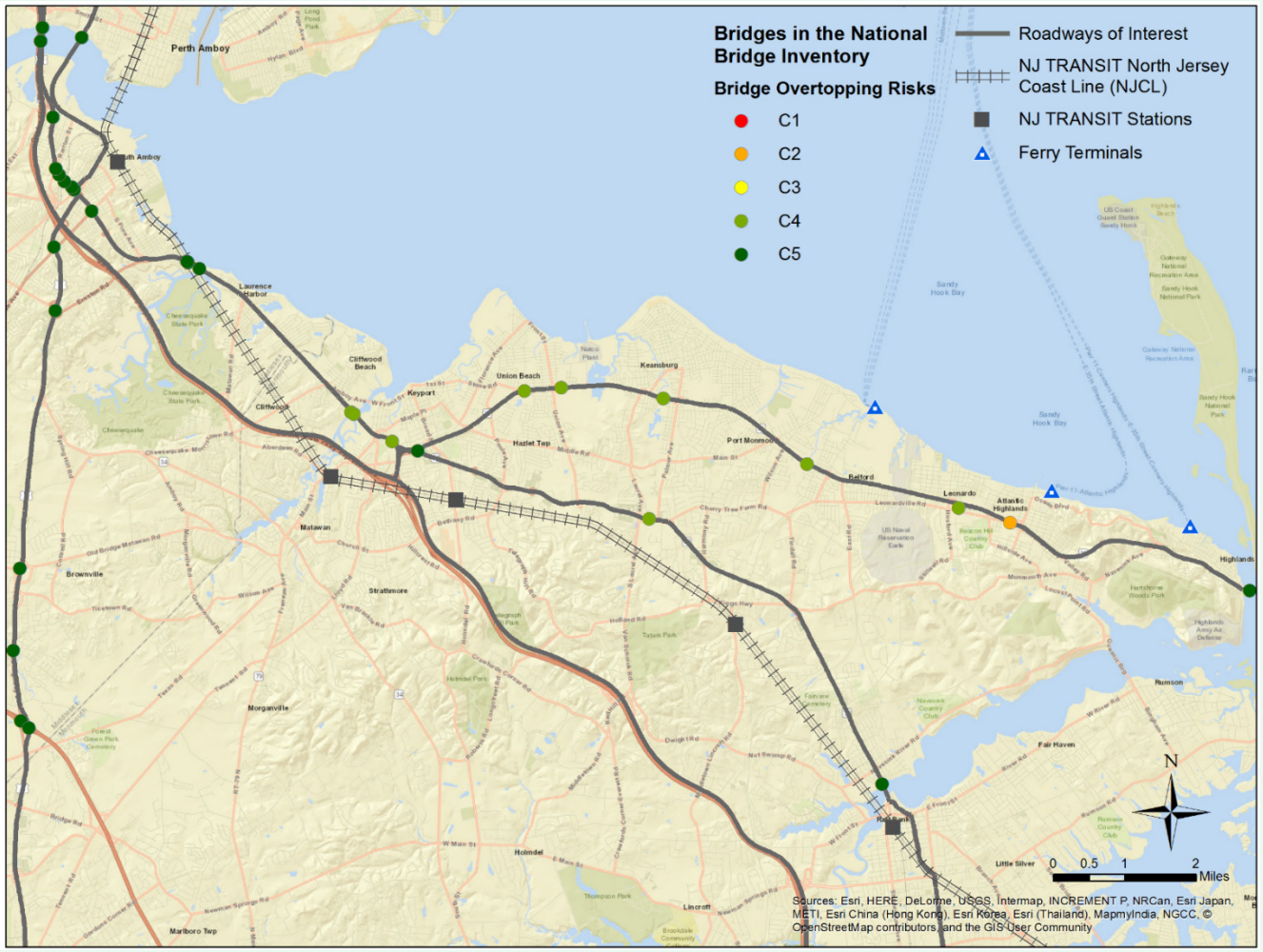


Figure D.6. Map. Bridge overtopping risk—Current year.

(Sources: Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.15 for explanation of Bridge Overtopping Risk codes. This map shows current year data based on field inspections.

Highways, Rail Lines, and Facilities: Depth of Inundation

The project team conducted a GIS-based analysis of the potential for exposure of key regional transportation assets to sea level rise and storm surge, with and without wave action. At the scale of this subarea assessment, the methodology does not incorporate detailed hydrologic modeling that might be done for an asset-specific analysis. The exposure analysis presented here is meant to be used as a sketch-level assessment of relative exposure to help identify the most vulnerable components of the transportation network in this subarea.

The following steps describe the methodology:

1. **Identify Water Levels** Under Storm Surge / Sea Level Rise Projection Scenarios. The “Current and Projected Climate Scenarios” section above summarizes water elevation data.
2. **Determine Elevation of Key Assets.** For polyline asset data, such as railroads and highways, two steps were followed. First, the polyline was converted into dense points along lines. Second, elevation data from a Digital Elevation Model (resolution: 6.56 x 6.56 feet) were extracted to the point layer.²⁶

For point asset data, such as rail stations, elevation data from the DEM were extracted to the point layer.

The DEM layer being used for the analysis only covers the land area, so the elevation of the parts of the rail/roadways that run across water bodies cannot be derived from the DEM. As an alternative, a DEM layer of lower resolution (32 x 32 feet) and Google Earth terrain data were used to identify the approximate elevation. Some discrepancies remained; discrepancies that were too large to be reconciled were labeled “No Data”.

3. **Calculate Inundation Depth.** After elevation data were extracted and associated with the asset data as an attribute, inundation depth was calculated by asset. To calculate the depth of inundation, the elevation of the asset was subtracted from the water level under different storm surge/sea level rise scenarios. A positive number indicates that the asset is exposed to inundation and shows the depth of exposure.

$$\text{Inundation Depth} = \text{Water Level} - \text{Asset Elevation}$$

This method provides a rough estimate of inundation depth for linear assets (see Table D.17). The results should be used to evaluate the relative magnitude of exposure rather than the projected depth of inundation. Further hydrologic analyses would be needed to obtain more accurate estimates of depth of inundation at specific assets.

²⁶ Generated from USGS-developed LiDAR data, available for New Jersey at the New Jersey Geographic Information Network: https://njgin.state.nj.us/NJ_NJGINEplorer/jviewer.jsp?pg=lidar.

The analysis identified several exposed assets in the study area. The affected transportation assets are grouped into six main exposure areas, shown in Table D.18 and Figure D.7. Transportation assets highly exposed to storm surge and sea level rise include the area just south of the Raritan River, the Laurence Harbor area and wetlands around Cheesequake Creek, and significant portions of NJ 36 near the coastline in the eastern portion of the study area. Bridges and culverts are not significantly affected, except for one in the Hosford Avenue/7th Avenue area in Atlantic Highlands. Three passenger ferry terminals in the study area, at Belford, Atlantic Highlands, and Highlands, all are exposed to coastal flooding under each of the 100-year flood event scenarios.

The study area also contains a pier that juts out from Atlantic Highlands into Raritan Bay. The pier is used to load and offload ships carrying munitions onto rail cars that travel from the pier southward to U.S. Naval Weapons Station Earle. The maps do not show this facility, but it is exposed under each of the 100-year flood event scenarios.

There are two electrical substations in the study area that support the North Jersey Coast Line. The South Amboy Substation is near the bridge over Raritan River, and the Matawan Substation is just east of the Aberdeen-Matawan stop. The maps do not show these substations, though the South Amboy Substation in particular is likely to be exposed to coastal flooding.

Figures D.8, D.9, and D.10 show inundation depths under the three scenarios for sea level rise (SLR) plus surge without wave action.²⁷

²⁷ The SLR plus surge with wave action levels are not mapped. Showing contours developed using elevations that include wave action for more inland areas could be misleading because wave heights dissipate relatively quickly as water travels further inland. Determining the boundary of wave action would require hydrologic modeling, which was not in the scope of this assessment.

Table D.17. Flood elevations in future scenarios.

Scenario	Projected Water Level
Storm Surge from Current Year 100-Year Storm	13 ft.
Storm Surge from Current Year 100-Year Storm with Wave Action	19.8 ft.
Storm Surge from 100-Year Storm in 2050 with High Range Sea Level Rise	15.22 ft.
Storm Surge from 100-Year Storm in 2050 with High Range Sea Level Rise + Wave Action	20.02 ft.
Storm Surge from 100-Year Storm in 2100 with High Range Sea Level Rise	20.1 ft.
Storm Surge from 100-Year Storm in 2100 with High Range Sea Level Rise + Wave Action	26.9 ft.

Table D.18. Areas with high potential for exposure to storm surge.

Areas with High Potential for Exposure	Affected Assets
1. Raritan River (South Bank, at Mouth)	US 9, NJ 35, Garden State Parkway, and North Jersey Coast Line near Raritan River.
2. Laurence Harbor (Cheesequake Creek)	NJ 35 and Garden State Parkway crossing Cheesequake Creek; North Jersey Coast Line from South Amboy through Cheesequake Creek/ Strump Creek flood plain
3. Matawan Creek	NJ 35 and Garden State Parkway across Matawan Creek.
4. Union Beach	NJ 36 in Union Beach.
5. Port Monmouth	NJ 36 in Port Monmouth.
6. Hosford Ave./7th Ave.	NJ 36 between Hosford Avenue and 7th Avenue, as well as a culvert near CR 516 intersection.

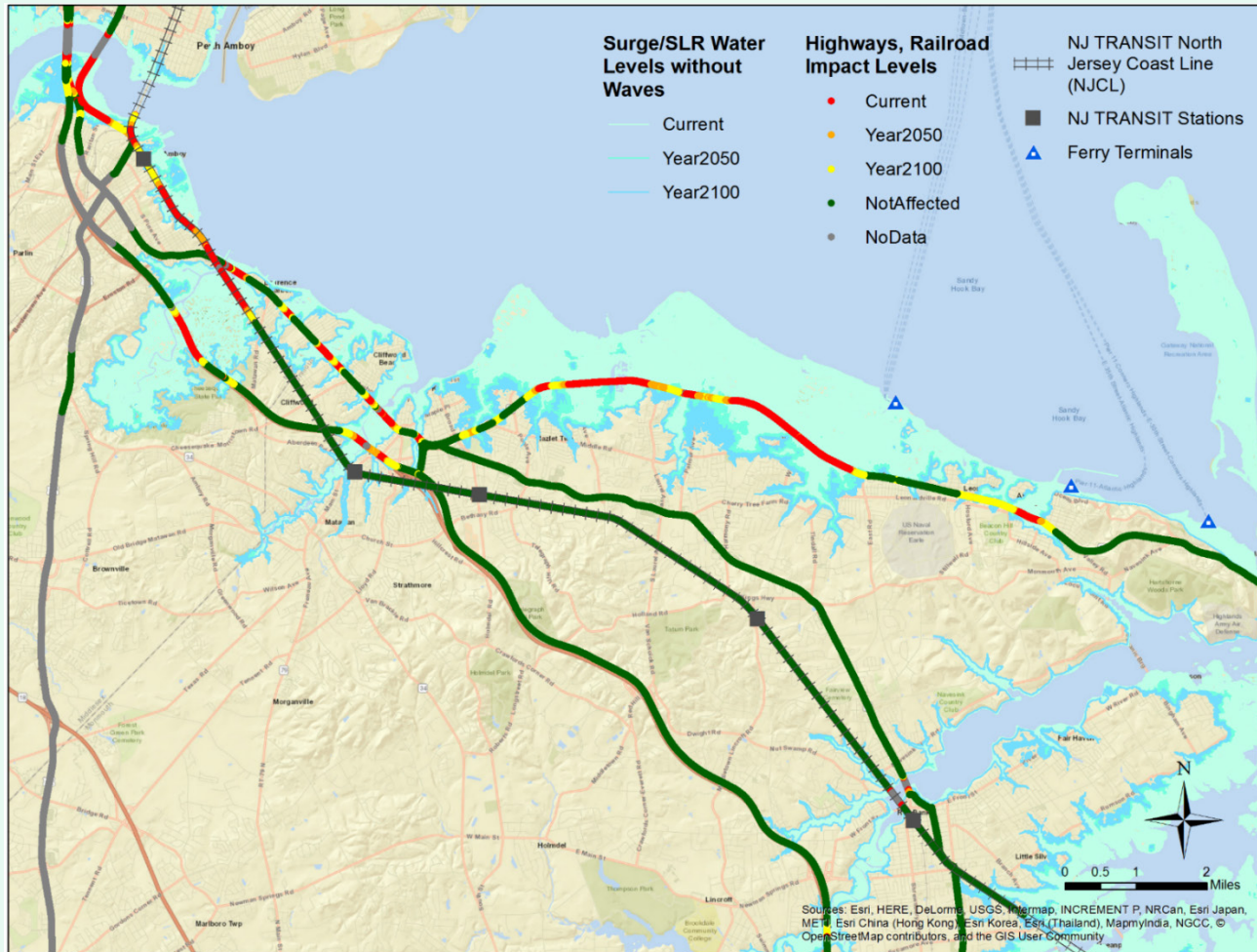


Figure D.7. Map. Extent of storm surge from 100-year storm event with high-range sea level rise (SLR).

(Sources: U.S. Army Corps of Engineers, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, January 2015; USGS-developed LiDAR data from the New Jersey Geographic Information Network.)

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place in the study area.

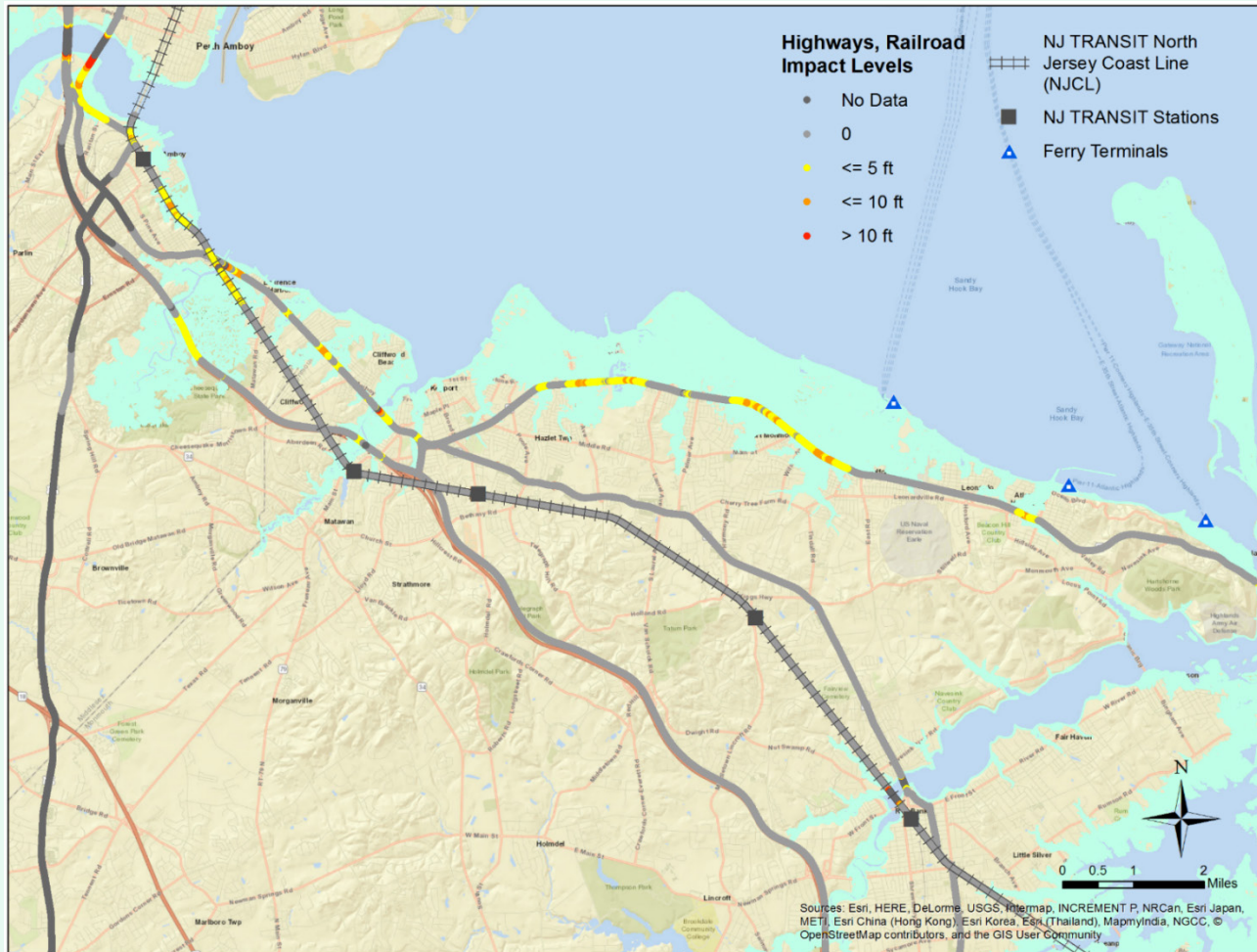


Figure D.8. Map. Extent of 3-foot storm surge from 100-year storm in 2016 (current year).

(Sources: U.S. Army Corps of Engineers, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, January 2015; USGS-developed LiDAR data from the New Jersey Geographic Information Network.)

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place in the study area.

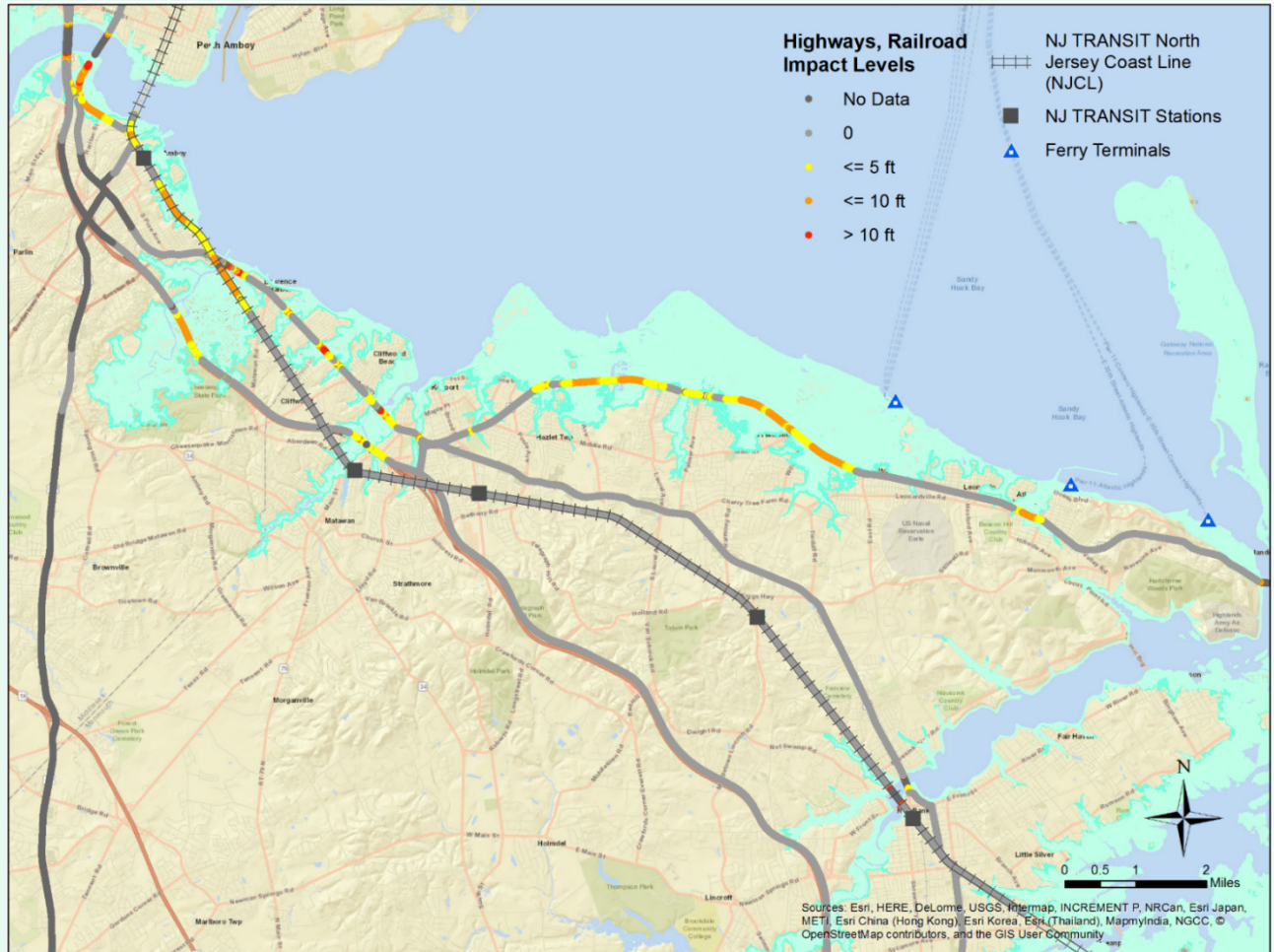


Figure D.9. Map. Extent of 15.22-foot storm surge from 100-Year Storm in 2050, with NOAA high sea level rise scenario.

(Sources: U.S. Army Corps of Engineers, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, January 2015; USGS-developed LiDAR data from the New Jersey Geographic Information Network.)

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place in the study area.

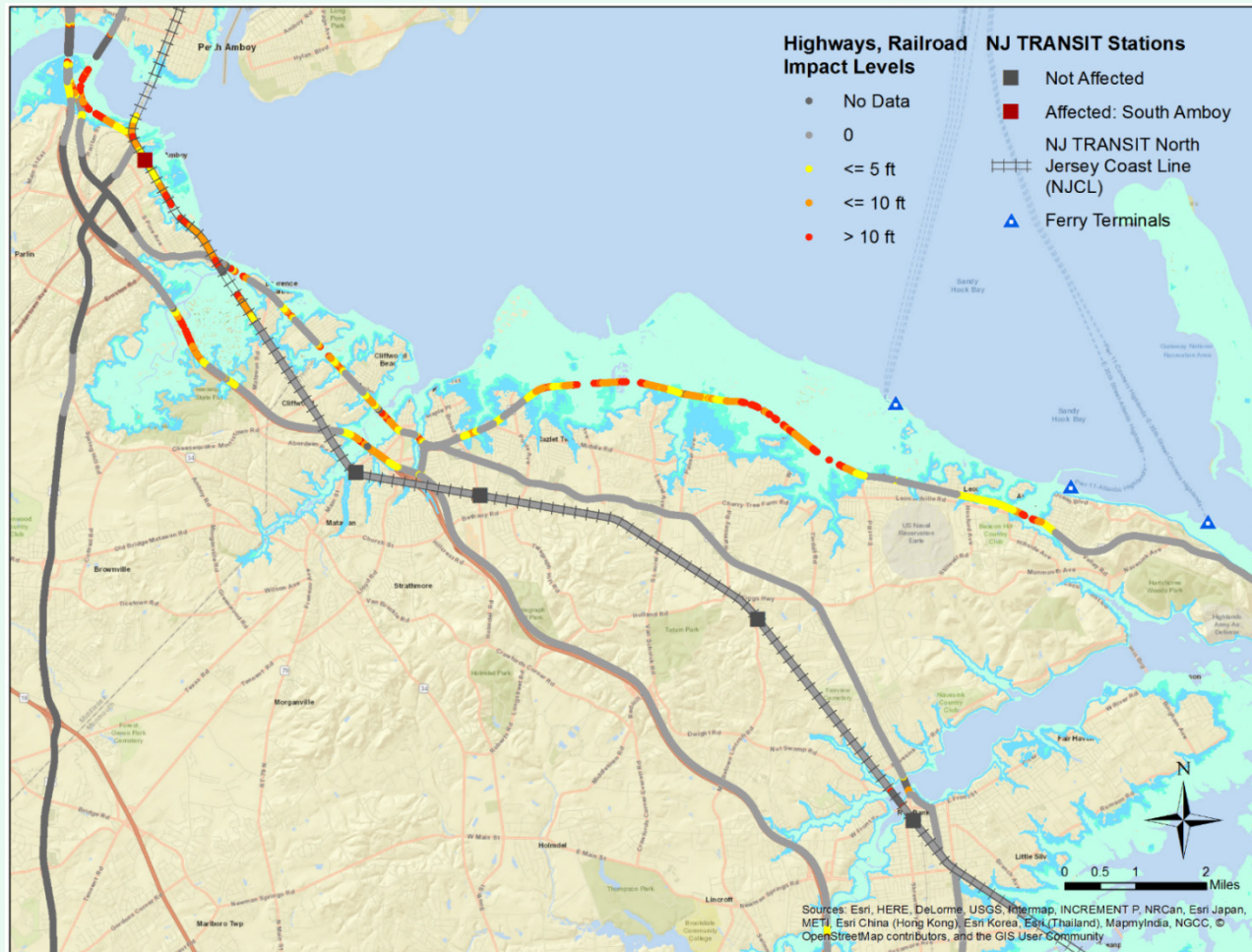


Figure D.10. Map. Extent of 20.1-foot storm surge from 100-Year Storm in 2050, with NOAA high sea level rise scenario.

(Sources: U.S. Army Corps of Engineers, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, January 2015; USGS-developed LiDAR data from the New Jersey Geographic Information Network.)

Note: The exposure analysis conducted in this study relies on current exposure data and does not take into account potential changes to flood elevations and extents that may occur if planned and proposed resilience efforts are put into place in the study area.

Exposure Analysis: Sea Level Rise

The impacts of sea level rise without storm surge can be observed at extreme high tide events, where water pools in low-lying areas and emerges from manhole covers and catch basins due to backed up storm sewers. When heavy rainfalls coincide with high tides, the outlet points of drainage systems can be below the water line, reducing the capacity of the drainage system and causing localized flooding. In addition, where roadways cross low-lying areas on embankments, the embankments can act as dams that impede drainage from flood plains, particularly when culverts and drainage pipes through the embankments are undersized.

There is anecdotal information about sections of the regional transportation network that are vulnerable to the impacts of sea level rise. Prior to 2015, portions of Route 35 in Cliffwood Beach regularly flooded when heavy rains coincided with high tide.²⁸ A New Jersey Department of Transportation project from 2013 to 2015 raised the elevation of 1.25 miles of Route 35 by up to 4 feet and replaced culverts over Long Neck Creek and Whale Creek to increase drainage capacity.²⁹ The U.S. Army Corps of Engineers is implementing an extensive array of flood mitigation measures from Sandy Hook to the mouth of the Raritan River which will protect portions of Routes 35 and 36, as well as local roads in the area, from exposure to flooding from sea level rise.

Exposure Analysis: Wave Action

This subarea analysis did not include the detailed hydrologic modeling that would be required to determine the precise extent of exposure to wave action. The North Jersey Coast Line runs adjacent to Raritan Bay from just south of South Amboy to the Cheesquake Creek bridge and could be vulnerable embankment erosion during moderate to severe storms, particularly as sea level rise reduces the elevation between the base flood elevation and the embankment. Portions of the Route 35 approaches to the bridge over Cheesquake Creek could similarly be vulnerable to wave action.

In an extreme storm surge scenario, portions of Route 35, the Garden State Parkway, and the North Jersey Coast Line running on embankments through the flood plains of Cheesquake Creek and Matawan Creek could be exposed to wave action. Sea level rise could increase the frequency of storm surges that cause flooding extensive enough to enable wave action impacts on these facilities.

It is assumed that planned flood mitigation measures would protect all of Route 36 from Keyport to Highlands from exposure to wave action.

²⁸ <http://patch.com/new-jersey/matawan-aberdeen/photos-heavy-rain-causes-severe-flooding-in-cliffwood-beach>.

²⁹ NJDOT announces Route 35 improvements in Aberdeen and Old Bridge: <http://www.state.nj.us/transportation/about/press/2013/031413a.shtm>.

Exposure Analysis: Temperature and Wind

Both temperature and wind are assumed to impact the study area uniformly. See the sensitivity analyses in the next section for a more detailed assessment of the potential impacts associated with these climate stressors.

Exposure Analysis: Past Damage and Disruption

Raritan Bayshore has long been affected by coastal storms, including Sandy. Figure D.11 shows the locations of major highway damages and disruptions from Sandy, Lee, Irene, and Alfred along the Raritan Bayshore. These cumulative impacts are categorized as damaged infrastructure, downed trees, flooding, and reduced service.

In the eastern portion of the study area (east of the Route 35/Route 36/Garden State Parkway interchange at the Keyport-Hazlet border), Route 36 experienced a number of impacts from these four storms. Impacts included multiple instances of roadway flooding in the Union Beach area, flooding and damaged infrastructure in the Port Monmouth area, and incidents in Atlantic Highlands and Highlands close to the Highlands Reach. In the eastern portion of the study area, Route 35 also experienced some impacts, albeit not as many as the more coastal Route 36.

In the western portion of the study area, Route 35 experienced flooding and damaged infrastructure just west of its interchange with Route 36 near the Luppataong Creek. Flooding occurred at multiple points along Route 35 in the Cliffwood Beach and Cliffwood area. The Laurence Harbor/Cheesequake Creek area has encountered a few incidents of downed trees, flooding, and damaged infrastructure. Farther inland, the Garden State Parkway has experienced fewer impacts, with downed trees and flooding affecting the Matawan Creek and Cheesequake Creek areas.

There were several emergency relief funding requests made to FHWA for damages from Sandy, Lee, Irene, and Alfred to transportation infrastructure located within the Raritan Bayshore study area in Middlesex and Monmouth Counties. One ER request was for the Route 35 bridge over Cheesequake Creek which failed due to erosion and washout. The \$800,000 request included repairing or replacing barrier gates, conducting a scour inspection, and replacing, repairing, or reprogramming equipment, lighting, and signage. Approximately \$200,000 of this request was expected to be funded. Another funding request was made for repairing Route 35 right-of-way fencing that was damaged by fallen trees in the South Amboy/Sayreville/Old Bridge/Aberdeen area.

NJ TRANSIT has received over \$1.7 billion in ER funding from FTA for projects associated with Hurricane Sandy.³⁰ The funding includes \$446 million for the replacing the North Jersey Coast Line's Raritan River Drawbridge, which was damaged by boats broken free of their moorings. The bridge, which lies at the western edge of the study area, was closed for three weeks after Sandy.^{31,32} Some funding was also allocated to raise signal and communications equipment from South Amboy to Aberdeen, a stretch of the North Jersey Coast Line within the study area.³³ Overall, the North Jersey Coast Line suffered the worst damages in the NJ TRANSIT system, with more 30 miles of track suffering severe damage and extensive washouts between South Amboy and Bay Head.³⁴ Downed trees were an issue throughout the system. The Morgan Drawbridge over Cheesequake Creek was severely damaged by collisions with boats and a storage container.³⁵

³⁰ http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=3005.

³¹ http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2939.

³² <http://njtransitresilienceprogram.com/raritanriveroverview/>.

³³ http://www.nj.com/traffic/index.ssf/2015/03/nj_transit_receives_147m_grant_to_fix_hurricane_sandy_damage.html.

³⁴ http://www.njtransit.com/tm/tm_servlet.srv?hdnPageAction=PressReleaseTo&PRESS_RELEASE_ID=2816.

³⁵ http://www.njtransit.com/var/var_servlet.srv?hdnPageAction=HurricaneSandyTo.

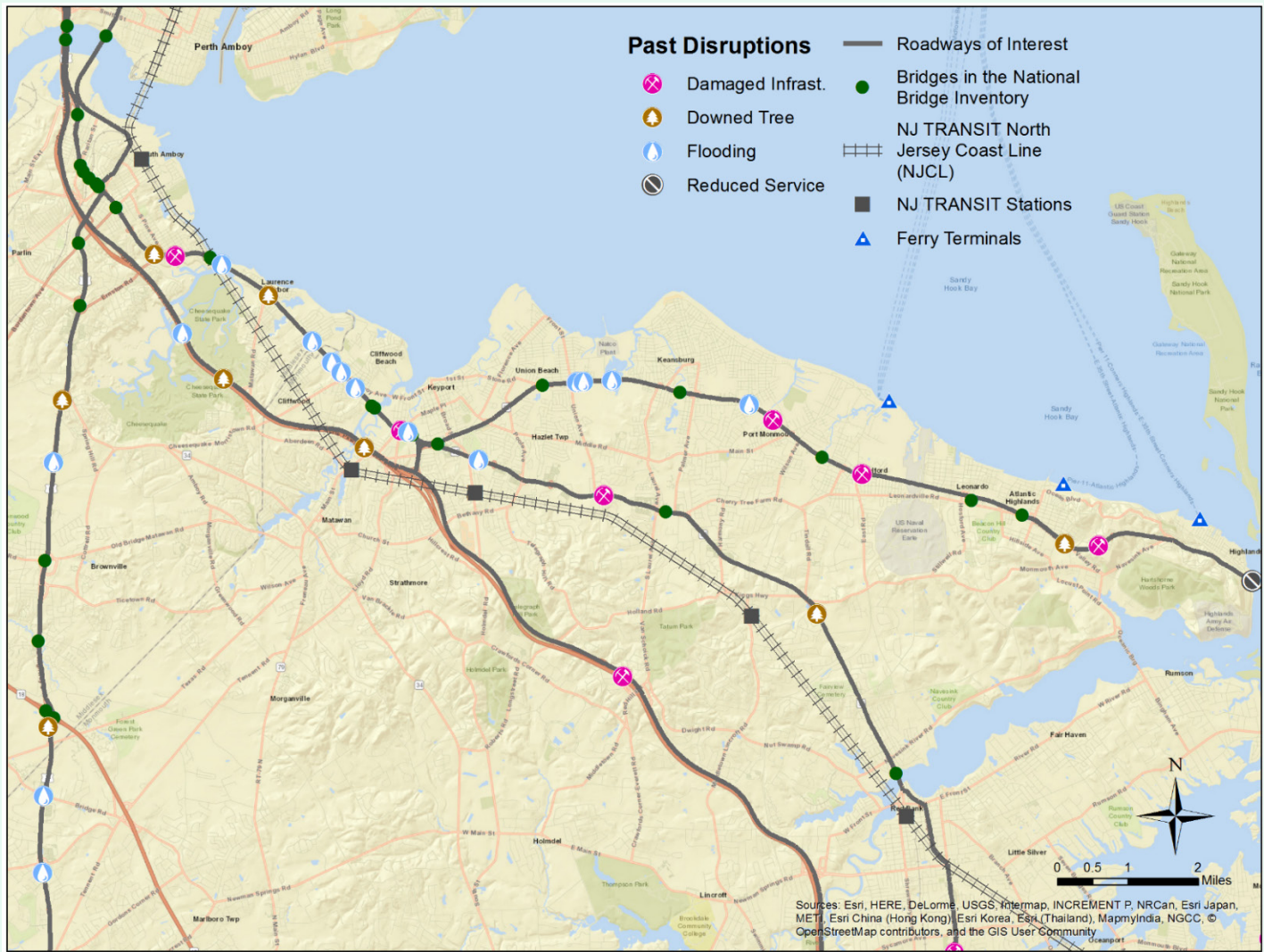


Figure D.11. Map. Past disruption overlay—Sandy, Irene, Alfred, and Lee.

(Source: New Jersey Department of Transportation, Federal Highway Administration Headquarters and New Jersey Division Office, TRANSCOM.)

Vulnerability Assessment: Sensitivity Analysis

The sensitivity of an asset or component to a given climate stressor depends on three variables:

- Intensity of each event,
- Duration per occurrence, and
- Frequency of occurrence.

The exposure analysis in the previous section showed representative outcomes associated with a 100-year storm in 2016, 2050, and 2100. Most of the assets included in the study area are sensitive to inundation from either coastal flooding due to storm surge, inland precipitation-based flooding, or nuisance flooding that is exacerbated over time by sea level rise. Roads and rail lines must be closed to traffic when they flood, and power substations and other electrical components can fail when exposed to water. Salt water exposure can have immediate impacts and also longer-term impacts because the corrosive properties of salt water accelerates deterioration of concrete, reinforcing bars, metal wires, pipes, conduits, and other metal components, reducing their remaining useful lives.

There is not a complete record of the extent or cost of damage in past events, and the duration of inundation in past events (and thus the ability to forecast duration of inundation in future events) is also not well-understood. Samples of archived incident reports from the regional transportation management coalition, TRANSCOM, indicate that the Halloween Nor'easter of 2011 resulted in flooding of Route 35 and downed trees in the area of Keyport. Hurricane Irene brought much more extensive damage and disruption to the area, with widespread flooding and closure of low-lying roads, downed trees, and other wind-blown debris.

Hurricane Sandy caused the worst damage to the transportation network along the south shore of Raritan Bay. In the aftermath of Sandy, the New Jersey Department of Transportation submitted requests for emergency relief funds for repairs to the Route 35 bridge over Cheesequake Creek, citing damage to barrier gates, washouts of the south abutment and the east side of the north abutment, possible damage to submarine cables, damage to the walkway on the fender; and damage to navigation lights and other electrical components. There were also requests for emergency relief funds to repair damage due to fallen trees and other wind-blown debris along Routes 9 and 35 in Aberdeen Township, Old Bridge Township, Sayreville Borough, and South Amboy City. NJ TRANSIT reported that three boats and two cargo containers collided with the Morgan Drawbridge over Cheesequake Creek at the height of Superstorm Sandy. Two boats were also reported lying on top of the drawbridge after Sandy's storm surge subsided.

The analysis in this assessment focuses on whether or not a transportation asset is likely to get "wet." In a more detailed, asset-level analysis, a transportation asset owner could use hydrologic modeling to get more information about projected depth of inundation and duration of inundation, which also could be an input to a benefit-cost analysis.

The sensitivity screening matrix in Table D.11 shows several other climate variables to consider. Extreme heat can warp steel rail tracks, with speed restrictions imposed on curves sections of track when temperatures reach 95 degrees and on straight sections of track when temperatures reach 105 degrees. Heat also can cause catenary wires to sag where constant tension catenary has not been installed, and moveable rail and roadway bridges with metal components can get stuck closed or can fail to reseal themselves in the proper position when closing if the metal expands on hot days, particularly during extended heat waves.

For both inundation and temperature, the sensitivity analysis in this section is binary: either an asset is “wet” or it is not, and either the temperature exceeds a threshold or it does not.

Vulnerability Assessment: Adaptive Capacity and Consequence Analysis

Adaptive capacity is a measure of how well a transportation system can accommodate a closure of one segment of rail line or roadway. This section summarizes the adaptive capacity of the transportation network in this subarea. It also addresses consequences associated with disrupting or damaging the network.

- All of the North Jersey Coast Line and the sections of the Garden State Parkway, US 9, and Route 35 north of Keyport are key components of the regional transportation network, serving heavy flows of commuters, tourists, students, and other residents. The close parallel spans of the Driscoll Bridge on the Garden State Parkway, the Vieser Bridge on US 9, the Victory Bridge on Route 35, and the NJ TRANSIT Raritan Bay Bridge together comprise one of the busiest river crossings in the world and one of the most vital evacuation routes from the Jersey Shore.
- Between the Raritan River and Matawan Creek, the Cheesequake Creek crossings on NJ 35, the Garden State Parkway, and the North Jersey Coast line are the biggest points of vulnerability. Both Route 35 and the North Jersey Coast Line crossings are in close proximity to Raritan Bay and are susceptible to the same climate stressors. For example, both are currently exposed to storm surge from a 100-year event; the frequency of inundation can be expected to increase as sea level rises in the future. The Garden State Parkway is further inland and is somewhat protected from storm surge and sea level rise by the roadway’s elevation and by the natural attenuation of storm surge and wave action provided by the marshes surrounding Cheesequake Creek. Route 34 and US 9 can serve as a detour route in the event that one or more of these crossings is damaged or inundated, but these roadways do not have excess capacity at peak periods for commuter and tourist flows. In addition, trucks are not permitted on the Garden State Parkway; therefore, Route 34 and US 9 become the next available route for trucks in the event that Route 35 is closed.
- South of Keyport, there are more parallel east-west roads on the state, county, and local networks that can be used to access coastal communities in the event that Route 36 is submerged or damaged.
- When the North Jersey Coast Line service is disrupted, people can use over-the-road NJ TRANSIT buses (including the 135, 815, and 817 routes) to travel to and from Northern New Jersey and the Port Authority Bus Terminal in New York City. People with access to a motor vehicle can switch to driving during off-peak hours, but there is not any excess capacity on the roadways during peak periods.

- NJ TRANSIT is currently building resilience into the signal and communication system on the North Jersey Coast Line that was damaged during Hurricane Sandy. These upgrades to the signal and communication system and complementary resilience efforts along the rail network all the way to New York Penn Station and Hoboken Terminal are intended to address the adaptive capacity of support systems in addition to efforts to improve the resilience of the rail track, structures, and stations physically located within the study area.
- There is no alternative to the military rail line connecting U.S. Naval Weapons Station Earle to the pier in Raritan Bay that is used to transfer munitions between rail and marine vessels.
- There are three passenger ferry terminals in the study area, each of which can be a partial substitute for the other, although there is not sufficient parking at any one terminal to accommodate all diverted trips.

Consequence

To roughly estimate how exposure would affect the examined assets, the project team looked at highway traffic volumes and North Jersey Coast Line ridership in different portions of the study area. In the event of exposure, segments with higher volumes and ridership are assumed to experience higher consequences.

According to NJ DOT traffic count data³⁶, Route 36 AADT was just over 23,000 in Atlantic Highlands, the eastern edge of the study area, in 2013. It was almost 30,000 in Port Monmouth in 2015 and over 34,000 farther west in Hazlet in 2014.

In the eastern portion of the study area, Route 35 AADT was over 44,000 near the Holmdel-Middletown border in 2015. West of the Route 36/Route 35/Garden State Parkway interchange in Keyport, Route 35 AADT was over 33,000 in 2014. Toward the western end of the study area, it was just under 29,000 near the Sayreville-South Amboy border in 2014.

Garden State Parkway (GSP) traffic volumes were unavailable in the study area on the NJ DOT traffic count reports website. But according to the NBI shapefile³⁷, more than 192,000 vehicles per day used the GSP in 2010 in the Matawan Creek/Wilkson Creek area west of the Route 35/Route 36/GSP interchange. Farther west, it more than 186,000 per day vehicles used the GSP in 2009 north of the Cheesequake Creek area.

³⁶ http://www.state.nj.us/transportation/refdata/roadway/traffic_counts/.

³⁷ Where multiple bridges exist for different lanes and/or directions, NBI ADT is sometimes given separately for each bridge. But these figures are added together here for bi-directional totals.

Three NHS facilities cross the Raritan River at the western edge of the study area. More than 80,000 vehicles per day used Route 9 in 2011 at the Edison Bridge. More than 20,000 vehicles per day used Route 35 in 2014 at the Victory Bridge. According to the NBI shapefile, almost 226,000 vehicles per day used the GSP in 2009 at the Driscoll Bridge.

While roadway volume data in the study area was incomplete in some places and in inconsistent years, these figures provide enough information to assess relative consequence for NHS facilities in the study area. Based on volume, the GSP is the highest consequence highway facility in the study area. The small portion of Route 9 examined is the next highest consequence facility. Route 35 is higher consequence in the eastern portion of the study area, though volume is still significant near the Raritan River crossing. Further westward, Route 36 faces similar disruption consequences as Route 35, though volume is somewhat lower at the eastern edge of the study area.

North Jersey Coast Line average weekday ridership was approximately 24,900 in 2012.³⁸ Figure D.12 shows average weekday passenger boardings by station, excluding NJ TRANSIT rail passengers transferring between trains. There are three stations in the study area, and they account for 18% of the line's total boardings: South Amboy with 1,050 boardings per weekday, Aberdeen-Matawan with 2,554 boardings per weekday, and Hazlet with 876 boardings per weekday. Over 13,000, or 54%, of the line's boardings occur farther inbound than the study area; these riders would be less affected by damage or disruption to the line in the study area. But over 7,000 boardings, or 28% of the line's total, occur at stations farther outbound than the study area. Thus, while consequences are likely to be somewhat higher if South Amboy, rather than Aberdeen-Matawan or Hazlet, is affected, due to its position farther inbound, relative consequences are fairly high for a disruption of the North Jersey Coast line at any point in the study area.

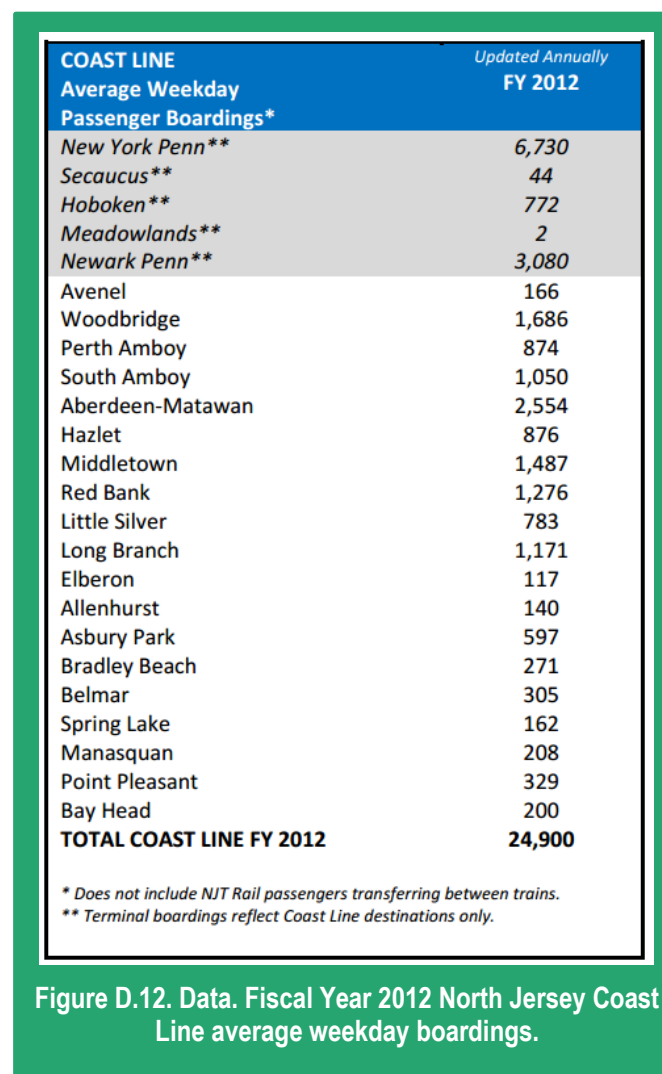


Figure D.12. Data. Fiscal Year 2012 North Jersey Coast Line average weekday boardings.

³⁸ http://media.nj.com/bergen_impact/other/1Q2013.pdf.

In addition to traffic volume and ridership, many other factors affect consequence. While this study does not cover them in detail, the project team did examine the presence of environmental justice (EJ) communities as a determinant of consequence. Communities that are already socially and economically vulnerable face even steeper challenges from environmental impacts such as coastal flooding.

Figure D.17 shows EJ communities in the study area along with the exposure areas and key transportation infrastructure. These were categorized based on NJTPA's definitions of Communities of Concern.³⁹ Using ACS data, communities were identified where (1) the percent of minority population was above the regional average of 42.2%; (2) the percent of households in poverty was above the regional average of 10.4%; or (3) both of these criteria were true. All six of the exposure areas contain EJ communities and are therefore particularly vulnerable to coastal flooding. Overall population density tends to be higher in the more western portions of the study area, which also contributes to climate impact consequences.⁴⁰

³⁹ http://togethernorthjersey.com/?page_id=18464.

⁴⁰ https://commons.wikimedia.org/wiki/File:New_Jersey_Population_Map.png.

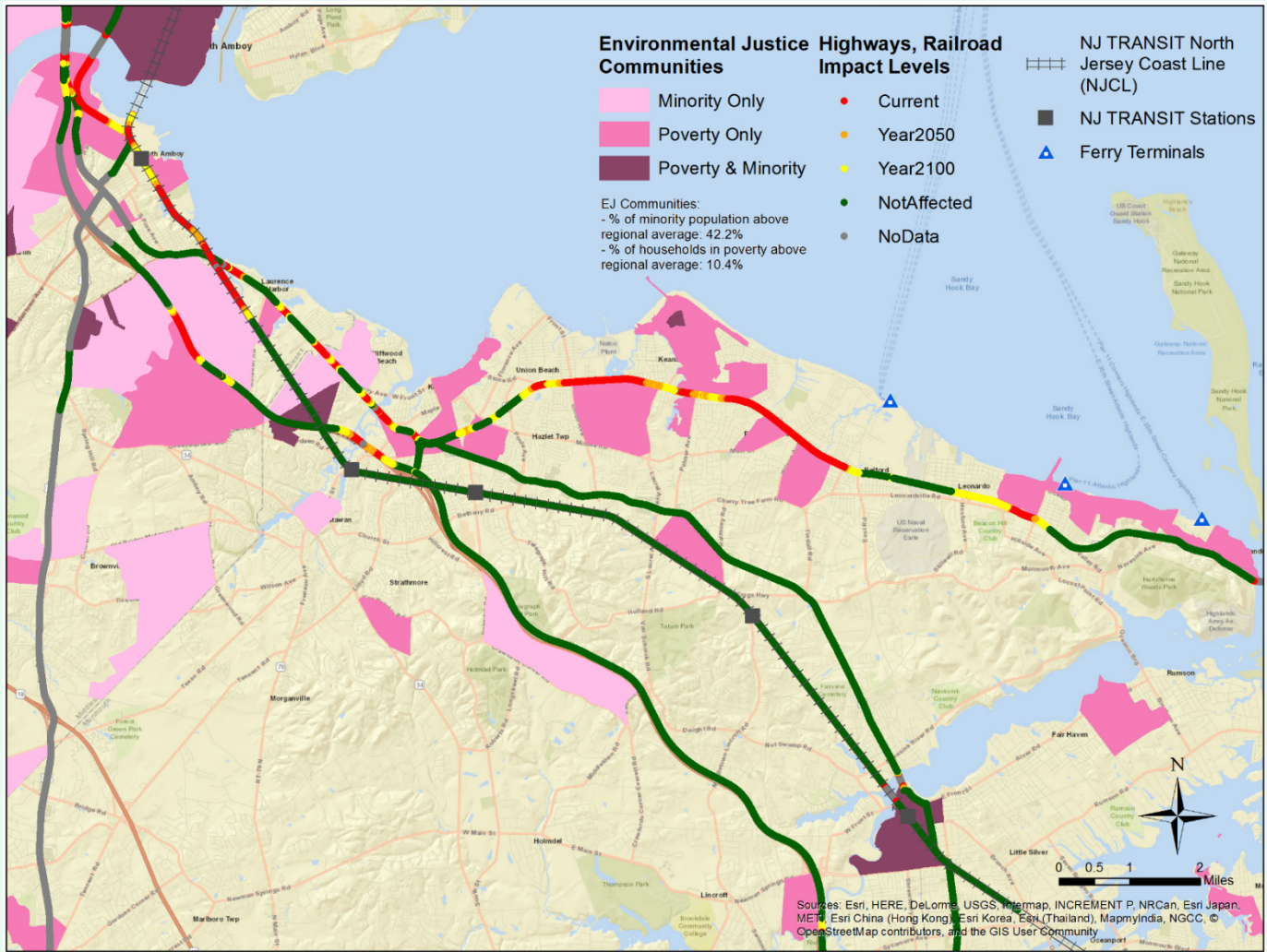


Figure D.13. Map. Exposure areas with environmental justice communities.

(Source: New Jersey Transportation Planning Authority.)

Risk Assessment

Risk is a function of likelihood and consequence. Overall, climate risks are high along the South Shore of Raritan Bay, particularly in the six identified exposure areas. This study did not include probabilistic calculations of likelihood, so exposure to the 100-year event for current, 2050, and 2100 under different inundation levels is used as a proxy for likelihood. Consequences are higher in the western portion of the study area, where volumes of people and freight are higher and facilities are more closely spaced—and thus subject to similar climate stressors. New Jersey Department of Transportation and NJ TRANSIT are already addressing this risk through resilience projects addressing the Raritan Bay and Cheesequake Creek bridges on NJ 35 and the North Jersey Coast Line, as well as other sections of NJ 35 and the North Jersey Coast Line in low-lying areas.

Per the analysis and conversations with local stakeholders, the three western exposure areas – Raritan River, Laurence Harbor, and Matawan Creek – were identified as the highest-risk sections of the study area.

The following list identifies some specific facilities that are higher risk than others examined in the corridor. The list emphasizes relative rather than absolute risks; of the transportation assets and stressors examined, these are the vulnerabilities that practitioners should consider first. Highest vulnerabilities from a transportation perspective include:

- Coastal flooding in the area of Cheesequake Creek, where Route 35 and the North Jersey Coast Line are both exposed to the current 100-year surge event and are adjacent to Raritan Bay, where wave action could exacerbate the impacts of storm surge. A portion of the Garden State Parkway, while further inland, also lies in the area exposed to inundation from a 100-year surge event. From a transportation perspective, this could be the highest vulnerability in the study area. Under the “NOAA High” sea level rise scenarios, inundation depths could be over 5 feet in 2050 and over 10 feet in 2100 for some sections of NJ 35 and the North Jersey Coast Line just southeast of Cheesequake Creek. Large portions of this area overlap communities with high minority and/or low-income populations.
- Coastal flooding in Matawan Creek exposure area where the Garden State Parkway and Route 35 both are exposed to the current 100-year surge event. With projected sea level rise, inundation depths could be over 5 feet at a few points in 2050 and for larger stretches in 2100. Inundation depths could be over 10 feet at a few points in 2100. Small portions of this area overlap communities with high minority and/or low-income populations.

Other relatively high risk coastal flooding vulnerabilities include:

- An extended portion of South Amboy section of North Jersey Coast Line from west of Matawan Road to the Raritan River crossing is subject to inundation and wave action, which will worsen and occur with increasing frequency with projected sea level rise.
- Route 36 in Union Beach and Port Monmouth. This section of Route 36 serves areas with high minority and/or low-income populations.

- Route 36 in the area of Hosford Ave./7th Ave in Leonardo and Atlantic Highlands. The approaches to the culvert over Many Mind Creek occasionally overtop at peak high tides and during relatively minor coastal storms. A large portion of this area is a community with high minority and/or low-income populations.
- Although it has recently been raised as much as four feet in a recent New Jersey Department of Transportation capital project, the section of Route 35 crossing Whale Creek between Cliffwood Beach and Laurence Harbor should be monitored to determine if further adaptation measures are necessary.
- The land in the vicinity of the South Amboy Substation serving the NJ TRANSIT North Jersey Coast Line is at risk of inundation in a 100-year storm surge event by 2050. A site-specific analysis would reveal whether the substation parcel and the equipment in the substation are at risk.
- The rail line and pier serving U.S. Naval Weapons Station Earle suffered extensive damage due to Sandy's storm surge and are being rebuilt. The rail line and pier can be considered high risk due to their strategic value and the consequences associated with any impact.
- Aside from storm surge, NJ TRANSIT may consider extreme heat to be a risk to the performance of the North Jersey Coast Line. Over time as the number of days above 95 degrees and 105 degrees increase, and as heat waves increase in frequency and duration, NJ TRANSIT could explore replacing rail, catenary, and other vulnerable components of the rail infrastructure with more heat-tolerant materials.

Adaptation Strategies

Adaptation strategy development should address not only climate risk and its components but also the wider range of risks that agencies face and the broader planning context and goals. Practitioners must address adaptation collaboratively with other agencies studies, projects, and stakeholders. Choosing the right adaptation strategy or strategies for a particular location or system often depends on what strategies are planned or implemented in nearby locations and systems.

Along the Raritan Bayshore, there are a number of relevant studies and projects. For example:

- NJ TRANSIT's Resilience Program includes:
 - Raritan River Bridge Replacement, which replaces the existing swing bridge used by the North Jersey Coast Line; and⁴¹

⁴¹ <http://njtransitresilienceprogram.com/raritanriveroverview/>.

- Raising and replacing North Jersey Coast Line signals and communication equipment from South Amboy to Aberdeen.⁴²
- The U.S. Army Corps of Engineers’ Raritan Bay and Sandy Hook Bay, Flood Risk Management Project is comprehensively addressing vulnerability and risk in the portion of the study area from Laurence Harbor to Sandy Hook. Example projects include:
 - Port Monmouth flood prevention measures, including levees, floodwalls, dune, and beach re-nourishment;⁴³
 - Keansburg Beach Hurricane and Storm Damage Risk Reduction Projection Project including beach, berm, and dune restoration;⁴⁴
 - Highlands Coastal Storm Risk Management Feasibility Study, which entails bulkheads, floodwalls, and dunes;⁴⁵
 - Keyport flood risk reduction feasibility study;⁴⁶
 - Union Beach flood risk reduction feasibility study;⁴⁷
 - Leonardo flood risk reduction feasibility study; and⁴⁸
 - Major rehabilitation of Route 35 drawbridge over Cheesequake Creek.⁴⁹

New Jersey Department of Transportation, Middlesex and Monmouth counties, and local municipalities should monitor sea level rise and storm surge impacts over time to determine if further mitigation and adaptation measures are needed to protect transportation infrastructure as well as electrical power distribution, communications systems, and structures.

⁴² http://www.nj.com/traffic/index.ssf/2015/03/nj_transit_receives_147m_grant_to_fix_hurricane_sandy_damage.html.

⁴³ <http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487398/fact-sheet-raritan-and-sandy-hook-bay-port-monmouth/>.

⁴⁴ <http://www.nan.usace.army.mil/Media/News-Stories/Story-Article-View/Article/488062/us-army-corps-of-engineers-begins-work-on-keansburg-beach-hurricane-and-storm-d/>.

⁴⁵ [http://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/nj/coast/SHtoBIHighlands/Highlands %20Draft%20FR-EA%20Main%20Report.pdf](http://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/nj/coast/SHtoBIHighlands/Highlands%20Draft%20FR-EA%20Main%20Report.pdf).

⁴⁶ <http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487426/fact-sheet-raritan-and-sandy-hook-bay-keyport/>.

⁴⁷ <http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487656/fact-sheet-raritan-bay-and-sandy-hook-bay-union-beach-new-jersey/>.

⁴⁸ <http://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487653/fact-sheet-raritan-bay-and-sandy-hook-bay-leonardo-new-jersey/>.

⁴⁹ <http://www.state.nj.us/transportation/about/press/2011/090711a.shtm>.

For the South Shore of Raritan Bay, the project team created an Adaptation Toolbox to provide examples of potential strategies that could be considered along the corridor. The matrix in Table D.19 shows these strategies organized by whether they are more suited for (1) higher risk tolerance and lower investment level versus lower risk tolerance and higher investment levels; and (2) shorter term versus longer term. The matrix is not meant to be a rigid structure; some strategies might appear in multiple quadrants, and some of the quadrants might blend together in some instances. Instead, the matrix is intended to illustrate the range of possible strategies for addressing climate vulnerabilities along the corridor with respect to risk tolerance and timeframe.

Strategies in the upper left quadrant (shorter term, higher risk tolerance) cater more toward managing rather than preventing disruptive events. In the upper right (longer term, higher risk tolerance), strategies are still focused more on adaptive capacity and consequence reduction but also consider issues with physical infrastructure as climate risks increase. Strategies in the bottom left (shorter term, lower risk tolerance) also manage disruption but consider more aggressive approaches and potential infrastructure damages that might arise in the future. In the bottom right (longer term, lower risk tolerance), there are some heavier damage and disruption prevention measures, including those that address the coastline and coastline property generally, rather than solely a transportation perspective.

Table D.19. Examples of potential adaptation strategies for south shore of Raritan Bay.

	Shorter Term	Longer Term
Higher Risk Tolerance/ Lower Investment	<ul style="list-style-type: none"> Update and maintain event notification and response system for roadways, including evacuation routes. Make explicit operational plans for sections of GSP in two highest vulnerability areas. Transit coordination and contingency plan for flooding and high-wind events on North Jersey Coast Line and of ferry terminals. Leverage bus lines. Be flexible enough to address different flooding scenarios. Regularly coordinate with USACE and other stakeholders to ensure complementary adaptation strategies and identify gaps. Better tracking of disruption and damage information to inform planning. Use resilience best practices and incorporate SLR projections for new infrastructure projects/ updates that are already planned - work this into existing process. Prune branches and other vegetation susceptible to wind along the major transportation corridors. Flood-proof South Amboy Substation. 	<ul style="list-style-type: none"> Implement flood prevention measures for most vulnerable sections of GSP (Matawan Creek, Laurence Harbor). Concrete sealant/surface treatment for surfaces not previously inundated. Cathodic protection for metal elements. Raise or relocate vulnerable electrical/communications assets (related to roadway or transit systems). Erosion control aimed at surface protection (e.g. vegetative cover, mats/blankets) for roadside areas that flood regularly. Revise rail speed guidance given effects of extreme heat on tracks. Consider capacity enhancements for bus transit and road network. More frequent inspection of infrastructure vulnerable to heat (e.g., rail buckling, catenary systems). Increase regular maintenance of drainage ways along the major transportation corridors More aggressive floodproofing for South Amboy Substation; consider raising or relocating.
Lower Risk Tolerance/ Aggressive Investment	<ul style="list-style-type: none"> Investigate and implement flood prevention measures for most vulnerable sections of GSP (Matawan Creek, Laurence Harbor), including raising the elevation of vulnerable and high-risk facilities. If NBI info outdated, conduct scour criticality assessment for bridges. Prioritize bridges over Raritan River given their high flooding consequences. Investigate and implement flood prevention measures for Route 36 at Many Mind Creek given its relatively high flooding likelihood. Enhanced ITS Infrastructure allowing for increased capacity on alternate roadways and demand management by giving up-to-date information to travelers. ITS can better inform event response system. Enhance capacity on North-South evacuation routes leading away from NHS facilities and North Jersey Coast Line in study area. More aggressive flood-proofing for South Amboy Substation; consider raising or relocating. 	<ul style="list-style-type: none"> Coordinate with stakeholders to add general coastal protection measures (e.g., floodwalls, levees, beach nourishment) in vulnerable areas that have do not already have them. For coastal bridges in areas of frequent flooding, consider superstructures that can resist lateral flow and wave forces. Berms and other measures in places on roads and North Jersey Cost Line with frequent flooding. More aggressive erosion control strategies. Further enhance capacity on North-South evacuation routes. Improve bus transit capacity. Enhance electricity infrastructure so that it remains functioning in extreme events and continues to power transit, traffic signals, ITS. Strengthen mooring/berthing fixtures at docks, ferry terminals, Earle. Fender or dolphin systems to protect vulnerable piers and other infrastructure from vessel impact. Flood-prone land acquisition / incentivized relocation.

Potential Next Steps

Federal, state, regional, and local agencies responsible for coastal resilience and emergency management would do well to work together to build a comprehensive adaptation strategy that addresses vulnerability and risk along the entire south shore of Raritan Bay. They agencies could monitor climate change over time and continue discussions about risk tolerance in northern New Jersey and the thresholds for taking actions in the areas of risk mitigation, infrastructure adaptation, and strategic retreat from areas that will be inundated due to sea level rise.

The findings of this research effort are specific to transportation and are meant to contribute to the discussion of options to help address vulnerability and assess risk for the entire south shore of Raritan Bay. The analysis was conducted for a “no-build” scenario in which there are no regional, site-specific, or asset-specific adaptation measures in place. Once potential adaptation scenarios (packages of complementary strategies) are identified, the SLOSH model could be re-run to determine before/after impacts.

Transportation agencies should consider working with the U.S. Army Corps of Engineers as coastal resilience projects progress through the planning, design, and implementation process, re-run SLOSH models, and use other sources of information to determine what elements of the transportation system may remain exposed and vulnerable to the impacts of climate change after coastal protection measures are put into place. Agencies could improve area-wide flood prevention measures, including seawalls, groins, breakwaters, bulkheads, beach/wetlands renourishment in vulnerable areas that current resilience projects are not addressing.

Specific to assets in this study area, New Jersey Department of Transportation, NJ TRANSIT, and local transportation agencies should consider the following actions:

- Develop area-wide adaptation strategies to address the vulnerability and risk of all infrastructure, including transportation assets, in populated areas directly adjacent to the bay. Transportation-specific adaptation strategies may not be as effective in these areas, aside from things like traffic signal boxes and rail communications and signal components that can be raised or relocated. Some targeted investments could minimize damage when facilities do flood (e.g., waterproofing or raising electric, communications, and lighting equipment on bridges crossing major estuaries and creeks).
- Continue monitoring climate conditions and impacts after the Raritan River crossing projects are completed. New Jersey’s investments in resilience represent a down payment that will protect those transportation assets for some time.
- Rerun the exposure analysis for Routes 35 and 36 and the North Jersey Coast Line (roads, embankments, and bridges) considering the impacts of sea level rise and storm surge once planned coastal resilience measures are in place. It is important to consider the current and future exposure, and the consequences of damage and disruption in current and future years, when planning and prioritizing adaptation measures on these facilities.

- Enhance ITS infrastructure, allowing for increased capacity on parallel roadways through integrated corridor management strategies, and maximize demand management by giving up-to-date information to travelers.
- Develop a transit contingency plan to facilitate evacuation and maintain access to the barrier islands via a bus bridge when the North Jersey Coast Line is out of service due to flooding.

There is a shortage of historical information on the extent, duration, and cause of transportation system disruptions, the cost of repairs, and the impacts of disruptions in service. New Jersey Department of Transportation, NJ TRANSIT, local transit operators, counties, and local governments should monitor how sea level rise, coastal and inland flooding, extreme heat, wind-blown debris, and other climate stressors are impacting the transportation system along the south shore of Raritan Bay over time. They should use this information to inform future vulnerability and risk assessments, help prioritize specific adaptation projects, and informing planning and design work that occurs as capital projects, major rehabilitation projects and normal replacement projects advance through planning and feasibility studies and into preliminary engineering.

Information on weather-related incidents that exceed a pre-determined threshold for reporting (similar to crash reporting thresholds) could be collected by first responders and recorded in incident reporting databases and transportation management systems and aggregated regionally by TransCOM. The following information would be useful:

- More comprehensive information about the geographic extent and duration of closures and service disruptions on roads, transit lines, and waterways. Extent and duration of major disruptions are collected inconsistently and for a limited portion of the regional highway system by state and local police. NJ TRANSIT maintains its own historical records on rail service disruptions. There is no mechanism to collect and aggregate information at a regional scale on closures and service disruptions for arterials, local road networks, local bus services, and human services transportation. There also are no consistently-used tags or indicators in existing reports so that disruptions due to weather events can be flagged, aggregated across all modes at a corridor or regional scale, and analyzed later.
- Primary and (if readily observable) secondary causes of road closures, transit service disruptions, drawbridge failures, and other incidents. For example, is rail service disrupted due to flooded tracks, or because water inundated a power substation and caused an electrical power failure? While detailed diagnostics and root cause analyses may take some time to complete after a major event, basic observations can be collected and reported on a standard incident reporting form by first responders (for example, a set of check boxes or drop down menus with pre-defined choices).
- Extend of damage and cost to repair or replace damaged infrastructure or components. Precise cost information may not be available until the repairs are completed, but again a set of simple qualitative choices could be included on an incident reporting form (no damage/minor to moderate damage/severe damage or total destruction)

- Other pertinent information to estimate the impacts of disruption. For example, for roadways: one or more lanes closed, total roadway closure with diversions to alternate routes, total roadway closure with diversion routes also impacted. For transit: Service operating with diversions and delays in service, service limited (lines truncated or suspended at some stations/stops); service suspended on entire line/system.

New Jersey Department of Transportation already is using its drainage management system to enable field maintenance personnel to record events that cause roadway closures. New Jersey Department of Transportation, NJ TRANSIT, and local governments should use the results of anecdotal and data-based analysis to refine how climate risk is integrated into asset management practices and procedures, project formulation and design decisions, and day-to-day maintenance and operations.

D.3 Connecticut: Norwalk-Danbury Corridor

Introduction

The regional transportation system vulnerability assessment conducted as part of the Federal Highway Administration's Post-Hurricane Sandy Transportation Resilience Study (Post-Sandy Study) identified 21 potential subarea candidates for a "meso-scopic" assessment of vulnerability and risk as an interim step between regional and asset-specific vulnerability and risk assessments. Stakeholders representing federal, state, regional, and local transportation agencies narrowed down the list to three subareas:

- Communities on barrier islands and lining interior bays along the South Shore of Long Island;
- The communities on the southern edge of Raritan Bay in New Jersey; and
- The Norwalk-Danbury corridor (U.S. 7 and Metro-North Railroad's Danbury Branch) along the Norwalk River in Connecticut.

The regional vulnerability assessment identified the transportation corridor along the Norwalk River in the City of Norwalk and the Town of Wilton as a particularly vulnerable subarea of the regional transportation network. This subarea analysis focuses on the transportation system in the corridor that has been affected by riverine flooding.

The assessment focuses primarily on riverine flooding. The major assets examined include:

- The portion of U.S. Route 7 from I-95 in Norwalk to the Wilton-Ridgefield town line (the expressway section plus portions of Main Avenue and Danbury Road), including the NBI bridges and bridge culverts along the corridor, and
- The Metro-North Railroad Danbury Branch from the CP241 Interlocking at the New Haven Line to the Wilton-Ridgefield town line, stations along this portion of the line (Merritt 7, Wilton, and Cannondale), and the Danbury Branch Dock Yard in Norwalk.

This assessment seeks to determine which portions of the transportation network in the corridor warrant a closer examination over the next 50 years due to the increased risks of damage and disruption associated with climate change, and what adaptation strategies could be appropriate given the magnitude of damage and disruption that could be expected before and after these strategies are implemented.

This subarea assessment generally follows the vulnerability and risk assessment process developed for the Post-Sandy study. See Appendix B - Engineering Informed Adaptation Assessment Process This assessment begins with a summary of climate impacts. The exposure analysis, sensitivity analysis, and adaptive capacity sections of the vulnerability assessment analyze how these climate impacts could affect the transportation assets examined. The risk assessment includes information on likelihood of exposure and consequences associated with exposure to climate stressors. Then, several sets of potential adaptation options are presented for areas with relatively high risks.

Additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through this assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Sensitivity Screening and Climate Impacts

Nor'Easter Alfred in 2011 caused widespread disruption and damage due to downed trees, downed power lines, and other wind-blown debris. Hurricane Irene caused flooding in many Connecticut river and stream valleys. This analysis focuses primarily on riverine flooding, but other climate stressors are shown in Table D.20.

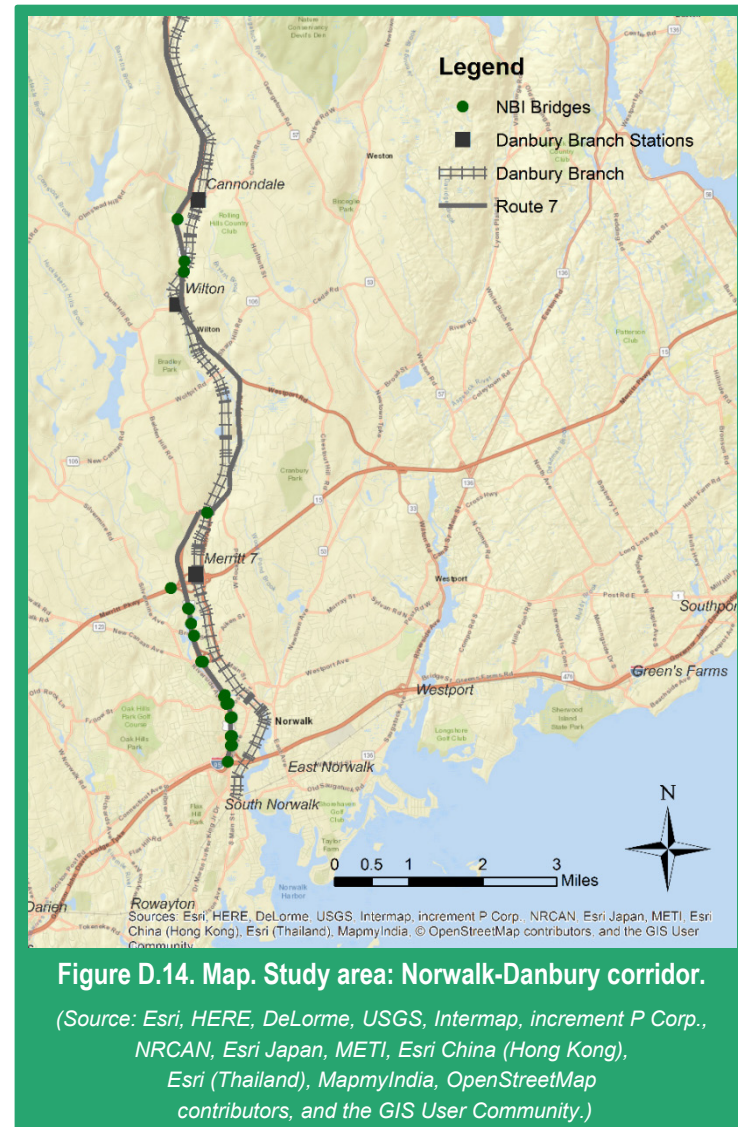


Table D.20. Transportation system sensitivity to climate stressors in the Norwalk-Danbury corridor.

Climate Stressors	Impacts	Relevant Transportation Facilities and Facility Components
Riverine Flooding	Inundation and overtopping Bridge scour due to velocity of water	<ul style="list-style-type: none"> • Low-lying segments of highways and rail track • Stations and park and ride lots • Maintenance, storage, and other facilities • Ground-level electrical power infrastructure • Bridges
Wind	Road and rail closures due to wind-blown debris Wind damage	<ul style="list-style-type: none"> • Roads and rail lines; bridges, culverts, and drainage structures • Signs and buildings (particularly roofs and other components sensitive to wind) • Catenary wires and other power transmission lines (for street lights and signals)
Temperature	Expansion of metal (e.g., rail track, moveable bridges, and catenary wires) during extreme heat events Power outages	<ul style="list-style-type: none"> • Rail lines, including tracks, moveable bridges, catenary, and electrical systems • Moveable bridges on roadways

Current and Projected Climate Scenarios

Precipitation

To examine how precipitation-based flooding risks might change in the future, the project team employed an approach from the FHWA Hydraulic Engineering Circular No. 17, 2nd Edition (HEC-17) report.⁵⁰ The approach involved calculating values for the Climate Change Indicator (CCI), a metric that relates projected

⁵⁰ https://www.fhwa.dot.gov/engineering/hydraulics/pubs/he17_announcement.cfm.

precipitation to historical precipitation while incorporating uncertainty. The CCI can be used to help determine whether practitioners can use historical streamflow information to assess future impacts, or whether they should use precipitation projections to estimate future streamflow.

24-hour precipitation projections were obtained from the Downscaled CMIP3 and CMIP5 Climate Hydrology Projections website for the two grid cells in the area (see Figure D.19) from January 1950 to December 2099.⁵¹ All available CMIP5⁵² projections for each Representative Concentration Pathway (RCP) were used. The CCI was calculated for each grid cell separately and examined the change in precipitation from 2000 (plus and minus 30 years) to 2050 (plus and minus 30 years).

Generalized extreme value distributions were fit to the Annual Maximum Series of 24-hour precipitation events from each downscaled climate model to determine projected 100-year 24-hour event levels. An observed 100-year 24-hour precipitation event estimate, along with its upper-end 90 percent confidence interval value, were obtained from the NOAA Atlas 14 for a station along the corridor (“Norwalk Gas PLT”).^{53,54}

Projected 2050 precipitation was then calculated by subtracting modeled 2000 precipitation from modeled 2050 precipitation and adding this change to the observed 2000 precipitation. The CCI was calculated with the following formula for an observed year of 2000 and projected year of 2050:

$$CCI = \frac{(Projected\ 100\ yr\ 24\ hr\ precip) - (Observed\ 100\ yr\ 24\ hr\ precip)}{(Observed\ upper\ 90\%\ confidence\ 100\ yr\ 24\ hr\ precip) - (Observed\ 100\ yr\ 24\ hr\ precip)}$$

For the average of all models, the CCI values for the two grid cells were 0.35 and 0.37. According to HEC-17, CCI values below 0.4 suggest “that evaluating a project based on the historical confidence limits...will provide a reasonable basis for evaluation project performance.” The CCI values for the average of all RCP 6.0 models were also below 0.4. Thus, historical confidence limits can be used in examining flooding risks in the region for 2050. While the subarea study does not look at specific streamflow levels affecting particular transportation assets, the CCI information can help local practitioners when determining how much additional analysis (e.g., hydraulic modeling) might be needed when further examining a particular asset.

⁵¹ http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

⁵² Coupled Model Intercomparison Project Phase 5.

⁵³ http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=md.

⁵⁴ NOAA documentation on observed precipitation was incomplete for Connecticut due to funding issues. A base year of 2000 was assumed.

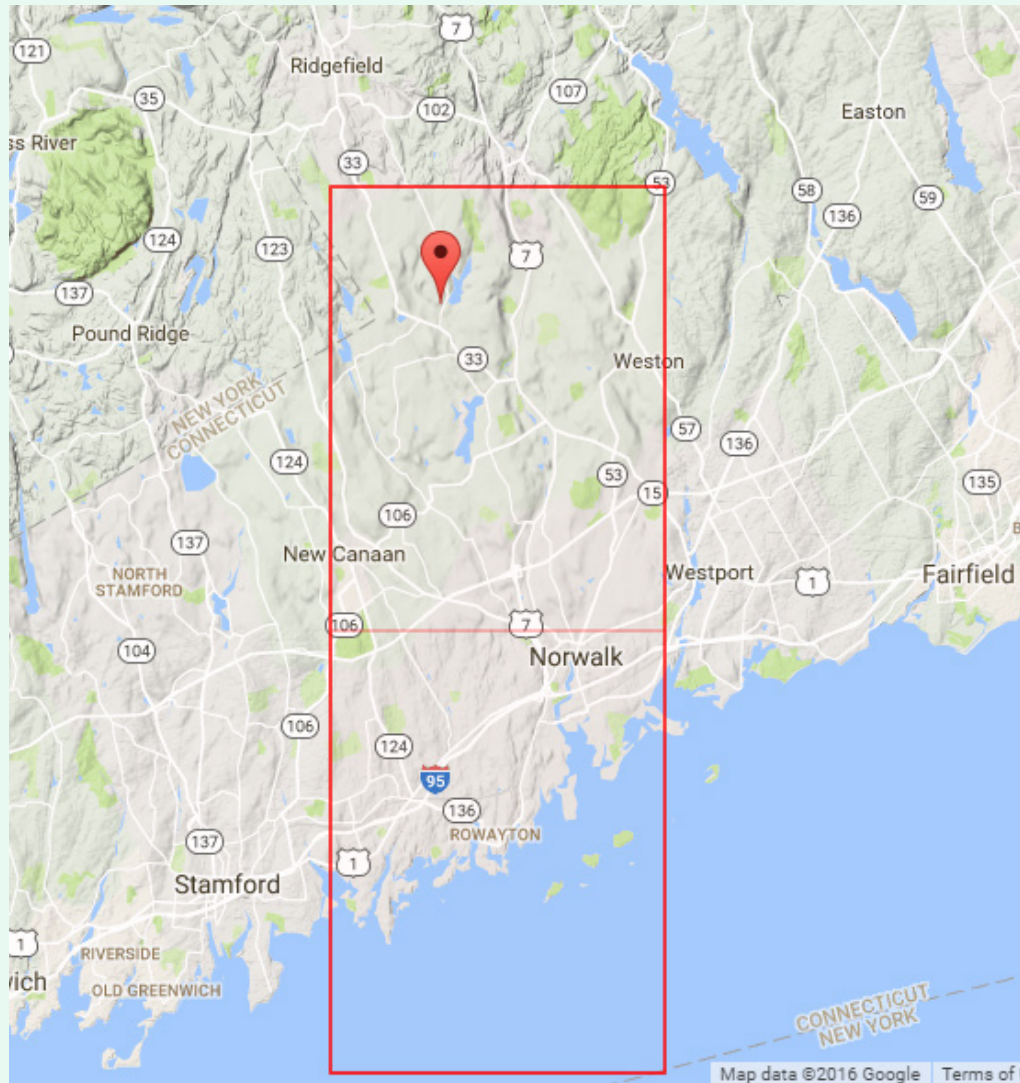


Figure D.15. Map. Downscaled precipitation projections grid cells.

(Source: Downscaled CMIP3 and CMIP5 Climate Hyrdology Projections website: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.)

Vulnerability Assessment: Exposure Analysis

The exposure analysis does not examine the impacts of sea level rise and storm surge, though areas along and near Norwalk Harbor should be considered for these stressors. Analyzing future riverine flooding risks is relatively difficult; while the project team has developed precipitation projections, hydrologic modeling is required to assess how future precipitation changes are likely to affect future flooding changes. This assessment did not include hydrologic modeling, so the project team employed a simpler proxy approach with the National Flood Hazard Layer 100-year and 500-year floodplains representing two different levels of exposure.

Exposure Analysis: Riverine Flooding

Highways, Rail Lines, and Facilities

The shapefiles for Route 7 (i.e., National Highway System shapefile), the Danbury Branch, and transit stations were overlaid on the National Flood Hazard Layer (NFHL) to identify the assets, or stretches of assets that are exposed to riverine flooding. The flood zones are categorized into 3 broad categories, as shown in Table D.21, 100-year flood, 500-year flood, and minimal hazard.

Table D.21. Categories of flood zones (NFHL).

Category	Zone Code
100-year flood	A, AE, AH, AO, VE, Open Water
500-year flood	0.2 PCT ANNUAL C*, 0.2 PCT PANNUAL CH
Minimal hazard	AREA NOT INCLUDED, AREA OF MINIMAL *, D, X

Bridges: Overtopping Risk

For bridges, the attribute information in the National Bridge Inventory (NBI)⁵⁵ was used to assess exposure. NBI Item 71 – Waterway Adequacy – identifies overtopping risks of bridges/culverts. Tables D.23 and D.24 summarize the coding schema for waterway adequacy and overtopping risk. Waterway adequacy codes can have different meanings when they are associated with different NHS functional classes; Table D.22 shows these associations.

The right-hand columns of Table D.23 list the NBI overtopping descriptions for each waterway adequacy category (a through j). The project team regrouped the codes into 6 broad categories – C0, C1, C2, C3, C4, and C5. The left-hand column of Table D.23 shows how these broader categories correspond with the waterway adequacy categories.

⁵⁵ Federal Highway Administration, National Bridge Inventory. Data available for download at <https://www.fhwa.dot.gov/bridge/nbi.cfm>

Table D.22. NBI item 71: Water adequacy.

NBI Item 71 Code	Principal Arterials, Interstates, Freeways, or Expressways	Other Principal and Minor Arterials; Major Collectors	Minor Collectors; Local Roads
N	a	a	a
9	b	b	b
8	c	c	c
7			d
6	d	d	e
5		e	f
4	e	f	g
3	f	g	
2	g, h, i	h, i	i
1			
0	j	j	j

Source: Federal Highway Administration, National Bridge Inventory, Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, 1995. <https://www.fhwa.dot.gov/bridge/mtguide.pdf>.

Note: See Table D.23 for code descriptions corresponding to each letter from a to j.

The definitions for the frequencies of bridge overtopping as used by the NBI Coding Guide are:

- **Remote** – greater than 100 years
- **Slight** – 11 to 100 years

Table D.23. NBI codes for overtopping risk.

Overtopping Risk Code	NBI Code Description
C5	a Bridge not over a waterway.
	b Bridge deck and roadway approaches above flood water elevation (high water), chance of overtopping is remote .
C4	c Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.
	d Slight chance of overtopping bridge deck and roadway approaches.
C3	e Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.
C2	f Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.
C1	g Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.
	h Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.
	i Occasional or frequent overtopping of bridge deck and roadway approaches with severe traffic delays.
C0	j Bridge closed.

- **Occasional** – 3 to 10 years
- **Frequent** – less than 3 years

The definitions for the levels of impacts of bridge overtopping as used by the NBI Coding Guide are:

- **Insignificant** – Minor inconvenience. Highway passable in a matter of hours.
- **Significant** – Traffic delays of up to several days.
- **Severe** – Long term delays to traffic with resulting hardship.

Exposure Analysis: Results

The analysis identified several exposed assets in the study area. The affected transportation assets are grouped into five main exposure areas. Table D.24 summarizes the affected assets in each of the areas, and Figure D.16 shows the exposure information with the exposure area circled. Bridges and culverts are not significantly affected – only three bridge structures are coded C4 (slight overtopping risk), and all other bridge assets are classified as C5 (remote or no overtopping risk).

Table D.24. Exposure areas.

Exposure Areas	Affected Assets
North Cannondale	Affected mainly Route 7, north of Scribner Hill Road.
Cannondale Station Area	Affected both the Danbury branch and Route 7 close to the Cannondale Station Area.
Danbury Rd./Main Ave.	Affected both the Danbury branch and Route 7; along Danbury Road and Main Avenue, but south of Wilton Station.
Merritt 7 Station Area	Affected the Merritt 7 station of the Danbury branch, and the railway and Route 7 close to the station.
Norwalk Harbor Area	Affected mainly the Danbury branch close to the Norwalk Harbor; specifically the stretch between I-95 and route 1. The Danbury Branch Dock Yard does not appear to be in the current 100-year-floodplain and overlaps the 500-year floodplain minimally. ^a

Note: Dock Yard is between Marshall Street (the first street north of where the Danbury Branch leaves the New Have Line) and Science Road (more of a driveway, just north of where the Danbury Branch passes under I-95).

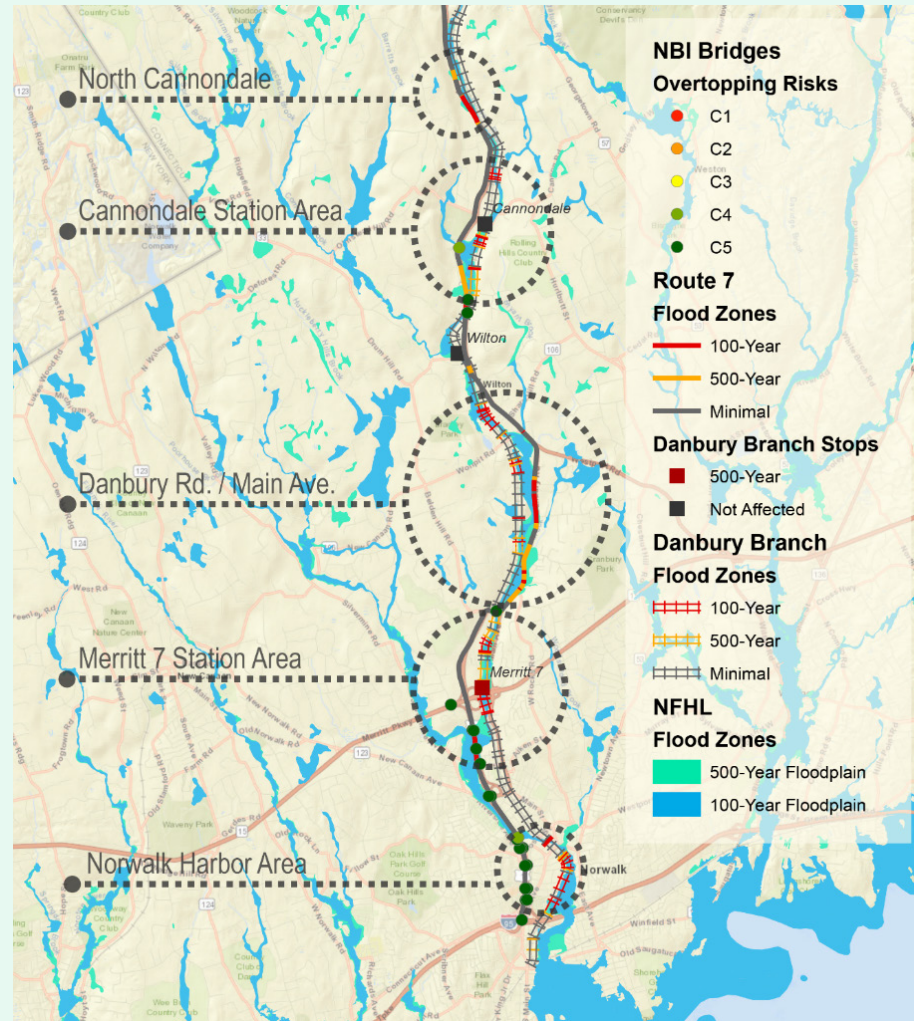


Figure D.16. Map. Summary of exposure analysis.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

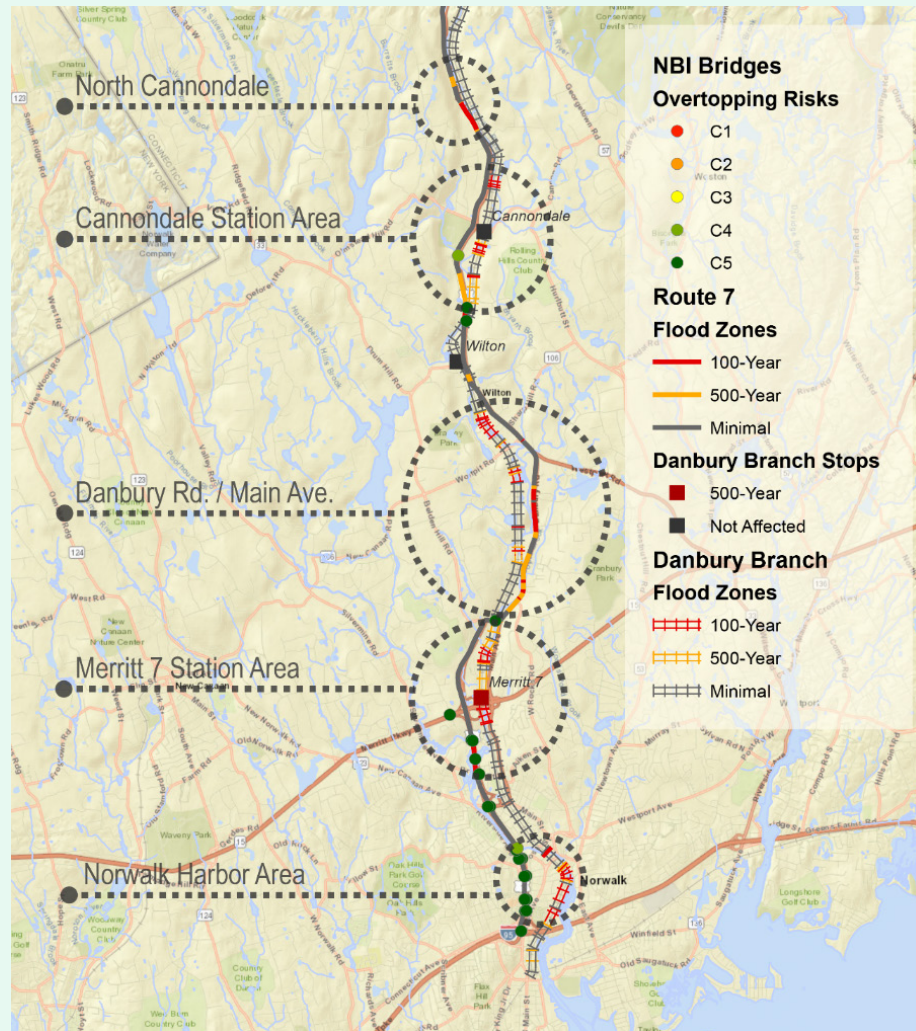


Figure D.17. Map. Exposure areas without National flood hazard layer.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

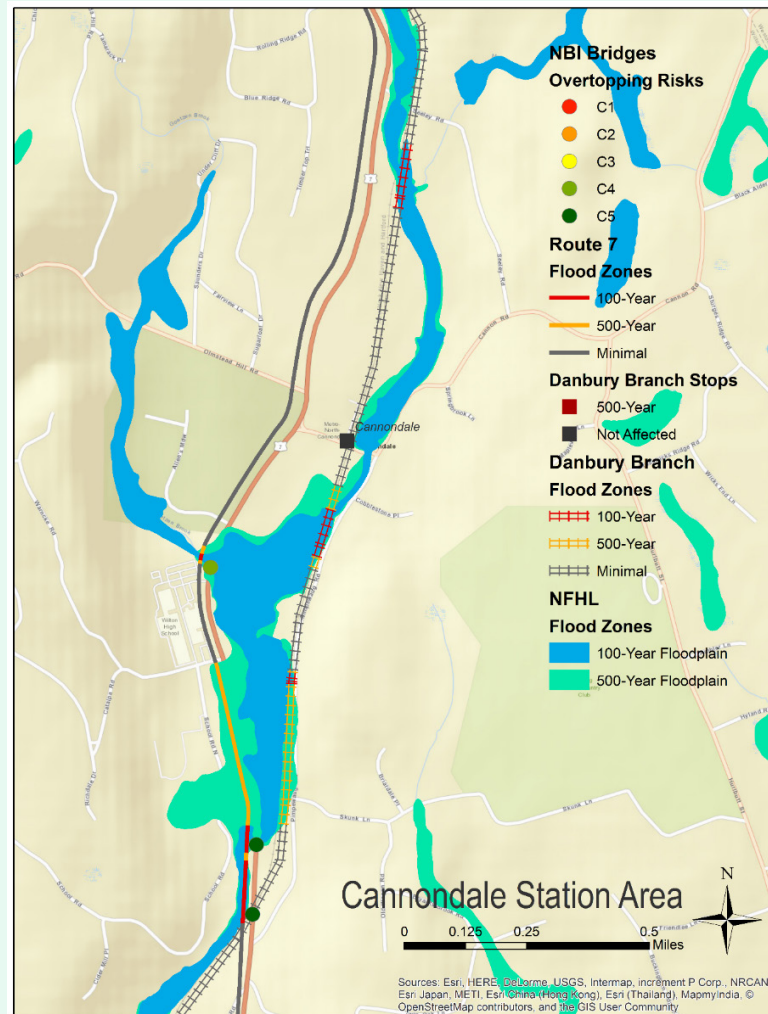


Figure D.18. Map. Cannondale Station area exposure.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

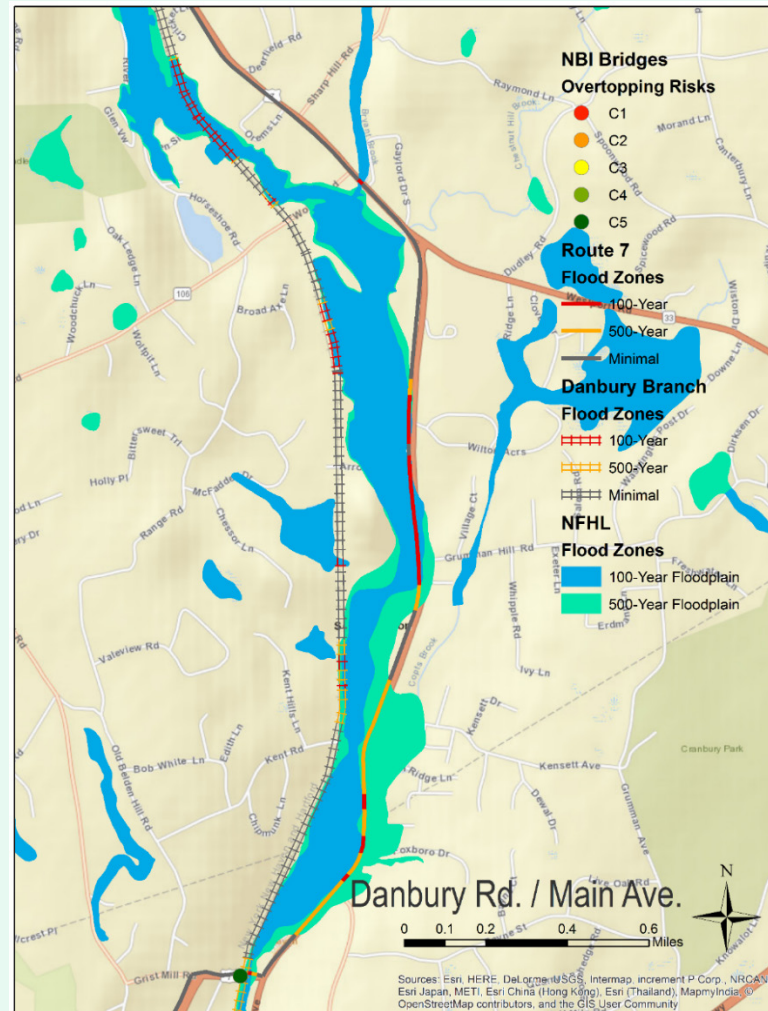


Figure D.19. Map. Danbury Road/Main Avenue area exposure.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

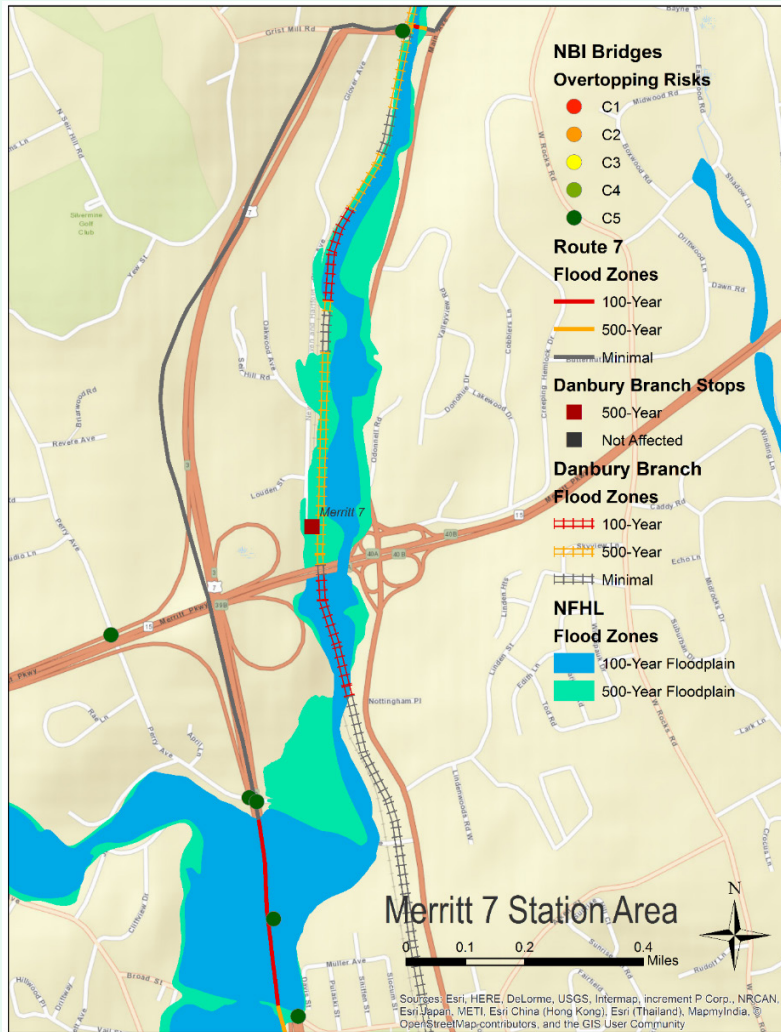


Figure D.20. Map. Merritt 7 Station area exposure.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

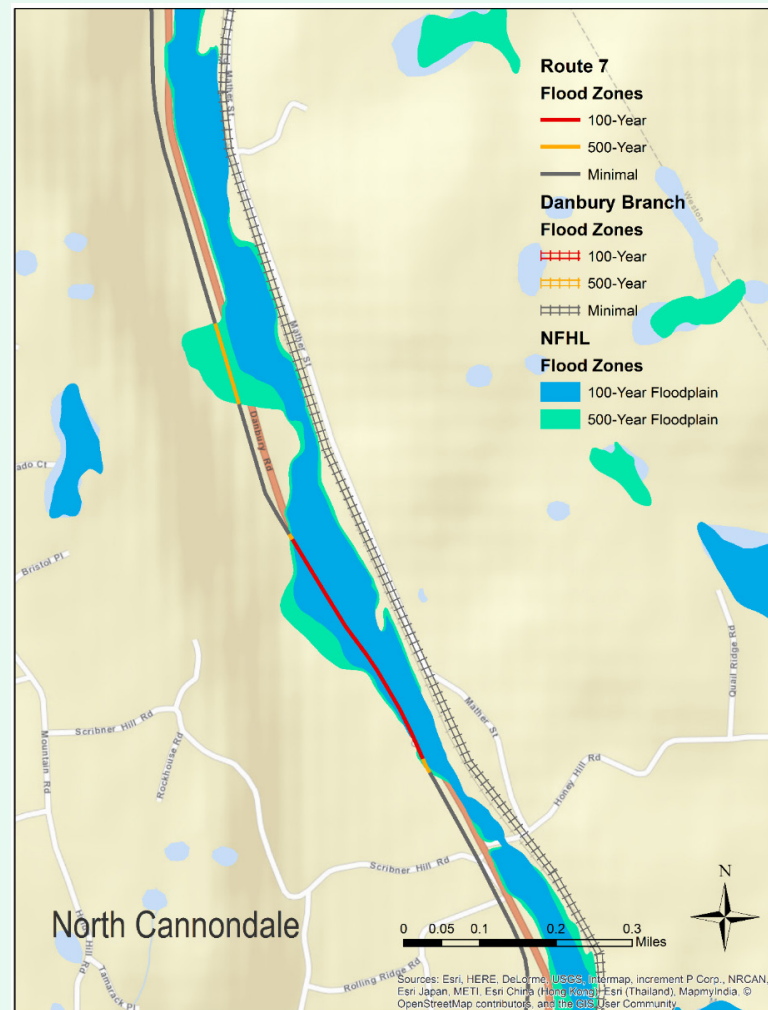


Figure D.21. Map. North Cannondale area exposure.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.



Figure D.22. Map. Norwalk Harbor area exposure.

(Source: Federal Emergency Management Agency (FEMA) National Flood Hazard Layer (NFHL) and Federal Highway Administration, National Bridge Inventory.)

Note: See Table D.23 for Explanation of National Bridge Inventory Overtopping Risk codes.

Past Damage and Disruption

Route 7 has only been shut down temporarily due to flooding-related events twice in the last 30 years, based on interviews of local business owners and newspaper accounts. The flooding events did not elicit emergency roadway repairs or prompt subsequent roadway improvements. The Route 7 bridge superstructures are well higher than the 100-year flood elevations according to the FEMA Flood Profiles. In addition, the NBI shows the foundations for these bridges to be stable for the assessed or calculated scour conditions.

In the study area, the Danbury Branch does not appear to have faced noteworthy instances of flooding. Connecticut stakeholders did mention downed trees on the railway during previous incidents being an issue. Based on available information and the project team's field investigation, the railroad has not experienced recent repairs in response to flooding events. Several railroad bridges are overtopped by the 100-year flood, and one bridge is overtopped during a 50-year flood (near Wilton High School just south of Cannondale station). However, the field investigation did not find evidence of scouring or recent repairs to the bridge structures.

Section 2 of the Post-Sandy Study shows cumulative impacts information on damaged infrastructure, downed trees, flooding, and high winds from Sandy, Irene, Alfred, and Lee. None of the coordinates for these impacts were along the Route 7/Danbury Branch corridor.

Vulnerability Assessment: Sensitivity Analysis

The sensitivity of an asset or component to a given climate stressor depends on three variables:

- Intensity of each event,
- Duration per occurrence, and
- Frequency of occurrence.

There is not a complete record of the extent or cost of damage in past events, and the duration of inundation in past events (and thus the ability to forecast duration of inundation in future events) is also not well-understood. Samples of archived incident reports exist from the regional transportation management coalition.

The analysis in this report focuses on whether or not a transportation asset is likely to get “wet.” In a more detailed, asset-level analysis, a transportation asset owner could use hydrologic modeling to get more information about projected depth of inundation and duration of inundation, which also could be an input to a benefit-cost analysis.

The sensitivity screening matrix in TableD.21 shows several other climate variables to consider. Extreme heat can warp steel rail tracks, with speed restrictions imposed on curves sections of track when temperatures reach 95 degrees and on straight sections of track when temperatures reach 105 degrees. Heat also can

cause catenary wires to sag where constant tension catenary has not been installed, and moveable rail and roadway bridges with metal components can get stuck closed or can fail to reseat themselves in the proper position when closing if the metal expands on hot days, particularly during extended heat waves.

For both inundation and temperature, the sensitivity analysis in this section is binary: either an asset is “wet” or it is not, and either the temperature exceeds a threshold or it does not.

Vulnerability Assessment: Adaptive Capacity

Adaptive capacity is a measure of how well a transportation system can accommodate a closure of one segment of rail line or roadway. This section summarizes the adaptive capacity of the transportation network in the study area. It also addresses consequences associated with disrupting or damaging the network.

- The study team focused mostly primarily on NHS rather than local roads. There is some redundancy in the NHS network on the expressway portion of Route 7, with Main Avenue, Route 123, Route 1, West Avenue, I-95, and the Merritt Parkway providing some redundancy. But adaptive capacity would be much lower north of Grist Mill Road, where there are not any close by parallel NHS facilities. Local roads could provide some options, but a disruption on that portion of Route 7 is likely to cause significant delays.
- The Metro-North Railroad Danbury Branch does not have redundancy with other railways. Norwalk Transit buses could provide some adaptive capacity in the study area, and HARTransit could serve stranded rail customers in the greater Danbury area north of the study area.

Risk Assessment

Risk is a function of likelihood and consequence. Given available information about past damage and disruption, exposure, and climate impacts, the likelihood of the corridor to experience riverine flooding is expected to be similar to the past, when damages have been relatively limited. The upper limit confidence intervals for historic precipitation are expected to be useful values when assessing future precipitation and streamflow. Several portions of the Danbury Branch and Route 7 do lie within the 100-year floodplain but are not expected to experience frequent flooding.

To roughly estimate how exposure (e.g., flooding) would affect the examined assets, the project team looked at Route 7 traffic volume and Danbury Branch ridership in different portions of the study area. In the event of exposure, segments with higher volumes and ridership are assumed to experience higher consequence in the form of disruption.

This approach focuses more on disruption rather than damage. But the field observations and available information on past damage and disruption indicate that damage was relatively limited historically. With the exception of the Danbury Branch Dock Yard, the project team did not locate any key storage or equipment facilities along the corridor.

In the limited access portions of Route 7, from the I-95 interchange at the southern terminus to Grist Mill Road, average daily traffic (ADT) tends to be higher than the unlimited access portions to the north in the northern end of Norwalk and in Wilton. According to maps from ConnDOT, bidirectional 2014 ADT was highest at 65,800 between the I-95 interchange and Exit 1 for U.S. 1/Belden Avenue.⁵⁶ It stayed near that level until Exit 2 for Route 123, where it dropped to the 40,000 to 46,000 range. Grist Mill Road bidirectional ADT was 40,900. At the Norwalk-Wilton border, ADT was 29,400.⁵⁷ In southern Wilton, ADT was 27,400 near the Wilton Metro North station and 23,500 near the Cannondale Metro North station.⁵⁸ ADT dropped to 20,400 at the Wilton-Ridgefield border. Thus, more southern portions of Route 7 in the study area are likely to experience higher disruption consequences.

Danbury Branch ridership was approximately 490,000 in 2015.⁵⁹ Station-specific boarding information was available from 2007. Table D.25 shows weekday inbound station boarding totals. About 60% of the Danbury Branch's 1,182 weekday boardings occurred north of the three stations in this project's study area (Cannondale, Wilton, and Merritt-7). While boardings continue to accumulate farther south closer to where the Danbury Branch joins the New Haven main line, the high proportion of accumulated boardings north of the study area means that disruption consequences are somewhat similar for all the rail segments in the study area. Given Wilton's relatively high number of boardings (and Merritt-7's relatively low number of boardings), the project team considers the segments south of Wilton to have the highest disruption consequences.

The Danbury Branch Phase II Study proposes extending the Danbury Branch much further north – potentially to New Milford, CT or Pittsfield, MA (see Figure D.23).⁶⁰ If this extension occurs, the disruption consequence of the southern portions of the Danbury Branch in the study area will increase considerably.

⁵⁶ <http://www.ct.gov/dot/lib/dot/documents/dpolicy/policymaps/adt/2014expresswaynew15/USRt7Norwalk.pdf>.

⁵⁷ <http://www.ct.gov/dot/lib/dot/documents/dpolicy/policymaps/adt/2007-2014pdf/102adt.pdf>.

⁵⁸ <http://www.ct.gov/dot/lib/dot/documents/dpolicy/policymaps/adt/2007-2014pdf/161adt.pdf>.

⁵⁹ <http://web.mta.info/mta/news/books/docs/2015-MNR-Annual-Ridership-Report.pdf>.

⁶⁰ <http://danburybranchstudy.com/Danbury%20RR%20-%20Final%20Report.pdf>.

Table D.25. 2007 Danbury branch total weekday inbound station boardings.

Station	Boardings	In Study Area?
Danbury	260	No
Bethel	188	No
Redding	58	No
Branchville	209	No
Cannondale	114	Yes
Wilton	232	Yes
Merritt-7	91	Yes
Total Boarding at Exclusively Danbury Branch Stations	1,182	--
South Norwalk (this station is also part of the New Haven main line)	2,189	No

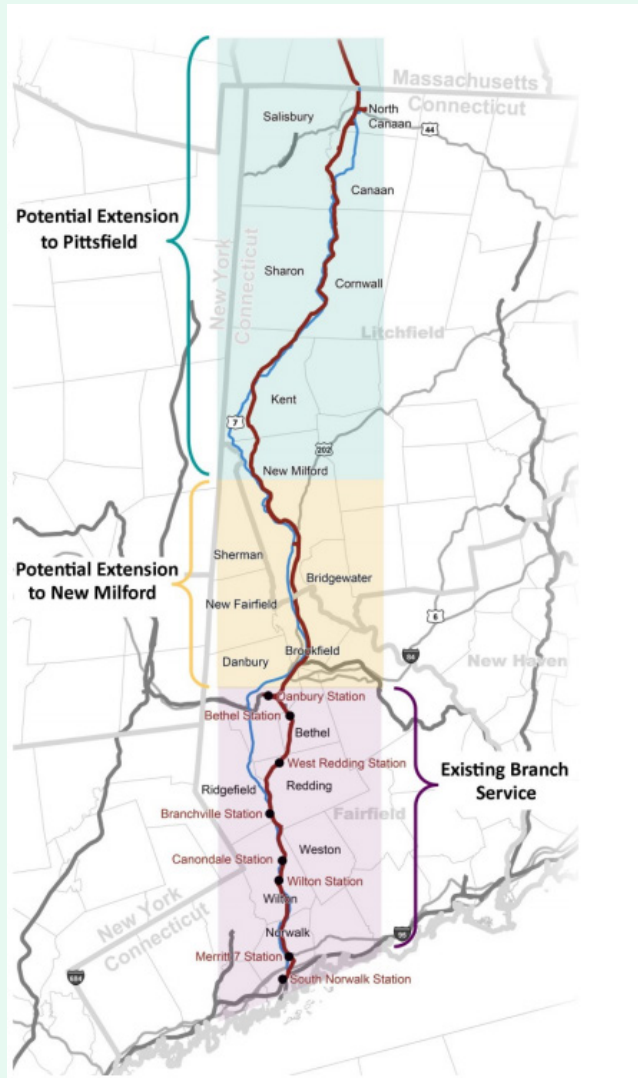


Figure D.23. Map. Potential Danbury branch extension.

Risk Assessment

Overall, climate risks along the corridor are expected to be relatively manageable. Available information suggests that likelihood and consequence are both moderate. Adaptive capacity is limited in the northern portions of the study area, but consequences are also lower there.

The following list identifies some specific vulnerabilities that are higher risk than others examined in the corridor. The list emphasizes relative rather than absolute risks; of the transportation assets and stressors examined, these are the vulnerabilities that practitioners should consider first. Potential vulnerabilities include:

- Disrupted service due to riverine/coastal flooding to portion of Danbury Branch that runs along western bank of Norwalk River between Branch's southern terminus and Wall Street in Norwalk. The Danbury Branch Dock Yard is unlikely to be inundated due to precipitation-based riverine flooding, but the combination of coastal sea level rise and surge (which was not the project team's focus in this corridor) is a potential vulnerability.
- Disruption due to flooding on portions of Route 7 without redundant routes (i.e., north of Grist Mill Road) and on 100-floodplain. E.g., portion of Route 7 that runs along eastern banks of Norwalk River in Wilton near Grumman Hill Road south of intersection with Route 33.
- Combination of (1) point disruption on the Danbury Branch due to flooding or high wind anywhere in the study area that affects passengers from destinations north and (2) lack of adequate contingency plan.
- Disruption on coastal portions of New Haven main line south of Danbury Branch (outside of study area) that strands Danbury Branch passengers.

Adaptation Strategies

Adaptation strategy development should address not only climate risk and its components but also the wider range of risks that agencies face and the broader planning context and goals. Practitioners must address adaptation collaboratively with other agencies studies, projects, and stakeholders. Choosing the right adaptation strategy or strategies for a particular location or system often depends on what strategies are planned or implemented in nearby locations and systems.

Along the Route 7 and Danbury Branch corridor, there are a number of relevant plans and studies. None of these efforts focus on climate adaptation, but each is relevant in considering how the corridor could evolve. Directly relevant plans and studies include:

- Danbury Branch Electrification and follow-up studies on short-term enhancements to the line and stations and longer-term options for extension farther north and electrification.⁶¹
- Route 7 Transportation and Land Use Study, which considers the regional significance of Route 7 and opportunities for improving service along the corridor.⁶²
- Route 7 Corridor Transit Study, which investigates options for enhancing transit along the corridor.⁶³
- Getting Back on Track study of the New Haven Line in Connecticut, which calls for improvements to the line’s power system, control and signaling, and bridges.⁶⁴
- system, control and signaling, and bridges⁶⁵

Adaptation should also consider a practitioner’s risk tolerance. For a practitioner with a lower risk tolerance and a higher appetite for investment, temporary shutdowns might warrant physical adaptation strategies to prevent disruption. But a practitioner with a higher risk tolerance and more constrained financial landscape, vulnerabilities might be better addressed by alleviating disruption through adaptive capacity and soft infrastructure solutions.

The project team created an Adaptation Toolbox (see Appendix B), a compendium of diverse adaptation strategies for different stressors, transportation infrastructure types, investment levels, timeframes, and risk tolerances. The introduction to the Adaptation Toolbox describes how a practitioner might go about identifying potential strategies from it for a particular context.

For the U.S. Route 7 and Danbury Branch corridor, the study team used the Adaption Toolbox and this guidance to select potential strategies that could be considered along the corridor. Table D.26 presents a matrix showing these strategies organized by whether they are more suited for (1) higher risk tolerance and lower investment level versus lower risk tolerance and higher investment levels; and (2) shorter term versus longer term. The matrix is not meant to be a rigid

⁶¹ <http://www.danburybranchstudy.com/index.html>.

⁶² https://westcog.org/wp-content/uploads/2015/09/route7_traffic_report_june2011_appendixontrends.pdf.

⁶³ http://www.envisionroute7.com/document_library/.

⁶⁴ <http://library.rpa.org/pdf/RPA-Getting-Back-on-Track.pdf>.

⁶⁵ <http://library.rpa.org/pdf/RPA-Getting-Back-on-Track.pdf>.

structure; some strategies might appear in multiple quadrants, and some of the quadrants might blend together in some instances. Instead, the matrix is intended to illustrate the range of possible strategies for addressing climate vulnerabilities along the corridor with respect to risk tolerance and timeframe.

Strategies in the upper left quadrant (shorter term, higher risk tolerance) cater more toward managing rather than preventing disruptive events. In the upper right (longer term, higher risk tolerance), strategies are still focused more on adaptive capacity and consequence reduction but also consider issues with physical infrastructure as precipitation and extreme heat increase. Strategies in the bottom left (shorter term, lower risk tolerance) also manage disruption but consider more aggressive approaches and potential infrastructure damages that might arise in the future. Given the relatively low levels of past disruption and damage due to extreme weather along the corridor, the shorter term strategies still do not involve heavy infrastructure overhauls. In the bottom right (longer term, lower risk tolerance), there are some heavier damage and disruption prevention measures and increased redundancy for both the roadway and transit networks.

Table D.26. Examples of potential adaptation strategies for south shore of Raritan Bay.

	Shorter Term	Longer Term
Higher Risk Tolerance/ Lower Investment	<ul style="list-style-type: none"> Update and maintain event notification and response system for roadways, including evacuation routes. Make explicit operational plans for sections of GSP in two highest vulnerability areas. Transit coordination and contingency plan for flooding and high-wind events on Danbury Branch. Should be flexible enough to address different flooding scenarios. Include local bus operators (Norwalk Transit, HARTransit) and Metro North. Consider potential flooding in study area outside study area along New Haven main line. Better tracking of disruption and damage information to inform planning. Use resilience best practices and incorporate SLR projections for new infrastructure projects/ updates that are already planned - work this into existing process. Prune branches and other vegetation susceptible to wind along the major transportation corridors. 	<ul style="list-style-type: none"> Implement flood prevention measures for most vulnerable sections of the corridor. Concrete sealant/surface treatment for surfaces not previously inundated. Cathodic protection for metal elements. Raise or relocate vulnerable electrical/communications assets (related to roadway or transit systems). Erosion control aimed at surface protection (e.g. vegetative cover, mats/blankets) for roadside areas that flood regularly. Revise rail speed guidance given effects of extreme heat on tracks. Consider capacity enhancements for bus transit and road network. More frequent inspection of infrastructure vulnerable to heat (e.g., rail buckling, catenary systems). Increase regular maintenance of drainage ways along the major transportation corridors. Protect equipment in Danbury Branch Dock Yard from SLR and surge.
Lower Risk Tolerance/ Aggressive Investment	<ul style="list-style-type: none"> Investigate and implement flood prevention measures for most vulnerable sections of U.S. 7 and the Danbury Branch, including raising the elevation of vulnerable and high-risk facilities. If NBI info outdated, conduct scour criticality assessment for bridges. Prioritize bridges over the Norwalk River given their high flooding consequences. Enhanced ITS Infrastructure allowing for increased capacity on alternate roadways and demand management by giving up-to-date information to travelers. ITS can better inform event response system. Enhance capacity on North-South evacuation routes leading away from NHS facilities and North Jersey Coast Line in study area. More thoroughly examine SLR and surge implications for Danbury Branch (including Dock Yard) and consider countermeasures. 	<ul style="list-style-type: none"> Implement strategies for better protecting southern end of Danbury Branch from surge – could include enhanced drainage capacity, berms or raising most vulnerable stretch of railway, depending on SLR levels. Berms and other measures in places with frequent flooding. More aggressive erosion control strategies. Further enhance capacity on North-South evacuation routes. Improve bus transit capacity. Enhance electricity infrastructure so that it remains functioning in extreme events and continues to power transit, traffic signals, ITS. Flood-prone land acquisition / incentivized relocation. Enhance capacity on higher ground local road as alternative to U.S. Route 7. Improve bus transit capacity. Enhance electricity infrastructure so that it remains functioning in extreme events and continues to power transit, traffic signals, ITS.

Potential Next Steps

In a multimodal transportation corridor, a package of complementary adaptation strategies can be particularly effective at addressing vulnerability and risk. These strategies can be location-specific, they can affect multiple assets in close proximity, or they can be corridor-scale improvements.

The Norwalk-Danbury corridor is a typical case of a multimodal transportation corridor where flooding has a low likelihood of occurring in any given year, but where the consequences of flooding are high. Connecticut Department of Transportation, Metro-North Railroad, and local governments in the corridor would do well to engage in conversations about risk tolerance and scale adaptation efforts to the level of impact that is acceptable. For example, measures could be put in place to prevent flooding from ever occurring, or infrastructure could be adapted so that it can tolerate periodic flooding without needing extensive repairs.

The findings of this research effort are specific to transportation and are meant to contribute to the discussion of options to help address vulnerability and assess risk for the Norwalk-Danbury Corridor. The optional adaptation strategies listed in Table D.21 should be assessed in the context of risk tolerance and benefit-cost analysis.

There is a shortage of historical information on the extent, duration, and cause of transportation system disruptions, the cost of repairs, and the impacts of disruptions in service. Connecticut Department of Transportation, Metro-North Railroad, local transit operators, counties, and local governments should consider monitoring how inland flooding, extreme heat, wind-blown debris, and other climate stressors are impacting the transportation system in Norwalk-Danbury Corridor and similar corridors around the state over time. They could use this information to inform future vulnerability and risk assessments, help prioritize specific adaptation projects, and inform planning and design work that occurs as capital projects, major rehabilitation projects and normal replacement projects advance through planning and feasibility studies and into preliminary engineering. Information on weather-related incidents that exceed a pre-determined threshold for reporting (similar to crash reporting thresholds) could be collected by first responders and recorded in incident reporting databases and transportation management systems aggregated regionally by TransCOM. The following information would be useful:

- More comprehensive information about the geographic extent and duration of closures and service disruptions on roads, transit lines, and waterways. Extent and duration of major disruptions are collected inconsistently and for a limited portion of the regional highway system by state and local police. Long Island Rail Road maintains its own historical records on rail service disruptions. There is no mechanism to collect and aggregate information at a regional scale on closures and service disruptions for arterials, local road networks, local bus services, and transportation services for communities of concern. There also are no consistently-used tags or indicators in existing reports so that disruptions due to weather events can be flagged, aggregated across all modes at a corridor or regional scale, and analyzed later.
- Primary and (if readily observable) secondary causes of road closures, transit service disruptions, and other incidents. For example, is rail service disrupted due to flooded tracks, or because water inundated a power substation and caused an electrical power failure? While detailed diagnostics and root cause

analyses may take some time to complete after a major event, basic observations can be collected and reported on a standard incident reporting form by first responders (for example, a set of check boxes or drop down menus with pre-defined choices).

- Extent of damage and cost to repair or replace damaged infrastructure or components. Precise cost information may not be available until the repairs are completed, but again a set of simple qualitative choices could be included on an incident reporting form (no damage/minor to moderate damage/severe damage or total destruction).
- Other pertinent information to estimate the impacts of disruption. For example, for roadways: one or more lanes closed, total roadway closure with diversions to alternate routes, total roadway closure with diversion routes also impacted. For transit: Service operating with diversions and delays in service, service limited (lines truncated or suspended at some stations/stops); service suspended on entire line/system.

Connecticut Department of Transportation, the Long Island Rail Road, and local governments should consider using the results of anecdotal and data-based analysis to refine how climate risk is integrated into asset management practices and procedures, project formulation and design decisions, and day-to-day maintenance and operations.

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Engineering Informed Adaptation Assessments



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

Bergen Avenue Engineering Informed Adaptation Assessment

BERGEN AVENUE, WEST BABYLON, NY

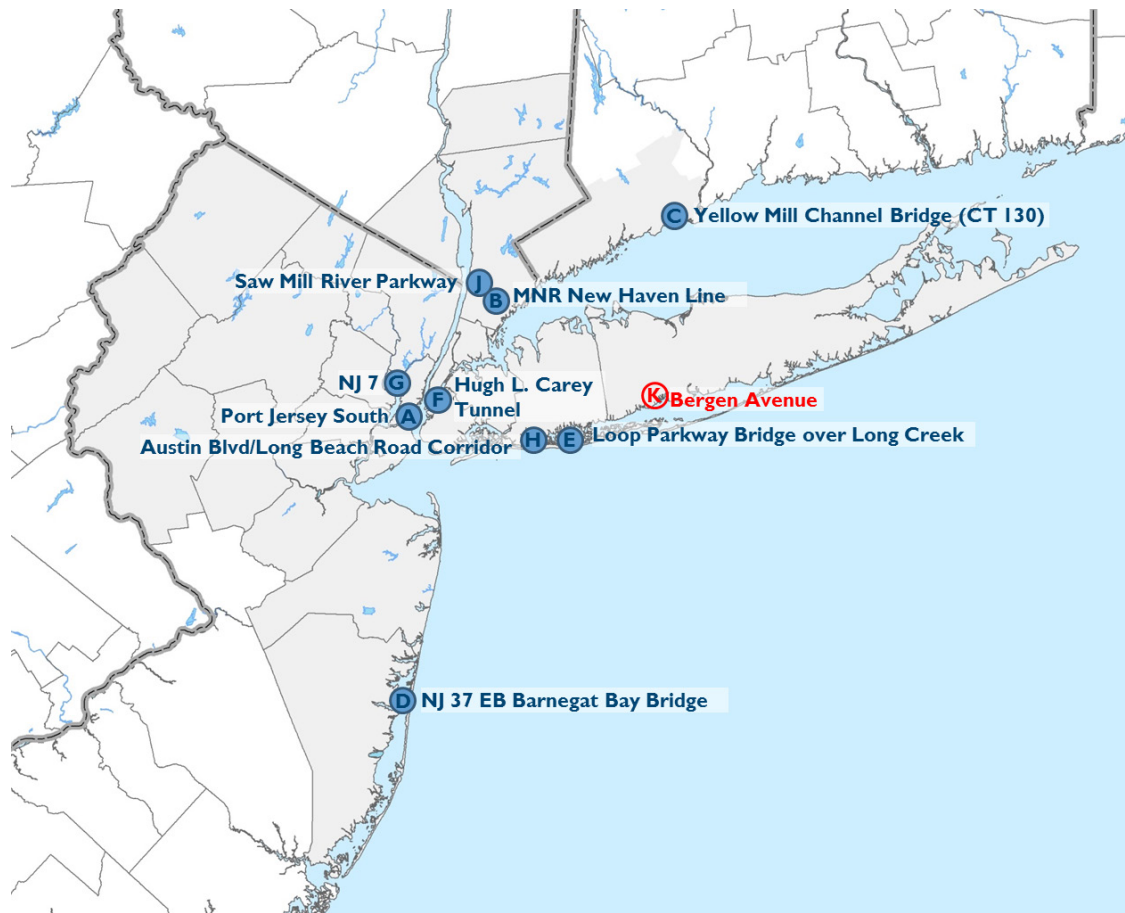
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

Bergen Avenue in West Babylon, NY is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the Bergen Avenue study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities

Figure 1: Context Map for Ten FHWA Study Areas (Bergen Avenue Study Area in Red)



2. FACILITY DESCRIPTION

Bergen Avenue is a roadway under the jurisdiction of Suffolk County. It runs north-south and supports one lane of traffic in each direction. This assessment focuses on a segment of Bergen Avenue between Kirby Lane and its southern terminus at the Bergen Point Wastewater Treatment Plant (WWTP) on the Great South Bay. The Bergen Point Golf Course and the Bergen Point Wastewater Treatment Plant (WWTP) are located to the west of this segment. A marina, residences, and local businesses are situated to the east (see Figure 2).

This segment of Bergen Avenue is low-lying, at an elevation of approximately 3.5 feet above mean sea level (MSL) at the Great South Bay, its terminus (roughly equivalent to 3.14 feet NAVD88¹). Bergen Avenue provides the only access to the WWTP for employees, fuel trucks, and scavenger trucks which unload sludge and waste from other treatment facilities and septic tanks throughout Suffolk County. The WWTP was built in the 1970s at a cost of approximately \$75 Million.² It serves a population of approximately 340,000. It has an average flow capacity of 30 Million Gallons per Day (MGD) and a

¹ NAVD88 stands for the North American Vertical Datum of 1988. According to benchmark data from the National Geodetic Survey for the tide station at Point Lookout, NY, MSL is at an elevation of -0.36 feet NAVD88.

² A similar WWTP today would cost approximately \$700 to \$800 Million to build/relocate, not including the costs of upgrading the wastewater collection system or effluent piping infrastructure that would be required as per current WWTP design guidelines (Source: Suffolk County).

scavenger waste flow capacity of 0.5 MGD. During a storm event, if the WWTP does not have access to electricity, it is able to operate for up to 24 hours using back-up generators, reserve fuel and other supplies stored on site. Once these reserves are exhausted, the plant would have to shut down if they cannot be replenished via Bergen Avenue. While the WWTP has not yet had to halt operations due to an extended closure of Bergen Avenue, this segment was selected for further analysis by Suffolk County in acknowledgement that a future coastal flooding event could potentially cause the roadway to close for more than 24 hours.

The topography of the segment of Bergen Avenue between Kirby Lane and the WWTP is flat. The segment contains curbed and uncurbed sections with paved shoulders. The overall condition of the roadway is fair to good. Daily traffic on this roadway includes approximately 300 vehicles to and from the WWTP, of which at least 100 are scavenger trucks that carry waste to the WWTP for treatment. The rest of the traffic to and from the WWTP includes approximately 100 employee vehicles, 60 construction workers' vehicles, and 40 general public vehicles.³

³ This information was compiled by the project team via phone interviews with representatives from the WWTP.

Figure 2: Bergen Avenue Segment and Access Roads to the Bergen Point Wastewater Treatment Plant



Source: Google Maps, annotated by AECOM, 2015.

Table 1 provides details on the age, condition, and use of the roadway segment.

Table 1: Facility details

Category	Details
Facility Type	Roadway
Facility Component	Roadway Segment
Estimated Age	Roadway segment reconstructed in 1979-1980, resurfaced in 2001.
Estimated Condition	Overall roadway segment: Fair to Good
Use / Ridership	Approximately 300 vehicles/day to WWTP (3,000 total AADT)

Source: Suffolk County.

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

Bergen Avenue currently experiences flooding during major Nor'easters and extreme tidal storms (e.g., Hurricane Irene and Hurricane Sandy), restricting access to the WWTP, residences, and businesses such as the Bergen Point Golf Course. During the Nor'easter events of March 2010 and Hurricane Irene in 2011, Bergen Avenue was completely flooded. When Hurricane Sandy hit in 2012, Bergen Avenue was submerged for a 10-hour period, with up to 4 feet of water at the peak of the storm. This roadway is projected to be impacted by sea level rise (SLR) and storm surge in the future. Therefore, SLR and storm surge were selected for further analysis by Suffolk County.

The scenarios for projected SLR were selected by Suffolk County based on a report developed by the New York State Energy Research and Development Authority (NYSERDA) entitled *Climate Change in New York State* (ClimAID, 2014).⁴ In discussions with Suffolk County, it was agreed to take a low risk tolerance (conservative) approach and examine the high estimate (90th percentile) projections for SLR for mid-century (2050s) and end-of-century (2100s) in this assessment. To account for storm surge, flood elevations from the following two storm types were considered:

- A Hurricane Sandy-equivalent storm, and
- The FEMA 100-year storm (as shown by FEMA's 2009 Flood Insurance Rate Map, or FIRM).

Four combinations of SLR and storm surge were investigated. The high estimates (90th percentile) for the mid-century and end-of-century projections for SLR are 2.5 feet and 6.25 feet, respectively. According to Suffolk County, the observed storm surge height at the WWTP during Hurricane Sandy was 12 feet. Assuming that this recorded height is referenced to MSL⁵, the peak elevation observed during the storm is 11.64 feet NAVD88 (-0.36 feet NAVD88 + 12 feet). The 100-year storm elevation (FEMA Base Flood Elevation, or BFE) ranges from 5 to 7 feet NAVD88. See Table 2 for a summary of this information along with the combined elevations of SLR and storm surge.

⁴ Horton, R., D. Bader, C. Rosenzweig, A. DeGaetano, and W. Solecki. 2014. *Climate Change in New York State: Updating the 2011 ClimAID Climate Risk Information*. New York State Energy Research and Development Authority (NYSERDA), Albany, New York.

⁵ Based on hydrographs from tide gauges in the region, the storm surge observed at the WWTP may have coincided with a higher tidal phase, which would mean that the actual height of the surge above the predicted astronomical tide elevation was lower than 12 feet. However, for the purpose of this assessment, the height of the surge is conservatively assumed to be 12 feet above MSL.

Table 2: Summary of SLR and Storm Surge Levels

Scenario	2050s	2100s
High-Estimate SLR (Feet)	2.5	6.25
Hurricane Sandy-equivalent Storm Elevation (Feet NAVD88)	11.64	11.64
100-year Storm Elevation (Feet NAVD88)	5 to 7	5 to 7
SLR + Hurricane Sandy-equivalent Storm (Feet NAVD88)	14.14	17.89
SLR + 100-year Storm Elevation (Feet NAVD88)	7.5 to 9.5	11.25 to 13.25

Source: NYSERDA and FEMA

Of the SLR scenarios summarized in Table 2, Suffolk County advised that adaptation strategies should focus on the mid-century time horizon.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

Historically, this segment has proven vulnerable to coastal inundation, a risk projected to increase as sea levels rise. The segment could be subject to the following modes of failure:

- 1. Overtopping/Inundation and Physical Damage:** The roadway segment currently experiences overtopping during Nor'easter events and extreme tidal storms. This trend is likely to continue in the future due to progressive sea level rise. The majority of the Bergen Avenue segment between Kirby Lane and the WWTP is below 5 feet NAVD88. Based on the combined mid-century SLR and storm elevations depicted in Table 2, most of the roadway would be submerged during a 100-year storm event (projected flood elevation of 7.5 to 9.5 feet NAVD88) and all of it would be submerged during a Hurricane Sandy-equivalent event (projected flood elevation of 14.14 feet NAVD88). The roadway would also be susceptible to erosion and washout due to its proximity to strong wave action, as indicated by the VE Zone⁶ adjacent to the roadway.
- 2. Service Disruption:** When Bergen Avenue floods during a major Nor'easter event, the duration of flooding is usually 4 to 6 hours during the high tide cycle. During Hurricane Sandy, the disruption due to flooding lasted for approximately 10 hours. In the past, flooding during these events has affected all lanes of the segment in and out of the area, preventing travel to and from the WWTP, residences, and businesses. Closure of the segment means that emergency personnel cannot reach the WWTP, homes, or businesses to respond to medical or other emergencies. In addition to disruption caused by flooding, the potential accumulation of debris on the roadway could further delay the resumption of service.

Hurricane Sandy, the most significant coastal inundation event in the recorded history of the region, did not disrupt operations at the WWTP, even though Bergen Avenue was not accessible. Although trucks were not able to deliver fuel to the WWTP and safety personnel did not have access to the plant during the storm, the WWTP was able to maintain operations due to emergency preparedness efforts. The WWTP maintains a supply of fuel on-site for day-to-day operations, which is replenished approximately once per week by fuel trucks. However, if the WWTP loses electricity (in this instance, due to a storm event), on-site fuel would be diverted to

⁶ A VE Zone in a FEMA FIRM marks areas subject to inundation by the 100-year storm with additional hazards due to storm-induced velocity wave action.

run backup generators, which would draw down the supply much more rapidly. Suffolk County estimates that the generator can operate for up to 24 hours without requiring additional fuel⁷. It is therefore possible that operations at the WWTP could be disrupted if the Bergen Avenue segment remains inaccessible for more than 24 hours, which could result in untreated waste flowing into streets, homes, and bodies of water.

3. **Premature Deterioration:** Prolonged periods of inundation could reduce the lifespan and performance of the surface materials of the roadway segment, increasing maintenance requirements and the likelihood of failure. Additionally, storm surge could wash debris and/or boats from the marina onto the roadway, causing further damage.

Table 3 summarizes estimates of the duration of disruption to the WWTP, based on past and potential future storm events.

Table 3: Estimated Duration of Disrupted Access to the WWTP

Event	Estimated Duration of Disruption
Past Nor'easters	4 to 6 hours
Hurricane Sandy	10 hours
Future Extreme Tidal Storms (with SLR)	Uncertain, but disruption exceeding 24 hours is plausible

Source: Suffolk County.

4.2 ADAPTIVE CAPACITY ANALYSIS

The transportation network which includes Bergen Avenue exhibits a low degree of adaptive capacity. When Bergen Avenue is flooded due to Nor'easters and extreme tidal storms, there are no alternative routes serving the WWTP and other users.⁸ Bergen Avenue provides the only access to the WWTP for employees, fuel trucks, and scavenger trucks, as well as emergency response personnel.

While the adaptive capacity of the local transportation network is low, the WWTP has exhibited a higher degree of adaptive capacity. Scavenger trucks that normally deliver waste to the WWTP on a daily basis can be redirected to an alternative facility in Deer Park, and some deliveries may be deferred until service is restored. When the WWTP loses electricity, operations can be maintained for up to 24 hours, roughly until on-site fuel supplies for backup generators are exhausted. Operations were maintained during the 10-hour loss of roadway access caused by Hurricane Sandy, but future events of potentially greater magnitude (amplified by SLR) could plausibly render the plant inaccessible by truck for more than 24 hours, risking a shutdown of WWTP operations.

⁷ The actual duration will depend on when supplies were last replenished.

⁸ In addition to the WWTP, Bergen Avenue is also the only means of ingress and egress for residences on the old Bergen Avenue, Sandpiper Lane, Dolphin Lane and Angelica Court, as well as businesses such as the Bergen Point Golf Course and the Bergen Point Yacht Basin.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL OR LOCAL MOBILITY

The closure of Bergen Avenue would have no impact on regional mobility. However, it would impact access to the WWTP. Bergen Avenue is the only access route for employees, fuel trucks, and scavenger trucks to the WWTP⁹. Annual average daily traffic on this roadway includes approximately 300 vehicles to and from the WWTP, of which at least 100 are scavenger trucks, 100 are employee vehicles, 60 are construction workers' vehicles, and 40 are general public vehicles.

5.2 EFFECT ON REGIONAL ECONOMY

Although closure of Bergen Avenue would directly impact the WWTP, local residences, and businesses, the mobility-related impacts of this closure would not be regionally significant (in terms of traveler delay or vehicle operating costs). Flooding of the study segment would prevent travel to and from nearly 60¹⁰ homes in the immediate vicinity, located near the north end of Bergen Avenue on Old Bergen Avenue, Sandpiper Lane, Dolphin Lane, and Angelica Court. Similarly, businesses such as the Bergen Point Golf Course and the Bergen Point Yacht Basin may be rendered temporarily inaccessible.

Of greater regional consequence is the WWTP, which serves a population of approximately 340,000 and treats over 30 million gallons of wastewater per day. Loss of access for greater than 24 hours could cause the WWTP to cease operations, resulting in significant regional impacts (e.g., untreated waste flowing into streets, homes and bodies of water).

5.3 EFFECT ON DISADVANTAGED POPULATIONS

Bergen Avenue is the only access route to and from residential streets serving nearly 60 homes. Based on a geospatial analysis of demographic and economic data from the U.S. census for this locality, Bergen Avenue does not provide access to disadvantaged communities.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

Two potential adaptation strategies were initially discussed with Suffolk County to address access to the WWTP due to coastal inundation. The first was to raise Bergen Avenue to an elevation sufficient to retain access during major coastal flooding events. However, this strategy was ruled out because all access points to the roadway (driveways, residential streets, etc.) would need to be reconstructed to meet the new elevation of the roadway, and because existing utility pipes would be subjected to greater weight.

The second strategy was to provide an alternative access route through the Bergen Point Golf Course between Kirby Lane (to the immediate north of the golf course) and the WWTP, following the path of an existing service road. Following scoping discussions with the County, this strategy was selected for assessment because it is less likely to impact surrounding areas.

This strategy is consistent with Suffolk County's low risk tolerance (conservative) approach in ensuring that operations at the WWTP are not disrupted due to the closure of Bergen Avenue. To complement this strategy, the County could also review and, if appropriate, bolster emergency preparedness measures to extend operations beyond 24 hours without requiring access to Bergen Avenue (for example, increasing

⁹ Bergen Avenue also provides sole access to the marina and local businesses and residences in the area.

¹⁰ Based on a review of aerial imagery in Google Maps.

the storage of fuel and other supplies on-site or connecting a protected, off-site generator to the WWTP via underground conduit).

6.1 ALTERNATIVE ACCESS ROUTE

Constructing an alternative access route through the Bergen Point Golf Course between Kirby Lane and the WWTP would allow emergency personnel in and out of the plant in case of an accident or injury and provide access for trucks carrying fuel and waste to keep the plant operational, should a closure of Bergen Avenue lasting greater than 24 hours occur. The route would only be used when Bergen Avenue is out of service. This strategy does not prevent Bergen Avenue from flooding during a storm event, but it would keep the plant operational and ensure the safety of its employees when Bergen Avenue is impassable.

There are existing service roadways through the Bergen Point Golf Course used by golf course maintenance vehicles, one of which connects to Kirby Lane at the north end. This existing route would be repurposed as an emergency access route to the WWTP. A new section would need to be built at the south end of this route to connect the current southern terminus to the parking lot of the WWTP. The proposed 0.75 mile route is highlighted in Figure 3 in red, with the new section identified. However, the grading of the golf course and the location of other existing routes should be examined closely when finalizing the proposed route.

Elevations along the proposed route vary between approximately 3 and 10 feet above MSL (2.64 and 9.64 feet NAVD88), so, in some sections, raised embankments would be required to avoid disruption, depending on the design elevation selected¹¹. Two options for the design elevation of the proposed route are explored, both of which could impact the current usage of the golf course and its layout:

- **Option A:** Design the route to withstand mid-century SLR and Hurricane Sandy-equivalent storms (14.14 feet NAVD88). This conservative design elevation would account for the most severe projected SLR and storm scenario at the site.
- **Option B:** Design the route to withstand mid-century SLR and 100-year storms. The 100-year storm elevation applicable to the proposed route is 5 feet NAVD88. Therefore, the design elevation for mid-century SLR and 100-year storms would be 7.5 feet NAVD88 (not accounting for changes in bathymetry and other factors). While this design elevation would not prevent some degree of inundation/disruption associated with a Hurricane Sandy-equivalent event, it may be adequate to allow passage of vehicles less than 24 hours after such an event, when the floodwaters have partially receded (an inquiry that should be further evaluated during project development).

The design of this route would need to consider the classification of vehicles it will be serving—primarily emergency vehicles and trucks carrying fuel and waste. Commensurately, the service road proposed is 8 feet wide (a standard width for emergency vehicles and trucks for travel in one direction), with a pavement section of approximately 7 inches of asphalt and 1 foot of sub-base. Road materials should meet NYSDOT specifications, and, when possible, blend with the surrounding golf course.

If the roadway is raised to an elevation of 14.14 feet NAVD88 (per Option A), the assumed net average increase will be 7 feet, with recommended side slopes of 1V on 6H for proper stability. If the roadway is raised to 7.5 feet NAVD88 (per Option B), the assumed net average increase will be 2 feet, with recommended side slopes of 1V on 12H. The design should consider the potential for erosion and washout due to wave action, although it is not within a VE Zone (see Figure 3).

¹¹ Specific embankment design criteria should be determined during the detailed design phase of the route.

The route should require minimal maintenance—no more than the normal maintenance required for the surrounding golf course grounds or Bergen Avenue. Central maintenance specifications will likely not need to be updated. The Bergen Point Golf Course is on public land, but privately operated. Therefore, permission would have to be sought to use the golf course as an emergency route. The golf course could remain operational during the majority of construction, provided that most of the construction is carried out during the off-season. If construction should impact normal operation of the golf course, a short-term closure or a temporary rearrangement of holes could be investigated. Golf course management should be involved in the discussion to determine possible feasibility issues associated with this recommendation.

Figure 3: Recommended Route through the Bergen Point Golf Course from Kirby Lane to the Bergen Point Wastewater Treatment Plant (Utilizing an Existing Route)



Source: FEMA Flood Map Service, annotated by AECOM, 2015.

Note: The blue layer indicates the extent of the FEMA 100-year flood zone. The elevation of the 100-year flood plain intersecting portions of the alternative route is 5 feet NAVD88.

6.1.1 ECONOMIC ANALYSIS

The proposed alternative route is not likely to lead to discernable economic benefits or impacts to homes or businesses because it only provides alternative access to the WWTP. While the WWTP is able to operate for up to 24 hours while Bergen Avenue is closed/impassable, the alternative route will play a critical role in ensuring the continuity of the WWTP operations beyond 24 hours, thereby preventing significant potential regional economic costs associated with failure of the facility.

6.1.2 ENVIRONMENTAL ANALYSIS

It is not anticipated that the construction or subsequent maintenance of this route would have any notable negative environmental impacts, but this preliminary conclusion should be evaluated during project development. Given that the route passes through a 100-year flood plain, coordination with FEMA is recommended to evaluate potential impacts to nearby flood zones.

6.1.3 EQUITY ANALYSIS

Given that the proposed alternative route does not directly serve disadvantaged communities or nearby homes, it is assumed that the proposed strategy would not result in direct benefits to disadvantaged communities.

6.1.4 COST ANALYSIS

The estimated costs of designing and constructing the proposed route, consistent with Options A and B as described in Section 6.1, are summarized in Table 4. For the 0.75 mile route, it will cost approximately \$10.2 Million for Option A and \$2.8 Million for Option B. The biggest component in this estimate is the construction cost, to which a 4% annual escalation has been added, assuming that the route will be constructed 5 years from now. This analysis does not include the costs associated with an easement purchase (if an easement is required), or with potential golf course realignment. This cost analysis also does not include potential payments that may need to be made to the Bergen Point Golf Course to compensate for revenue loss while the route is being constructed.

Table 4: Cost estimate for Alternative Route

Cost Component	Option A Cost (\$)	Option B Cost (\$)
Asphalt (7 inches)	1,390 Tons x \$200/Ton = \$278,000	1,390 Tons x \$200/Ton = \$278,000
Sub-base (12 inches)	2,380 Tons x \$50/Ton = \$119,000	2,380 Tons x \$50/Ton = \$119,000
Topsoil	53,590 Cubic Yards x \$120/Cubic Yard = \$6,430,800	9,880 Cubic Yards x \$120/Cubic Yard = \$1,185,600
Excavation (4")	4,110 Cubic Yards x \$45/Cubic Yard = \$184,950	2,350 Cubic Yards x \$45/Cubic Yard = \$105,750
Sod	37,470 Square Yards x \$15/Square Yard = \$562,050	21,200 Square Yards x \$15/Square Yard = \$318,000
Total Construction Cost	\$7,600,000	\$2,010,000
Survey Stake-Out (2% of total construction cost)	\$152,000	\$40,200
Engineering Cost (10% of total construction cost)	\$760,000	\$201,000
Escalation (4% of construction, survey, and engineering/yr for 5 yrs)	\$1,702,400	\$450,240
Total Cost (Rounded)	\$10.2 Million	\$2.8 Million

Source: The construction costs were calculated with unit prices based on the New York State Department of Transportation Pay Item Catalog (PIC), which includes Regional and State-wide average awarded price history as soon as a project has been awarded.

6.1.5 TIMING FOR IMPLEMENTATION

The estimated time for design and permitting is 5 years. Construction will take approximately 1 year. It is assumed that the golf course can remain operational for the majority of construction—likely all but two months. The feasibility of off-season construction and/or temporarily rearranging the layout of the golf course to avoid closure could be investigated by the County.

7. CONCLUSION

This assessment identified existing and potential future vulnerabilities of a segment of Bergen Avenue to flooding from tidal storms and sea level rise. Bergen Avenue serves as the only access route to the Bergen Point Waste Water Treatment Plant for employees, fuel trucks, and scavenger trucks. In the event that Bergen Avenue is rendered inaccessible due to flooding, the WWTP is able to function for up to 24 hours on a backup generator without interrupting normal operations.

This assessment focused on identifying transportation-related strategies to maintain operations if Bergen Avenue should be inaccessible for more than 24 hours. The suggested strategy is construction of an alternative access route via the Bergen Point Golf Course, following an existing service road. Two design elevation options are provided: Option A recommends elevating the route to withstand mid-century SLR and Hurricane Sandy-equivalent storms, which would cost an estimated \$10.2 million. Option B recommends elevating the route to withstand mid-century SLR and 100-year storms, which would cost an estimated \$2.8 million. In both instances, the alternative route would only be used when Bergen Avenue is inaccessible, and access would be limited to vehicles serving the WWTP.

In addition to the proposed alternative route, this assessment also suggests that the County consider complementary emergency preparedness strategies (such as stockpiling more fuel and supplies on site and/or or connecting a protected, off-site generator to the WWTP via underground conduit) to enable operations beyond 24 hours without requiring access via Bergen Avenue.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT – Barnegat Bay Drawbridge Engineering Informed Adaptation Assessment

NJ 37 EB BARNEGAT BAY DRAWBRIDGE (THOMAS A. MATHIS BRIDGE), TOMS RIVER/SEASIDE HEIGHTS, NJ

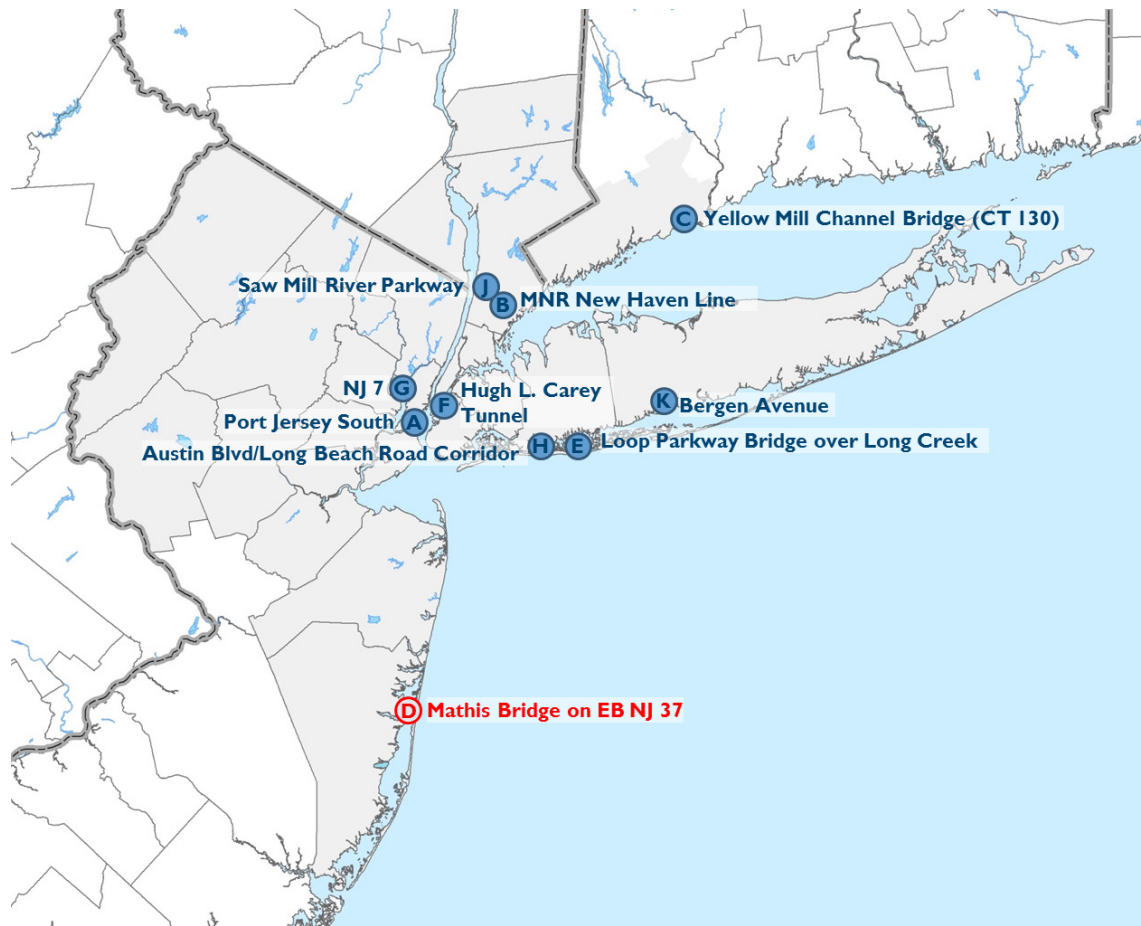
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched an initiative to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Thomas A. Mathis Bridge (Mathis Bridge), on eastbound New Jersey State Route 37 (EB NJ 37) over Barnegat Bay, is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all ten study areas. The Mathis Bridge study area is highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for Ten FHWA Study Areas (Mathis Bridge on EB NJ 37 in Red)

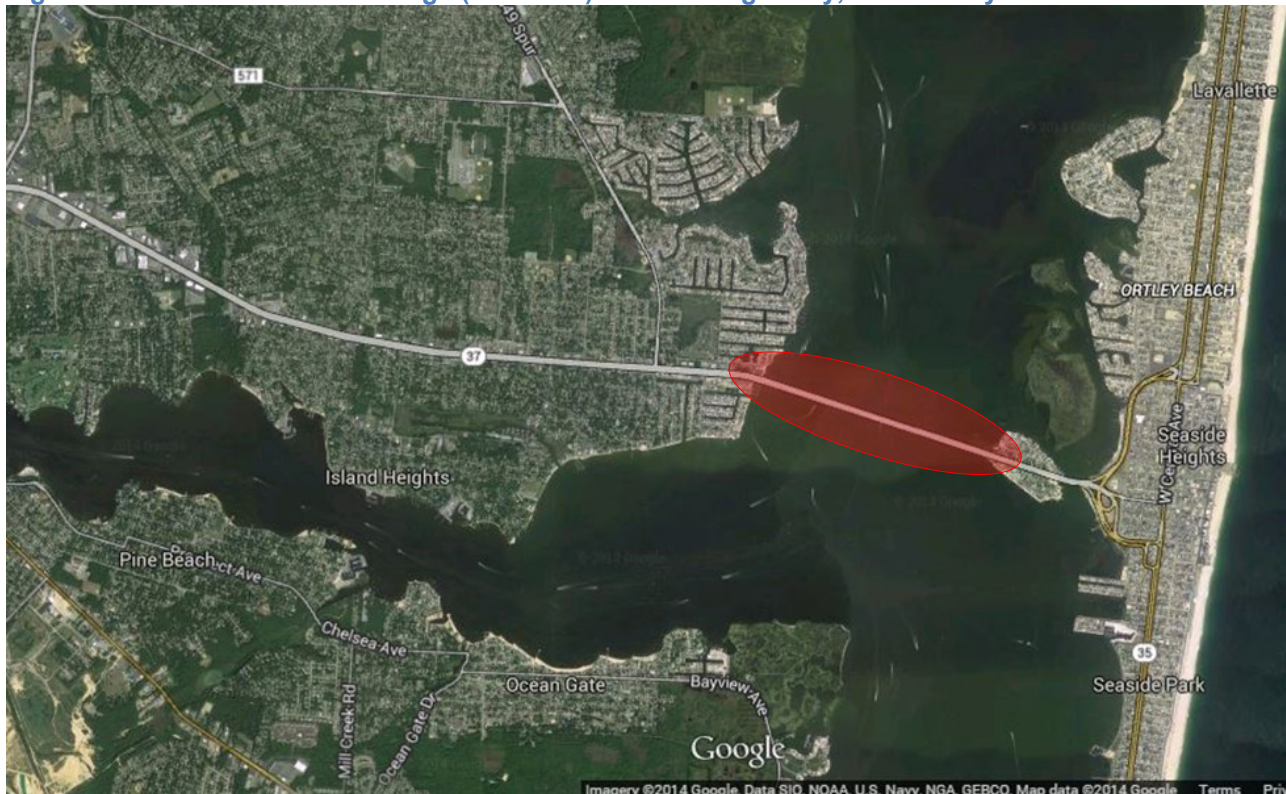


2. FACILITY DESCRIPTION

The Thomas A. Mathis Bridge (National Bridge Inventory (NBI) Structure Number 1508150) is a bascule bridge on EB NJ 37¹ that connects the mainland west of Barnegat Bay with the Barnegat (Island Beach) Peninsula (also called “the barrier island”), including the communities of Seaside Heights, Seaside Park, Ortley Beach, and Lavellette (see Figure 2). NJ 37 is a part of the National Highway System (NHS) network. The bridge is owned and maintained by the New Jersey Department of Transportation (NJDOT). The North Jersey Transportation Planning Authority (NJTPA) is the Metropolitan Planning Organization for this region of New Jersey.

¹ The J. Stanley Tunney Bridge on westbound NJ 37 (WB NJ 37), running parallel to and immediately north of the Mathis Bridge, is not the focus of this assessment.

Figure 2: Thomas A. Mathis Bridge (EB NJ 37) over Barnegat Bay, New Jersey



Source: Google Earth, 2014.

The bridge carries three lanes of vehicular traffic on EB NJ 37. It includes a two-leaf bascule span, flanked by 45 fixed spans at the western approach and 20 fixed spans at the eastern approach. The bridge was constructed in 1950, and various components of the bridge have undergone rehabilitation over the years (e.g., the bridge was refurbished in the mid-1980s and its mechanical and electrical components were replaced in 1989). According to recent NJDOT updates², components of the bridge are in poor to fair structural condition. The deck is in poor condition due to spalling and exposed rebar, cracks, and protruding curb sections. The superstructure and substructure are in fair condition due to corrosion throughout the bascule span and deterioration of pile caps/pier caps, respectively. The mechanical systems located outside the machinery enclosure and the span locks have experienced “extensive deterioration.” Electrical system inspections show that that the gates do not meet current standards, and the control system, motors, generator, switches, conduits, and wiring need replacement. Many of these deficiencies are currently being addressed through an improvement contract, which will be executed in stages during the off season (November 1 – April 30) from 2015 to 2018³.

Mathis Bridge is used by travelers between the mainland and the Peninsula (eastbound only). The bridge has a one-way Annual Average Daily Traffic (AADT) count of 11,140 vehicles (2010), with higher seasonal volumes during the summer months. The bridge also serves truck traffic, with Annual Average Daily Truck Traffic (AADTT) of 445 (4 percent of AADT). There is no dedicated bikeway or pedestrian sidewalk on the bridge (use is prohibited for both bicyclists and pedestrians). NJ 37, including both the

² Construction updates on Mathis Bridge, 2015.

² <<http://www.nj.gov/transportation/commuter/roads/rte37mathisbridge/faq.shtm>>

³ <http://www.nj.gov/transportation/commuter/roads/rte37mathisbridge/staging.shtm>

westbound and eastbound bridges, also serves as a coastal evacuation route from the Peninsula to the mainland.⁴

The bridge also plays an important role in facilitating local maritime activity, as the bascule span must be operational to allow passage to vessels exceeding the navigational vertical clearance (listed by NBI as about 28.9 feet, with no datum cited).

Figure 3: Eastern Approach during Hurricane Sandy (Looking West from Peninsula)



Source: NJTPA

The bridge was selected for assessment because it has demonstrated vulnerabilities to coastal storms that may worsen due to projected sea level increase as the century progresses. Most recently, storm surge from Hurricane Sandy exacerbated pre-existing scour, caused erosion and washout of the bridge's approach embankments, and resulted in the accumulation of debris at the approaches. In response, NJDOT performed emergency structural repairs to the bridge in 2013 and also implemented other long-term projects to address deficiencies previously identified.⁵ Permanent scour countermeasures, consisting of grout bags and A-Jacks systems, were implemented at the eastern piers (including the bascule piers) shortly after Hurricane Sandy, at an estimated cost of \$3 to \$4 million.

In addition, at the time this assessment was conducted in 2015, planning was underway to upgrade the bridge's mechanical and electrical components. Planned mechanical work includes the installation of a hand crank mechanism as well as upgrades to the machinery that lifts the bascule span. Planned

⁴ Both EB and WB NJ 37 routes serve as evacuation routes. WB NJ 37 is the primary route, as the direction of traffic on this route is from the barrier island to the mainland; however, if this route goes out of service, EB NJ 37 is designated as an alternative route.

⁵ See, for example, *Highway Carrying Bridges in New Jersey*, 2007.
<<http://www.state.nj.us/transportation/refdata/bridgereport102007.pdf>>

electrical work includes upgrades to the back-up generator system and replacement of primary electrical systems including roadway lighting, traffic gates, and signals. Other proposed measures include deck replacement for specific spans, safety improvements to the gates and railings, sub-structural and structural steel repairs, bearing replacement, painting, and improvements to guide rails and approaches. In particular, the need for approach roadway work at each end has been identified as critical in order to maintain compatibility between the roadway and the soon-to-be modified bridge deck geometry.

In the context of the emergency repairs performed in the wake of Hurricane Sandy and planned improvements in the imminent future, NJDOT suggested focusing this assessment specifically on issues of debris accumulation and other flooding impacts at the approaches and embankments. Also considered are potential vulnerabilities of the mechanical and electrical components to coastal inundation, of concern particularly given projections for sea level rise. These components are located in two towers on either side of the bascule span. The west tower houses the Operator House and the east tower houses the Gate Tender House. Both towers have a Generator Room, each containing a generator providing power to the lift mechanism, and a Machinery Room, containing mechanical components. The Operator House also has a Control Room.

Table 1 provides details on the age, condition, and use of the bridge.

Table 1: Facility Details

Facility Type	Roadway Bridge with Moveable and Fixed Spans		
Facility Component	Structural	Electrical	Mechanical
Estimated Age	65 years	26 years	26 years
Condition Rating	Poor/Fair	Good	Good
Estimated Remaining Life	50 years	25 years	25 years
Use (2010)	AADT: 11,140 vehicles AADTT: 445 vehicles as a subset of AADT (4% of AADT) Annual bridge openings for vessels: Not known ⁶ Vessel traffic: Not known		

Source: *Electrical and Mechanical Rehabilitation NJDOT Construction Contract, 1989 and NJDOT/NJTPA, 2014.*

⁶ Not considered material to the specific objectives of this assessment.

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

The Mathis Bridge is exposed to periodic Nor’easters and hurricanes (the bridge was adversely affected by Hurricane Sandy), which, among other potential impacts, may lead to debris accumulation and other flooding impacts at the approaches and embankments. These risks may worsen due to projected sea level rise (SLR) in the course of the bridge’s estimated useful life.

3.1 SEA LEVEL RISE

The scenarios for projected SLR selected by NJDOT are based on a recent NJDOT/NJTPA vulnerability assessment (the “Pilot”), funded in part by FHWA⁷. The scenarios are summarized in Table 2. Following the Pilot approach, the mid-estimate SLR scenario was applied in this assessment.

Table 2: Projected Sea Level Rise Scenarios (Middle Estimate⁸)

Year	Subsidence (feet)		Regional SLR (feet)		Relative SLR (feet)
2050s	0.26	+	0.93	=	1.19
2100s	0.60	+	3.33	=	3.93

Source: *Climate Change Vulnerability and Risk Assessment of New Jersey’s Transportation Infrastructure*, 2011.

3.2 STORM SURGE

The Federal Emergency Management Agency’s (FEMA) 1-percent (100-year) annual chance flood, sourced from the Preliminary Flood Insurance Rate Map (FIRM) for Ocean County, NJ, was selected to account for storm surge. The 1-percent annual chance flood elevation, also known as the Base Flood Elevation (BFE)⁹, ranges from 7 to 10 feet NAVD88¹⁰ on the western end of the bridge (see Figure 4) and 8 to 10 feet NAVD88 on the eastern end of the bridge (see Figure 5), corresponding with AE and VE zones¹¹ respectively. These values are summarized in Table 3. The project team used the BFE corresponding to the VE zone (10 feet NAVD88), represented with pink shading, as it accounts for wave action.¹² A red dashed line indicates the Mathis Bridge (the westbound Tunney Bridge, which is not indicated, is immediately north).

⁷ http://www.njtpa.org/Planning/Regional-Studies/Recently-Completed-Studies/Vulnerability-and-Risk-Assessment-of-NJ-Transporta/FHWAConceptualModel/CCVR_REPORT_FINAL_4_2_12_ENTIRE.aspx

⁸ A1B emissions scenario, ensemble of selected General Circulation Models.

⁹ As the elevations considered are from a Preliminary (i.e., not yet effective) FIRM, the “BFE” is not official and is cited for illustrative purposes only.

¹⁰ NAVD88 stands for North American Vertical Datum of 1988.

¹¹ VE zones represent areas subject to high velocity wave action (a 3-foot breaking wave). AE zones, while still high risk flooding areas, are not subject to high velocity wave action.

¹² While the flood elevation during Hurricane Sandy was not recorded at the bridge site, recordings from the tide gauge at the Battery (in New York City) show that the flood elevation exceeded 11.2 feet NAVD88 during Hurricane Sandy, which is greater than the BFE estimates of 7 to 10 feet NAVD88 at the bridge.

Figure 4: Preliminary FIRM at the Mathis Bridge (Western End)



Figure 5: Preliminary FIRM at the Mathis Bridge (Eastern End)



Source (both): FEMA Region II Coastal Analysis and Mapping for Ocean County
<<http://apps.femadata.com/preliminaryviewer/?appid=98d40c43cc2548c8877ea408086b0ac9>>

Table 3: Base Flood Elevations at/around the Mathis Bridge

Location	BFE Range (Feet NAVD88)	Selected BFE (Feet NAVD88)
Western Approach	7 (AE Zone) to 10 (VE Zone)	10
Eastern Approach	8 (AE Zone) to 10 (VE Zone)	10

Source: FEMA

3.3 SEA LEVEL RISE + STORM SURGE

Table 4 shows projected flood elevations resulting from the combination of SLR and the Base Flood Elevation. The scenarios do not account for changes in bathymetry (e.g., they represent the simple addition of SLR and surge elevations, not remodeled surge heights). Given that the bridge will reach its expected design life by approximately 2065, only the mid-century combination was used to identify potential vulnerabilities, described in the next section.

Table 4: Combined Projections for SLR and BFE

Analysis Year	Relative SLR (Feet)		BFE (feet NAVD88)	=	Combined Elevation (feet NAVD88)
2050s	1.19	+	10	=	11.19
2100s	3.93	+	10	=	13.93

Source: FEMA

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

As noted in previous sections, historically the bridge has been exposed to Nor'easters and hurricanes, and most recently sustained damage during Hurricane Sandy. Based on sea level rise projections, the bridge may be increasingly subject to the following modes of failure associated with coastal inundation:

Physical Damage: Hurricane Sandy caused significant inundation of the bridge's approaches, leading to the accumulation of large amounts of waterborne debris (see Figure 3). The bridge's eastern approach has an estimated¹³ minimum elevation of 6 feet above the Mean Lower Low Water (MLLW) level of Barnegat Bay (equivalent to 3.39 feet NAVD88¹⁴). Although the western approach's minimum elevation could not be ascertained based on drawings provided by NJDOT and should be verified, it appears to be similar (and is almost certainly below projected flood elevations). The combination of mid-century SLR and a 100-year flooding event yields water levels of 11.19 feet NAVD88. At its lowest elevation, the eastern approach would be overtopped by an estimated 7.8 feet.

¹³ The original bridge drawings, dating from 1949, do not specify the vertical datum, but do list Mean Low Water at EL +0.4. For the purposes of this assessment, it was assumed that EL 0 corresponds to Mean Lower Low Water. The vertical datum should be confirmed as part of any subsequent, more detailed investigation, especially as sea level change and local subsidence have likely shifted these reference elevations over the course of 66 years.

¹⁴ According to benchmark data from the NOAA tide station at Atlantic City, NJ, MLLW is at an elevation of -2.61 feet NAVD88. <<http://tidesandcurrents.noaa.gov/datums.html?id=8534720>>

Figure 7 shows the Mathis Bridge divided into two segments for display purposes, which together cover the eastern section of the bridge. Segment 1 (top) commences at the bascule span and proceeds east, toward the Peninsula, where it is overlapped by Segment 2 (bottom), which follows the approach farther eastward to the roadway on Pelican Island. A significant portion of the eastern approach is projected to be inundated by the mid-century, 100-year flood.

Figure 9 shows the western section of the bridge in three segments. Segment 1 (bottom) commences at the bascule span and proceeds west towards Segment 2 (middle), which in turn proceeds towards Segment 3 (top), and includes the approach on the west side of the bridge. A significant portion of the western approach is also projected to be inundated by the mid-century, 100-year flood.

The mid-century, 100-year flood could damage the approaches and embankments, as well as the structural components of the bridge closest to the approaches. Overtopping of the approaches could cause erosion and instability of roadway beds and embankments¹⁵. Waterborne debris could cause structural damage by impacting or lodging against and beneath the bridge. Damage to bridge bearings or displacements of the bridge superstructure could result¹⁶. If debris is not removed, it could result in obstructions that alter flows and increase flow velocities in and around the piers, increasing the potential for scour. Other bridge components that could be sensitive to debris include piers and abutments (which are a part of the substructure), superstructure, and ancillary components such as utilities and light poles.

The bascule towers of the bridge's moveable span were minimally impacted by Hurricane Sandy. The bottom floor of both towers experienced minor flooding, but equipment was not damaged. Nor has flooding from previous storm events compromised equipment, meaning that the bascule span has remained operational, allowing marine traffic to pass through without interruption.

The Generator Room and Machinery Room in both towers are located at 20.66 feet NAVD88 and 24.04 feet NAVD88, respectively (equivalent to 23.27 feet above MLLW and 26.65 feet above MLLW). The Control Room in the west tower (the Operator House) is located at 39.09 feet NAVD88 (41.70 feet above MLLW). Given the projected mid-century SLR + 100-year storm elevation of 11.19 feet NAVD88, these rooms are not likely to be flooded in the foreseeable future. Figure 6 provides a graphical depiction of projected SLR and 100-year storm elevations at the west tower.

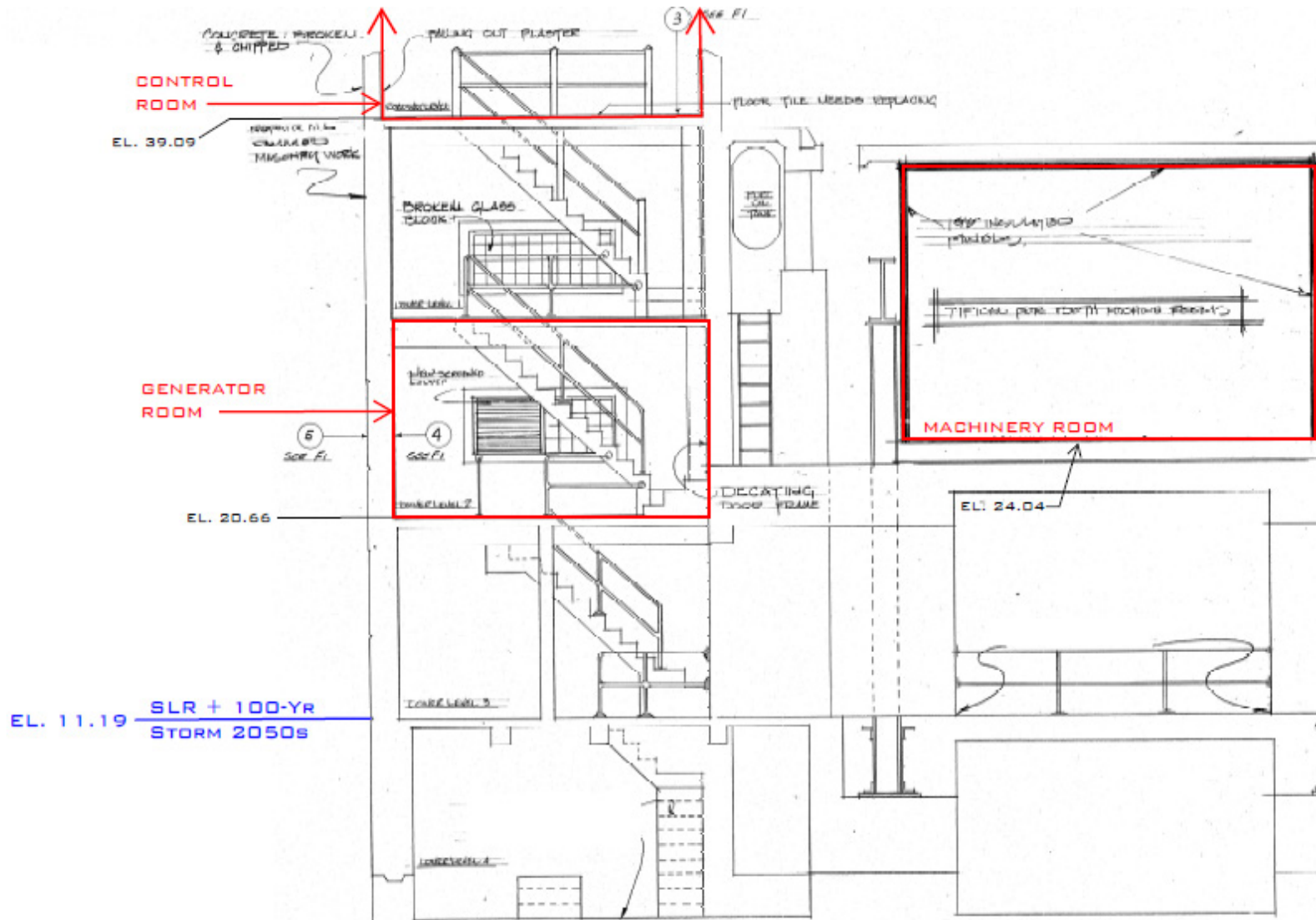
Service Disruption: Impacts to the approaches due to overtopping, erosion, and debris accumulation (as described previously) would disrupt eastbound traffic operations. In the wake of Hurricane Sandy, the Mathis Bridge was closed to the public for over a month—primarily to limit general access to the Peninsula, both for public safety and to avoid impeding emergency operations, repair work, and debris removal. For this assessment, the estimated duration of service disruption associated with post-storm inspections and debris removal ranges from 2 to 7 days. The estimated duration of disruption associated with structural repairs, if required, ranges from 2 weeks to 2 months.

Premature Deterioration: Based on an assessment of the age and current condition of the bridge and its components (see Table 1), as well as recently completed or planned repairs, the bridge is expected to be in operation until approximately 2065. However, flooding of greater frequency and/or magnitude could accelerate deterioration of the bridge and its components.

¹⁵ A slope stability analysis would be needed to more definitively make this determination.

¹⁶ For more details on the impacts to the bridge structure and components from debris forces, a structural assessment would be necessary. Field condition inspections would be needed to consider and account for existing structural conditions.

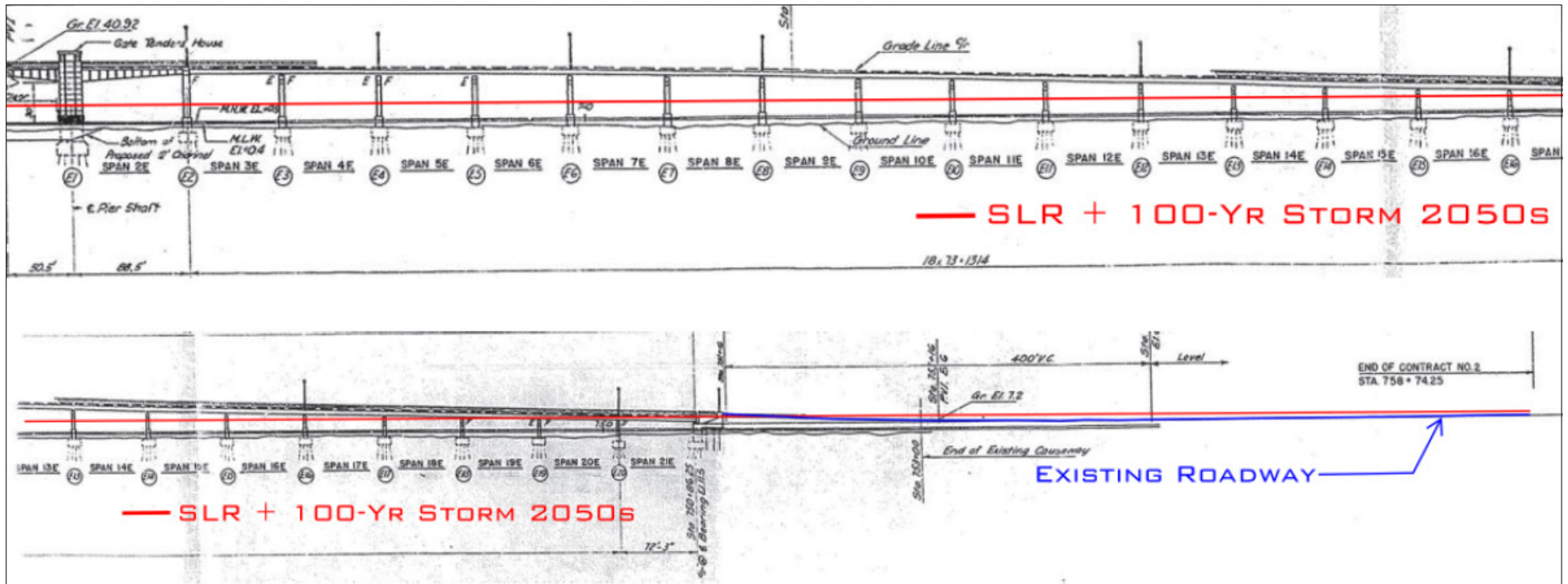
Figure 6: Mathis Bridge, Projected Mid-Century, 100-year Flood (with SLR) and elevations of West Bascule Tower



Source: Route 37 Mathis Br - Misc Mech_Elec Repairs, NJDOT, 1989 and AECOM, 2014.

Note: All elevations are referenced to the NAVD88 datum.

Figure 7: Mathis Bridge Eastern End Projected Mid-Century, 100-year Flood (with SLR)



Top: Segment 1, proceeding east from the bascule span to Span 17E. Bottom: Segment 2, continuing from Span 13E farther eastward to Pelican Island.

Source (Figures 7 and 8): Route 37 1927 Contract 2 Seaside Heights Bridge Superstructure, NJDOT, 1949 and AECOM, 2014.

Note: The Thomas A. Mathis Bridge was previously known as the Seaside Heights Bridge.

Figure 8: Mathis Bridge, Location of Bridge Segments Shown in Figure 7 Relative to Entire Bridge (Shaded)

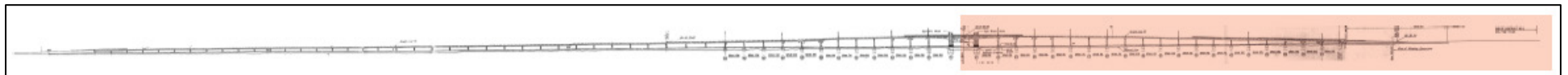
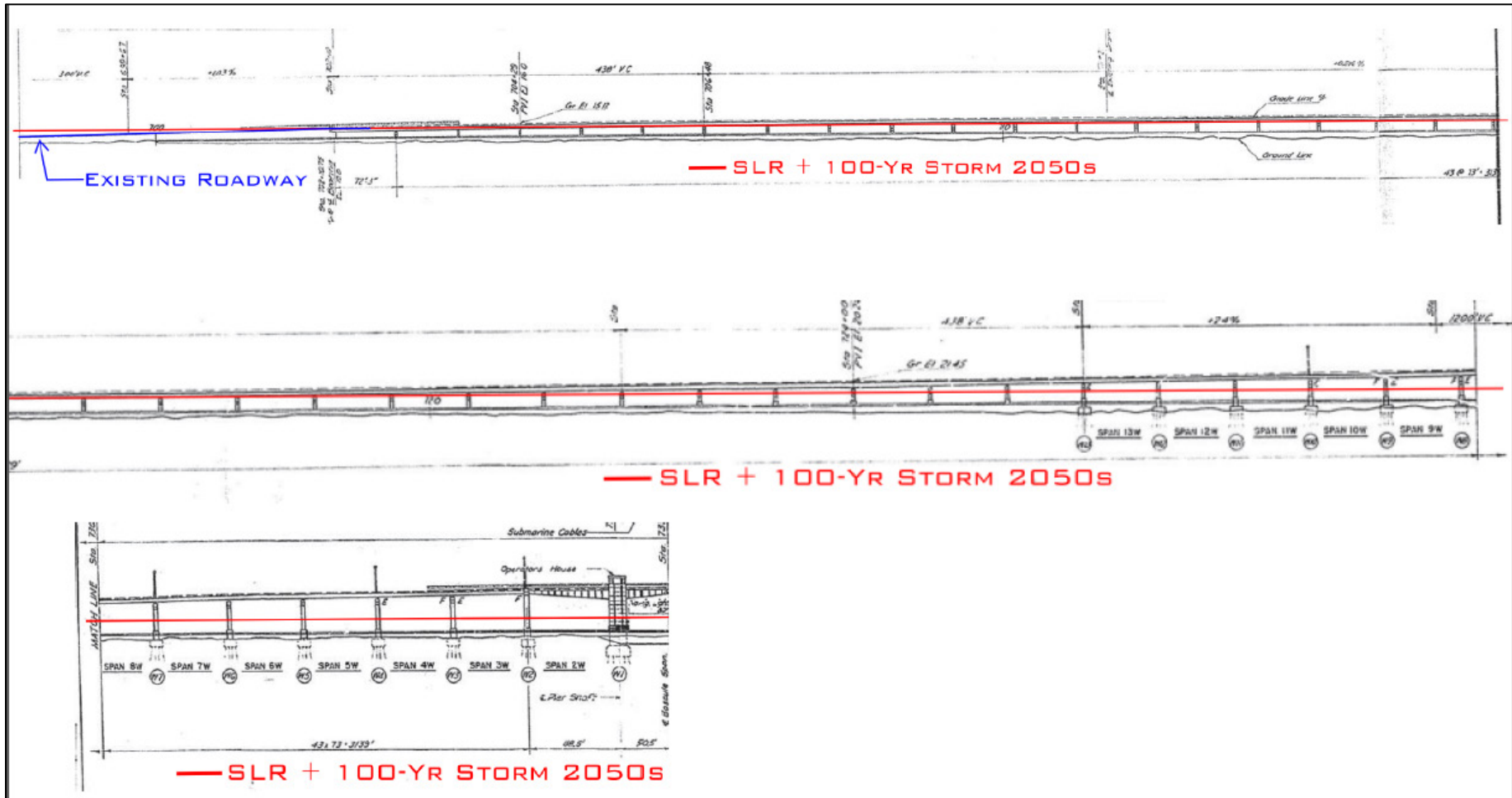


Figure 9: Mathis Bridge Western End Projected Mid-Century, 100-year Flood (with SLR)



Bottom: Segment 1, west from the bascule span to Span 8W. Middle: Segment 2, continuing west from Span 8W. Top: Segment 3, continuing west to the approach roadway on the mainland.
 Source (Figures 9 and 10): Route 37 1927 Contract 3 Seaside Heights Bridge Superstructure, NJDOT, 1949 and AECOM, 2014.

Figure 10: Mathis Bridge, Location of Bridge Segments Shown in Figure 9 Relative to Entire Bridge (Shaded)

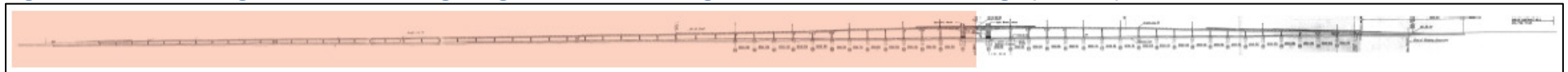


Table 5 provides estimates of the repair cost and recovery time for restoring bridge operations after a flooding event. The repair costs are informed by NJDOT’s weighted unit prices for typical bridge rehabilitation and replacement work items. After a major coastal storm, once floodwaters recede, it is likely to take 2 days to complete a clean-up and start assessment of the bridge condition. Assuming no structural damage has occurred, operations likely can resume within 2-7 days. However, if the post-storm inspection reveals that structural damage has occurred, then it may take 2 weeks to 2 months for the crossing to reopen, depending on the nature of the repairs.

Table 5: Mid-Century 100-Year Flood, Estimated Component Repair Cost and Recovery Time

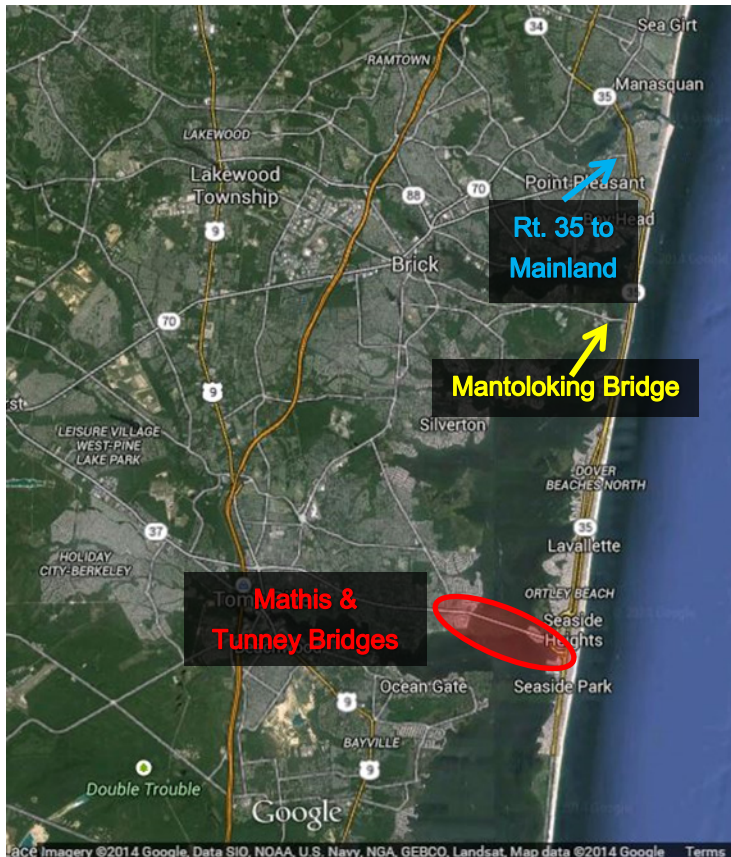
Time and Cost	Magnitude
Estimated Repair Cost	Electrical/Mechanical Repair: <ul style="list-style-type: none"> • None (no impacts expected) Roadway Debris Clean Up/Condition Assessment: <ul style="list-style-type: none"> • \$25,000 to \$150,000 Structural Repair: <ul style="list-style-type: none"> • \$100,000 to \$750,000
Estimated Recovery Time	Electrical/Mechanical Repair: <ul style="list-style-type: none"> • None (no impacts expected) Roadway Debris Clean Up/Condition Assessment: <ul style="list-style-type: none"> • 2 to 7 days Structural Repair: <ul style="list-style-type: none"> • 2 weeks to 2 months

Source: NJDOT Weighted Unit Prices for typical Bridge Rehabilitation and Replacement Work Items

3.2 ADAPTIVE CAPACITY ANALYSIS

The transportation network exhibits some degree of adaptive capacity. The J. Stanley Tunney Bridge—the westbound span directly north of the Thomas A. Mathis Bridge—is newer, wider, and has greater vertical clearance (it does not require a bascule span to meet clearance requirements). To facilitate post-disaster relief and debris removal, one or more of the Tunney Bridge’s three lanes temporarily could be operated in the reverse direction (eastbound) if the Mathis Bridge is out of service. North of NJ 37, two other routes connect the Peninsula with the mainland (see Figure 11). The Mantoloking Bridge (County Route 528) provides access across Barnegat Bay to inland points, and NJ 35 connects directly to the mainland. Both would require significant detours, particularly for origins and destinations south of the Mathis Bridge. These two routes were adversely affected by Hurricane Sandy—particularly Route 35, which facilitates north-south travel along the Peninsula—but were not evaluated for potential vulnerabilities as part of this assessment. Figure 12 depicts the impacts of Hurricane Sandy on the Mantoloking Bridge and Route 35, which not only resulted in costly repairs but also completely disrupted travel.

Figure 11: Mathis Bridge Potential Alternative Routes to/from the Mainland



Source: Google Earth, 2014

Figure 12: Damage from Hurricane Sandy to Mantoloking Bridge and Route 35



Source: Route 35 Reconstruction Project – NJDOT

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of the Mathis Bridge would restrict mobility between the Peninsula and the mainland. The bridge has an AADT (one-way) of 11,140, of which AADTT is 445. Volumes are significantly higher during summer months. The Mantoloking Bridge and NJ Route 35 provide alternative connections between the Peninsula and the mainland. The Mantoloking Bridge is 7 miles north and the NJ Route 35 crossing is 10 miles north. If these routes remain in service during a closure of the Mathis Bridge, these detours likely would be heavily congested, especially during summer months, adding significantly to normal travel times.

5.2 EFFECT ON REGIONAL ECONOMY

An analysis of the effect on the regional economy was not performed on this assessment due to resource constraints.

5.3 EFFECT ON DISADVANTAGED POPULATIONS

An investigation of potential impacts to disadvantaged populations associated with closure of the Mathis Bridge was not performed as part of this assessment due to resource constraints.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This section highlights options to address the vulnerability of the bridge's approaches and other components to debris accumulation and damage associated with major coastal storms, which may increase in frequency and severity due to projected sea level rise.

Although the approaches also may be vulnerable to overtopping, this issue was not evaluated due to resource constraints, although strategies for mitigating debris accumulation may also provide ancillary flood protection benefits.

6.1 INSTALL FENDER SYSTEMS TO PROTECT APPROACHES AND ROADWAY APPURTENANCES FROM WATERBORNE DEBRIS DAMAGE

This strategy focuses on protecting the bridge approaches and other associated components from waterborne debris by installing a fender system (or systems) to deflect 1) floating debris, which could accumulate on the roadway approaches during a storm event, and 2) heavy debris, which could cause damage to the bridge abutments. The fender systems would be designed both to absorb the force of an impacting object and to direct the object away from sensitive bridge components along the roadway approaches. A detailed analysis would be required to determine the suitability and requirements for each fender system option presented subsequently.

To prevent the accumulation of debris on the bridge's approaches and abutments, options include the installation of vertical sheet pile walls extending above the approach roadway surface, the creation of earthen berms, or the installation of pile fender systems.

Pile Fender Systems: Pile fender systems comprise an integrated array of piles that are installed forward of a vulnerable bridge approach to limit debris passage. To be effective, the array of pilings would need to extend above the projected flood elevation, with each pile appropriately spaced. Depending on the spacing of the piles, netting may be required to capture smaller debris.

Vertical sheet pile walls: Sheet piles are thin, interlocking sections of steel, commonly used in marine environments to create a continuous barrier. In the proposed application, the vertical face of the wall would be exposed on the roadway side (creating the impression of a partially depressed roadway for drivers), while the other face of the wall would be covered with riprap (rock rubble) to provide stability. This type of fender system is likely to be more costly than a non-continuous piling system, although it also could be designed to provide ancillary flood protection benefits.

Earthen Berms: Earthen berms are constructed mounds composed predominantly of natural materials. In the proposed application, the berm footprint would likely extend beyond the existing highway boundaries and may require right-of-way (ROW) acquisition or property easements. Earthen berms can also be designed to provide ancillary flood protection benefits, but attaining sufficient elevation would add considerable cost. To reduce the potential for washout and scour, the core of the earthen berm could include vertical sheet pilings to strengthen and protect the embankment.

6.1.1 ECONOMIC ANALYSIS

An economic analysis was not performed for these strategies due to resource constraints.

6.1.2 ENVIRONMENTAL ANALYSIS

Potentially, the options presented may have adverse impacts on adjoining private property and cultural, coastal, and wetland resources. In order to evaluate and compare the environmental impacts of these options in detail, site-specific analyses would be required. These analyses likely would include architectural and cultural assessments, land use and coastal waterfront evaluations, hydraulic analyses, and habitat and wetlands impact studies.

6.1.3 EQUITY CRITERIA ANALYSIS

An analysis of potential impacts to disadvantaged populations associated with closure of the Mathis Bridge was not performed as part of this assessment due to resource constraints.

6.1.4 COST ANALYSIS

The likely cost components of each strategy are shown in Table 6. These costs do not include permitting, ROW acquisition, or property easements, if required.

The length of the abutment and approach areas at the western and eastern ends of the Mathis Bridge were approximated using Google Maps, and are delineated below in Figure 13 and Figure 14. The delineation was extended to include the approaches of the Tunney Bridge as well, under the practical assumption that, if this strategy were to be implemented, it would make sense to protect the abutments and approaches of both bridges.

Table 6: Estimated Cost Components for Strategy Options

Cost Components	Pile Fender System (\$)	Vertical Sheet Piles (\$)	Berms (\$)
Cost of Field Condition Inspections	\$75,000	\$75,000	\$75,000
Cost of Environmental Studies	\$75,000	\$100,000	\$150,000
Cost of Fender System*	\$500,000**	\$1,500,000	\$1,250,000
Cost of Storm Resilient Upgrades – Embankment Stability	\$75,000	Not applicable	Not applicable
20% Construction Contingency	\$145,000	\$335,000	\$295,000
Total Construction Cost:	\$870,000	\$2,010,000	\$1,770,000
Mobilization/Construction Survey (4% of Construction Cost)	\$34,800	\$80,400	\$70,800
Engineering Cost (13% of Construction Cost)	\$113,100	\$261,300	\$230,100
Escalation (4% for 4 Years)	\$139,200	\$321,600	\$283,200
Total Cost (Rounded)	\$1.2 Million	\$2.7 Million	\$2.4 Million

*Cost estimate assumptions are shown in Table 7.

**Cost does not include netting system.

Source: AECOM, 2015. Cost estimates are provided in 2015\$ and are approximate only.

The assumptions used to develop the estimates in Table 6 are detailed below in Table 7.

Table 7: Cost Estimate Assumptions

Type of Fender System	Length of Abutment and Approach Area	Unit Costs (\$)	Total Cost (\$)
Pile Fender Systems	1500 Feet (equivalent to ~333 piles with a spacing of 4.5 feet)	\$1500/Pile	\$500,000
Vertical Sheet Piles	1500 Feet	~\$1000/Linear Foot (\$75/Square foot x 12.5 feet of height)	\$1,500,000
Earthen Berms	1500 Feet	\$400/Linear Foot (\$300/Linear Foot of Riprap + \$100/Linear Foot of Fill) *2.1 cubic yards / linear foot	\$1,250,000

Source: AECOM, 2015. Cost estimates are provided in 2015\$

Figure 13: Delineation of Abutments and Approaches, west end of Mathis and Tunney Bridges



Figure 14: Delineation of Abutment and Approaches, east end of Mathis and Tunney Bridges



Source (both figures): Google Maps, 2015.

6.1.5 TIMING FOR IMPLEMENTATION

Because the Mathis Bridge is currently vulnerable to debris accumulation and damage—and debris protection is not included in currently contracted improvements—preparations for more detailed study and, as warranted, implementation could be considered in the near term. The design and permitting process is estimated to take approximately 1- 2 years. Construction likely would take up to a year to complete.

7. CONCLUSION

This assessment considered potential vulnerabilities of the Mathis Bridge to major (100-year) coastal storms by mid-century, with primary emphasis on the impacts of waterborne debris. To address the potential for debris accumulation and damage, the installation of fender systems was investigated. This strategy focuses on protecting the bridge approaches and other components from waterborne debris by installing a fender system (or systems) to deflect 1) floating debris, which could accumulate on the roadway approaches during a storm event, and/or 2) heavy debris, which could cause damage to the bridge approaches and abutments. Vertical sheet pile walls, earthen berms, and pile fender systems were considered. A detailed analysis would be required to determine the suitability and requirements for each.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

Hugh L. Carey Tunnel Engineering Informed Adaptation Assessment

GOVERNORS ISLAND VENTILATION BUILDING, THE HUGH L. CAREY TUNNEL (I-478), NEW YORK, NY

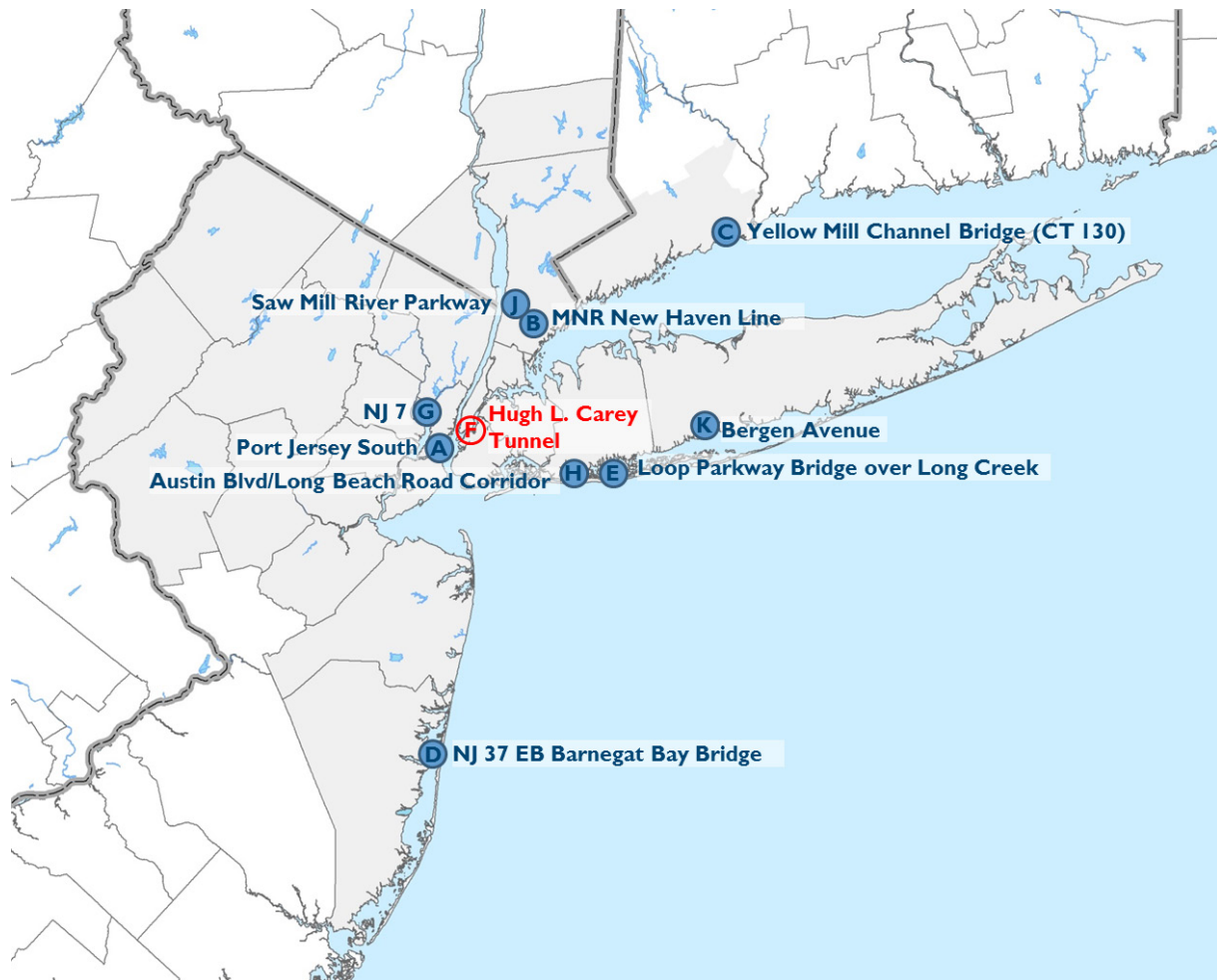
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Hugh L. Carey Tunnel site is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the Hugh L. Carey Tunnel study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for 10 FHWA Study Areas (Hugh L. Carey Tunnel Study Area in Red)



2. FACILITY DESCRIPTION

The Governors Island Ventilation Building (GIVB) is one of four ventilation buildings serving the Hugh L. Carey Tunnel (HLCT, formerly known as the Brooklyn Battery Tunnel), which was constructed in the 1940s and opened to traffic in 1950. The HLCT is an approximately 1.7-mile long road tunnel under the jurisdiction of MTA Bridges and Tunnels (an affiliate agency of the Metropolitan Transportation Authority, or MTA), and connects Lower Manhattan with Brooklyn (see Figure 2). The HLCT is a critical transportation asset heavily used by commuters and other travellers between Manhattan and Brooklyn, with an Annual Average Daily Traffic (AADT) of 46,606 (2013). It also serves truck traffic with an Annual Average Daily Truck Traffic (AADTT) of 2,047 and bus traffic with a daily traffic count of 1,475 (2013).¹

Past extreme weather events (notably Hurricane Sandy) have highlighted the tunnel's current and potential future vulnerabilities to coastal inundation. The HLCT was in good condition until it was damaged by Hurricane Sandy, during which it was flooded with approximately 60 million gallons of contaminated salt water. Floodwater entered from the Manhattan portal, submerging approximately 65% of the tunnel and destroying 65% of the lighting.

¹ MTA Bridges and Tunnels

The GIVB is the focus of this assessment. It was selected because its functionality is critical to the operation of the HLCT, and other critical components of the HLCT, such as other ventilation buildings and the Manhattan and Brooklyn portals, are already under study to address the coastal flooding risks. The GIVB provides critical ventilation services to the HLCT by pulling vehicle emissions out and pumping fresh air into the tunnel, exchanging the air every 90 seconds.

During Hurricane Sandy, water came within approximately one foot of the top of the existing GIVB seawall (elevation of 9.6 feet NAVD88).² While the existing GIVB seawall was not overtopped, future Sea Level Rise (SLR) is projected to heighten the risk associated with severe storm surge as the century progresses. Accordingly, MTA Bridges and Tunnels requested that the study team assess raising the existing seawall based on projected mid- and end-of-century sea level rise (SLR) and storm surge.

Table 1 provides details on the condition, lifespan, and use of the GIVB and HLCT.

Table 1: Facility details

Category	Details
Facility Type	Hugh L. Carey Tunnel (HLCT, Roadway Tunnel)
Facility Component	Governors Island Ventilation Building (GIVB)
Estimated Age	63 years (This estimate applies to the GIVB and HLCT)
Estimated condition	Fair to Good (This ranking applies to the GIVB)
HLCT Use / Ridership	AADT: 46,606 (2013) AADTT: 2,047 as a subset of AADT (2013) Daily Bus Traffic Count: 1,475 as a subset of AADT (2013)

Source: MTA Bridge and Tunnels

² For comparison, the Highest Observed Water Level (HOWL) at the Battery tide station associated with Hurricane Sandy was 11.27 feet NAVD88.

Figure 2: Governors Island Ventilation Building and Hugh L. Carey Tunnel



Note: The red dotted line shows the location of the Governors Island Ventilation Building. The red oval shape indicates the approximate location of the Hugh L. Carey Tunnel. Google basemap, 2015.

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

Although the GIVB seawall was not overtopped during Hurricane Sandy, a storm of similar magnitude on top of future SLR could cause overtopping of the existing seawall, which could damage critical structural, mechanical and electrical systems.

Projections for SLR considered in this assessment are summarized in Table 2. The MTA selected climate change projections from the New York City Panel on Climate Change (NPCC) *Climate Risk Information* draft memorandum (NPCC2, 2013) to identify scenarios for this assessment³. MTA agreed that this assessment would consider SLR values in the 25th, 75th, and 90th percentiles, which equate to approximately 0.9, 1.8, and 2.5 feet respectively by mid-century (2050), and 1.8, 4.2 and 6.3 feet respectively by the end of the century (2100), relative to a baseline year range of 2000–2004.

³ This draft memorandum, issued in December 2013, updates SLR projections from the subsequently cited NPCC Climate Risk Information 2013 report, issued in June 2013. The draft memorandum is referenced as “NPCC2.” http://www.nyc.gov/html/planyc2030/downloads/pdf/NPCC2_Climate%20Methods%20Memorandum_2013.pdf

Table 2: Sea Level Rise Projections

Horizon	Low Estimate (10 th percentile)	Mid-Range (25 th to 75 th percentile)	High Estimate (90 th percentile)
Mid-century	0.7 feet	0.9 to 1.8 feet	2.5 feet
End-of-Century	1.3 feet	1.8 to 4.2 feet	6.3 feet

Source: NPCC2, 2013. "Draft NPCC2 Climate Risk Information 2013."

To account for storm surge, FEMA's Preliminary Flood Insurance Rate Maps (PFIRMS) and FEMA's Flood Insurance Study (FIS) were referenced. These sources are not directly comparable, although both provide valuable information. The FIS provides Stillwater Elevations (SWEL) and wave setup, whereas the PFIRM provides Base Flood Elevations (BFEs), which account for SWEL and wave setup *in addition to* wave height above SWEL and wave runup above SWEL⁴. The FIS publishes water surface elevations for a variety of flood recurrence intervals (e.g., 10% chance, 2% chance, etc.) for transects⁵—straight lines extending from the shore—which may not directly cross the coastal feature identified for assessment, whereas PFIRMs display continuous elevations along the shoreline (see Figure 3 for depictions of each).

According to the PFIRM (2013), the 100-yr (1% annual chance) BFE is 12 feet NAVD88 for the GIVB artificial island (see Figure 3). According to FEMA's FIS for New York City (2013)⁶ the 100-yr SWEL is 11.3 feet NAVD88 for the NY-39 transect, and the 500-yr SWEL is 14.8 feet NAVD88⁷. Table 3 depicts these elevations when added to mid-century NPCC SLR estimates (see Table 2). The project team considered this information in developing recommendations for a Project Flood Elevation (PFE) for the seawall under mid- and end-of-century conditions (see Section 6).

Table 3: Projected Elevations for Flood Events Combined with SLR, Mid-century

Source	Base Value	Mid-Estimate SLR Scenario (25 th to 75 th percentile)	High Estimate SLR Scenario (90 th percentile)
BFE associated with 100-year flood at GIVB artificial island (FEMA PFIRM, 2013)	12 feet	12.9 to 13.8 feet	14.5 feet
SWEL associated with 100-year flood at NY-39 transect (FEMA FIS, 2013)	11.3 feet	12.2 to 13.1 feet	13.8 feet
SWEL associated with 500-year flood at NY-39 transect (FEMA FIS, 2013)	14.8 feet	15.7 to 16.6 feet	17.3 feet

⁴ "BFEs are calculated by taking into account: 1) the storm surge stillwater elevation [SWEL], 2) the amount of wave setup, 3) the wave height above the storm surge stillwater elevation, and 4) the wave runup above the storm surge stillwater elevation (where present)." BFEs are rounded. <http://www.region2coastal.com/resources/glossary>

⁵ Transects represent locations along the shoreline along all sources of primary flooding in each New York City County. They are placed with consideration given to topography, land use, shoreline features and orientation, and the available fetch distance. Each transect is placed to capture the dominant wave direction, typically perpendicular to the shoreline and extended inland to a point where coastal flooding ceases.

⁶ FEMA, 2013. "Preliminary Flood Insurance Study, City of New York, New York."

⁷ <http://www.region2coastal.com/view-flood-maps-data/view-preliminary-flood-map-data/>

⁷ NY-39 is the closest transect to the GIVB artificial island.

Note: All elevations are referenced to NAVD88.

Figure 3: FEMA Preliminary FIRM for GIVB with FIS NY-39 Transect (1% chance)



Source: <http://apps.femadata.com/PreliminaryViewer/> and FEMA FIS, 2013.

In addition to SLR and storm surge, because extreme precipitation could cause accumulation of standing water (ponding) between the GIVB and the seawall, projections for future 100- and 500-year (24 hour) return intervals were retrieved using SimClim, a commercial downscaling software product.

Table 4: Projected Precipitation Trends, 2050 and 2100

Return Period (years)	1995 Baseline Precipitation Value	2050 Precipitation Values and Percentage Change			2100 Precipitation Values and Percentage Change		
		Median GCM	5th % GCM	95% GCM	Median GCM	5th % GCM	95% GCM
100	9.3	10.2(+9%)	9.1(-3%)	11.0(+18%)	11.4(+23%)	n/a	13.3(+43%)
500	15.1	16.8(+11%)	14.3(-5%)	18.7(+24%)	19.1(+24%)	n/a	24.0(+58%)

Source: SimClim. Representative Concentration Pathway (RCP) 8.5. All General Circulation Models (GCM) were sourced from the Coupled Model Intercomparison Project (CMIP) Phase 5.

The median and 95th percentile climate models projected significant increases in 24-hour precipitation for both events, whereas the 5th percentile model projected marginal decreases by mid century (end-of-century values for the 5th percentile model could not be computed with confidence). However, a site-specific analysis is needed to determine whether additional pumping capacity would be required.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

The GIVB is projected to be exposed to flooding from SLR and storm surge in the future. If exposed, it could be sensitive to the following modes of damage or failure:

- Service Disruption:** As noted in previous sections, during Hurricane Sandy, the GIVB shaft flooded from the tunnel portals (not from wave overtopping or flooding from the GIVB openings). Based on MTA's account, it took nearly two weeks to dewater the tunnel and approximately one month before the tunnel was entirely operational again. In the event that the GIVB is flooded from overtopping, the duration of service disruption could be significant *even if the two tunnel entrances are properly protected* (although the rate of inundation would likely be slower).
- Physical Damage:** Flooding of the GIVB could cause substantial damage to electrical and mechanical equipment inside the Building. The GIVB contains significant electrical and control gear, large centrifugal-type tunnel ventilation supply and exhaust fans and their motors, drainage pumps and their motors, as well as elevators and their machine rooms. The vent structure has stairs and vent shafts that connect to the tunnel itself, potentially providing a path for flood waters to damage lighting, lane signals, and cabling throughout the tunnel. Inundation could destroy electrical items acutely by short circuit if they are energized, and more gradually by degradation of insulation if they are not energized. All metal items would be subject to corrosion from brackish-to-saline water with potential contamination issues. The impacts to specific equipment in the GIVB would depend on the elevations at which the components are located, and the depth of flooding.

4.2 ADAPTIVE CAPACITY ANALYSIS

The system of ventilation buildings serving the HLCT that includes the GIVB exhibits a very limited degree of adaptive capacity. While there are three other ventilation buildings in this system, the GIVB provides ventilation for approximately 50% of the length of the HLCT and is therefore the most critical. The HLCT could be operated under very limited circumstances if the GIVB is not operational, but operating under such conditions would not provide the ventilation capacity needed in case of a fire in the tunnel. An analysis of the other three ventilation buildings was not conducted as part of this assessment. It is possible that one or more of those ventilation buildings may also be vulnerable to SLR and storm surge, in which case the adaptive capacity of the ventilation system would be even lower.

Should the operations of HLCT cease, there are three major alternative routes in the vicinity that also connect Manhattan to Brooklyn: Brooklyn Bridge (cars only), Manhattan Bridge, and Williamsburg Bridge. For some passengers originating in Brooklyn or Manhattan, other modes may be available. Several subway lines cross the East River, either via the Manhattan Bridge (the B, D, N, and Q lines), the Williamsburg Bridge (J, M, and Z lines) or via tunnel (the 2, 3, 4, 5, A, C, R, and F lines).⁸ There is also scheduled East River passenger ferry service between Brooklyn and Manhattan at the Fulton Ferry Landing, but no capacity to transport vehicles by water. A vulnerability assessment of these alternatives under similar conditions was beyond the scope of this study, although notably the R line was out of service for over a year after Hurricane Sandy due to repairs required for the Montague Street Tunnel.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Failure of the GIVB and/or related flooding of the tunnel would likely lead to the closure of the HLCT to traffic, which could have significant negative impacts on regional mobility. The HLCT connects Manhattan with Brooklyn (and vice versa) and has an AADT of 46,606 (2013), which includes AADT (auto) of 43,084 an AADTT (trucks) of 2,047 (2013), and a daily transit bus traffic count of 1,475. The HLCT serves transit buses between Manhattan and Brooklyn, as well as Manhattan and Staten Island⁹. Closure of the HLCT could either lead to the cancellation of these trips or the rerouting of these trips to alternative routes (e.g., via the Manhattan Bridge or Williamsburg Bridge¹⁰) or modes (the subway and ferry systems). The HLCT is designated as an evacuation route, and its closure during emergencies could have greater repercussions beyond disrupting daily commutes.

⁸ Not accounting for lines north of the Williamsburg Bridge.

⁹ Specifically, the HLCT carries 26 express bus routes, of which 4 are operated by MTA Bus Company (Routes BM1, BM2, BM3, and BM4) and 22 are operated by MTA New York City Transit (Routes X1, X2, X3, X4, X5, X7, X8, X9, X10, X11, X12, X14, X15, X17A, X17, X19, X27, X28, X31, X37, X38, and X42).

¹⁰ The Brooklyn Bridge is closed to heavy vehicle traffic.

5.2 EFFECT ON REGIONAL ECONOMY

The HLCT is an important component of the transportation system in the New York City region, connecting Manhattan to Brooklyn, which allows for the essential movement of people and goods within the city and beyond—a driver of local and regional economic activity. The GIVB is critical to maintaining the functionality of the HLCT, and therefore its failure would result in economic losses.¹¹ If the GIVB were to fail, travelers would bear travel time and travel operating costs due to rerouting, or cancel trips entirely.

As the GIVB has never flooded, no data are currently available that reflect the actual amount of time during which the GIVB would be inoperable due to the overtopping of the seawall.¹² Additionally, the duration of the GIVB failure and any resulting HLCT closure would be a function of the severity of flood-related mechanical and electrical damage to GIVB and the duration of dewatering, debris removal, and repair within the tunnel itself. Since the duration of closure is unknown, a per-weekday cost of closure was estimated (in \$2012). This per-day cost would be multiplied by the duration of the closure to estimate the simple economic cost of an event. Even if the cumulative economic losses were known, the probability of the triggering event would have to be factored into the cost over time (i.e., to mid- or even end-of-century).

The daily cost incurred to all travelers who could be affected by the tunnel closure is based on AADT, which includes AADTT (trucks) and bus traffic for the tunnel. To determine the cost per day, the 2013 AADT (46,606) was utilized to calculate the daily auto, bus, and truck impacts per day of closure. The 2013 AADTT is 2,047 and the transit bus traffic count is 1,475.¹³ During a closure of the HLCT, it is assumed that all traffic would be forced to take an alternative route (detour). Because the destinations of travelers using the HLCT may vary significantly, the net detour lengths cited below originate at the split between I-278 (the Brooklyn-Queens Expressway) and I-478 (the HLCT) and terminate at the Manhattan portal of the HLCT (with the exception of trucks, as explained below)—recognizing that, because detour lengths will vary depending on the direction of travel (Brooklyn-Manhattan vs. Manhattan-Brooklyn) and traveler origins and destinations, the distances and times considered represent rough approximates. The route for autos was estimated to be an additional 2.3 miles long, equivalent to an estimated added travel-time of 25 minutes.¹⁴ The route for buses is estimated to be an additional 9.6 miles long, or equivalent to an estimated added travel-time of 52 minutes.¹⁵ According to MTA's current Manhattan Bus Map, there are no bus routes on the Manhattan Bridge. Therefore, based on current routes, it is assumed that buses would travel to the nearest current access point to Manhattan, which is the Williamsburg Bridge. The route for through trucks is an additional 1.4 miles long, or equivalent to an estimated added travel-time of

¹¹ As the GIVB is one of multiple components that are critical to the functionality of the HLCT, the economic losses evaluated in this section could potentially result from failure of any critical component. However, for the purpose of this assessment, economic losses are attributed to failure of the GIVB.

¹² As noted in previous sections, during Hurricane Sandy, the GIVB was flooded from water entering through the HLCT portals and not due to overtopping.

¹³ MTA Bridges and Tunnels, 2013.

¹⁴ The distance and travel time for autos from Brooklyn to the Manhattan portal via the Brooklyn Bridge are based on Google Maps. Estimated added travel time of the bridges is roughly 6 minutes without traffic. However, during a tunnel closure, there will be additional congestion due to displaced travelers. Therefore, the time delay is increased by 100% to account for typical congested traffic and another 100% penalty is applied to account for additional volume due to diversions.

¹⁵ Estimated using Google Maps. It is assumed that riders will take a bus route that travels via the Williamsburg Bridge back to the Manhattan portal via FDR Drive—the most conservative estimate. This equates to an estimated additional travel distance of 9.6 miles. Estimated added travel time without traffic is 26 minutes; however, a 100% increase is applied to account for typical traffic congestion. Only one penalty of 100% is applied since autos and trucks primarily will divert to the Brooklyn or Manhattan bridges, applying a reduced impact on additional congestion at the Williamsburg Bridge. Bus routing options were obtained from the MTA.
<http://web.mta.info/nyct/maps/busbkln.pdf>

20 minutes.¹⁶ The alternative routes/bridges are not tolled; travelers in the region save the toll expense associated with using the HLCT when it is closed to traffic, while MTA would lose toll revenues. Because the result is financially neutral, tolls are not included in subsequent estimates. During the HLCT closure for Hurricane Sandy, the MTA Bridge and Tunnels Division lost \$270,000 in daily toll revenue.¹⁷

Not every traveler was assumed to be affected by closure of the HLCT. Some commuters traveling by auto or bus could commute by rail or choose to not travel (e.g., telecommute instead). For the purpose of this assessment, it was assumed that 95% of auto and bus travelers will incur a cost when the tunnel is closed,¹⁸ and that 100% of trucks will incur a cost due to the inelasticity of commercial truck trips.

To estimate the travel time costs per day of closure, the daily volumes were multiplied by net delay and the cost per minute of delay per automobile, bus, and truck (respectively). For automobile drivers and persons traveling by bus, the primary cost of the delay is personal/user time. The cost per minute per traveler was derived from the hourly Metropolitan Statistical Area (MSA) 2012 median household income (\$30.76 per hour).¹⁹ The analysis conservatively assumed that automobile and bus travel are composed entirely of personal or commute trips (50/50 split). Based on US DOT guidance²⁰, only commute trips are factored, meaning that the value of time considered is 50% of the hourly median household income for the region (\$15.38 per hour, or \$0.26 per minute in \$2012). The value of business time is a function of the total cost of an employee's time, and therefore a function of total compensation. The value of commute (personal) time reflects the opportunity cost of travel time versus time spent doing something else, and is therefore expressed as a fraction of household income.

For autos, the vehicle occupancy rate (1.55)²¹ was used to translate daily vehicle hours of delay to person hours of delay. Similarly, the daily bus ridership on affected lines (40,000)²² was used to obtain person hours of delay for bus transit commuters. For trucks, the cost of delay is a commercial value of time that includes the costs of tires, fuel, driver wages, and driver benefits totaling \$48.70 per hour or \$0.81 per minute in \$2012.²³

To determine the additional auto and bus operating costs incurred per day of closure, the daily auto and bus traffic impacted was multiplied by estimated operating costs for each additional mile traveled due to the detour. For autos this includes the cost of gas, maintenance, tires, and half of depreciation, and is estimated at \$0.32/mile (\$2012)²⁴. For buses, the 2012 NYCT bus operating expense per revenue

¹⁶ Estimated using Google Maps. It is assumed that trucks will travel from the vicinity of the Brooklyn tunnel portal via the Brooklyn Queens Expressway to Manhattan via the Manhattan Bridge. All through-trucks are expected to cross to New Jersey through the Holland or Lincoln Tunnels, based on the 2011-2012 NYC Truck Route Map (www.nyc.gov/html/dot/downloads/pdf/2011_truck_route_map.pdf). If detoured via the Manhattan Bridge, through-trucks would likely travel along Canal Street to access the Holland or Lincoln Tunnels (depending on size—trucks with four axles or more must use the Lincoln Tunnel or George Washington Bridge).

Estimated added travel time is roughly 5 minutes without traffic. However, during a tunnel closure, there will be additional congestion due to displaced travelers. Therefore, the time delay is increased by 100% to account for typical congested traffic and another 100% penalty is applied to account for additional volume due to diversions.

¹⁷ MTA Bridge and Tunnels Division.

¹⁸ A conservative assumption based on professional judgment. Analysis of origin-destination details was outside of the scope of this assessment.

¹⁹ Census.gov, New York-Northern New Jersey-Long Island, NY-NJ-PA Metro Area,

<http://www.census.gov/prod/2013pubs/acsbr12-02.pdf>

²⁰ Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, US DOT, June 2014,

<http://www.dot.gov/sites/dot.gov/files/docs/USDOT%20VOT%20Guidance%202014.pdf>

²¹ National Highway Transportation Survey, U.S. DOT, 2009,

http://nhts.ornl.gov/tables09/fatcat/2009/avo_TRPTRANS_WHYTRP1S.html

²² MTA, <http://www.mta.info/news/2012/10/30/hugh-l-carey-tunnel-back-normal-operation>

²³ ATRI, Operational Cost of Trucking, 2013

²⁴ AAA; Your driving Costs, 2013

vehicle mile of \$26.30 (\$2012)²⁵ was applied. Operating cost estimates were not performed for trucks because these costs are captured by the commercial value of time estimate developed previously. Table 5 highlights the per-day cost for autos, buses, and trucks in \$2012.

Table 5: Estimated Per-Day Costs of Disruption (Not Discounted), in Millions \$2012

Vehicle Type	Travel Time Costs (\$2012M)	Travel Operating Costs (\$2012M)	Total
Auto	\$0.41	\$0.03	\$0.44
Bus	\$0.51	\$0.35	\$0.86
Truck	\$0.03	Included in Travel Time Costs	\$0.03
Total	\$0.95	\$0.38	\$1.33

Source: AECOM, 2014

5.3 EFFECT ON DISADVANTAGED POPULATIONS

This section examines the potential impacts on disadvantaged communities (primarily in Brooklyn) served by the HLCT if disruptions to the GIVB lead to its closure. The HLCT carries 9 express bus routes between Brooklyn and Manhattan, of which 4 are operated by MTA Bus Company (Routes BM1, BM2, BM3, and BM4) and 5 are operated by MTA New York City Transit (Routes X17 (which provides a connection from Manhattan to Staten Island via one stop in Brooklyn), X27, X28, X37, and X38).²⁶ These routes connect neighborhoods in Brooklyn to Manhattan, many of which include disadvantaged populations. There are approximately 25 block groups in Southwest Brooklyn (West of Ocean Parkway, Prospect Expressway, and Gowanus Expressway), in which an average of 56% of the population is below the poverty line (ranging from 48% to 83%). Closure of the HLCT could potentially lead to increased travel time and cost for populations in this part of Brooklyn, and the consequences could be greater for low-income populations because of lower private vehicle ownership rates, typically. Also, because the HLCT is a designated emergency evacuation route, its closure may have greater consequences for disadvantaged communities.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This assessment considered various Project Flood Elevation (PFE) options for enhancing the seawall around the GIVB to withstand mid-century SLR and storm surge. To manage uncertainty toward the end of the century, the seawall should be designed to accommodate modification if dictated by future trends or projections.

This assessment considered projected water elevations by mid century (2050s) from SLR and both 100- and 500-year coastal flood events, and compared these against end-of-century (2100) SLR projections.

²⁵ NTD Transit Profiles, MTA New York City Transit, 2012

http://www.ntdprogram.gov/ntdprogram/pubs/top_profiles/2012/agency_profiles/2008.pdf

²⁶ It should be noted that there are 26 bus routes that use the HLCT, of which 9 provide service between Manhattan and Brooklyn, and the remaining 17 provide service between Manhattan and Staten Island via Brooklyn (but with no stops in Brooklyn). In Section 4.3, only the bus routes serving Brooklyn neighborhoods are analyzed. Source:

<http://web.mta.info/nyct/maps/busbkln.pdf>

This assessment also accounted for FEMA’s optional recommendations for the incorporation of freeboard (see Table 6). The following adaptation strategy was proposed to manage flooding risk of the GIVB.

6.1 DESIGN A SEAWALL FOR 2050 SLR AND STORM SURGE

STRATEGY SUMMARY

This strategy involves designing a seawall around the GIVB at a **PFE of 18.3 feet NAVD88**, which accounts for the 90th percentile estimate of mid-century SLR (2.5 feet), the 500-year FEMA FIS SWEL (14.8 feet NAVD88, not including wave action), and a minimum of 1 foot of freeboard. The 90th percentile estimate for mid-century SLR represents a conservative, low-risk approach to planning for SLR. The 500-year SWEL was selected because FEMA requires protection against 500-year flood events. One foot of freeboard is incorporated to compensate for the many unknown factors that could contribute to greater flood heights, such as wave action. The value of and need for freeboard in the context of this project should be evaluated by MTA Bridges and Tunnels based on the agency’s risk tolerance.

PROCESS FOR DETERMINING THE RECOMMENDED PFE

The recommended PFE for the seawall was determined based on an evaluation of several options. In Table 6 and Figure 4 below, various PFE options are provided for comparison.

Table 6: Recommended Seawall PFE (Shaded) and Comparisons with other PFE Options

PFE Option	=	Baseline (feet)	+SLR (feet)	+Freeboard* (feet)	=	Result (feet NAVD88)
#1 PFE*	=	12 ¹	+1.8 ^A	+1.0	=	14.8
#2 PFE	=	14.8 ²	+1.8 ^A	+1.0	=	17.6
#3 PFE	=	14.8 ²	+2.5 ^B	+1.0	=	18.3
#4 PFE	=	14.8 ²	+6.3 ^C	+1.0	=	22.1

¹ Base Flood Elevation (BFE) for 100-year flood based on 2013 FEMA PFIRM (2013)

² SWEL for 500-year flood based on Preliminary 2013 FEMA FIS (2013)

A 2050 NPCC2 75th percentile

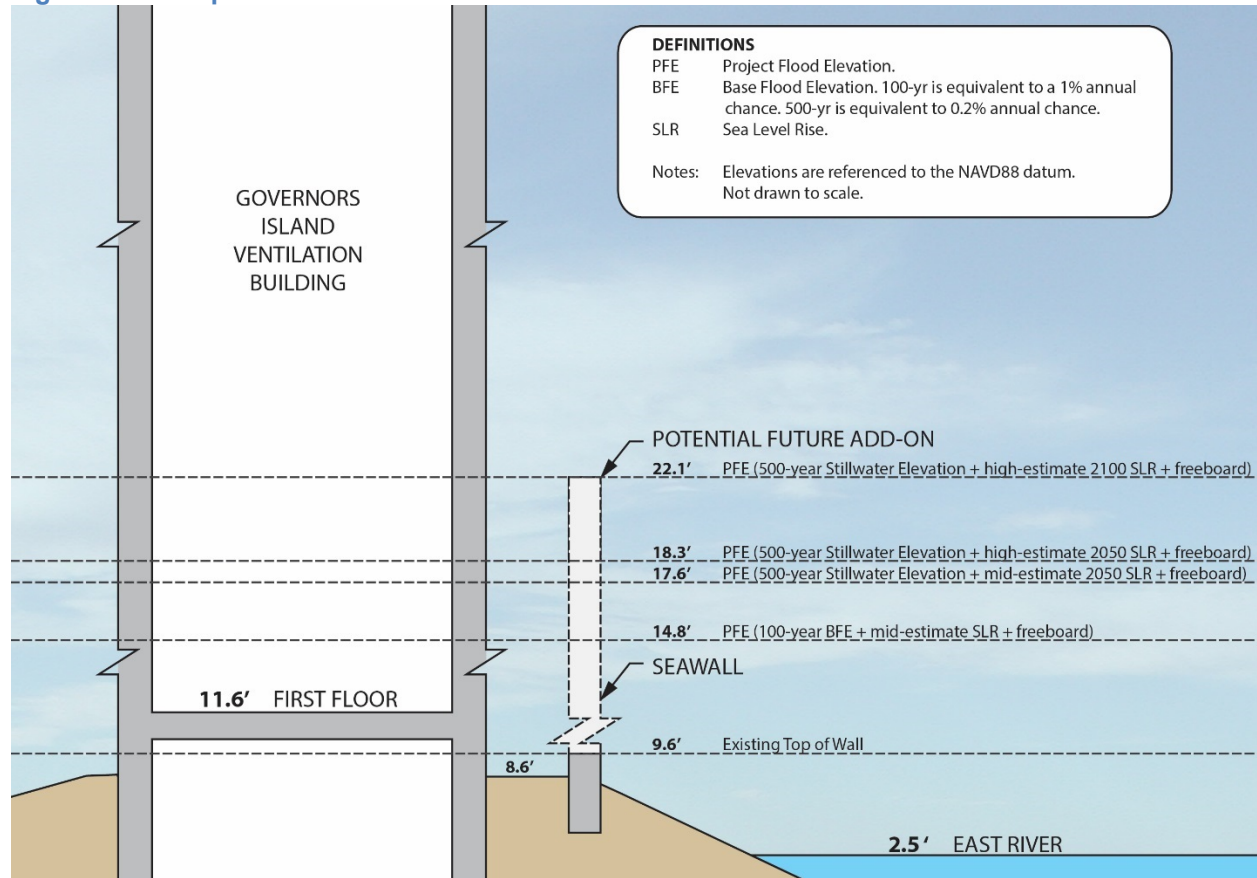
B 2050 NPCC2 90th percentile

C 2100 NPCC2 90th percentile

* Minimum suggested freeboard

PFE option [#3] was recommended for the project because it accounts for a conservative mid-century SLR scenario and satisfies the current FEMA requirement to account for 500-year flood events in post-disaster mitigation projects. The recommended PFE option is about 3.8 feet below the PFE option which accounts for end-of-century SLR and 500-yr storm surge (SWEL) [#4]. This difference could be bridged after mid-century with an addition to the seawall if it is properly designed to accommodate future modifications of this scale.

Figure 4: PFE Options for the GIVB Seawall



Source: AECOM, 2014

LIMITATIONS OF SELECTED PFE:

As previously noted, wave impacts were not explicitly included in the PFE (although freeboard would account for some wave action). The project team recommends further study to fully account for wave heights.

ADAPTABILITY OF RECOMMENDED PFE:

As trends and projections become clearer after mid century, the seawall could be adapted accordingly. Incorporating adaptability in design and construction of the seawall can minimize the risk of under designing given future uncertainties. As the end-of century SLR projections are further refined, the seawall could be adapted accordingly.

Among the different design options for the seawall, if a sheet-pile or a concrete block option is selected, the top elevation of the seawall can be increased via the use of a cap wall (as the expected increase would be on the order of a few feet). Deflectors could be installed on the cap as a structural feature to limit wave overtopping. Order of magnitude cost estimates per vertical foot and cumulative costs of raising the height of the existing seawall to mid-century conditions are provided in Table 7.

SUPPLEMENTARY FLOOD PROTECTION MEASURES

This strategy also considers the installation of additional flood protection measures in the event that intense precipitation causes water to accumulate between the GIVB and the seawall. Suggested

measures include flood gates and pumps with dedicated generators. The design for these flood protection measures should consider interior drainage patterns. MTA Bridges and Tunnels has already installed flood panels for the doors and windows of the GIVB as a short-term flood mitigation strategy following Hurricane Sandy. The adequacy of these panels and their impact on the final design flood elevation should further be evaluated. Order of magnitude cost estimates for suggested additional flood protection measures are provided below in Table 8.

6.1.1 ECONOMIC ANALYSIS

The installation of a seawall to protect the GIVB could potentially prevent adverse impacts on mobility and the economy from disruptions to the HLCT. As a result of this strategy, it is expected that the HLCT's functionality would be maintained, and therefore, the estimated economic losses detailed in section 5.2 might be prevented. It should be noted that the GIVB is only one of multiple components that are critical to the functionality of the HLCT, such as the other ventilation buildings and the tunnel portals. The estimates of avoided losses assume that these other critical components are similarly resilient (do not fail). The tunnel, as a complex system, is only as resilient as its weakest link. If other critical components fail, losses would be incurred despite the efficacy of strategies in place to protect the GIVB.

If the suggested strategy is implemented (along with other parallel strategies to protect other critical components of the HLCT), the estimated per-day avoided economic cost due to a closure of the HLCT is \$1.33 million (\$2012). This estimate includes the elements summarized in Table 5. In addition, the implementation of this strategy would also prevent the loss of revenue (\$270,000 per day) which would otherwise be incurred by MTA Bridges and Tunnels if the HLCT is closed.

6.1.2 ENVIRONMENTAL ANALYSIS

The proposed seawall strategy will require Federal and state permits and coordination with Federal, state, and local resource (ecological and cultural) agencies. The co-ordination process should include the following:

- Determining the possibility of amending existing approved plans versus the need to prepare completely new plans,
- Ascertaining potential physical constraints to project design and identifying structural/operational concerns expressed by the regulatory agencies,
- Coordination with MTA Bridges and tunnels to obtain access to the GIVB artificial island via land and water and identifying other interested parties to be contacted (e.g., Governors Island Alliance).

The environmental impact analysis for this strategy should include the following considerations:

- Whether and how the strategy may impact species protected under the Endangered Species Act in the project area,
- Construction restrictions specific to the time of year,
- Acoustic impacts of driving piles or steel bulkheads on protected fish species, including Shortnose and Atlantic sturgeon, which migrate through the project area.

6.1.3 EQUITY ANALYSIS

This strategy could potentially prevent adverse equity-related impacts from disruptions to the HLCT, which would otherwise occur. As stated in Section 6.1.1, the GIVB is only one of multiple components that are critical to the functionality of the HLCT, such as the other ventilation buildings and tunnel portals. If they fail, equity impacts would be incurred despite the efficacy of strategies in place to protect the GIVB.

In the absence of this strategy (and parallel strategies to protect other critical components of the HLCT), a detour would be required, which would add travel time and cost, and some trips may need to be cancelled altogether. The HLCT also serves as an evacuation route. As a result of this strategy, service to disadvantaged populations could continue uninterrupted (or the duration and severity of disruptions could be limited).

6.1.4 COST ANALYSIS

Table 7 below presents the estimated, order-of-magnitude incremental cost for each one-foot increase in the height of the seawall. The table also provides an estimate of the cumulative costs of raising the seawall from its current elevation to the recommended PFE for mid-century by multiplying the per-foot costs with the recommended increase in height. The elevation of the existing seawall is 9.6 feet NAVD88, and the recommended PFE is 18.3 feet NAVD88, an increase of 8.7 feet. The cumulative cost of an 8.7 foot increase in the height of the seawall ranges from \$14.4 - \$19.6 Million. This cost analysis does not account for changes in the existing seawall foundation that may be required, or for installing a new seawall. The effect of the suggested seawall extension on the foundations and any associated costs should be further studied as part of the design process.

Table 7: Incremental Seawall Costs

Cost Components	Total Cost (\$) per vertical foot	Recommended Increase in Seawall Height (Mid-century)	Cumulative Costs (\$)
Cofferdam Sheet-piling	\$0.75-1 Million	8.7	\$6.5-8.7 Million
Seawall Rockwall/Stone	\$0.4-0.5 Million	8.7	\$3.5-4.4 Million
Concrete Cap	\$0.5-0.75 Million	8.7	\$4.5-6.5 Million
Total	-	-	\$14.4-\$19.6 Million

Note: Material unit costs used for the estimates above are presented in below.
Source: AECOM.

Order-of-magnitude cost estimates for flood control systems (two common options) to mitigate ponding between the seawall and GIVB are provided below in Table 8.

Table 8: Cost of Additional Flood Protection Components

Flood Protection Components	Cost (\$)
Flood gates (22 total installed)*	\$32K
Pumps**	\$50-100K

Note: Material unit costs used for the estimates above are presented in Table 9 below.

*Source: MTA Bridges and Tunnels

**Source: Vendor quotes

The unit costs and contingencies for each of the aforementioned components are shown below in Table 9.

Table 9: Material Unit Costs and Contingency used for estimates

Components	Cost (\$)	Cofferdam Sheet-piling	Seawall Rockwall/Stone	Concrete Cap
Steel Sheeting	\$75/SF	4,000 SF		
Sand Fill	\$100/ton	700 tons		
Rock Fill	\$300/ton	700 tons		
Marine Concrete	\$6,000/Cubic Yard		40 Cubic Yards	80 Cubic Yard
Riprap	\$300/ton		1,000 tons	
Coping Stone	\$300/ton		70 tons	70 tons
Core Gravel	\$200/ton		1,000 tons	
General & Administrative Expenses	20%	20%	20%	20%
Contingency	20%	20%	20%	20%

Source: AECOM.

6.1.5 TIMING FOR IMPLEMENTATION

Timing will depend on the Agency's implementation strategy for the seawall project. Given the options included in this assessment, MTA Bridges and Tunnels would likely need to conduct a scoping study to determine the feasibility of options and compare them using a variety of rating criteria including capital cost, maintenance cost, effectiveness, reliability, difficulty in permitting, ease of implementation, and ease of operation. Determination of the most favorable option should also account for seismic hazards and marine vessel collision potential. This process can take up to a year, followed by the full design and preparation of the procurement package for construction, which would take another year or more, mainly depending on the timing of permitting. The timing of construction would greatly depend on the alternative selected and would likely take one to two years to complete.

As mentioned in previous sections, incorporating adaptability in the design and construction of the seawall can minimize the need for redesigning and reconstructing the GIVB in the future, as trends and projections become clearer. An adaptable solution would reduce the initial cost and duration of construction.

7. CONCLUSION

This assessment identified potential vulnerabilities of the GIVB to inundation due to overtopping of its existing seawall under mid- and end-of-century SLR and storm surge scenarios. Long-term flood mitigation strategies being considered by MTA Bridges and Tunnels for the GIVB include raising the existing seawall or installing a new, taller seawall. This assessment considered various seawall elevation options to account for SLR and storm surge under mid-century conditions. A Project Flood Elevation of 18.3 feet NAVD88 was suggested for the seawall, which takes into account FEMA's 500-yr SWEL, the 90th percentile of the New York City Panel on Climate Change's SLR projections by mid-century, and 1 foot of freeboard. The project team suggests incorporating adaptability into the design to permit cost-effective enhancements to the seawall in the future as trends and projections—particularly those pertaining to the end-of-century and beyond—become clearer.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

Long Beach Road Engineering Informed Adaptation Assessment

LONG BEACH ROAD/AUSTIN BOULEVARD CORRIDOR, TOWN OF HEMPSTEAD, NY

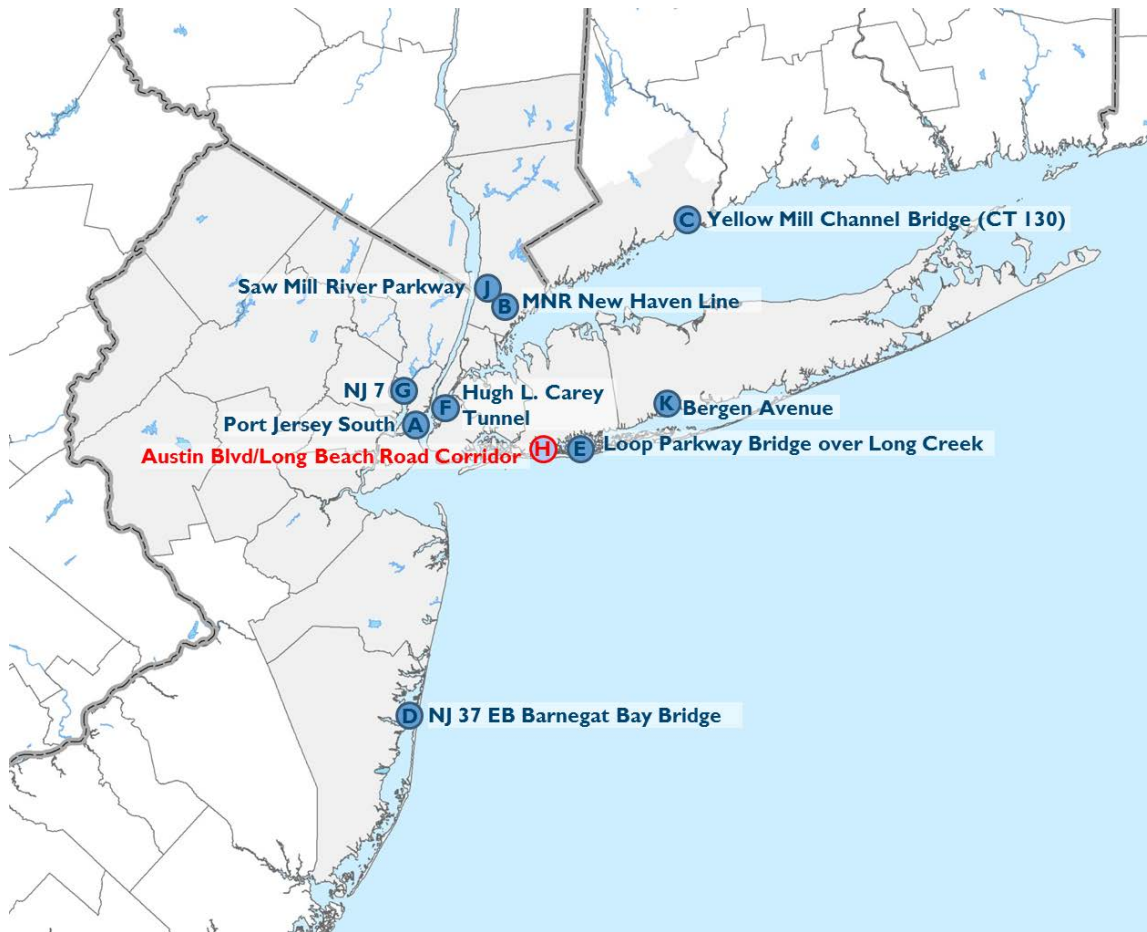
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Long Beach Road/Austin Boulevard corridor is one of ten transportation facilities selected for an engineering-informed adaptation assessment. In addition, Nassau County requested a supplement to this assessment to examine existing drainage issues during precipitation events, the results of which are summarized in full in Annex B. See Figure 1 for a context map of all 10 study areas, with the Long Beach Road/Austin Boulevard corridor highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for 10 FHWA Study Areas (Long Beach Road/Austin Boulevard Corridor in Red)



2. FACILITY DESCRIPTION

Long Beach Road is a north-south arterial roadway under the jurisdiction of Nassau County in New York State. Along with a 1.4-mile stretch of Austin Boulevard, which serves as a bypass to the portion of Long Beach Road on Barnum Island, the Long Beach Road corridor is designated as a primary evacuation route serving the Long Beach Barrier Island, Barnum Island, Harbor Isle, Island Park, Oceanside, and the southern portions of Rockville Centre. In addition, the Town of Hempstead has designated the Long Beach Road/Austin Boulevard corridor as a truck route to and from the Long Beach Barrier Island.

At Nassau County's direction, this assessment focuses on a 0.7-mile segment of Long Beach Road in the Hamlet of Oceanside between Mott Street and the Barnum Island Bridge (see Figure 2). This segment supports 3 lanes of traffic in each direction and has a grass median.

As reported by Nassau County, partial flooding occurs on this segment of Long Beach Road during storms with 3 to 5 inches of precipitation, particularly those that coincide with high tide. The inadequacy of the existing drainage system was identified as a contributor to the flooding. Therefore, this assessment specifically focuses on the drainage system of this segment.

Figure 2: Long Beach Road between Mott Street and Barnum Island Channel



Source: Google Maps, 2014

2.1 DESCRIPTION OF DRAINAGE SYSTEM

The drainage system serving the study area includes drainage structures (catch basins, manholes, drywells and outfalls) and networks of storm drainage pipes ranging in size from 15 to 48 inches. A subset of this drainage system was evaluated at a key junction, located south of the intersection of Mott Street and Long Beach Road, where two 30-inch storm drainage pipes feed into a manhole, with a 36-inch pipe exiting the manhole. This 36-inch pipe feeds into another 36-inch pipe, which in turn feeds into a 42-inch pipe, forming a pipe run¹ along the east side of Long Beach Road that connects the manhole to a 48-inch outlet pipe at the south end of the shopping center. The Nassau County Department of Public Works *Standard Specifications and Detail Sheets for Civil Engineering and Site Development Construction* (2009) indicates an 8-inch precipitation threshold for roadway design, which equates approximately to a 100-year, 24-hour rainfall event. Additional detail on the existing conditions of the drainage system can be found in Annex B of this assessment.

Table 1 provides details on the age, lifespan, condition, and use of the roadway segment's drainage system.

¹ A pipe run is a path formed by a piping system.

Table 1: Facility details

Category	Details
Facility Type	Roadway
Facility Component	Drainage System
Estimated Age (Lifespan)	<ul style="list-style-type: none">- Roadway was originally built approximately 80-100 years ago. Improvements to drainage were made in 1960.- Remaining lifespan of roadway = ~50 years. Remaining lifespan of drainage is unknown
Estimated Condition	Fair (but limited capacity)
Roadway Use / Ridership	40,000 AADT

Source: Nassau County

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

Most of the roadway segment is located in a FEMA-designated Special Flood Hazard Area (SFHA) and currently experiences partial flooding during storms with 3 to 5 inches of precipitation of unspecified duration, which may be exacerbated when intense rainfall coincides with higher tidal phases. For reference, according to current Intensity Duration Frequency (IDF) curves², 3 inches of rainfall correspond (approximately) with a 12-hour duration for 5-year storms, a 3-hour duration for 25-year storms, and a 1-hour duration for 100-year storms. Circumstantially, this indicates that drainage serving this segment of Long Beach Road does not perform to the Nassau County standard.

Based on projected potential increases in the frequency and magnitude of precipitation in the region (paired with increased sea levels), this roadway segment may experience more frequent and more severe flooding as the century progresses (all else being equal). Therefore, in consultation with Nassau County, precipitation-caused flooding events were selected as the focus of this assessment.

² IDF curves from two locations near the study area: Mineola, NY and John F. Kennedy (JFK) International Airport in Jamaica, NY. These projections were developed for NYSERDA, in partnership with NYSDOT.

3.1 FREQUENCY AND MAGNITUDE OF PRECIPITATION EVENTS

The frequency and magnitude of extreme precipitation events are projected to increase in the region, based on IDF curves developed by the Northeast Regional Climate Center (NRCC) at Cornell University. The two greenhouse gas (GHG) emissions scenarios for which projections were developed are RCP³ 4.5 and RCP 8.5. RCP 4.5 is the lower of two intermediate emissions scenarios, while RCP 8.5 is a high emissions scenario. For each RCP, NRCC provided the project team with the projected percent change in the magnitude of precipitation over a 24-hour duration for 5-, 25-, and 100-year return periods for mid-century (2040-2069) and late-century (2070-2099) horizons (Table 2). Illustratively, the 100-year, 24-hour design storm referenced in Nassau County’s specifications is projected to increase from a baseline of 8 inches to 8.6 – 9.1 inches by mid-century, and 9.4 – 10.2 inches by end-of-century.

Table 2: Mean Percent Change in Precipitation Amounts over 24 Hours for 5-, 25-, and 100-Year Storms, Mineola, NY and JFK International Airport, NY

Precipitation Event Return Period	RCP4.5 Emissions Scenario		RCP8.5 Emissions Scenario	
	(2040-2069)	(2070-2099)	(2040-2069)	(2070-2099)
5-Year Return Period	+9%	+16%	+15%	+24%
25-Year Return Period	+9%	+17%	+15%	+26%
100-Year Return Period	+10%	+18%	+13-14%	+28%

Source: Northeast Regional Climate Center, Cornell University

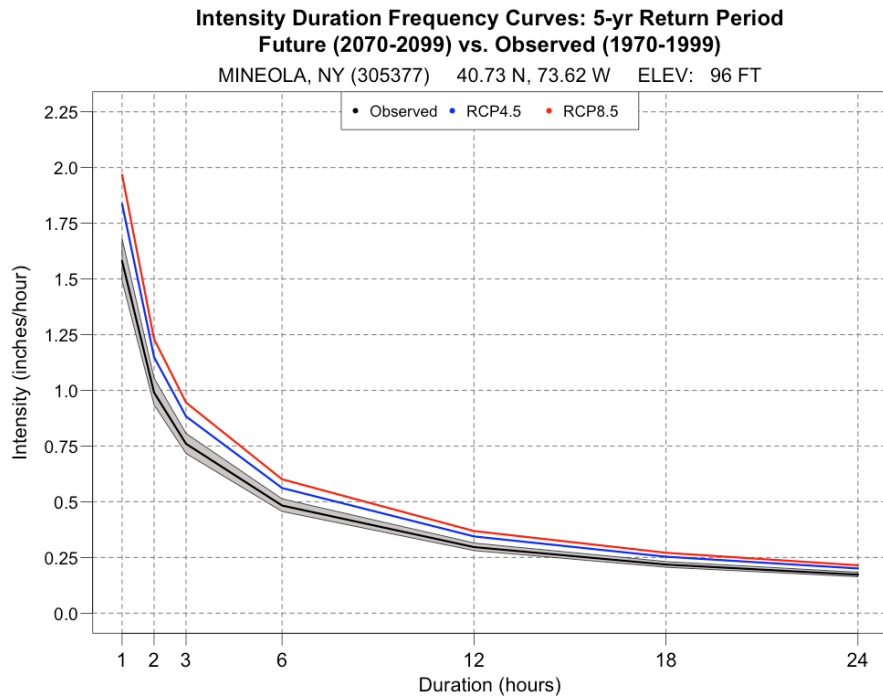
Note: Projections for the Mineola, NY and JFK International Airport, NY locations were found to be identical when rounded to the nearest whole number, except for the 100-year return period, RCP 8.5, 2040-2069, as noted.

Given the anticipated lifespan of the storm drainage systems along the Long Beach Road/Austin Boulevard corridor, end-of-century precipitation projections should be considered in identifying adaptation solutions.

See Figures 3, 4, and 5 for examples of current and future IDF curves developed by NRCC for 5-, 25-, and 100-year storms for late-century (2070-2099) at Mineola, NY (curves for JFK Airport, which are very similar, are included in Annex A of this assessment). The shaded area indicates the 90th percentile confidence interval of baseline rainfall intensities.

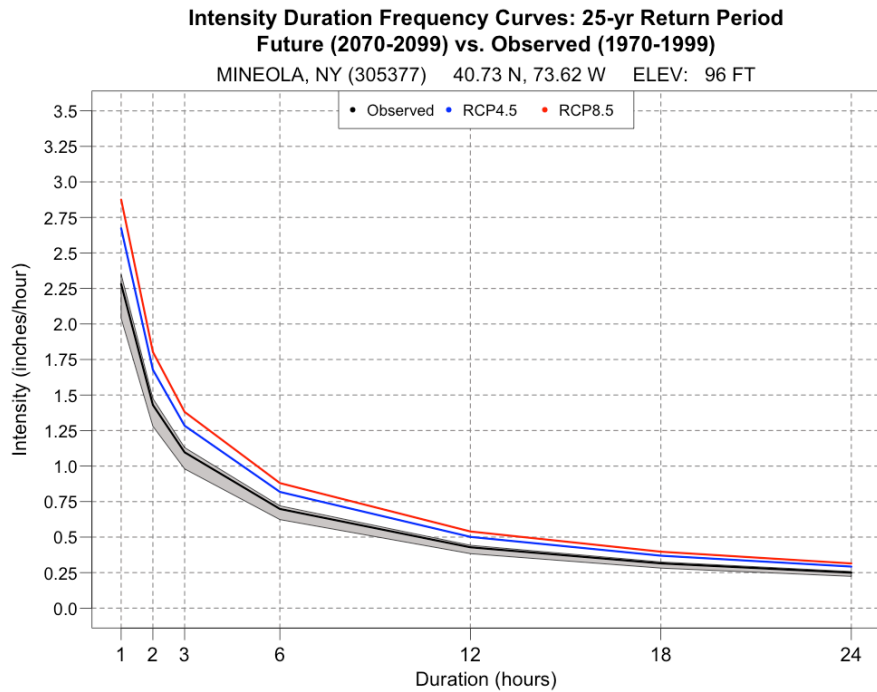
³ RCP = Representative Concentration Pathway.

Figure 3: Historical and Future IDF Curves for 5-Year Return Period, Mineola, NY



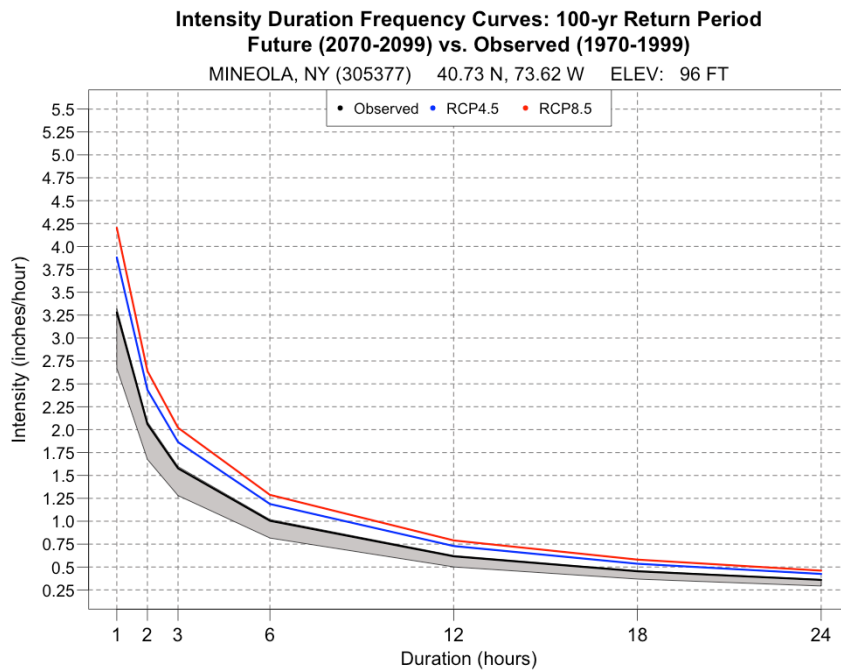
Source: Northeast Regional Climate Center, Cornell University

Figure 4: Historical and Future IDF Curves for 25-Year Return Period, Mineola, NY



Source: Northeast Regional Climate Center, Cornell University

Figure 5: Historical and Future IDF Curves for 100-Year Return Period, Mineola, NY



Source: Northeast Regional Climate Center, Cornell University

3.2 COASTAL INUNDATION

Sea level rise (SLR) is also projected to affect the roadway, either by permanent overtopping, temporary overtopping during a storm event (due to surge), or by increasing sea levels at the drainage outfall. As outfalls are submerged—whether due to incremental sea level increase, tidal phase (e.g., high tide vs. low tide), or a combination of the two—gravity-based conveyance becomes less effective, potentially resulting in a back-up in the pipe network during intense rainfall events. This phenomenon, while of critical importance for drainage design, is considered qualitatively in this assessment due to resource constraints.

The SLR scenarios considered were developed by the New York City Panel on Climate Change (NPCC, 2013⁴). In discussions with Nassau County, it was agreed that a low risk tolerance (conservative) approach would be taken, and therefore, NPCC's high estimate (90th percentile) SLR projections were adopted: 2.5 feet by mid-century (2050s) and 6.25 feet by end-of-century (2100s).

The study area was almost entirely flooded during Hurricane Sandy. To account for storm surge, scenarios of 9 feet and 18 feet above mean sea level (MSL) were selected in consultation with Nassau County, consistent with thresholds applied by New York State DOT as part of a parallel assessment in the vicinity.

Illustratively, four composite SLR and storm surge scenarios were developed by applying the mid- and end-of-century SLR projections, respectively, to each storm surge scenario. The scenarios, shown in Table 3, are measured from current MSL and do not account for tidal phases or wave action. Nor do they account for changes in bathymetry (e.g., they represent the simple addition of SLR and surge elevations,

⁴ New York City Panel on Climate Change, 2013: Climate Risk Information 2013: Observations, Climate Change Projections, and Maps. C. Rosenzweig and W. Solecki (Editors), NPCC2. Prepared for use by the City of New York Special Initiative on Rebuilding and Resiliency, New York, New York.

not remodeled surge heights). These scenarios were used to identify potential vulnerabilities, described in the next section.

Table 3: Summary of SLR and Storm Surge Heights (from current MSL)

	2050		2100	
SLR (high – 90 th percentile)	2.5 ft.		6.25 ft.	
Storm Surge	9 ft.	18 ft.	9 ft.	18 ft.
SLR + Storm Surge	11.5 ft.	20.5 ft.	15.25 ft.	24.25 ft.

Sources: SLR: NPCC, 2013. Storm surge: NYSDOT.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

As previously discussed, the segment of Long Beach Road under evaluation is already subject to partial flooding during intense rainfall events of 3 - 5 inches, particularly coinciding with high tide. These rainstorms are projected to increase in frequency and magnitude in the future. The segment is also projected to be vulnerable to storm surge, particularly in the context of future SLR. When exposed to these stressors, the segment could be subject to the following modes of failure:

1. **Coastal Inundation:** According to Nassau County Department of Public Works plans from 1960, elevations along this segment of Long Beach Road vary between approximately 5.5 and 10 feet above MSL. FEMA Flood Insurance Rate Maps (FIRMs) from 2009 indicate that most of the Long Beach Road segment is within a Special Flood Hazard Area (SFHA), subject to flooding by the 100-year storm. A Base Flood Elevation (BFE)⁵ of 8 feet NAVD88 (approximately equivalent to 8.36 feet above current MSL)⁶ applies to this section of roadway—exceeding the elevation of most of the segment. Particularly after mid-century, this segment is projected to be increasingly exposed to inundation from SLR and storm surge—projected end-of-century SLR alone (e.g., without storm surge) could potentially result in overtopping based on current elevations, especially at high tide. Table 4 compares the elevation range of this segment with projected water elevations under various SLR and storm surge scenarios.

⁵ The Base Flood Elevation (BFE) is the water-surface elevation of the 100-year storm.

⁶ Flood elevations on FEMA Flood Maps are referenced to the North American Vertical Datum of 1988 (NAVD88). According to the National Geodetic Survey’s bench mark at permanent identifier (PID) 1530, at Point Lookout, NAVD88 is 0.36 feet above MSL.

Table 4: Comparison of Roadway Elevations with Various SLR + Surge Scenarios

Asset	Elevation (Feet Above MSL)	Time Period, Scenario	Water Elevation (Feet Above Current MSL)
Long Beach Road	5.5 to 10 feet	Mid-century, SLR	2.5
		Mid-century, SLR + MHW ⁷	4.7
		End-of-century, SLR	6.25
		End-of-century, SLR + MHW	8.45
		Mid-century, SLR + 9 feet of storm surge	11.5
		End-of-century, SLR + 9 feet of storm surge	15.25
		Mid-century, SLR + 18 feet of Storm Surge	20.5
		End-of-century, SLR + 18 feet of Storm Surge	24.25

By the end-of-century timeframe, the mean high water (MHW) elevation is projected to be approximately 8.45 feet above current MSL, which could result in chronic or even permanent inundation of the majority of this portion of Long Beach Road if no action is taken. The combined effect of 2.5 feet of SLR (mid-century) and 9-foot storm surge is projected to result in water elevations of 11.5 feet above current MSL, which may overtop the entire roadway.⁸

- 2. Drainage Failure:** The existing storm drainage system is, circumstantially, inadequate to handle either current or future precipitation events of even 3 to 5 inches (well below the design threshold of 8 inches), particularly during higher tidal phases. This situation is projected to worsen as sea levels increase.

The 48-inch outfall structure at the end of the drainage pipe network serving this segment has an assumed low invert elevation of 1.91 feet below current MSL (equivalent to about -2.27 feet NAVD88 when the datum is adjusted).⁹ According to a Nassau County inter-departmental memo, investigations conducted on November 21, 2000 and April 23, 2002, both near low tide, showed the outfall pipe (located near the south end of the Sands Shopping Center, see Figure 2) to be approximately half full of water, indicating decreased flow capacity for the entire drainage system. If the flow at the outfall is further restricted, a back-up in the pipe network may occur during heavy

⁷ According to the most recent data available from the National Oceanic and Atmospheric Administration’s (NOAA) National Ocean Service, the mean high water (MHW) elevation in Long Beach (the closest tide station to this project site) is 2.2 feet above MSL.

⁸ Does not include high tides and/or waves.

⁹ A pipe’s invert is the elevation at the lowest interior point. A drawing of the study area containing information on the elevation of the outfall, provided to the County by the Sands Shopping Center, does not reference a vertical datum. Based solely on the “3-21-86” date on the drawing, this elevation is assumed to be 1.91 feet below MSL, as the North American Vertical Datum of 1988 debuted in June of 1993.

rains.¹⁰ Based on projected SLR, the outfall pipe will be completely under water during low tide by mid century.

4.2 ADAPTIVE CAPACITY ANALYSIS

The transportation network which includes the Long Beach Road/Austin Boulevard corridor exhibits some degree of adaptive capacity in that there are two alternate routes/bridges – the Atlantic Beach Bridge/Nassau Expressway corridor and the Loop Parkway/Meadowbrook Parkway corridor – from Long Beach Barrier Island to inland portions of Long Island. A vulnerability assessment of alternate routes was not conducted, and it is possible that these routes may be vulnerable to and impacted by the same climate stressors as the Long Beach Road/Austin Boulevard corridor. For example, all three routes were inundated by Hurricane Sandy's storm surge and were closed to traffic simultaneously. In addition, the Loop Parkway/Meadowbrook Parkway route is not suitable for truck traffic due to low-clearance bridges.

In the event that Long Beach Road/Austin Boulevard were to be closed but other routes remained open, detour delays and added costs could be incurred due to a need to travel an additional distance to destinations via the parallel routes. Potential detour delays are discussed in more detail in Section 5.1. New York State is advancing significant investments in both the Atlantic Beach Bridge/Nassau Expressway corridor and the Loop Parkway/Meadowbrook Parkway corridor to withstand the future anticipated impacts of climate change; therefore, absent any modifications to Long Beach Road, a future scenario in which Long Beach Road/Austin Boulevard closes but the other two routes remain open is plausible.

In addition to the roadway alternatives, the barrier island communities are also served by the Long Island Rail Road's Long Beach Branch, which provides passenger service along a route that runs parallel to the Long Beach Road/Austin Boulevard corridor.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of the study segment could result in delays associated with detours to alternate routes (the Atlantic Beach Bridge/Nassau Expressway corridor and the Loop Parkway/Meadowbrook Parkway corridor). The route from the Long Beach Bridge (which leads to the Long Beach Road/Austin Boulevard corridor) to the Atlantic Beach Bridge/Nassau Expressway corridor would require people and freight to travel approximately 5 miles west (10-15 minute drive in normal conditions and longer with congestion) and then potentially backtrack to the ultimate destination once on Long Island. The route from the Long Beach Bridge to the Loop Parkway in Point Lookout would require people and freight to travel approximately 4 miles east (10 minute drive in normal conditions and longer with congestion), again potentially backtracking to the ultimate destination. It should be noted that trucks are not allowed on the Loop Parkway or Meadowbrook Parkway, which means that mobility for freight would be more restricted than mobility for people if the Long Beach Road segment were to be disrupted. In the event of an emergency detour, the additional travel times via these alternate routes, compared to the travel time via the Long Beach Road/Austin Boulevard corridor, could be significantly greater.

The Long Beach Road corridor, the Atlantic Beach Bridge/Nassau Expressway corridor, and the Loop Parkway/Meadowbrook Parkway corridor all are designated as hurricane evacuation routes for the south shore of Long Island. The closure of any of these routes would adversely impact the efficiency of evacuation prior to or during emergencies and the ability of personnel and equipment to access south

¹⁰ There must be enough hydraulic head (a measure of liquid pressure) built up in the drainage system upstream from the outlet in order to push water through the submerged outlet.

shore communities to support response and recovery efforts. Also, either or both of these alternate routes could experience some degree of service loss or failure associated with flooding due to precipitation and/or coastal inundation.

5.2 EFFECT ON REGIONAL ECONOMY

An analysis of the regional economic impacts of disruption to the segment of Long Beach Road under study was not conducted as part of this assessment. First, a thorough disruption assessment would need to consider the extent and duration of flooding that occurs on other segments of the Long Beach Road/Austin Boulevard as part of a corridor-wide economic impacts assessment. Second, it is difficult to estimate the portion of the economic impacts attributable to a temporary or permanent closure of Long Beach Road, given that the two alternate routes are subject to similar disruptions during similar storm events. Third, there are no data available currently to help estimate what portion of the trips by people and freight on Long Beach Road are flexible and/or discretionary and can tolerate a temporary disruption (e.g., a flood that closes the roadway for a few hours around high tide) and what portion is more time-sensitive.

5.3 EFFECT ON DISADVANTAGED POPULATIONS

Long Beach Road is part of the network of routes that connect the barrier island communities of Long Beach, Lido Beach, and Point Lookout with the mainland. Approximately 10.2 percent of the population in Long Beach is below the poverty line.

There are three census block-groups in the northern part of Long Beach in which between 38 to 50 percent of the population are below the poverty level. The New York Metropolitan Transportation Council's Environmental Justice and Title VI appendix to its 2040 Regional Transportation Plan identifies one census tract at the southern end of Long Beach Road in the City of Long Beach as a "community of concern," defined as an area with both 1) a minority population of 56 percent or greater, and 2) persons below the poverty level of 15 percent or greater. More than 10 percent of the residents of the City of Long Beach rely on public transit to get to work. Additionally, there is one block-group in the northern part of Island Park in which approximately 16 percent of the population are below the poverty line. Closure of the Long Beach Road/Austin Boulevard corridor could impact residents of these block groups that routinely use this route to access the mainland, either by driving or using public transportation.

Nassau Inter-County Express (NICE) operates bus service (Route N15) on Long Beach Road from the Long Beach barrier island through the communities of Island Park and Oceanside to points in central Nassau County including employment centers, government offices, one-stop career centers and other social service providers, medical and professional services, and shopping destinations. Disadvantaged populations without access to personal vehicles could be adversely impacted by closure of the Long Beach Road/Austin Boulevard corridor, as the only other transit options from Long Beach to the mainland are the Long Island Rail Road (Long Beach Station) and NICE's Bus N33, which travels off the island via the Atlantic Beach Bridge/Nassau Expressway corridor. While NICE has an emergency routing plan in place, which was effective in the period after Hurricane Sandy, the impacts to disadvantaged populations from disruption to Long Beach Road could be significant and could include lost wages, inability to access medical and other services, and inability to access food and other essential supplies. Paratransit services for the disabled and operators of human services transportation that use the Long Beach Road/Austin Boulevard corridor to connect residents of south shore communities to the rest of Long Island could be disrupted as well, with disproportionate impacts on those with mobility impairments.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This assessment focuses on the drainage system at a segment of Long Beach Road in Oceanside, between Mott Street and the Barnum Island Bridge. Based on the current and projected flooding issues faced by this roadway (as discussed in Section 3) caused by precipitation and exacerbated by higher sea levels, one strategy to consider is to update drainage design guidelines that can be applied to all future drainage system construction in Nassau County. This strategy is the essential precursor to future engineering-based modifications at this and other similar sites in the County or in similar corridors elsewhere in the tri-state region. In addition, Nassau County requested a supplement to the assessment to examine options to address existing drainage issues along the segment during precipitation events, the results of which are summarized in full in Annex B.

The area surrounding the roadway segment is low-lying and would require comprehensive, multi-sectoral and regional-scale solutions to mitigate the potential impacts of SLR and storm surge—an effort exceeding the resources of this assessment. Adaptation to SLR and coastal inundation should, however, be considered in future investigations.

6.1 UPDATED DESIGN GUIDELINES

Although this assessment focuses on a specific 0.7-mile segment of Long Beach Road, the conditions and potential vulnerabilities applicable to this segment are likely similar throughout the roadway corridor and elsewhere in the County and region. If other segments fail under similar stresses—whether upstream or downstream along this corridor or elsewhere in the roadway network—there is little benefit in preserving the functionality of an isolated segment.

To accommodate projected changes in the frequency and magnitude of precipitation events County wide, an adjustment of the drainage design guidelines could be considered for new drainage systems as well as existing systems subject to significant modification. For reference, Chapter 8 of the NYSDOT Highway Design Manual specifies that storm drain systems shall have a design life and anticipated service life equal to 70 years. Therefore, consistent with this guidance and the low tolerance for risk expressed by the County current design guidelines could be updated to reflect end-of-century precipitation projections, following, for example, the 100-year event IDF curves developed by NRCC for 2070-2099 (the 100-year return period 2070-2099 curves for Mineola, NY are provided in Figure 5 while curves for JFK International Airport are provided in Annex A). Note that potential changes in other hydrological factors, such as land cover, are not considered in this analysis—but would impact the efficacy of drainage designs.

Updating current design standards to incorporate projected IDF curves may increase the number and size of drainage structures required in comparison with existing standards. For example, the 100-year, 24-hour design storm referenced in Nassau County's specifications is projected to increase from a baseline of 8 inches to 8.6 – 9.1 inches by mid-century, and 9.4 – 10.2 inches by end-of-century. Drainage structures should be spaced to stay within a maximum allowable spread (width of rainwater flowing along the roadway gutter measured laterally out from the curb) on the roadway. The greater the rainfall intensity, the smaller the maximum distance between inlets—resulting in a greater number of inlets required along the roadway.

6.1.1 ECONOMIC ANALYSIS

Future projects following updated design guidelines may entail specific economic, environmental, and equity-related benefits and disbenefits, which should be evaluated on a case-by-case basis during project development and design.

6.1.2 ENVIRONMENTAL ANALYSIS

Not applicable (See Section 6.1.1.)

6.1.3 EQUITY ANALYSIS

Not applicable (See Section 6.1.1.)

6.1.4 COST ANALYSIS

If revisions are limited to updating the current design storm specified in the Nassau County guidelines, then costs could be minimal, depending on requirements for further research and validation.

6.1.5 TIMING FOR IMPLEMENTATION

Once the update is performed, this strategy can be initiated immediately for projects in the conceptual design phase and for all future new or replacement drainage projects.

6.2 DRAINAGE PIPE OPTIONS

Annex B of this assessment describes a series of options that could be considered for further investigation to address the drainage pipes in the existing system along Long Beach Road.

7. CONCLUSIONS

This assessment identified potential drainage-related vulnerabilities of a segment of Long Beach Road in Nassau County, NY. As reported by Nassau County, partial flooding occurs on this segment of Long Beach Road during storms with 3 to 5 inches of precipitation, particularly those that coincide with high tide. The inadequacy of the existing drainage system has been identified as a contributor to the flooding, an issue that may worsen with projected increases in the magnitude and frequency of extreme precipitation events and rising sea levels.

Circumstantially, the existing storm drainage system serving the roadway is not adequate to handle more frequent and intense precipitation events in the future, particularly by end-of-century, when the 100-year, 24-hour storm (Nassau County's design storm) is projected to increase by 18 to 28 percent. The challenge is amplified by the low-invert elevation of the drainage outfall, which is currently 1.91 feet below MSL and is half full of water during current low tides. Due to rising sea levels, the outfall is projected to be completely underwater during low tides by mid-century.

This assessment considers an update to Nassau County drainage design guidelines to account for projected increases in the frequency and magnitude of the future 100-year storm. Because drainage constructed today has an estimated design life of 70 years—and may well serve significantly longer—the end-of-century (2070-2099), 100-year return period IDF curves for Mineola, NY and/or JFK International Airport (the closest available sites to the study segment) could be leveraged for the update. In addition, Annex B of this assessment describes a series of options that could be considered for further investigation to address the drainage pipes in the existing system along Long Beach Road.

The entire area surrounding the roadway segment is low-lying and would require comprehensive, multi-sectoral and regional-scale solutions to mitigate the potential impacts of SLR and storm surge—an effort exceeding the resources of this assessment. Adaptation to SLR and coastal inundation should, however, be considered in future investigations.

ANNEX A: IDF Curves for JFK International Airport, NY

Figure 6: Historical and Future IDF Curves for 5-Year Return Period, JFK Intl Airport, NY

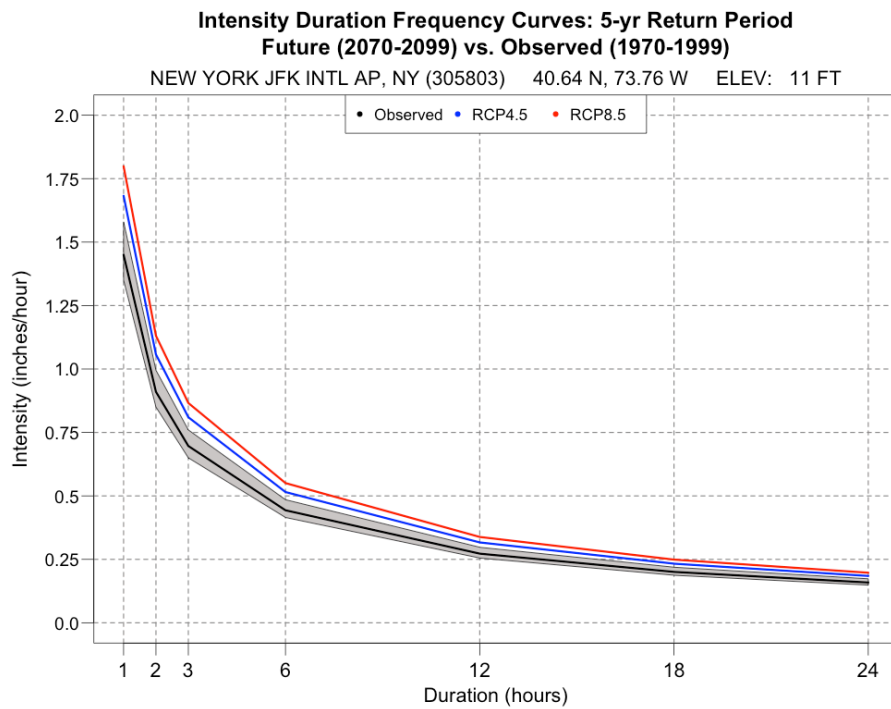


Figure 7: Historical and Future IDF Curves for 25-Year Return Period, JFK Intl Airport, NY

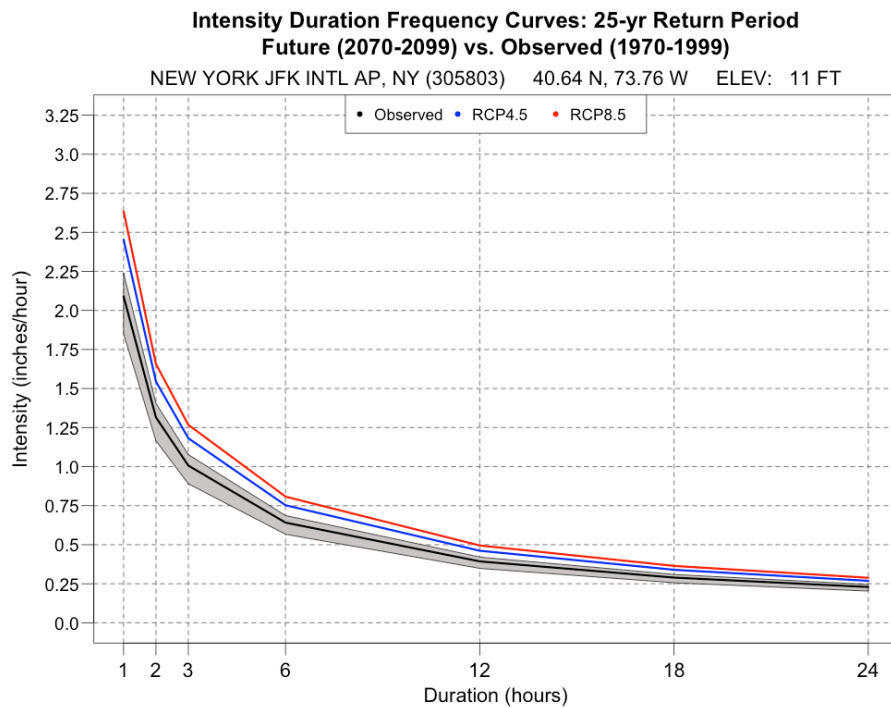
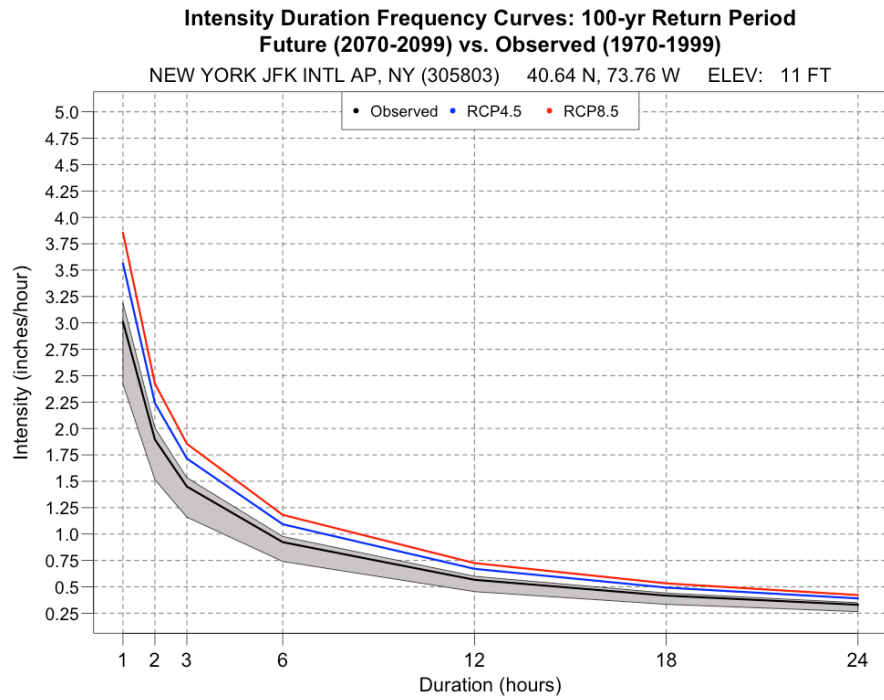


Figure 8: Historical and Future IDF Curves for 100-Year Return Period, JFK Intl Airport, NY



Source: Northeast Regional Climate Center, Cornell University

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ANENX B: SUPPLEMENTAL MEMORANDUM LONG BEACH ROAD/AUSTIN BOULEVARD CORRIDOR, TOWN OF HEMPSTEAD, NY

INTRODUCTION

Nassau County selected the Long Beach Road/Austin Boulevard Corridor in the Town of Hempstead, New York for investigation via an engineering informed climate vulnerability assessment. Long Beach Road and Austin Boulevard are arterial roadways under the jurisdiction of Nassau County. The climate vulnerability assessment examined the impacts of projected changes in the frequency and magnitude of extreme precipitation events on a segment of Long Beach Road in Oceanside, between Mott Street and the bridge over Barnum Island Channel and suggested an update to the County's drainage design guidelines to address these future impacts.

Given that this segment of Long Beach Road has a long-standing, recurring flooding condition that occurs during periods of intense rainfall, Nassau County requested a supplement to the assessment to examine existing drainage issues along the segment during precipitation events, the results of which are summarized in this memorandum.

BACKGROUND INFORMATION ON EXISTING CONDITIONS

Nassau County provided the project team with inter-departmental memos dating back to 2002, documenting complaints of flooding on Mott Street, the Sands Shopping Center at the corner of Long Beach Road and Mott Street, and Kings Highway, located behind the shopping center. Preliminary investigations conducted by the County in 2000 and 2002, both near low tide, showed the outfall pipe located near the south end of the Sands Shopping Center to be approximately half full of water, indicating a decreased flow capacity for the drainage system. However, further investigations by the County concluded that the flooding problem at this location appeared to originate at the junction of two County-owned 30-inch drainage pipes located south of the intersection of Mott Street and Long Beach Road. Therefore, this analysis focuses on the capacity and flow at the junction.

At this junction, two 30-inch storm drainage pipes feed into a manhole with a 36-inch drainage pipe exiting the manhole. This 36-inch pipe feeds into two more 36-inch pipes, which in turn feed into a 42-inch pipe, forming a pipe run¹¹ that connects the manhole to a 48-inch outlet pipe at the south end of the shopping center. Preliminary calculations of pipe capacity performed by the Nassau County Department of Public Works show that the 36-inch drainage pipe does not have the capacity to handle the flow from both of the 30-inch pipes.

This analysis does not examine the outfall in depth, as under current conditions it is not considered a key contributor to drainage problems at the study area. Although current conditions allow for enough hydraulic head (a measure of liquid pressure) to build up in the drainage system upstream in order to push water through the partially submerged outlet, future sea level rise (SLR) will likely require a greater amount of hydraulic head to maintain this condition. Based on SLR projections, this outfall pipe will be completely under water during low tide events by mid-century. Further investigation is needed to determine if and to what extent the invert elevation of this outfall should be raised to account for impacts of SLR.

¹¹ A pipe run is a path formed by a piping system.

FURTHER ANALYSIS OF EXISTING CONDITIONS

A high level calculation, using the following methodology, was performed to compare the total flow into the 36-inch pipe with the capacity of the pipe.

A map was created with contours derived from the USGS National Elevation Dataset to aid in determining the tributary area for the drainage system up to the junction where the two 30-inch pipes connect to the 36-inch pipe. The tributary area was determined to be approximately 47 acres. The Rational Method equation $Q=CIA$ was used to determine the total flow into the 36-inch pipe. For this calculation, the runoff coefficient (C) was determined from Table 3-1 of the Hydraulic Engineering Circular No. 22, Second Edition, Urban Drainage Design Manual published by FHWA. The C value is dependent on the ground cover. The site's tributary area along Long Beach Road is primarily occupied by businesses; however, the remainder of the area comprises residences. According to Table 3-1, the C value for downtown areas is within the range 0.70 to 0.95, and the C value for neighborhood areas varies between 0.50 and 0.70. A runoff coefficient C of 0.70 is used in the calculation. The estimated time for runoff to travel from the most distant point of the tributary area to the junction is 23 minutes. The rainfall intensity at the site was determined from an Intensity Duration Frequency (IDF) Curve based on historical weather for Nassau County.¹²

Table 5. Extreme Precipitation Estimates, Long Beach Road Vicinity (Rainfall in Inches)

Years/Minutes	5	10	15	30	60
1	0.35	0.53	0.66	0.86	1.08
2	0.42	0.64	0.80	1.04	1.30
5	0.48	0.75	0.94	1.25	1.61
10	0.54	0.84	1.06	1.44	1.88
25	0.62	0.99	1.26	1.74	2.31
50	0.70	1.12	1.44	2.01	2.71
100	0.79	1.28	1.65	2.33	3.18
200	0.89	1.45	1.88	2.70	3.73
500	1.06	1.74	2.27	3.29	4.61

Source: Northeast Regional Climate Center

The 5-year storm frequency was used for the primary analysis (consistent with State guidance for minor arterials). With an estimated time of concentration equal to 23 minutes and a 5-year design storm, the intensity is 3.00 inches per hour. Using these values, the maximum flow (Q) was calculated to be approximately 99 cubic feet per second (cfs). Manning's Equation for circular storm drains flowing full¹³ considers the pipe's diameter (36"), slope (0.15%) and Manning's coefficient ($n=0.011$) to calculate the capacity of the 36-inch pipe as approximately 30 cfs. Therefore, the estimated flow into the 36-inch pipe is over 3 times the capacity of the pipe, for a 5-year rainfall event.

¹² Data to create the IDF curve provided by the Northeast Regional Climate Center (NRCC) at Cornell University (<http://precip.eas.cornell.edu/>).

¹³ Equation 7-1 Federal Highway Administration Hydraulic Engineering Circular No. 22, Second Edition, Urban Drainage Design Manual.

Estimated peak flow (Q) and associated minimum pipe diameters¹⁴ (in inches) were also calculated for the 25- and 100-year recurrence interval events, employing the assumptions detailed above (results shown in Table 2. Estimated Peak Flow and Minimum Pipe Diameters for 5-, 25-, and 100-year Rainfall).

Table 6. Estimated Peak Flow and Minimum Pipe Diameters for 5-, 25-, and 100-year Rainfall

Recurrence Interval (Yrs)	Rainfall Intensity (i) (in/hour)	Peak Flow (Q) (cfs)	Slope (%)	Min Pipe Diameter (in)
5	3.00	98.5	0.15%	57
25	4.17	137.1	0.15%	64
100	5.60	184.3	0.15%	71

The same procedure was used to compare the total flow at the outlet point of the pipe network with the capacity of the 48-inch outlet pipe. The tributary area was determined to be approximately 52.5 acres. As in the previous calculation, the runoff coefficient (C) of 0.70 was used. With an estimated time of concentration equal to 27 minutes¹⁵ and a 5-year design storm, the intensity was 2.71 inches per hour. Using these values, the maximum flow rate (Q) was calculated to be approximately 100 cubic feet per second (cfs). Manning's Equation for circular storm drains flowing full¹⁶ considers the pipe's diameter (48-inch), slope (1.0%) and Manning's coefficient (n=0.011) to calculate the capacity of the 48-inch outfall pipe as approximately 169 cfs. Therefore, the estimated flow into the 48-inch pipe is less than the capacity of the pipe for a 5-year rainfall event.

Estimated peak flow (Q) and associated minimum pipe diameters (in inches) were also calculated for the 25- and 100-year recurrence interval events, employing the assumptions detailed above (shown in Table 3).

Table 7. Estimated Peak Flow and Minimum Pipe Diameters for 5-, 25-, and 100-year Rainfall

Recurrence Interval (Yrs)	Rainfall Intensity (i) (in/hour)	Peak Flow (Q) (cfs)	Slope (%)	Min Pipe Diameter (in)
5	2.71	99.7	1.00%	40
25	3.79	139.4	1.00%	45
100	5.12	188.0	1.00%	50

However, the outlet pipe would actually receive more than 100 cfs during a 5-year rainfall event. The Sands Shopping Center is located on Long Beach Road, north of the outfall. A system of drywells was designed and constructed to provide storage for the rainfall runoff for the approximately 9 acres of the shopping center's paved and landscaped areas. The calculation above assumes that the stormwater runoff from the shopping center is contained in the drywells and completely dissipates into the ground; however, to accommodate for overflow within the drywells, they are connected to each other with 4- and 5-inch pipes and ultimately to the drainage system leading to the 48-inch outfall pipe. Most, if not all, of the stormwater runoff from the shopping center should seep into the ground through the drywells. During heavy rainfall events (i.e., during which the capacity of the drywell is exceeded) and when the ground is already saturated, there will be flow from the drywells into the drainage system. The exact flow into the

¹⁴ In practice, the next available pipe size would be required (e.g., 58 inches minimum would require a 60 inch pipe).

¹⁵ The time of concentration equal to 27 minutes is calculated as the 23 minutes for the runoff to travel to the junction plus the 4 minutes it will take for the runoff to flow through the pipe network and reach the outlet.

¹⁶ Equation 7-1 Federal Highway Administration Hydraulic Engineering Circular No. 22, Second Edition, Urban Drainage Design Manual.

drainage system along Long Beach Road is not known. A conservative calculation assumes that all of the runoff from the shopping center enters the pipe system connecting to the 48-inch outfall. The outfall's new tributary area is equal to 61.5 acres (52.5 acres + 9 acres). Calculating the peak flow using an area equal to 61.5 acres produces a flow of approximately 117 cfs¹⁷, which is still less than the capacity of the outfall pipe.

Therefore, while there is a capacity limitation at the 36-inch pipe, there is not a capacity problem at the outfall at this time, with the potential exception of the 100-year event.

PROPOSED OPTIONS

The drainage pipes in the existing system along Long Beach Road between the 30-inch to 36-inch junction and the outlet have minimal pitch, with a slope of about 0.15% and approximately 4 to 5 feet of cover. Based on the existing conditions and the calculations described above, the following options are recommended for further investigation.

1. **Option 1:** Replace the existing 36-inch and 42-inch pipes between the junction and the outlet with 48-inch pipes. Additionally, the slope of the pipes should be increased slightly from approximately 0.15% to 0.35%. This proposed increase in the size of the pipes and slope will increase the capacity of the pipe at the junction from 30 cfs to 100 cfs, allowing it to accommodate the peak flow associated with today's 5-year rainfall event.
2. **Option 2:** Replace the pipes between the junction and the outlet with 60-inch pipes to achieve the capacity needed. By increasing the size of the pipe at the junction from 36 inches to 60 inches, the capacity increases from approximately 30 cfs to 119 cfs. In this option, the existing slopes can be maintained to allow for all connections to other branches of drainage pipe to remain.
3. **Option 3:** Investigate combining Options 1 and 2 (a 60-inch pipe with a slope of 0.35%), which would result in a capacity increase to approximately 182 cfs—enough to handle the peak discharge of today's 50-year rainfall event (about 159 cfs). The downstream impacts of this option would require evaluation.
4. **Option 4.** As a supplement to Options 1 through 3, reduce impervious surfaces within the drainage area (e.g., by adding landscaping, pervious pavements), thereby decreasing the runoff coefficient.

A detailed drainage design is required to confirm that the recommended size and slope of the new pipes will provide a capacity greater than the peak flow. Additionally, the requirements for pipe flow velocity and cover must be met, which will require further investigation.

¹⁷ This calculation uses a runoff coefficient equal to 0.70 for the entire 61.5 acres; however, the shopping center is mostly paved and a higher runoff coefficient may be appropriate for the 9-acre area.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT –

Loop Parkway Bridge Engineering Informed Adaptation Assessment

LOOP PARKWAY BRIDGE OVER LONG CREEK, TOWN OF HEMPSTEAD, NY

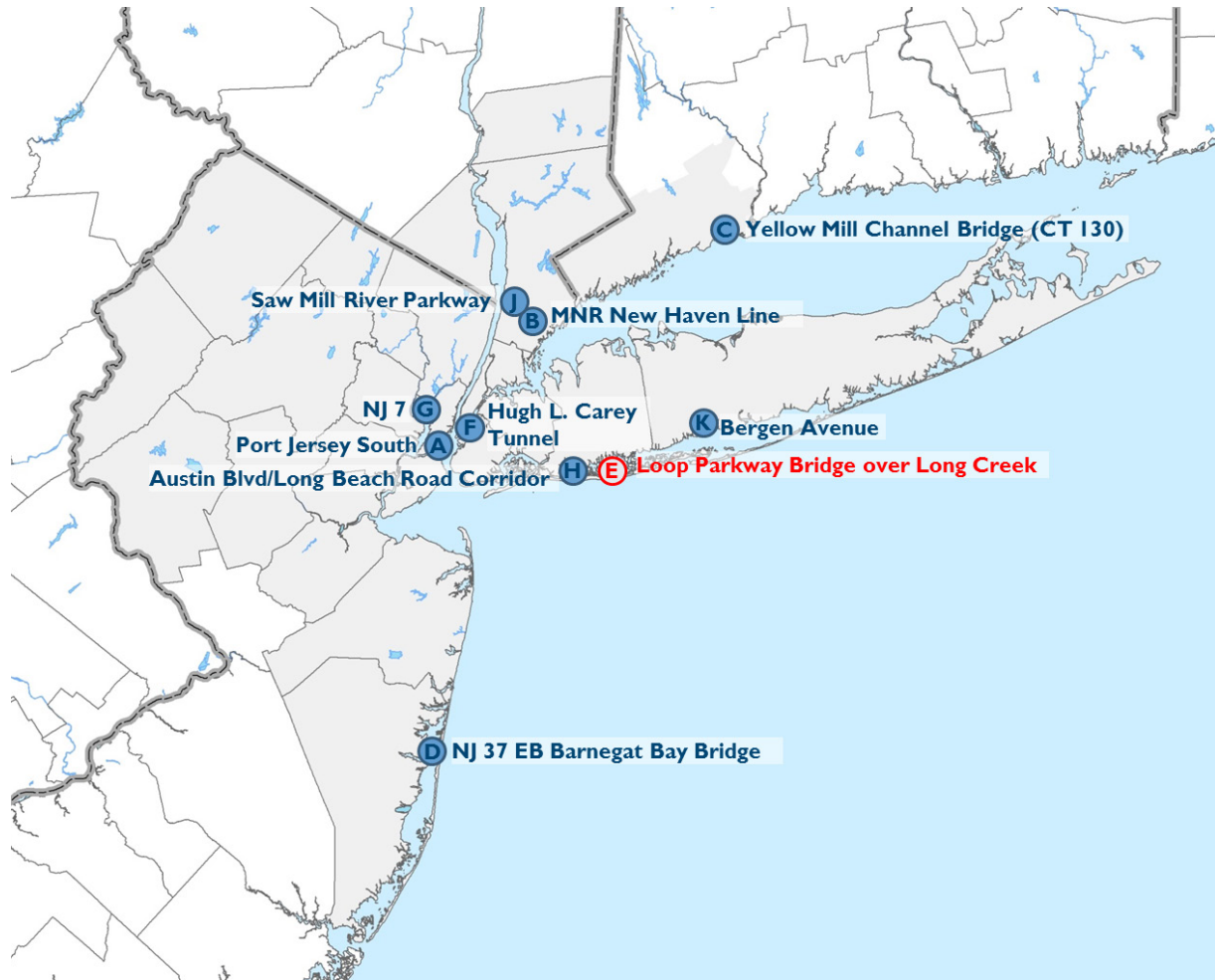
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Loop Parkway Bridge over Long Creek is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all ten study areas. The Loop Parkway study area is highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for Ten FHWA Study Areas (Loop Parkway Study Area in Red)



2. FACILITY DESCRIPTION

The Loop Parkway Bridge over Long Creek (National Bridge Inventory Structure Number 1056769) is a bascule bridge on Loop Parkway in Nassau County, NY. The bridge connects the South Shore barrier island communities of Long Beach, Lido Beach, and Point Lookout to the Meadowbrook State Parkway (see Figure 2), which in turn connects to Long Island, NY. The historic parkway, which opened in 1934, is a part of the National Highway System (NHS) network. The bridge is owned and maintained by the New York State Department of Transportation (NYSDOT), Region 10, and is within the domain of the New York Metropolitan Transportation Council (NYMTC), the Metropolitan Planning Organization (MPO) for New York City, Long Island, and the Lower Hudson Valley.

Figure 2: Facility Location – Loop Parkway Bridge Over Long Creek



Source: Google Maps, 2014

The Loop Parkway Bridge carries two lanes of vehicular traffic in each direction. It comprises a two-leaf bascule span (shown in Figure 3) and is flanked by nine fixed spans at each approach (shown in Figure 4). The bridge is over 80 years old (built in 1934), and various components of the bridge have undergone significant rehabilitation, most recently in 1992. Its mechanical and electrical components are reported to be in fair condition, despite having been affected by Hurricane Sandy.

Loop Parkway is a limited access facility used heavily by commuters between the barrier island communities (approximate population of 41,000 as of 2010) and population and employment centers on Long Island. Annual Average Daily Traffic (AADT) volumes are approximately 30,302 at the bridge crossing. The parkway serves as a hurricane coastal evacuation route for several barrier island communities. There is no dedicated bikeway or pedestrian sidewalk on the bridge.

As part of the State Boat Channel Network, the most utilized navigable channel in this area, Long Creek plays an important role in local maritime activity. Bridge openings over Long Creek occur daily to allow for passage of marine vessels, including 10 to 20 commercial fishing vessels each day.¹ Annual openings typically exceed 4,000.

¹ Source: NYSDOT.

Figure 3: Bascule span in open position on Loop Parkway Bridge



Source: AECOM, 2014

The bridge was selected for assessment in part because it is representative of older bascule bridges in New York State and throughout the region, and because it has demonstrated vulnerabilities to coastal flooding that may worsen due to projected sea level increase as the century progresses. Flooding from Hurricane Sandy compromised the bridge's electrical systems, contributed to scour², and caused erosion and washout of its approach embankments—requiring emergency repairs to the bridge's electrical components and structure³.

As directed by NYSDOT, the specific bridge components considered in this assessment include the electrical and mechanical systems which drive the bascule span. A control room houses the wiring and electrical switches and gears that are used to operate the bascule span, roadway traffic signals, and gates. A power room houses the motors and machinery that drive the opening of the span. NYSDOT also considers some junction boxes (particularly those above the waterline and therefore less protected against water intrusion) to be potentially vulnerable to inundation, as these components were adversely affected by Hurricane Sandy. A back-up generator is located at the northeast approach, connected to electrical and mechanical systems via submarine cables (which may be vulnerable to scour). The impacts of scour, erosion, and other impacts of flooding and wave action are not assessed due to resource constraints, although all of these factors should be considered and, as appropriate, assessed prior to making major investment decisions.

At the time this assessment was conducted in 2015, NYSDOT was progressing two projects to improve the routine mechanical operation and resilience of the Loop Parkway bridge (see footnote⁴).

² The Loop Parkway Bridge is classified as scour critical.

³ Scour countermeasures at the piers and abutments were underway as of the time of writing (an approximately \$3 million project).

⁴ Contract D262994 (PIN 0809.25) - Drawbridge Repairs Loop Pkwy and Meadowbrook Pkwy and Contract D262801 (PIN OCBOW1) – Scour Critical Bridge Improvements.

Figure 4: Loop Parkway Over Long Creek – South Side



Source: AECOM, 2014

Table 1 provides a summary of the use of the bridge and the age and condition of its electrical and mechanical components.

Table 1: Facility Details

Facility Type	Roadway Bridge with Moveable and Fixed Spans	
Facility Component	Electrical	Mechanical
Estimated Age	23 years (1992)	23 years (1992)
Estimated condition	Fair	Fair
Use (2010)	AADT: 30,302 vehicles (<1% trucks, estimated) Annual bridge openings for vessels: 4,000 Fishing vessel traffic: 10 to 20 per day	

Source: NYSDOT

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

The Loop Parkway Bridge is exposed to periodic Nor'easters and hurricanes (the bridge was adversely affected by Hurricane Sandy) due to the proximity of Long Creek to the Atlantic Ocean. Long Creek is located near Jones Inlet, separating Long Beach Barrier Island and Jones Beach State Park, and is subject to high-volume and high-velocity flows. These flows can potentially inundate junction boxes and equipment in electrical and mechanical rooms, and they may also lead to scour and erosion of bridge abutments and foundations (the latter two structural issues are not addressed in this assessment due to resource constraints). The risk of coastal flooding may worsen due to projected sea level rise (SLR) in the course of the bridge's estimated useful life.

Extreme heat, particularly for sustained periods of time, may also affect the operation of moveable bridges due to thermal expansion, failure of electrical or mechanical equipment, and/or power outages (although the back-up generator is activated automatically). While not likely a dire threat relative to issues such as scour and structural failure, extreme heat can negatively affect the reliability of bridge operations, and is therefore worthy of consideration.

3.1 SEA LEVEL RISE

The scenarios for projected SLR were selected by NYSDOT and are based on estimates for New York City from a report developed by the New York State Energy Research and Development Authority (NYSERDA) entitled *Climate Change in New York State* (ClimAID, 2014).⁵ The scenarios are summarized in Table 2. Consistent with NYSDOT's low risk-tolerance approach to this assessment, high-estimate (90th percentile⁶) SLR projections were examined for mid- and end-of-century time horizons. These projections are relative to a baseline year range of 2000 – 2004.

Table 2: Projected Sea Level Rise Scenarios (Feet)

Year	Baseline MHW* Elevation**	Regional SLR Magnitude	Projected MHW Elevation
2050s	3.1	2.5	5.6
2100s	3.1	6.3	9.4

Source: ClimAID, 2014.

*MHW stands for Mean High Water Level.

** Vertical datum is Mean Sea Level (MSL)

3.2 STORM SURGE

Two storm surge⁷ scenarios (9 feet and 18 feet) were also recommended by NYSDOT and are consistent with past NYSDOT planning efforts. They are summarized in Table 3. For the purpose of this assessment, the 9-foot and 18-foot storm surge scenarios are referred to as “moderate” and “extreme” storm surge scenarios, respectively. The 18-foot scenario is consistent with flood depths observed during

⁵ Horton, R., D. Bader, C. Rosenzweig, A. DeGaetano, and W. Solecki. 2014. *Climate Change in New York State: Updating the 2011 ClimAID Climate Risk Information*. New York State Energy Research and Development Authority (NYSERDA), Albany, New York.

⁶ Percentile indicates the value below which x% of projections are found (e.g., 90% of projections are found below the 90th-percentile value).

⁷ According to FEMA Region 2, “Storm surge is the water, combined with normal tides, [which] is pushed toward the shore by strong winds during a storm.” Elevations referenced in this section are in *addition* to normal tidal elevations.

Hurricane Sandy in the nearby region, although the recorded depth at the Loop Parkway Bridge was 9 feet.

Table 3: Storm Surge Scenarios

Storm Surge Type	Storm Surge Height (Feet)
Moderate	9
Extreme (Hurricane Sandy-equivalent)	18

Source: NYSDOT

Table 4 shows the projected water elevations from combinations of these SLR and storm surge scenarios for both mid- and end-of-century time periods.

Table 4: Combined Projections for SLR and Storm Surge at MHW

Stressor Type	Elevation (Feet above MSL)	Analysis Year and Scenario
SLR + Moderate Storm Surge	14.6	2050s high range-estimate (90 th Percentile)
	18.4	2100s high range-estimate (90 th Percentile)
SLR + Extreme storm surge	23.6	2050s high range-estimate (90 th Percentile)
	27.4	2100s high range-estimate (90 th Percentile)

Source: NYSDOT

3.3 EXTREME HEAT EVENTS

Scenarios for the projected changes in the frequency and magnitude of extreme heat events were developed by the project team using the SimClim model⁸, and are summarized in Table 5 and Table 6. Table 5 shows the projected high-estimate (95th percentile) increase in the magnitude and frequency of single-day maximum temperatures for July by mid- and end-of-century. Table 6 shows the corresponding projections for three-day average maximum temperatures. These events, both of which are associated with an increased risk of failure for moveable bridges once they approach 110° F, approximately, were selected based on the experience and professional judgment of the engineering team for this assessment (i.e., neither are found in formal design guidelines). These projections are associated with the nearby Wantagh Cedar Creek weather station, and reflect change over baseline values for that station. As this weather station is inland (and therefore not subject to coastal cooling) and the bridge components may be subject to additional solar gain (which can result in significantly higher surface temperatures), the projected change (i.e., the delta) may be more useful to consider than projected absolute temperatures.

Because, under the current maintenance schedule, the bridge is likely to undergo rehabilitation by mid-century and full replacement by end-of-century, the adaptation strategies proposed subsequently are designed to withstand end-of-century climate impacts. It is recommended that the implementation of these strategies coincide with the bridge's anticipated mid-century rehabilitation.

⁸ SimCLIM is a software tool designed to facilitate the assessment of risks from climate change. <<http://www.climsystems.com/simclim/>>

Table 5: Projected Increase in Max. Temperature/Frequency during 1-day Extreme Heat Events

Time Horizon	Baseline Scenario (1995)		Projected Return period (years) for Base Temperature (°F)	Projected Temperatures (°F) for Respective Return Period
	Return Period (years)	Temperature °F	High-Estimate (95th Percentile, RCP-8.5)	
2050s	2	93.1	1.3	98.3
	5	98.1	1.9	103.3
	10	100.4	2.7	105.6
	20	102.0	3.7	107.2
	50	103.5	5.4	108.8
	100	104.4	6.8	109.6
2100s	2	93.1	1	105.6
	5	98.1	1.1	110.6
	10	100.4	1.3	112.9
	20	102.0	1.4	114.5
	50	103.5	1.6	116.1
	100	104.4	1.7	116.9

Table 6: Projected Increase in Max. Temperature/Frequency during 3-day Extreme Heat Events

Time Horizon	Baseline Scenario (1995)		Projected Return period (years) for Base Temperature (°F)	Projected Temperatures (°F) for Respective Return Period
	Return Period ⁹ (years)	Temperature °F	High-Estimate (95th Percentile, RCP-8.5 ¹⁰)	
2050s	2	86.4	1.2	91.6
	5	91.3	1.9	96.5
	10	94.0	2.9	99.2
	20	96.2	4.6	101.4
	50	98.5	8.4	103.7
	100	100.0	13.0	105.3
2100s	2	86.4	1	98.9
	5	91.3	1.1	103.8
	10	94.0	1.2	106.5
	20	96.2	1.4	108.7
	50	98.5	1.9	111.1
	100	100.0	2.4	112.6

Source (both tables): Coupled Model Inter-comparison Project phase 5 (CMIP5) data in SimClim, queried by Abt Associates.

⁹ A return period is defined as the average time between events.

¹⁰ RCP stands for Representative Concentration Pathway. RCP 8.5 is the highest global GHG emissions scenario for which CMIP5 projections are available.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

As noted in previous sections, historically the bridge has been exposed to Nor'easters and hurricanes, and most recently sustained damage during Hurricane Sandy. Based on projected trends in SLR, storm surge, and extreme heat events, the bridge may be increasingly subject to the following modes of failure:

Physical Damage: During Hurricane Sandy, the junction boxes were inundated with seawater, causing essential electrical equipment to short circuit when the back-up generator activated. The power room and control room are located at elevations of 13 and 42 feet above MSL, respectively (see Figure 5). The combination of mid-century SLR and moderate storm surge would result in water levels of 14.6 feet above MSL, indicating that the power room could experience temporary flooding. In particular, salt water could infiltrate electrical and mechanical components in the power room and cause immediate or latent damage through anodic degradation and corrosion. However, the control room, due to its higher elevation, is not likely not be impacted by flooding from either a moderate or extreme storm event through the end of the century, even with SLR.

The bridge's electrical and mechanical components have not experienced physical damage due to extreme heat events historically, and there is no record of the bascule span jamming or locking up due to extreme temperatures. However, there is precedent for this concern. For example, NYSDOT reported that a bascule bridge in Albany, New York has experienced temporary inoperability due to thermal expansion of its mechanical components, causing it to lock down in closed position. Given the potential for significant temperature increases by mid century, extreme heat could become a factor other bascule bridges in the region as well, including the Loop Parkway Bridge. Mechanical systems subjected to very high temperatures can thermally expand and potentially cause increased friction between parts, causing the mechanisms to freeze up or fail.

Service Disruption: During Hurricane Sandy, due to inundation-related damage to equipment in the power room, the bridge's bascule span was locked in its closed position (a storm preparation measure) for 3 days and could not open for high mast recreational and commercial vessels that typically navigate the channel below. Future inundation of equipment would likely yield a similar result.

If extreme heat events damage electrical and mechanical components (as discussed above), disruption to marine vessel operations or vehicle travel may result, depending on whether the bridge is in the down or up position, respectively, at the time of failure. Both the frequency and magnitude of extremely hot days and heat waves is projected to increase significantly as the century progresses (see Table 5 and Table 6).

Past storm and extreme heat events have not resulted in notable disruptions to roadway traffic; the bridge has been locked down in the closed position prior to storm events (the standard protocol) and has been able to maintain normal operations during heat events. Therefore, roadway traffic is not likely to be significantly more vulnerable to disruption in the future, except in the case of extreme storm events. This exception is discussed in the next section.

Premature Deterioration: Based on an assessment of the age and current condition of the bridge and its components (see Table 1), as well as recently completed or planned repairs, the bridge is not expected to undergo rehabilitation until mid-century nor full replacement until end-of-century. However, both coastal flooding and extreme heat could accelerate deterioration of the bridge and its components. NYSDOT

currently performs a voluntary, in-depth inspection of mechanical and electrical equipment every 5 – 7 years, an interval that could be adjusted if failure rates increase. If premature deterioration compromises the bridge’s safety or resilience to extreme weather events, earlier implementation of adaptive strategies could be warranted (i.e., prior to mid-century).

Table 7: Loop Parkway Bridge Component Estimated Emergency Repair Cost and Recovery Time

Time and Cost	Magnitude
Estimated Emergency Repair Cost for electrical/mechanical equipment	Moderate and Extreme Storms: \$50,000 or more Extreme Heat: <ul style="list-style-type: none"> - Physical damage to electrical/mechanical equipment: \$50,000 or more - Power-outage related costs: None
Estimated Recovery Time for electrical/mechanical equipment	Storms <ul style="list-style-type: none"> - Moderate Storms: 3 days - Extreme Storms: Several days to several months Extreme Heat: <ul style="list-style-type: none"> - Regional Power Outage: a few minutes to a few days - Electrical/Mechanical: 3 days

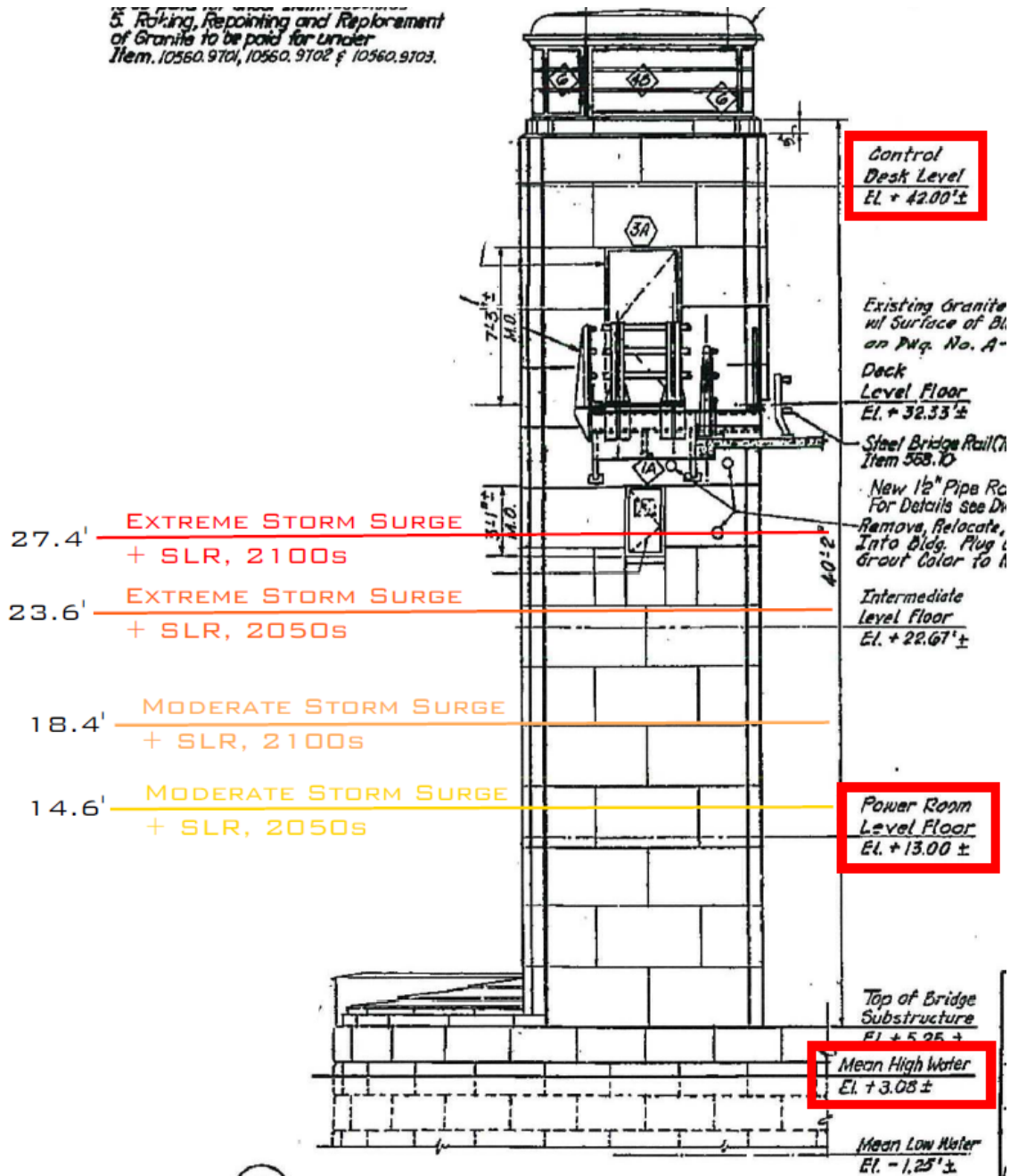
Source: Estimates are based on observed costs and times associated with Hurricane Sandy, and are provided by NYSDOT.

Note: Costs include labor and equipment and are expressed in \$2015.

Table 7 provides estimates of the recovery time and repair cost for restoring services at the bridge after a flooding or extreme heat event. Based on observed conditions after Hurricane Sandy, a moderate storm event with SLR (mid- or end-of-century) could flood the power room, causing the bridge’s bascule span to remain in locked-down position for around three days following the event. Unless this failure is coupled with structural damage, the bridge is likely to remain open to roadway vehicular traffic, but will cause disruption to marine vessel operations.

Additional impacts are anticipated due to extreme storm events, which could result in overtopping of the bridge approach roads and deck (see Figure 6 and Figure 7), debris overflow, and potential structural damage (i.e., washout), and would require inspections as well as clean-up efforts after the event. Should these conditions occur, the bridge would likely be closed to roadway vehicular traffic and the channel would likely be closed to marine vessels. Full restoration of vehicular and marine vessel operations could range from several days to several months. Strategies to address these and other impacts of extreme storms (especially on top of sea level rise) were not analyzed because impacts would be widespread, affecting much of the barrier island, and therefore require a regional approach to adaptation.

Figure 5: SLR and Storm Elevations at East Bascule Pier



Source: NYSDOT Rehabilitation of Loop Parkway over Long Creek, 1991 and AECOM, 2014.

Note: All elevations are relative to MSL.

Figure 6: Flood Elevations for Eastern Half of Loop Parkway Bridge

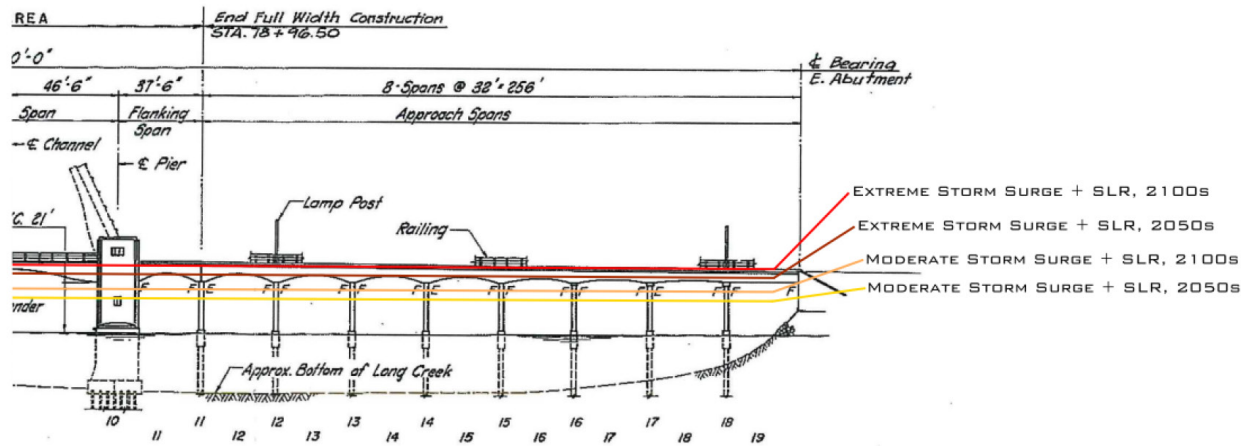
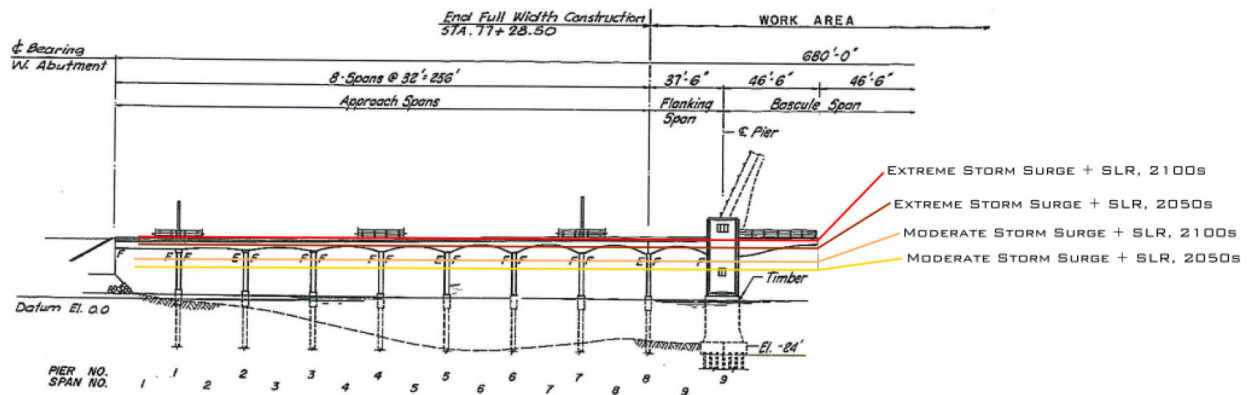


Figure 7: Flood Elevations for Western Half of Loop Parkway Bridge



In the context of extreme heat, a power outage would result in temporary operational disruption, lasting the duration of the outage or until the back-up generator could be placed into service. However, if extreme heat were to cause physical damage to the equipment, a three-day recovery timeframe is estimated, following the precedent set in the wake of Sandy.

The estimated repair cost of electrical/mechanical equipment due to flooding is approximately \$50,000, which corresponds to the recorded repair cost after Hurricane Sandy, given that the same power room equipment would be affected. The repair cost of electrical/mechanical equipment due to extreme heat events could be \$50,000 or more, as equipment in both the power room and control room may be affected. No repair costs are anticipated due to power outages.

4.2 ADAPTIVE CAPACITY ANALYSIS

The roadway transportation network which includes Loop Parkway exhibits some degree of adaptive capacity. There are two alternate roadway routes available to and from the barrier island communities—the Nassau Expressway and Long Beach Boulevard—in addition to Long Island Railroad’s Long Beach branch. However, a vulnerability analysis of these routes was not conducted, and it is possible that they may exhibit the same vulnerabilities as the Loop Parkway. The roadway detours are only a few miles longer than the route via the Loop Parkway Bridge, and it is estimated that each detour would add roughly 27 minutes to vehicle trips (under congested emergency conditions). The only potential alternative for commercial and recreational vessels depending on the Loop Parkway Bridge for access is via Reynolds Channel, which would require transiting three moveable bridges (i.e., if one of those bridges fails, access would be cut off). There is no alternative featuring a high span, stationary bridge.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Most of the failure modes previously discussed would affect only maritime operations, given that the span is locked in the down position prior to a major storm event. However, these impacts could not be quantified due to lack of data on the economic value associated with commercial and recreational traffic passing through the channel.

In the unlikely event that electrical and mechanical equipment fail while the bascule span is up and the backup generator fails, vehicular mobility between the barrier island communities (home to nearly 40,000 people) and Long Island would be restricted. The parkway has an AADT of 30,302, less than 1% of which are trucks (estimated). Travelers could either detour via the Nassau Expressway or Long Beach Boulevard, or use the Long Beach LIRR line, assuming that these routes are not similarly affected. Roadway detours would add approximately 27 minutes to trips, including additional delays associated with increased congestion.¹¹ Delay estimates due to mode-shift from automobiles to the train route would depend on the destination.

NYS DOT plans to add a hand crank to minimize the duration of disruption due to mechanical/electrical failures.

5.2 EFFECT ON REGIONAL ECONOMY

The bridge crossing at Long Creek is an important part of the vehicular and marine transportation networks in the area, allowing for the movement of people, goods and the provision of services, all of which are important drivers to the local and regional economies.

As noted previously, roadway traffic utilizing the bridge is not likely to be substantially impacted by moderate storms or by extreme heat events as long as the bridge is closed, consistent with storm preparation protocols (or, in the instance of extreme heat, enabled by the back-up generator). However, roadway traffic may be disrupted by extreme storm events by mid- and end-of-century due to potential overtopping of the bridge deck, accumulation of debris, or structural impacts. For perspective, the impacts

¹¹ Based on Google Maps from the entrance of Loop Parkway and Lido Blvd to the junction of Meadowbrook Parkway and West Sunrise Highway. When the bridge is operable, the traffic travels via Loop Parkway and Meadowbrook Parkway. When the bridge is inoperable, traffic would travel via Austin Blvd and Atlantic Avenue, resulting in an additional 18 minutes of travel time without traffic. A 50% penalty is applied to the additional travel time to account for the additional congestion for a total additional travel time of 27 minutes.

of this scenario on the regional economy are examined in this section—although, as explained previously, adaptation strategies were not developed for this scenario.

While maritime traffic is likely to be disrupted under any circumstance that results in closure of the bascule span for substantial periods of time, resulting in potentially significant costs, this scenario was not analyzed due to lack of data.

5.2.1 IMPACT OF EXTREME STORMS TO THE REGIONAL ECONOMY (VEHICLES ONLY)

This analysis estimates the per-event cost (in \$2012) of any event or condition which would make the bridge inoperable to vehicular traffic, requiring detours either to or from the barrier island. The cost estimate includes net travel time and operating costs associated with detours. In the event of a 7-day bridge closure, the cost incurred is based on the annual average daily traffic (AADT) for the parkway. The 2010 passenger vehicle AADT was multiplied by 7 days to derive an estimate of the total vehicle trips disrupted for purposes of this analysis. Actual daily traffic counts vary greatly by time of year.

For automobiles, the cost per vehicle per minute of delay was derived from the hourly New York-Northern New Jersey-Long Island, NY-NJ-PA Metropolitan Statistical Area (MSA) median household income (\$30.76 per hour or \$0.51 per minute in 2012¹²). Based on the conservative assumption that automobile travel is composed entirely of personal or commute trips, the value of time is set at 50% of the hourly median household income (\$15.38 per person per hour, or \$0.26 per person per minute in \$2012), based on U.S. DOT guidance.¹³ An automobile occupancy rate of 1.55 persons per vehicle was used to determine the delay cost per vehicle per minute.¹⁴ For trucks, the cost of delay is the commercial value of time that includes the costs of tires, fuel, driver wages, and driver benefits (\$48.70 per vehicle per hour or \$0.81 per vehicle per minute in \$2012).¹⁵ The per-minute cost for total automobile and truck traffic was then multiplied by the number of minutes per delay per vehicle to capture the economic cost for total traffic impacted for the duration of the delay. The additional delay per vehicle was assumed to be 27 minutes¹⁶, which includes a 50% penalty to account for congestion.

To determine additional vehicle operating costs, the detour distance (5.6 miles¹⁷) was multiplied by the number of trips (resulting in additional vehicle miles traveled) and vehicle operating cost per mile. The vehicle operating cost per mile includes the cost of gas, maintenance, tires, and half of depreciation, amounting to \$0.32 per mile (in \$2012)¹⁸. This calculation only applies to automobiles as the value of the truck time delay already includes operating costs.

Not every would-be traveler would be affected by a disruption to the operations of the Loop Parkway Bridge. It was assumed that 80% of passenger vehicle travelers would be forced to take an alternate route and incur both additional travel time and operating costs, whereas the remaining 20% of travelers

¹² Census.gov, New York-Northern New Jersey-Long Island, NY-NJ-PA Metro Area, <http://www.census.gov/prod/2013pubs/acsbr12-02.pdf>

¹³ Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, US DOT, April 2015, <http://www.transportation.gov/sites/dot.gov/files/docs/Revised%20Departmental%20Guidance%20on%20Valuation%20of%20Travel%20Time%20in%20Economic%20Analysis.pdf>

¹⁴ National Household Travel Survey, U.S. DOT, 2009, http://nhts.ornl.gov/tables09/fatcat/2009/avo_TRPTRANS_WHYTRP1S.html

¹⁵ ATRI, Operational Cost of Trucking, 2013.

¹⁶ Based on Google Maps from the entrance of Loop Parkway and Lido Blvd to the junction of Meadowbrook Parkway and West Sunrise Highway. When the bridge is operable, the traffic travels via Loop Parkway and Meadowbrook Parkway. When the bridge is inoperable, traffic would travel via Austin Blvd and Atlantic Avenue, resulting in an additional 18 minutes of travel time without traffic. A 50% penalty is applied to account for the additional congestion, for a total additional travel time of 27 minutes.

¹⁷ Based on Google Maps from the entrance of Loop Parkway and Lido Blvd to the junction of Meadowbrook Parkway and West Sunrise Highway. When the bridge is operable, the traffic travels via Loop Parkway and Meadowbrook Parkway. When the bridge is inoperable, traffic would travel via Austin Blvd and Atlantic Avenue, resulting in an additional 5.6 miles of travel.

¹⁸ AAA; Your driving Costs, 2013.

would not travel (e.g., telecommute or take vacation time) or would utilize other modes of transportation. 95% of trucks are assumed to be impacted, while the remaining 5% would not make the trip¹⁹.

The sum of the travel time and vehicle operating costs (over 7 days) reflects the total per-event economic costs of disruption to travelers. These costs are summarized in Table 8 below.

Table 8: Economic Impacts of an Extreme Storm under a No-Action Scenario

Vehicle Type	Per-Event Travel Time Cost (\$2012 Millions)	Per-Event Vehicle Operating Cost (\$2012 Millions)	Total Per-Event Cost (\$2012 Millions)
Passenger vehicles	\$1.75	\$0.29	\$2.04
Trucks	\$0.18	n/a	\$0.18
Total	\$1.92	\$0.29	\$2.21

5.3 EFFECT ON DISADVANTAGED POPULATIONS

The Loop Parkway connects the barrier island communities of Long Beach, Lido Beach, and Point Lookout to Long Island. There are no identified bus services on the Parkway (commercial vehicles or trucks are typically not permitted, although, at a minimum, garbage trucks use this route) which indicates that populations reliant on public transit do not use the Parkway. There are two other vehicular routes available (Nassau Expressway and Long Beach Boulevard) with bus services (N33 and N15, respectively) that provide alternative access for the barrier island communities, as well as one train route (the Long Beach Branch of the LIRR).

Approximately 10.2 percent of the population in Long Beach is below the poverty line.²⁰ There are 3 block groups in the northern part of Long Beach in which between 38 and 50 percent of the population is below the poverty level. The repercussions of Parkway closure for these groups may be higher than for others if they work on Long Island (this population may be less likely to receive paid time off, for example). Closure of the parkway would also restrict access to fire and emergency vehicles serving the barrier island communities, which could have disproportionately higher effects on disadvantaged populations.

Impacts on disadvantaged populations as a result of disruption to marine vessels were not analyzed due to lack of data.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This section discusses options to address the vulnerability of the bridge’s power room to inundation and extreme heat events (which could also affect the control room), and a potentially complementary strategy to improve the redundancy of the bridge’s power supply system via the installation of an additional generator. A manual hand crank also could be included as an alternative mechanical means to lift or lower the bascule span. The hand crank system would only be used for emergency situations, and would include multiple gears to reduce the force needed to lift the span. A full lift of the span using this manual technique would likely take several hours.

¹⁹ The trip purpose for trucks is unknown, but it is assumed that most truck trips are not discretionary.

²⁰ U.S. Census, 2008-2012.

NYS DOT is also considering developing written operational policies to mitigate damage and disruption from coastal inundation events, such as temporarily disconnecting the backup generator prior to a major storm to avoid short circuiting the system, as occurred during Hurricane Sandy.

As noted previously, the impacts of scour, erosion, and other impacts of flooding and wave action are not assessed in this assessment due to resource constraints. These factors should be considered and, as appropriate, assessed prior to making major investment decisions.

6.1 ADAPTATION OPTIONS FOR POWER ROOM AND CONTROL ROOM

Option A: Elevate Power Room to Address Flood Vulnerabilities and Install HVAC System to Address Extreme Heat Vulnerability

This strategy involves relocating flood-vulnerable equipment in the power room to an elevation of approximately 29.4 feet above MSL, which is 2 feet above the projected water elevation for an end-of-century extreme storm event (27.4 feet above MSL). A new enclosure would be required to accommodate this equipment. The enclosure would be built as a new extension at the east bascule pier and could either be supported by the existing pier, or on a separate adjacent structure (wind load studies are recommended for each option). In either case, the proposed enclosure would require consultation with the State Historic Preservation Office due to the historic significance of the existing bridge structure. The design would need to minimize adverse visual impacts to the bridge.

This strategy also recommends the installation of a Heat, Ventilation, and Air-Conditioning (HVAC) system in the new enclosure to prevent impacts from anticipated extreme heat events, particularly toward the end of the century. The HVAC system can maintain favorable temperatures for sensitive equipment year-round (the control room is currently air conditioned).

Option B: Protect Power Room in Place to Address Flood Vulnerabilities and Install HVAC System to Address Extreme Heat Vulnerability

This strategy involves securing the power room in place by installing a flood barrier wall (within the room) and other waterproofing measures to protect equipment from inundation. This strategy also includes the installation of an HVAC system to address extreme heat events. All openings of the HVAC system should be above the maximum end-of-century flood elevation of 27.4 feet above MSL.

This strategy is offered in case the previous option is deemed unfavorable due to historic preservation concerns. From a technical perspective, protection in-place is less favorable than elevation of the power room. Under this option, the existing windows and door openings of the power room would need to be sealed and made watertight. Flood barrier walls would need to be added inside the room. Impermeable waterproofing membrane sheets would have to be applied to the surface of the new walls, floors, and ceilings. The enclosure would be equipped with a sump and hydraulic pump to remove any standing water that may accumulate over time or any flood waters that may breach the system.

6.1.1 ECONOMIC ANALYSIS

These options could potentially prevent adverse impacts to the area's maritime economy. Although these impacts could not be quantified, according to NYS DOT the bridge opens approximately 4,000 times annually, meaning that a week-long delay could result in nearly 80 missed openings, and likely significantly more during the peak season²¹. These options could also potentially mitigate the unlikely instance of equipment/power failure in the open position (e.g., due to equipment failure resulting from

²¹ As sea levels rise, the number of vessels exceeding the bridge's maximum vertical clearance may increase, requiring commensurately more frequent bridge openings (and increasing associated wear and tear).

extreme heat or a power outage and associated generator failure), which would otherwise disrupt vehicular traffic.

6.1.2 ENVIRONMENTAL ANALYSIS

Architectural, cultural and historic assessments, Section 4(f) consultation, and land use evaluations may be required.

6.1.3 EQUITY ANALYSIS

Impacts on disadvantaged populations as a result of disruption to marine vessels were not analyzed due to lack of data.

6.1.4 COST ANALYSIS

The cost components of these options are summarized in Table 9. HVAC costs may be removed if NYSDOT does not wish to consider extreme heat impacts at this time.

Table 9: Sample Scope of Work and Estimated range of Costs for Adaptation Options

Option A: Elevate Power Room to Address Flood Vulnerabilities and Install HVAC System to Address Extreme Heat Vulnerability
Raising Electrical/Mechanical Room
New State-of-Art Equipment (see footnote below)
HVAC System
Architectural Treatments
Handling Hazardous Material
Construction Contingency
Mobilization/Construction Survey
Engineering Cost
Escalation
Total Estimated Range of Costs: \$0.5 Million to \$50 Million
Option B: Protect Power Room in Place to Address Flood Vulnerabilities and Install HVAC System to Address Extreme Heat Vulnerability
Sealing Windows, Doors, Structure
Flood Protection Walls
HVAC System
Sump Pump System
Handling Hazardous Material
Construction Contingency
Mobilization/Construction Survey
Engineering Cost
Escalation
Total Estimated Range of Costs: \$0.5 Million to \$10 Million

Note: Use of new, state-of-art equipment for mechanical and electrical systems when repairs or replacements are necessary will provide added resilience, the degree of which could be further explored during project development.

6.1.5 TIMING FOR IMPLEMENTATION

Mid-century implementation should be considered, coincident with the bridge’s current rehabilitation schedule. Although the potential for climate-related impacts will remain in the interim, the estimated cost and time of repairs (and the broader economic and social costs of disruption) are expected to be relatively minor, based on observed impacts from Hurricane Sandy.

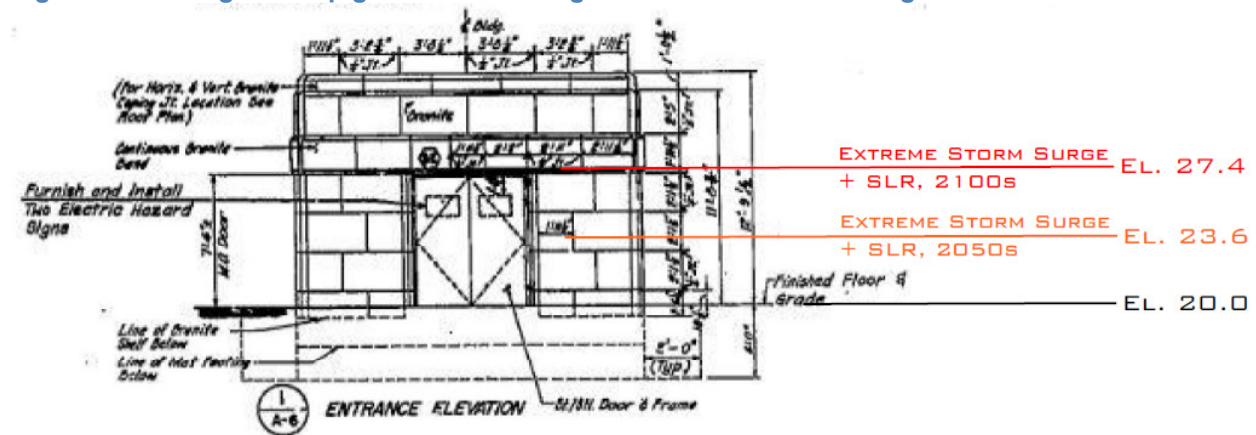
It is estimated that the design and permitting process for Option A for the power room would take approximately two years (this estimate includes the time needed for conceptual, preliminary, and final design, as well as permitting), and construction would take approximately two years. Design and permitting for Option B for the power room would take approximately one year, and construction would take one year. Design, permitting and construction for Option A for the control room could likely be completed within a year.

6.2 INCREASE POWER SUPPLY REDUNDANCY AND PROTECT ADDITIONAL POWER SUPPLY EQUIPMENT FROM FLOODING AND HEAT VULNERABILITIES

Uninterrupted electrical power is critical to maintaining full functionality of the bridge. In addition to the machinery powering the bascule leaves, roadway traffic signals, gates, and alarms are used to stop vehicular traffic from crossing the bridge when the bascule span is lifted. Operation of the bascule span and traffic control equipment is managed from the control room.

The primary power source for all of the bridge's electrical systems is the public power grid (Long Island Power Authority). Power is brought up to the bridge's east bascule pier via a NYSDOT-owned submarine cable, which in turn is transmitted to power traffic signals, gates and roadway lighting via conduits installed in the bridge parapets. A secondary power source is provided by a diesel back-up generator located at the northeast approach to the bridge, approximately 500 feet east of the span. When required, the generator produces electricity and delivers it to the main electrical panel in the bascule pier control room. It is diesel-powered, and utilizes an above-ground fuel storage tank. The floor of the existing back-up generator and fuel tank are at an elevation of 19.96 feet above MSL, which is below the sea level rise plus extreme storm surge flood elevations of 23.60 feet and 27.40 feet above MSL for mid- and end-of-century, respectively (see Figure 8).

Figure 8: Existing back-up generator housing elevation with storm surge elevations



Source: NYSDOT Rehabilitation of Loop Parkway over Long Creek, 1991 and AECOM, 2014.

Note: The vertical datum is MSL.

This adaptation strategy proposes installing an *additional*, state-of-art back-up electric generation system at an elevation of approximately 29.40 feet above MSL, which is 2 feet above the projected end-of-century combined sea level rise and storm surge elevation. The proposed design includes an electric generator station housed in an enclosure at the east approach to the bridge, near the existing generator house. The enclosure would be designed for a 100-year service life. The additional generator would be capable of running off of both diesel and gasoline. Electrical distribution would include a new load panel, transformer, watertight electrical boxes, corrosion resistant conduit, and spare, redundant circuit wiring. The back-up power circuit would be routed into the submarine cable through the new electrical load panel and continue up the bridge to the east bascule pier.

6.2.1 ECONOMIC ANALYSIS

This option could potentially prevent adverse impacts to the area’s maritime economy. However, these impacts could not be quantified due to lack of data on maritime activity dependent on passage through this section of Long Creek. This option could also potentially mitigate the unlikely instance of equipment/power failure in the open position (e.g., due to equipment failure resulting from extreme heat or a power outage and associated generator failure), which would otherwise disrupt vehicular traffic.

6.2.2 ENVIRONMENTAL ANALYSIS

This strategy may have potential impacts on coastal and wetland resources. In order to evaluate the environmental impacts of this strategy in detail, site specific analyses will be required. These analyses may include architectural and cultural assessments, land use evaluations, and wetland impact studies.

6.2.3 EQUITY ANALYSIS

Impacts on disadvantaged populations as a result of disruption to marine vessels were not analyzed due to lack of data.

6.2.4 COST ANALYSIS

The cost components of this option are summarized in Table 10.

Table 10: Sample Scope of Work and Estimated Range of Costs for the Installation of a New Backup Power System and Protecting New and Existing System from Climate Stressors

Cost Component
Relocating Secondary Electric Power System
New State-of-the-Art Equipment
Environmental Mitigation
Construction Contingency
Mobilization/Construction Survey
Engineering Cost
Escalation
Total Estimated Cost: \$0.5 Million to \$10 Million

6.2.5 TIMING FOR IMPLEMENTATION

The timing for implementation is described in Section 6.1.5. It is estimated that the design and permitting process would take approximately two years (this estimate includes the time needed for conceptual, preliminary, and final design, as well as permitting), and construction would take approximately one year.

7. CONCLUSION

This assessment identified potential vulnerabilities of the Loop Parkway Bridge’s electrical and mechanical components to coastal inundation and extreme heat. The bridge’s power room has already proven vulnerable to coastal inundation, which is expected to occur more frequently as sea levels increase. Equipment in both the power and control rooms may be susceptible to extreme heat, which is projected to increase in frequency and magnitude as the century progresses—and extreme heat may also tax the public power grid, on which the bridge depends as its primary source of electricity. To address the flooding-related vulnerabilities of the power room, equipment could either be raised to an elevation above the end-of-century SLR and extreme storm event elevation (27.4 feet above MSL), or be protected in place via the use of internal flood barrier walls and other waterproofing measures.

The installation of HVAC (climate control) systems for both the power room and control room could address potential extreme heat-related vulnerabilities. Additionally, this assessment considers improving the redundancy of the bridge's power supply by installing an additional generator above the projected maximum flood elevation.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

MNR New Haven Line Engineering Informed Adaptation Assessment

MTA METRO-NORTH RAILROAD (MNR) NEW HAVEN LINE, PELHAM, NY

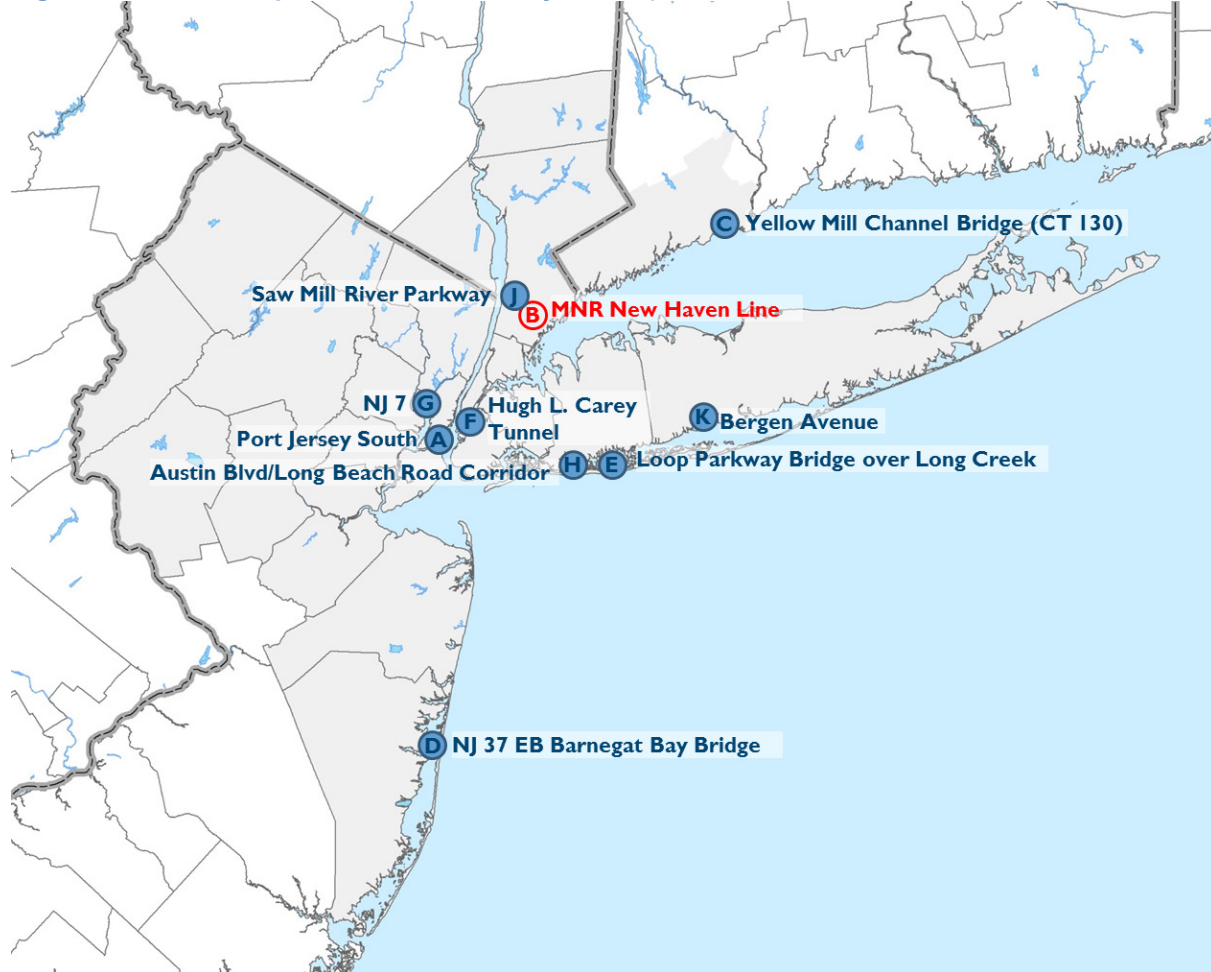
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Metro-North Railroad's New Haven Line is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the Metro-North Railroad study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for Ten FHWA Study Areas (Metro-North Railroad New Haven Line in Red)



2. FACILITY DESCRIPTION

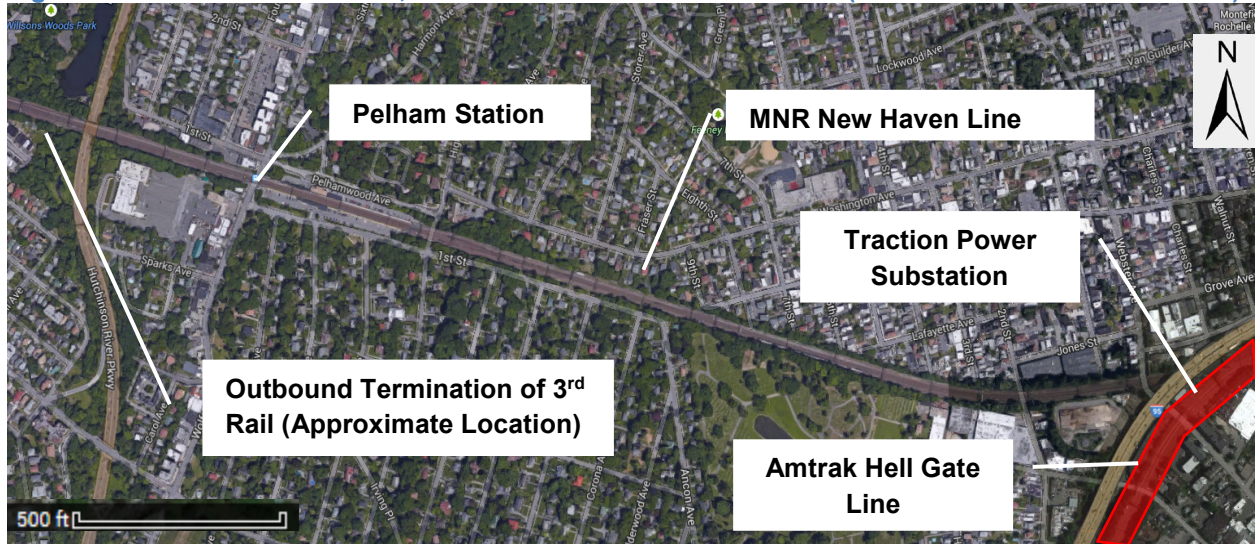
The Metro-North Railroad (MNR) is a commuter rail service operated by the Metropolitan Transportation Authority (MTA). This assessment examines a segment of MNR located along the New Haven Line in the town of Pelham, NY. This segment begins immediately west of Pelham Station and extends up to Control Point (CP) 216, at the junction to Amtrak's Hell Gate Line (see Figure 2 below). This 1.4 mile railroad right-of-way (ROW) and the surrounding study area consist of a track bed, track (rails, ties, attachments and ancillary retaining devices), traction power systems (both 3rd rail and catenary), signaling and communications apparatus and cabling, bridges (overpasses and underpasses) traversing roads and waterways, culverts, drainage, retaining walls, property protection (e.g., fencing), embankments, and stations. This segment includes the transition between the 3rd rail and overhead catenary power systems.

As requested by the MTA, this assessment focuses on the track and catenary power system of the rail segment. Existing tracks on the New Haven Line are continuously welded rail (CWR), and nearly all of the existing overhead catenary system is constant tension catenary, with a few discrete locations that are variable tension catenary. These remaining segments of variable tension catenary are due for replacement with constant tension catenary in the near future.

In terms of ridership, MNR is the second-busiest commuter railroad in the United States. MNR runs service between New York City's Grand Central Terminal and northern suburbs in New York State and

Connecticut. In 2013, the New Haven Line carried nearly 39 million customers. This line is also used by Amtrak, CSX Corporation (freight), and the Providence & Worcester Railroad (freight). New Jersey Transit also runs “football” trains on this line from Connecticut to the Meadowlands Sports Complex in New Jersey (these services diverge at the Hell Gate Line).

Figure 2: MNR New Haven Line, West of Pelham Station to CP 216 (Junction of the Hell Gate Line)



Source: Google Maps and AECOM.

Table 1 provides details on the condition, age/lifespan, and use of the railroad segment.

Table 1: Facility details

Category	Details
Facility Type	Railroad
Facility Component	Track & Catenary
Estimated Age (Lifespan)	Varies by segment and component (dependent upon replacement program). The main line was last rehabilitated in in the 1980s. The average replacement schedule is 10 to 15 years.
Estimated condition	Good (both track and catenary)
Use / Ridership	110,000 per weekday on MNR 15,700 per weekday on Amtrak.

Source: MNR and Amtrak

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

Average temperatures are projected to increase as the century progresses, as are the frequency, duration, and intensity of extreme heat events¹. Projected increases in average temperature are based on the New York City Panel on Climate Change (NPCC) *Climate Change Risk Information* report (2013), and are summarized below in Table 2.

Table 2: Projected increases in Average Annual Temperature, Change from Baseline to 2050s

Stressor Type	1971-2000 Baseline	2050s 25 th to 75 th percentile	2050s 90 th percentile
Average Annual Temperature	54°F	+4°F to +5.5°F	+6.5°F

Source: New York City Panel on Climate Change (NPCC) *Climate Change Risk Information* report (2013)

The project team also developed supplemental projections for extreme heat using the SimClim model², which are summarized in Table 3. Extreme heat events are more indicative of the potential for slow speed orders, sunkening, and sagging catenary than temperature averages. Table 3 shows the projected high-estimate (95th percentile³) increase in the magnitude and frequency of single-day maximum temperatures and three-day average maximum temperatures for July by mid century (2050s). Results are associated with the Wantagh Cedar Creek weather station, and reflect change over baseline values for that station.

¹ Inundation from heavy precipitation is also of concern, but is already being studied under another project.

² SimCLIM is a software tool designed to facilitate the assessment of risks from climate change.
<<http://www.climsystems.com/simclim/>>

³ Because these projections were originally retrieved for another assessment, the percentiles do not match those used by NPCC for average temperature.

Table 3: Projected Increase in Maximum Temperature and Frequency during 1-day and 3-day Extreme Heat Events, Mid-Century

Event	Baseline Scenario (1995)		2050, Projected Return period (years) for Base Temperature (°F)	2050, Projected Temperatures (°F) for Respective Return Period
	Return Period ⁴ (years)	Temperature °F	High-Estimate (95th Percentile, RCP-8.5 ⁵)	
One day maximum temperature	2	93.1	1.3	98.3
	5	98.1	1.9	103.3
	10	100.4	2.7	105.6
	20	102.0	3.7	107.2
	50	103.5	5.4	108.8
	100	104.4	6.8	109.6
Three-day average maximum temperature	2	86.4	1.2	91.6
	5	91.3	1.9	96.5
	10	94.0	2.9	99.2
	20	96.2	4.6	101.4
	50	98.5	8.4	103.7
	100	100.0	13	105.3

Source: Coupled Model Inter-comparison Project phase 5 (CMIP5) data in SimClim, Stratus Consulting, Inc.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

This section assesses potential failure modes associated with extreme heat: rail buckling (kinking) and catenary sagging.

Extreme Heat Damage – Rail Buckling

Before understanding the sensitivity of rails to extreme heat, it is important to first understand the process by which rails are laid onto a track. Running rail supports and carries the load of the train’s wheelsets. Running rail comes as jointed rail or continuously welded rail (CWR). CWR is becoming the prevailing standard on mainline track and most commuter rail/passenger rail service tracks. CWR is laid onto the track via a highly prescribed process to ensure long-term functionality of the rail under an expected range of temperatures, related to the Zero Thermal Stress Temperature. The Zero Thermal Stress Temperature is the design and construction specification temperature that minimizes thermal stresses to rail in the axial (longitudinal) direction. The Zero Thermal Stress Temperature is carefully calculated for a specific geographic region and is based on historical average annual rail temperatures for a given area. Without adjustments to the Zero Thermal Stress Temperature over time, future increases in extreme heat event

⁴ A return period is defined as the average time between events.

⁵ RCP stands for Representative Concentration Pathway. RCP 8.5 is the highest global GHG emissions scenario for which CMIP5 projections are available.

duration, frequency and intensity will likely deteriorate CWR's functionality and potentially increase failure rates.

The process prior to laying CWR onto a track has two steps. The first step is to determine the Zero Thermal Stress Temperature using the railroad operator's standards and/or the American Railway Engineering and Maintenance-of-Way Association (AREMA) guidelines for a specific region or climate zone. The design intent of the Zero Thermal Stress Temperature is to match and accommodate the average annual rail temperature as closely as possible in order to minimize stresses inside the rail throughout the year—balancing between the risk of a rail break in cold conditions and rail buckling in very hot conditions. During hot weather, the actual temperature in the rail can be 30 to 40 degrees F above the ambient air temperature⁶. The Zero Thermal Stress Temperature is a temperature of the rail (and not the ambient air), and is currently calculated by the railroad operator based on historical average rail temperatures. The current Zero Thermal Stress Temperature used by MTA is 95°F⁷.

The second step prior to laying CWR is to calculate the rail gap. The rail gap enables track engineers to further mitigate the risk of buckling from extreme heat and rail breaks from extreme cold. As the rail temperature climbs, the gap will begin to close as the steel expands beyond its installed length. An example of a rail gap in a CWR expansion joint is shown below in Figure 3.

Figure 3: A CWR Expansion Joint With Rail Gap



Source: Wikimedia Commons <http://upload.wikimedia.org/wikipedia/commons/a/a6/Expansion_joint,_Hayle.jpg>

Given that the Zero Thermal Stress Temperature informs both steps prior to laying CWR onto tracks, it is the primary focus of this assessment. As ambient temperatures rise over the course of the century, MTA's Zero Thermal Stress Temperature of 95°F will likely become outdated, based on current projections. The projected increase in extreme temperatures would likely result in previously calculated/installed rail gaps that are too small to mitigate the effects of thermal expansion, increasing the likelihood of rail buckling/kinks. Rail buckling occurs when the running rail deviates significantly in either the horizontal or vertical direction from the originally intended geometric alignment of the rail. An example of rail buckling is shown in Figure 4.

⁶ Railway Tie Association.

<<http://www.rta.org/assets/docs/ComprehensiveRail/sec9/temperature%20and%20rail%20laying.pdf>>

⁷ The average annual ambient air temperature in the New York City metropolitan area is approximately 54-55 degrees F. Adding 40 degrees for rail heat gain approximates the MTA Zero Thermal Stress Temperature of 95 degrees F.

Figure 4: Aftermath of a Rail Buckling Event



Source: Maryland MTA.

A 2009 AREMA paper on *Changes in Amtrak's Heat Order Policy*⁸ uses the CWR-Buckle Model to determine a temperature threshold at which buckling is possible. The CWR-Buckle Model predicted no buckling up to an ambient air temperature of 100°F, corresponding to a rail temperature of about 140° F. According to Table 3, events exceeding 100°F are projected to occur approximately every 2.7 years by mid century (baseline average of approximately every 10 years), and 3-day events during which the average maximum temperature exceeds 100°F are projected to occur every 13 years (baseline average of approximately every 100 years). Without action, the frequency of rail buckling could be expected to increase significantly.

Rail buckling is created by both the increase in temperature (causing the rail to expand/lengthen), and a complex/dynamic interaction between the rails and the rolling stock (vehicles that move on a railway). Especially where there is a diverse range of rolling stock (heavy locomotives mixed with lighter weight electrified vehicles), kinks can begin to propagate through the rails in times when the rail temperature is significantly hotter than the Zero Thermal Stress Temperature. The danger of sun kinks is most prevalent where both heavy locomotives/freight cars are mixed with lighter electric / passenger equipment that operate at higher speeds— an operating situation applicable to this corridor.

Rail buckling is typically difficult to detect remotely from a dispatch center. The buckling event may not trigger a Red/Stop signal because the signal voltage loop is not interrupted (i.e., there is no physical separation/break in the rail). As a result, train dispatchers may be unable to forewarn or stop trains proceeding towards the problem spot, increasing the risk of derailment. Therefore, during prolonged extreme heat events, most railroad operators impose speed restrictions to mitigate the risk of buckling

⁸ Source: 2009 AREMA paper on *Changes in Amtrak's Heat Order Policy*
<https://www.arena.org/files/library/2009_Conference_Proceedings/Changes_in_Amtraks_Heat_Order_Policy.pdf>

(examples of MNR's and Amtrak's restriction guidelines are included below). Speed restrictions cause substantial delays, particularly on heavily travelled corridors and rail networks.

MNR-Engineering provided information on temperature thresholds beyond which speed restrictions are imposed to minimize rail buckling-related failures. Table 4 displays information from MNR's operations bulletin for temperature-related speed restrictions on the New Haven Line. For example, when ambient air temperatures cross the 95°F threshold, maximum speeds are restricted to 80 MPH.

Table 4: MNR's New Haven Line Temperature-related Speed Restrictions

Weather Restriction Level	In effect for:	Required for temperatures of:	Maximum Speed
Level 4	All trains	95°F or above	80 MPH Maximum Speed; other speed restrictions may be designated in the DTOBO
Level 5	All trains	100°F or above	70 MPH Maximum Speed; other speed restrictions may be designated in the DTOBO

Source: MNR-Engineering and MNR-Energy Group

Note: DTOBO stands for Daily Train Operations Bulletin Order

As another example, until June of 2008, Amtrak's policy was to slow order all traffic to a maximum speed of 80 Miles per Hour (MPH) when the ambient air temperature exceeded 95°F. However, the 2009 AREMA paper on *Changes in Amtrak's Heat Order Policy* recommended a stepped program of speed restrictions starting with a 100 MPH restriction at 98° F and proceeding to a 80 MPH restriction at 105° F (see Figure 5). The difference between rail temperature and ambient temperature thresholds is noteworthy. In this instance, an air temperature of 98° F is correlated with a rail temperature of 130° F, while 105° F equates to a rail temperature of 140° F.

For additional perspective, at CSX Corporation (a Class 1 railroad) heat orders are issued when the forecast is for temperatures to be around or above 90 °F. The requirement is to reduce speeds of freight trains by 10 MPH, but not lower than 30 MPH, and to reduce the speed of passenger trains by 20 MPH, but not lower than 40 MPH.

Figure 5: Temperature-related Speed Restrictions to Minimize Buckling

Temperature Rail / (Air)	General Speed Restriction	Comments
128°F / (95°F)	NONE	ALERT: Approaching threshold values.
> 130°F / (>98°F)	100 MPH	LEVEL 2 ALARM: Threshold value exceeded. Apply 100 MPH General Heat Restriction for the block(s) governed by the specific weather station(s) exceeding the threshold as defined in Appendix A. Apply Latent Heat Restrictions as defined in MW 1000 for affected work zones. Begin Special Heat Inspections in affected areas.
≥ 140°F / (≥105°F)	80 MPH	LEVEL 1 ALARM: Threshold value exceeded. Apply 80 MPH General Heat Restriction for the block(s) governed by the specific weather station(s) exceeding the threshold as defined in Appendix A. Latent Heat Restrictions to remain in effect. Continue Special Heat Inspections in affected areas.
<p><i>NOTE 3: Ambient air temperatures are only to be used in locations where weather stations have not been installed OR where weather stations have malfunctioned. At locations where weather stations are in service, the rail temperature readings will govern the placement of general heat restrictions and the initiation of special heat inspections.</i></p> <p><i>NOTE 4: The Division Engineer or the Designated Heat Officer may apply more restrictive heat restrictions at specific locations where experience has shown that the track is tight or that problems may occur as warranted by local track conditions.</i></p>		

Source: 2009 AREMA paper on *Changes in Amtrak's Heat Order Policy*
https://www.arena.org/files/library/2009_Conference_Proceedings/Changes_in_Amtraks_Heat_Order_Policy.pdf

Estimates of the replacement cost and recovery time for track buckling are provided in Table 5.

Table 5: Replacement Cost and Recovery Time for Track

Time and Cost	Magnitude
Estimated Replacement Cost	Track - \$250 per Linear Foot per Track (includes both tracks)
Estimated Recovery Time	A maximum of two days for buckled rail (from heat). This could be less than one day if re-establishing service is critical to the railroad. Approximately half a day to repair kinks (kinks don't cause the circuit to drop, which means that the agency is not alerted immediately to the need for repair. Repairs cannot be made until the temperature cools down, and as a short-term measure, speed restrictions are imposed. Therefore, the recovery time is longer).

Source of replacement cost: AECOM unit prices for cost of ballasted track used in 2014 projects in the Northeastern United States. Cost estimates only include material and labor costs

Source of recovery time: MNR-Engineering

Based on the temperature projections in Table 3, without action, the frequency of speed restrictions and rail buckling could increase significantly by mid century.

Extreme Heat Damage – Overhead Catenary Wire Expansion

Extreme heat presents consequences for the overhead electrification system (overhead catenary) that powers trains on the New Haven Line (until the switch-over to 3rd rail between Pelham and Mt. Vernon East stations). During extreme heat events, the overhead catenary wires can expand in length, causing them to sag. Sagging can cause the pantograph system (the mechanical equipment on the top of the train that collects power from the catenary wire) to lose contact with the overhead wires, which causes trains to stall, leading to service disruptions. In some instances, the pantograph system will snag the catenary wire and pull it down. Sagging can also occur on inter-locking wires, meaning that wires could potentially be pulled down on multiple tracks. In other instances, the wire can sag over the edge of the pantograph contact rod and the train (having lost power) will stall and roll to a stop without damaging the catenary wire. In this case, the overhead wires must be de-energized and crews must pull the sagging wire into tension, a time-consuming and complex repair.

While most of MNR's territory has constant tension catenary, meaning that the catenary system is pulled into a high tension condition by large counterweights (and is thereby less prone to sagging), some of MNR's territory still has variable tension catenary, which is susceptible to sagging caused by high temperatures. Variable tension catenary remains a relatively common feature of commuter railroads in the United States that rely on overhead electrification.

MNR-Engineering provided information relating to temperature thresholds beyond which speed restrictions are imposed to minimize sagging-related failures. Table 7 below displays information from MNR's operations bulletin for temperature-related speed restrictions on the New Haven Line. For example, when temperatures cross the 90°F threshold, maximum speeds are restricted to 70 MPH (and 50 MPH at curves). This table makes no distinction between electric trains receiving propulsion power from 3rd rail, versus electric trains receiving propulsion power from overhead catenary systems (either constant tension or variable tension).

Estimates of the replacement cost and recovery time for catenary wires are provided in Table 6.

Table 6: Replacement Cost and Recovery Time for Constant Tension Catenary Wires

Time and Cost	Magnitude
Estimated Replacement Cost	Constant Tension Catenary - \$610 per Linear Foot per Track (assumes poles also damaged during a "Pull Down")
Estimated Recovery Time	Approximately half a day to repair overhead catenary wires that have exceeded their useable sag point.

Source of replacement cost: AECOM unit prices for cost of catenary (with poles) used in 2014 projects in the Northeastern United States. Cost estimates only include material and labor costs

Source of recovery time: MNR-Engineering

Based on the temperature projections in Table 3, without action, the frequency of catenary sagging, speed restrictions, and failures could increase significantly by mid century. However, the resilience of this particular segment's catenary system is likely high, as it has already been converted from variable to constant tension catenary, and similar improvements are expected elsewhere along the line.

Extreme Heat Damage – Track Maintenance Disruption

Extreme heat makes typical track maintenance difficult and sometimes requires shifting track maintenance schedules. Figure 6 below contains data provided by MNR-Engineering for temperature-related restrictions on maintenance and on speed during the reintroduction of train service following track maintenance. These restrictions go into effect when the temperature exceeds 95°F.

Figure 6: Temperature-related Restrictions on Track Maintenance (Red Dashed Outline) and Speed during Reintroduction of Train Service after Track Maintenance (Blue Dotted Outline)

§4.10 General Speed Restrictions and Suspension of Work

(a) When air temperatures are 95°F or above, a general speed restriction of 80 MPH will be placed over the affected territory for the period that the air temperature is 95°F or above. The restriction will be placed and removed by the Assistant Vice President - Maintenance of Way or his representative, specifying the affected territory.

(b) In addition, the following work will be suspended when air temperatures are expected to be 95°F or above during a 24-hour period:

- (1) Out-of-face surfacing or lining (except for working on concrete tie track treated with the dynamic track stabilizer)
- (2) In Track Classes 1-5, spot surfacing or lining (from 11:00 am to 8:00 pm)
- (3) Out-of-face tie renewal and undercutting (except under a continuous track outage)

§4.11 Working Under a Continuous Track Outage

When undercutting, renewing ties out-of-face, and other work that disturbs the ballast is in progress under a continuous track outage, and it is expected that the air temperature will be 95°F or above at the time track is returned to service, the 60 MPH speed restriction will remain in effect until the air temperature drops below 95°F.

Source: MNR-Engineering

Table 7: MNR’s New Haven Line Temperature-related Speed Restrictions

Restriction Level	In effect for:	Required for temperatures of:	Maximum Speed
Level 1	Electric trains only	80°F or above; 32°F or below	60 MPH (curves only) Permanent 60/50 MPH speed signs, blue and white in color, installed on catenary poles at the point of restriction
Level 2	Electric trains only	90°F or above; 15°F or below	50 MPH (curves only)
			70 MPH
Level 3	Electric trains only	5°F or below	50 MPH (curves only)
			60 MPH
Level 4	Electric trains only	95°F or above	All restrictions shown in Level 3 are in effect
	All trains	95°F or above	80 MPH Maximum Speed; other speed restrictions may be designated in the DTOBO
Level 5	Electric trains only	100°F or above	40 MPH (curves only)
	All trains	100°F or above	50 MPH
			70 MPH Maximum Speed; other speed restrictions may be designated in the DTOBO

Source: MNR-Engineering and MNR-Energy Group

Note: DTOBO stands for Daily Train Operations Bulletin Order

4.2 ADAPTIVE CAPACITY ANALYSIS

The transportation network which includes the New Haven Line rail segment exhibits some degree of adaptive capacity, as some commuters on this line may have access to alternative modes of transport, such as buses, personal vehicles, or alternative rail lines (e.g., the Harlem Line— though the Harlem Line may be similarly vulnerable).

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of rail service on the New Haven Line would severely impact people and freight in the region. The line has a ridership of 110,000 per weekday on MNR and 15,700 per weekday on Amtrak. Closure of rail service would likely cause congestion on roadways as typical train commuters resort to driving and bus transit, and alternative train routes may experience overcrowding—although a share of workers are likely to work from home instead. As there will be no connection between the Long Island Railroad (LIRR) tracks accessing the new/future East Side Access (ESA) station beneath Grand Central Terminal and MNR’s existing New Haven Line, it is assumed that a closure of rail service on the New Haven Line would have minimal or no impact on ESA.

5.2 EFFECT ON REGIONAL ECONOMY

Delays are expected to be brief—even as they potentially increase in frequency—and alternatives, although potentially more costly and less convenient, are available. Therefore, the economic impact of rail buckling and catenary failures is not likely to significantly impact the regional economy. Increasing delays may, however, significantly burden individuals and businesses, and may, over time, erode MNR’s ridership if problems are persistent.

5.3 EFFECT ON DISADVANTAGED POPULATIONS

Although the income distribution of MNR’s riders was not examined, the New Haven Line likely serves a share of commuters without the financial means to drive to work on a regular basis. These commuters would be reliant on replacement bus service, and may have to forgo wages if alternative transportation is temporarily unavailable.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This assessment identified potential vulnerabilities of the track (buckling) and catenary (sagging/failure) systems of a rail segment on the New Haven Line to projected increases in the frequency, duration, and intensity of extreme heat events by mid-century. To address these vulnerabilities, the following adaptation strategies are proposed:

- Modifying the Zero Thermal Stress Temperature for the rail segment to reduce the risk of rail buckling;
- Painting the web of the running rail to reduce the risk of rail buckling;
- Replacing variable tension catenary with constant temperature catenary to reduce the risk of catenary wire expansion (already planned).

6.1 MODIFY ZERO THERMAL STRESS TEMPERATURE

MNR could work with AREMA and other agencies maintaining and operating rail assets to modify guidance pertaining to the Zero Thermal Stress Temperature.

AREMA influences railroad design throughout the United States and Canada, providing guidelines developed by industry leaders through Committee membership. Currently, using a Zero Thermal Stress Temperature value of 95°F is common practice in the Northeastern United States, as shown in sample guidance below on how to estimate rail gaps (see Figure 7 below).

Figure 7: Sample Recommended Zero Thermal Stress Temperature Value (Red Dotted Outline) in Sample Specifications for Estimating Rail Gaps

D. Rail Movement and Rail End Cap	
1.	During thermal adjustment, determine the gap or rail movement between CWR strings and between CWR and bolted rail by the equation:
	$G = (t - T) L K + Q$
Where: G =	Rail gap (inches)
t =	Zero Thermal Stress temperature of 95 degrees Fahrenheit.
T =	Actual rail temperature at time of laying (degrees Fahrenheit)
L =	Length of CWR being laid (feet)
K =	Coefficient of thermal expansion for rail steel (0.000078 inches per foot per degree Fahrenheit).
Q =	Rail gap as required by respective manufacturers of field weld kit and bonded standard joint. For bolted standard joint Q = 0.125 inches, and for insulated joints Q equals the end post thickness. Q shall be deleted from above formula if field weld is not expected to be completed prior to operation of the first train over newly installed rail.

Source: AECOM – Typical Railroad Construction Specification

The risk of sun kinks must be balanced against the risk of breaks during the cold winter months, so the Zero Thermal Stress Temperature should be considered for incremental update by decade (i.e., a threshold increase of several degrees today, to account for projected temperatures in the 2050s, may result in marginally fewer kinking incidents and significantly more breaks in the near term⁹). Table 8 provides suggestions for incremental revisions to the Zero Thermal Stress Temperature, taking into account the historical average annual temperature rise of 2°F since 1970 and the projected increase in average annual temperature by mid century. According to NPCC projections, average annual temperature is projected to increase by 4°F to 5.5°F relative to baseline conditions (See Table 2). For the purpose of estimating the climate change-adapted Zero Thermal Stress Temperature, the projected increase in average annual temperature is illustratively assumed to be approximately 1°F per decade from 2010s to 2050s. MNR could (and should) update temperature guidance once per decade, or as needed, to account for updated projections, condition information, and other knowledge evolutions.

⁹With this noted, rail pull-aparts are more easily discovered than buckled rail in signalized railroad territory as a pull-apart would be visible to train dispatchers in the train control center while buckled rail typically would not be.

Table 8: Suggested Incremental Climate Change Adapted Zero Thermal Stress Temperatures

Year of Construction (Year Rail is Laid)	Current Zero Thermal Stress Temperature (Design/Construction Spec Temperature)	Average Temperature Rise Since 1970 for NY Region	Rise in Temperature From Previous Decade Per NPCC 2013 Data (1°F Per Decade)	Incremental Climate Change Adapted Zero Thermal Stress Temperature
2010s	95°F	+2°F	+1°F	= 98°F
2020s	→		+1°F	= 99°F
2030s	→		+1°F	= 100°F
2040s	→		+1°F	= 101°F
2050s	→		+1°F	= 102°F
			Sum of column above = 5.0°F (Annual Air Temperature Projection in the 25th to 75th Percentile by 2050 = 4.0 to 5.5°F Increase)*	

Source: AECOM 2015

It should be noted that the above climate change-adapted Zero Thermal Stress Temperatures are preliminary suggestions. As a first step in the process of revising guidelines, additional research should be conducted on how industry experts at major railroad/railway and transportation entities are preparing for, and possibly altering, construction specifications in response to extreme temperature trends and/or projections.¹⁰ The European Commission, in their report titled *Impacts of Climate Change in Europe: A Focus on Road and Rail Transport Infrastructures* (October, 2012), suggested updating the “stress free temperature” as one adaptation measure for rail infrastructure. Similarly, a white-paper developed by the European Journal of Transport and Infrastructure Research (EJTIR) entitled *Climate Adaptation of Railways: Lessons from Sweden* (March 2009) notes that “maps for neutral temperatures have been updated recently in order to better reflect the true mean temperatures” regionally in Sweden.

Once modified guidelines for Zero Thermal Stress Temperature are developed, a thorough quality control review of the new design temperatures and a test case should be conducted by MTA’s Track Engineering Department prior to final approval. This process could include:

- Installation of CWR in only a few strands/locations at the incremental climate change-adapted Zero Thermal Stress Temperature as test cases to facilitate comparison of failure frequencies. This could be completed by Railroad Force Account or by the Federal Railroad Administration’s (FRA) Pueblo, Colorado test facility. It is likely that tests would need to be completed on non-revenue service track, prior to testing on MNR’s property.
- Material science research, investigation, and/or testing of axial tensile and compressive forces¹¹ generated by higher temperatures and the interaction of these forces with certain industry standards for running rail sections and types.

¹⁰ Note that International Union of Railways, TTCI/ARR, VOLPE, AREMA Committee 5 (Track), AREMA Committee 4 (Rail), APTA and other relevant industry organizations in Australia, the U.K., India and Canada were contacted and could not provide any details of new research or guidance relating to adjustment of construction methods/specifications relating to rails and future increases in extreme temperatures.

¹¹ Axial tensile forces are those that act to expand or lengthen an object. Compressive forces are those that act to compress or shorten an object.

- Material science research, investigation, and/or testing to understand how long-term fatigue (damage inflicted upon a material due to repetitive loading or stress/strain cycles) may have consequences for the service life, reliability and structural performance of various rail sections and rail metallurgy dynamics resulting from changes in temperatures.
- A peer/collaboration review by AREMA Technical Committees Number 4 (Rail) and Number 33 (Electric Energy Utilization) of:
 - This assessment, and
 - How data and adaptation methods explained in this assessment may be related to and have implications for AREMA (2013) Sections 5.3 (Temperature Expansion for Laying Rails) and 5.2.4 (Laying Procedure for CWR on Existing Track).

6.1.1 COST ANALYSIS

As stated in Table 5, replacing the running rails using the updated Zero Thermal Stress Temperature is estimated to cost \$250 per linear foot per track (including all materials and labor). Re-stressing rails at an adjusted Zero Thermal Stress Temperature, or laying new rail using an adjusted Zero Thermal Stress Temperature could be complementary to activities prescribed under the USDOT's State of Good Repair (SOGR) program.

6.1.2 TIMING FOR IMPLEMENTATION

An education program for field engineers, Railroad Force Account (i.e., internal railroad labor), construction managers, and the railroad's most common track construction contractors is recommended to help members of the MTA community understand why the changes are taking place and how they are implemented. Full implementation would be a multi-year effort.

6.2 PAINT THE WEB OF THE RUNNING RAIL

A relatively low-cost option for decreasing the risk of kinking/buckling is to paint the sides (web) of the running rail white—a strategy common in the UK and Europe. High albedo (white or light colored) surfaces absorb less heat energy from sunlight, which, in this application, would reduce rail temperatures. According to Network Rail (United Kingdom), a painted rail could be five to ten degrees C (about 9-18 degrees F) cooler than unpainted rail.¹² The paint specified should be thick, non-corrosive, and UV resistant. Application to the track web will not prevent the rails from conducting signal currents, but it is important to avoid painting in any turnouts or special track work. See Figure 8 below as an example of painted rail.

Additional research is recommended to understand any potential drawbacks to painting the web of rail, specifically related to whether painting inhibits visual inspections conducted by MNR and how the application performs in winter vs. summer. A pilot could also be initiated in-house by the MNR.

¹² http://www.nationalrail.co.uk/service_disruptions/80830.aspx (reviewed November 2014)

Figure 8: Running Rail with Web Painted White in Northern Italy



Source: AECOM

6.2.1 COST ANALYSIS

Numerous factors would influence the cost of painting the rails, such as:

- Inclusion of Railroad Force Account (internal railroad labor)
- The cost associated with shutting down the tracks
- The length of the track painted
- The material procurement, specification and testing processes.

Paint could cost upward of \$15 per linear foot, for each rail (i.e., \$30 per linear foot per track).¹³

6.2.2 TIMING FOR IMPLEMENTATION

This strategy could be implemented immediately after specifications are determined.

¹³ Based on AECOM engineers' estimates

6.3 REPLACEMENT OF VARIABLE TENSION CATENARY WITH CONSTANT TENSION CATENARY

At the time this assessment was conducted in 2015, MNR had some remaining sections of track where the overhead catenary system is variable tension. These sections are scheduled to be replaced with constant tension catenary. Constant tension catenary systems utilize a counterweight system that pulls the overhead wires into constant tension as the wires heat up and expand, preventing the wires from sagging (see Figure 9). The rail segment being evaluated in this assessment has already undergone replacement from variable tension catenary to constant tension catenary. However, this strategy has been included in this assessment as it is relevant to other segments that have not undergone replacement, and also because several commuter rail operators in the United States still use variable tension catenary (although only a handful of agencies use overhead electrification as their propulsion source). These include: Metra Electric (Chicago), NICTD (Chicago), SEPTA (Philadelphia), MARC (Maryland/DC), New Jersey Transit (New Jersey), and MTA. Many of these agencies are switching to constant tension catenary.

This strategy recommends that all variable tension catenary systems be incrementally replaced at the end of their useful life cycle with constant tension catenary systems. This will reduce the frequency of failure due to sagging.

Constant tension catenary systems are specifically designed to automatically adjust for temperature changes within certain criteria limits. As an example, New York Metro area constant tension catenary systems have a design ambient temperature range from -10°F to 120°F. If the ambient temperature extremes of the future exceed this design range, the performance of the catenary (even if constant tension) will degrade, thereby affecting operations and raising maintenance costs. The 95th percentile (higher estimate) projections for extreme heat events by mid-century do not exceed the 120°F failure threshold, even at the 100-year recurrence interval. This indicates that constant tension catenary systems likely are an effective, durable solution to minimizing rail disruptions caused by sagging.

6.3.1 COST ANALYSIS

As stated in Table 6, the approximate cost of constant tension catenary is \$610 per linear foot per track, which includes overhead catenary and poles.

6.3.2 TIMING FOR IMPLEMENTATION

The timing of incremental replacement of the catenary would depend on when current systems reach their replacement lives. Each track segment will have a different schedule depending on geometry (tangent or curve), drainage conditions, track materials used for construction, quality of construction, etc.

Figure 9: Constant Tension Catenary System



Source: <http://www.railway-technology.com/uploads/newsarticle/647405/images/135796/large/3-auto-tension.jpg>

7. CONCLUSION

This assessment identified potential vulnerabilities of the track (buckling) and catenary (sagging/failure) systems of a rail segment on the New Haven Line to projected increases in the frequency, duration, and intensity of extreme heat events by mid-century. To address these vulnerabilities, the following adaptation strategies are considered:

- Modifying the Zero Thermal Stress Temperature for the rail segment to reduce the risk of rail buckling;
- Painting the web of the running rail to reduce the risk of rail buckling;
- Replacing variable tension catenary with constant temperature catenary to reduce the risk of catenary wire expansion (already planned).

Among the adaptation options to address buckling, adjusting the Zero Thermal Stress Temperature is suggested as a longer-term strategy. More collaborative research will be required among academics and industry experts to evaluate how the Zero Thermal Stress Temperature guidelines should be modified regionally. In the interim, painting the web of the running rail is suggested as a relatively quick and cost-effective way of mitigating the risk of rail buckling from extreme heat.

With regard to the catenary system, most of MTA's catenary systems (including the one evaluated in this assessment) have already been converted from variable tension catenary to constant tension catenary. Continuing to convert all catenary systems to constant tension catenary would reduce the frequency of failure due to sagging as temperatures increase.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

NJ Route 7 Engineering Informed Adaptation Assessment

NJ ROUTE 7 CORRIDOR, KEARNY, NJ

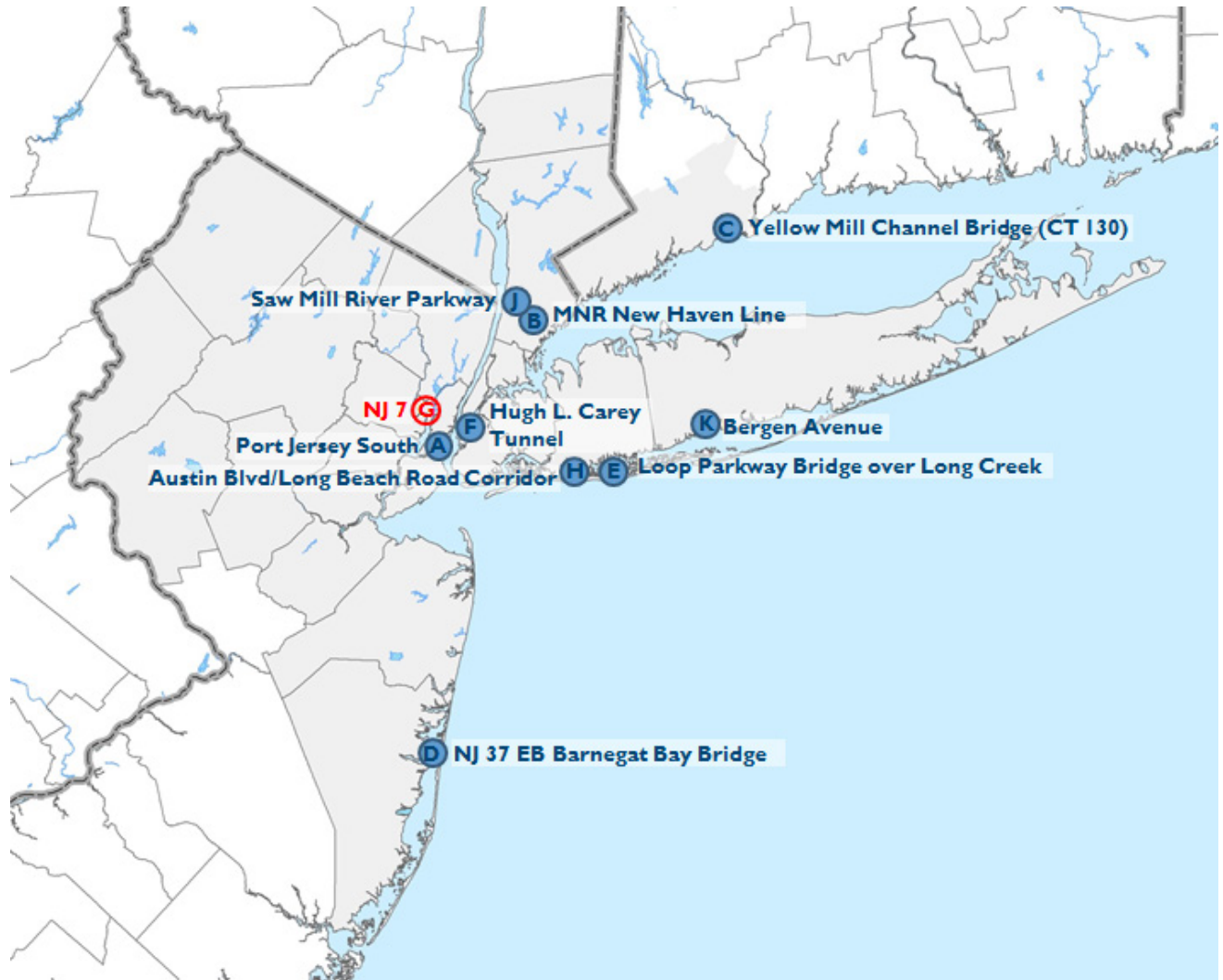
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The NJ Route 7 Corridor is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the NJ Route 7 study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for Ten FHWA Study Areas (NJ Route 7 in Red)



2. FACILITY DESCRIPTION

Route 7 is a state highway in Hudson County, New Jersey under the jurisdiction of the New Jersey Department of Transportation (NJDOT). This assessment focuses on a segment of Route 7 (see Figure 2) which starts at the Conrail railroad at the northern end (MP¹ 1.7) and ends at County Road (CR) 659 (Fish House Road) at the southern end (MP 0.6). This segment is the sole approach to the Whitpenn Bridge crossing over the Hackensack River. CR 508 crosses over the southbound side of Route 7 at roughly MP 1.4. In selecting this segment for further analysis, several considerations were made. Originally, a different segment of Route 7 (MP 1.7—3.8) had been proposed for this analysis, as it had been significantly inundated during Hurricanes Irene and Sandy. However, on further investigation, it was learned that the a drainage improvement plan had already been developed to address flooding issues at that segment (see call out box)².

The Pulaski Skyway Rehabilitation Project also informed this assessment. The Pulaski Skyway includes a segment which runs parallel to the Route 7 segment examined in this assessment. The goal of the Pulaski Skyway Rehabilitation Project is to replace the 3.5 mile Pulaski Skyway deck. In addition, the project also includes rehabilitating the ramps, steel superstructure and substructure; strengthening the structure against seismic events; improving drainage and lighting; and repainting the structure³.

In light of these existing initiatives, the Route 7 segment between MP 0.6 and MP 1.7 was selected for analysis because it provides critical connectivity between the Whitpenn Bridge and the Concept Development segment (MP 1.7-3.8), and has not yet been the subject of a substantial study. Although this segment is not currently flooded during minor events, it is projected to be impacted by tidal flooding by the end of the century. The inundation risks analyzed (Section 3) and adaptation strategies proposed (Section 5) are consistent with those considered in the Concept Development study to ensure that these connecting, interdependent segments are resilient to a similar degree.

The area surrounding the study segment of Route 7 is generally flat. This entire segment is at an elevation of 7.0 feet or greater (referenced to North American Vertical Datum of 1988, or NAVD 88), except for a small portion near MP 1.7 on the southbound side at the northern end of the study area. The study segment is predominantly curbed and has grades that meet or exceed the minimum grades required by the NJDOT Roadway Design Manual. Roadway runoff is collected through various types of inlets⁴ (type B at the curb along either side of Route 7, type D at the median barrier, and type E in the roadside area) and bridge drains, discharging directly into roadside areas. Overall, the pavement of this segment of Route 7 is in fair to good condition (see Table 1 for more details).

NJ Route 7 Concept Development Report on Drainage Improvements

In 2012, a detailed study of the flooding conditions on Route 7 between MP 1.7 and 3.8 was performed by McCormick Taylor, Inc. This work began in 2005 with a screening process to determine the scope, which ultimately was limited to drainage improvements accomplished by adjusting the roadway profile. Three alternatives were prepared by McCormick Taylor, Inc. to address flooding issues at the segment. Of these, the preferred alternative was to raise the roadway where possible and install sheeting where raising the profile was not practicable due to vertical clearance limitations. This alternative also included new storm drainage facilities and three pump stations to remove stormwater from areas where sheeting provides flood mitigation (which would cause pooling on the roadway if overtopped).

¹ MP stands for Milepost

² More details on this project can be found here: “Concept Development Report, NJ Route 7, MP 1.70-3.80, Drainage Improvements, Town of Kearny, Hudson County”, prepared by McCormick Taylor for the New Jersey Department of Transportation (NJDOT), Dated September 2012.

www.state.nj.us/transportation/business/procurement/ProfServ/documents/Route7FinalCDReport.pdf

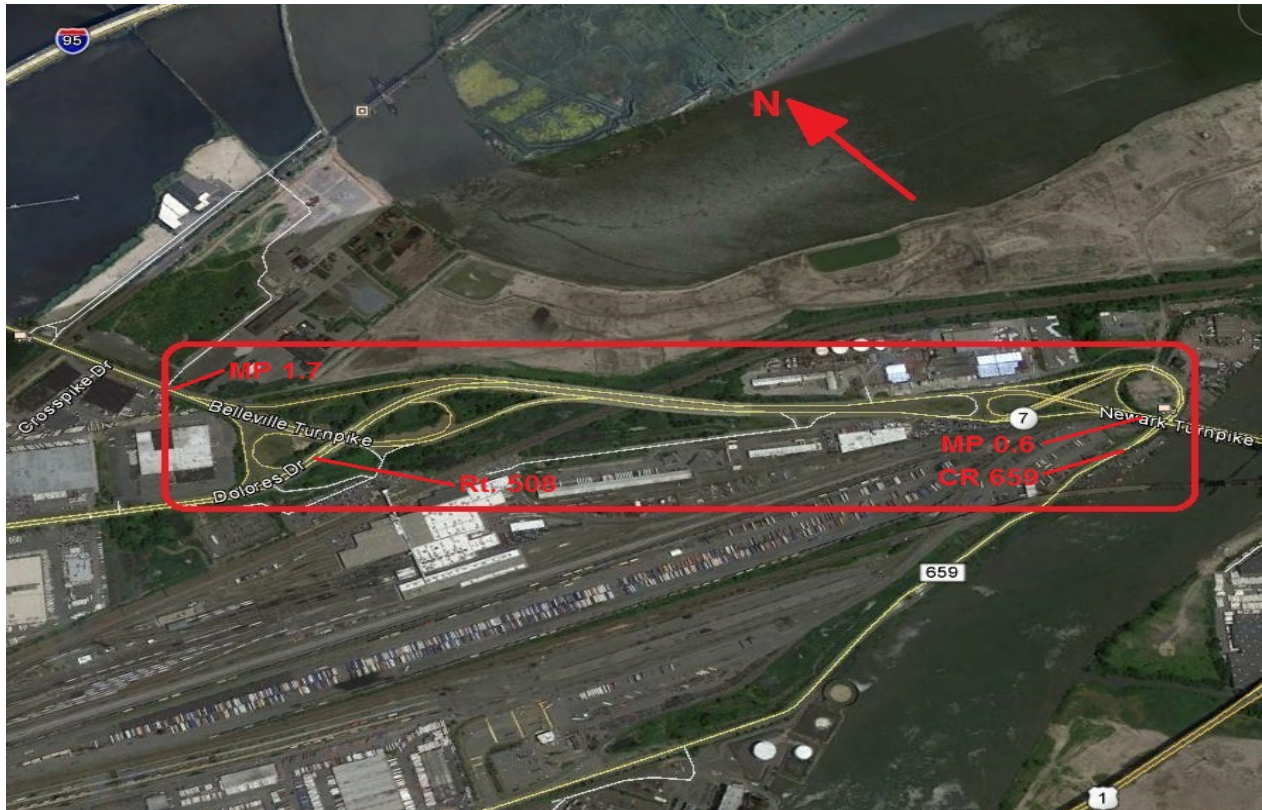
³ More details on this project can be found here: www.state.nj.us/transportation/commuter/roads/pulaski/details.shtm

⁴ Inlet definitions can be found in the NJDOT Roadway Design Manual:

www.state.nj.us/transportation/eng/documents/RDM/sec10.shtm#TypesOfInlets

Route 7 is heavily used by commuters from the Town of Kearny and other neighboring towns going to Jersey City and New York City, and has an passenger vehicle Annual Average Daily Traffic (AADT) of 19,120 for the portion north of the Route 508 interchange and 39,276 for the portion south of it. The segment also serves heavy truck traffic, with an Annual Average Daily Truck Traffic (AADTT) of approximately 3,250 for the portion north of the Route 508 interchange, and 8,071 south of it⁵, much of it originating from the surrounding warehouses and industrial facilities.

Figure 2: Section of Route 7, Kearny, NJ under study



Source: Google Maps, 2014

⁵ AADT and AADTT for the portion of Route 7 south of the Route 508 interchange were obtained from NJTPA and are based on the New Jersey Congestion Management System's (NJCMS) counts from 2009. The overall counts for each direction were 23,675 (westbound/northbound) and 23,672 (eastbound/southbound) which includes truck counts of approximately 4,004 (westbound/ northbound) and 4,067 (eastbound/southbound). AADT for the portion north of the Route 508 interchange is taken from the traffic counts published in the NJ Route 7 Concept Development Report (2012), which also matches what is shown on the NJDOT's straight line diagram (SLD). Given that AADTT was not available for this portion of the segment, the truck share from the CMS was applied to estimate the AADTT.

Table 1 provides details on the condition, lifespan, and use of the Route 7 segment.

Table 1: Facility details

Category	Details
Facility Type	Roadway (Urban Principal Arterial)
Facility Component	Drainage
Estimated Age (Lifespan)	Information on the age and remaining lifespan of drainage is not available. In general, drainage systems can be robust and in New Jersey, it is not uncommon to see drainage systems that have been in use for over 100 years. They usually require replacement if their capacity needs to be increased, and not because of physical deterioration. Overall, the alignment and basic characteristics of the roadway are expected to last through the end of the century. Other components such as pavement may require replacement every 20-30 years.
Estimated condition	Information on the current condition of the drainage is not available. Other roadway elements such as pavement are in fair to good condition.
Use / Ridership	<ul style="list-style-type: none"> - 19,120 AADT & 3,250 AADTT (2012) for the portion north of the Route 508 interchange - 39,276 AADT & 8,071 AADTT (2009) for the portion south of the Route 508 interchange

Note: The sources of data on volumes is cited in a preceding footnote. The other data on overall roadway conditions in the table is based on assumptions informed by the NJ Route 7 Concept Development Report on Drainage Improvements.

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

While the segment of Route 7 being evaluated in this assessment is not currently exposed to coastal inundation, historically, other sections of Route 7 have experienced flooding. As the century progresses, the study segment may be impacted by climate stressors such as sea level rise (SLR) and storm surge, as well as increases in precipitation intensity. SLR and storm surge were selected for analysis based on conversations with NJDOT and the North Jersey Transportation Planning Authority (NJTPA).

Projections of SLR and storm surge considered in this assessment are summarized below in Table 2 and Table 3 respectively. SLR projections were compiled by the project team based on a recent NJDOT/NJTPA vulnerability pilot assessment (the “Pilot”) ⁶, and were approved for use in this assessment by those agencies. Following the Pilot approach, the mid-range scenario for SLR was adopted, and the high-range scenario was also considered.

To account for storm surge, the current estimated 2-year tidal surge elevation and the observed Hurricane Sandy-equivalent water elevation near the study area were used as proxies for future storm surge events. The 2-year tidal surge scenario⁷ was identified in the Concept Development Report as the flood mitigation threshold adopted by the Preliminary Preferred Alternative (PPA), and was specifically included in this assessment to ensure consistency between studies.

⁶ “Climate Change Vulnerability and Risk Assessment of New Jersey’s Transportation Infrastructure”, prepared by Cambridge Systematics for a partnership of New Jersey state agencies and Metropolitan Planning Organizations (the “New Jersey Partnership”), Dated 2011. www.njtpa.org/Planning/Regional-Studies/Recently-Completed-Studies/Vulnerability-and-Risk-Assessment-of-NJ-Transporta/FHWAConceptualModel/CCVR_REPORT_FINAL_4_2_12_ENTIRE.aspx

⁷ Equivalent to 5.06 feet, based on the FEMA Flood Insurance Study (FIS) for Hudson County, NJ (2006).

The Hurricane Sandy-equivalent water elevation was obtained from NOAA records (2012) at the closest tide station to the NJ 7 segment⁸. It represents the Highest Observed Water Level (HOWL) at the tide station, which was recorded on 10/31/2012 in the immediate wake of Hurricane Sandy. Pre-Sandy, the Pilot project adopted HOWL to assess potential storm surge impacts in New Jersey, so using the updated, post-Sandy HOWL is methodologically consistent. Table 4 shows the projected water elevations when SLR is added to a 2-year tidal surge and a Hurricane Sandy-equivalent storm for mid-century and end-of-century horizons (mid- and high-range SLR scenarios).

Table 2: Sea Level Rise Projections

Year	Low-range SLR			Mid-range SLR			High-range SLR		
	Subsidence (Feet)	Regional SLR (Feet)	Total Relative SLR (Feet)	Subsidence (Feet)	Regional SLR (Feet)	Total Relative SLR (Feet)	Subsidence (Feet)	Regional SLR (Feet)	Total Relative SLR (Feet)
2050	0.3	0.5	0.7	0.3	0.9	1.2	0.3	1.7	1.9
2100	0.6	1.5	2.1	0.6	3.3	3.9	0.6	5.4	6.0

Source: Pilot assessment.

Note: The values for total relative SLR may not sum due to rounding.

Table 3: Storm Surge Elevations

Event	Elevation (feet NAVD88)
2-year Tidal Storm	5.06
Hurricane Sandy-equivalent Storm	11.26

Source of 2-year Tidal Storm Elevation: FEMA-FIS for Hudson County, NJ (2006).

Source of HOWL: NOAA, 2012. The HOWL at The Battery, New York Harbor, New York; Station ID 8518750; NOAA Chart 12335.

Table 4: Projected Elevations for SLR and Storm Surge Events

Stressor Type	Elevation (feet NAVD 88)	Analysis Year and Scenario
SLR + 2-year Tidal Storm	6.3	2050 mid-range SLR
	7.0	2050 high-range SLR
	9.0*	2100 mid-range SLR
	11.1	2100 high-range SLR
SLR + Hurricane Sandy-equivalent Storm	12.5	2050 mid-range SLR
	13.2	2050 high-range SLR
	15.2	2100 mid-range SLR
	17.3	2100 high-range SLR

Note: Depths in bold are likely to overtop study segment.

* Selected for analysis.

The segment of Route 7 examined in this assessment is almost entirely at an elevation above 7.0 feet NAVD88, which is the approximate projected water level for the 2050 high-estimate SLR + 2-year tidal surge scenario (see Table 4). A short, 150-foot stretch at the northern end of the segment is at an elevation of approximately 6.4 feet NAVD88 (see Stretch 1, shown in Figure 4 on page 12)—still marginally above the lowest future coastal inundation scenario of 6.3 feet. However, the mid-century high-range SLR + 2-year tidal surge scenario, with a projected flood elevation of 7.0 feet NAVD88, could result in inundation of this short stretch, and possibly threaten other points along the segment. By 2100,

⁸ The Battery, New York Harbor, New York; Station ID 8518750; NOAA Chart 12335.

both mid-range and high-range SLR + 2-year tidal storm scenarios (9.0 feet and 11.1 feet, respectively) would cause widespread inundation and potential erosion-related failures along the segment.

All SLR scenarios, Hurricane Sandy-equivalent storm elevations would result in widespread inundation and likely lead to erosion-related failures. Widespread inundation of the study area was observed under current conditions during Hurricane Sandy, as illustrated in the U.S. Geological Survey's Hurricane Sandy Mapper (see Figure 3).

Figure 3: USGS Hurricane Sandy Storm Tide Mapper



Source: U.S. Geological Survey Hurricane Sandy Mapper <<https://water.usgs.gov/floods/events/2012/sandy/sandymapper.html>> The transparent blue layer shows the extent of inundation observed during Hurricane Sandy. Areas that are not highlighted in blue were not inundated.

In consultation with NJDOT and NJTPA, the the mid-range SLR scenario for 2100 was adopted for the vulnerability assessment (consistent with the Pilot approach). For storm surge, the 2-year tidal surge was used (consistent with the NJ Route 7 Concept Development Report), recognizing that the resulting adaptation strategies would not protect against more significant coastal flooding events. The total elevation of inundation associated with this scenario (the “study scenario”) is approximately 9.0 feet NAVD88.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

The study segment of NJ Route 7 would be exposed to flooding under the selected future SLR and storm surge scenario (and all scenarios considered, save for 2050 mid-range SLR + 2-year surge). If exposed, the segment could be subject to the following potential modes of failure.

- **Overtopping/Inundation:** A small stretch of the study segment would be overtopped by a 7-foot flood elevation, associated with the mid-century high SLR + 2-year tidal surge. However, by the end of the century the study segment would experience widespread inundation under all SLR and storm scenarios.
- **Service Disruption:** Widespread inundation of the roadway under the 2100 mid-estimate SLR + 2-year surge scenario (9.0 feet NAVD88) or greater would likely cause disruption to traffic, which may last for up to 48 hours⁹ until water and debris can be cleared and the roadway inspected for stability.
- **Premature Deterioration:** Information requests to NJDOT revealed no evidence that major work (such as roadway reconstruction) has occurred along this segment for approximately the last 40 years. The most recent as-built plans¹⁰ are from 1966, and the National Bridge Inventory (NBI) indicates that all three overpasses/underpasses along the study segment were built between 1973 and 1975. Although the segment's pavement is currently in fair to good condition, flooding would prematurely reduce the lifespan of surface materials, increase maintenance requirements, and increase the likelihood of failure. Also, frequent flooding might cause the drainage pipes flowing under pressure more frequently than normal and premature failure of the pipes might happen, although this is not highly likely.
- **Physical Damage:** Coastal flooding could lead to pavement deterioration, erosion and washouts, and foundational/structural failures due to scour.

These impacts are representative of the plausible effects of coastal flooding on the study segment, although a more detailed engineering assessment would be required to determine the specific degree of susceptibility associated with each scenario.

Table 5 provides estimates of the potential cost and recovery time required to restore service on the study segment after a moderate flooding event. Once flood waters subside, clean-up and damage assessment activities are likely to take 24 hours to complete. If no damage occurs, this segment could be operational within 48 hours. However, if repairs are required due to erosion or foundation/structural failure, then recovery could take four months or more and cost nearly \$8 million.¹¹

Table 5: Replacement Cost and Recovery Time for Route 7 Segment

Time and Cost	Magnitude
Estimated Replacement Cost	Ranges from Negligible to \$7.9 million depending on extent of impact
Estimated Recovery Time	48 hours to 4 months

Replacement Cost Estimate Assumptions: The estimated replacement cost includes MPT, lighting, lump sum items, construction engineering, utility relocation, and contingencies, in current-year dollar terms. The cost is estimated using NJDOT's preliminary construction cost estimate spreadsheet in conjunction with the latest NJDOT Construction Cost Estimating Guide. Unit costs from recent projects, including the NJ Route 7 Concept Development Report on Drainage Improvements, are used. The railroad

⁹ These estimates are based on assumptions and/or findings stated in the NJ Route 7 Concept Development Report on Drainage Improvements.

¹⁰ As-built plans are plans that are produced for infrastructure projects upon the completion of construction of the project.

¹¹ These estimates are based on assumptions and/or findings stated in the NJ Route 7 Concept Development Report on Drainage Improvements.

overpass is not expected to be impacted and therefore excluded from the estimate. The estimate shown in the NJ Route 7 Concept Development Report on Drainage Improvements is also used as a reference.

4.2 ADAPTIVE CAPACITY ANALYSIS

The study segment is part of a transportation network that exhibits some degree of adaptive capacity, because there are existing alternative highway (Pulaski Skyway (Route 1 & 9) and New Jersey Turnpike) and transit (Port Authority Trans-Hudson) routes. Alternative roadway routes may add 30 to 45 minutes to the journey between Jersey City and the Town of Kearny, NJ or Jersey City and the Town of Harrison, NJ. Analyses of the potential vulnerability and capacity of these alternative routes were not included in the scope of this assessment. They may be vulnerable to the same climate stressors as the study segment.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of the road would severely impact mobility to and from the Town of Kearny and surrounding areas. Route 7 has a total traffic count of approximately 22,370 for the portion north of the Route 508 interchange and 47,347 south of it (the source of this data is cited in a previous footnote), and is heavily used by commuters from the Town of Kearny and other neighboring towns going to and coming from Jersey City and New York City. The route also facilitates heavy truck traffic originating from the surrounding warehouses and industrial facilities. In the event that Route 7 is disrupted, Pulaski Skyway is among the detour routes that could be used to cross Hackensack River, which will add an estimated 30-45 minutes (potentially more under highly congested conditions) to the journey between Jersey City and the Town of Kearny, NJ, as well as Jersey City and the Town of Harrison, NJ.

5.2 EFFECT ON REGIONAL ECONOMY

Estimating the broader economic impacts of disruption to transportation assets can be challenging, as there are multiple factors that influence these impacts, such as the nature of the event causing the disruption, the probability and magnitude of the event, the duration of the disruption, the use of the asset, the adaptability of asset users, and behavioral responses of travelers. To quantify the economic impacts of disruption to the segment of NJ Route 7 while managing uncertainty and data deficiencies, a series of assumptions was developed, as detailed below.

Closure of the study segment could have significant negative impacts on the regional economy due to the resulting detours and time lost as a result. The Pulaski Skyway detour (adding an estimated 30-45 minutes of travel time) was used to estimate the economic impacts of closure of the study segment. Cumulative economic impacts were estimated from 2050 to 2100, and were based on the value of time lost for passenger vehicles as well as value of commercial time lost for trucks, as described below.

This analysis considered the economic effects of a 2-year tidal storm (resulting in 2-day closure of the segment)¹² and Hurricane Sandy-equivalent storm (resulting in 120-day closure of the segment)¹³, with

¹² Analysis assumes that the 2-year storm surge events would close the road for 48 hours. The time of recovery/duration of disruption depends on the extent of damage, however, the most likely scenario with a 2-year storm surge event is that there is no major damage and the roadway only needs an inspection and cleanup, which can be completed in 48 hours. However, it is possible that a 2-year event could seriously damage portions of the roadway that's below the elevation, which could cause the roadway to be closed for a period longer than 48 hours.

¹³ Analysis assumes that the Hurricane Sandy-equivalent storm is equivalent to 100-year flood event, which would close the road for 4 months. The most likely scenario with the 100-year event is that there would be major damage that would require full or partial reconstruction of the roadway. It should be noted that while 100-year flood elevation is not available for the Route 7 segment, the Flood Insurance Rate Maps (FIRMs) published by FEMA (2006) for show that surrounding areas have a 100-year Base Flood Elevation (BFE) of 9 to 10 feet NAVD88. The water elevation for Hurricane Sandy was recorded at 11.26 feet NAVD88, and while it is acknowledged that this level is

the addition of sea level rise. To estimate the cost on a per event basis, AADT and AADTT were utilized to calculate the total traffic impacted over the duration of an event. This means that for a 2-day event, AADT and AADTT were doubled, while for a 120-day event, AADT and AADTT were multiplied by 120. The values for AADT and AADTT vary north and south of the interchange (see prior footnote for details). The lower volumes north of the interchange are represented in the “lower bound” estimate; the higher volumes south of the interchange are the basis of the “upper bound” estimate.

The cost of delay for automobiles and trucks, respectively, was estimated based on an average delay duration of 37.5 minutes (the mid point between 30 and 45 minutes), multiplied by the average vehicle cost per hour. The passenger vehicle cost is derived from the hourly median household income of \$30.76 per hour¹⁴ in the New York-Northern New Jersey-Long Island, NY-NJ-PA Metropolitan Statistical Area (MSA). The analysis conservatively assumed that automobile travel is composed entirely of personal or commute trips; therefore, the value of time (\$15.38 per hour) is 50% of the hourly median household income for the region, based on US DOT guidance¹⁵. For trucks, the value of time is derived from the hourly cost for a truck (\$48.70), which includes costs for fuel, tires, driver wages, and driver benefits, provided by ATRI¹⁶.

The total travel delay cost was calculated by multiplying the cost of the delay (2012 dollars) by the total traffic impacted. Automobile occupancy was assumed to be 1.55 (U.S. DOT)¹⁷. In addition, the team assumed that only 50% and 70% of automobile and truck traffic¹⁸, respectively, are affected by the event and incur a cost. Based on these assumptions, a total cost per event was estimated (Table 6). Further research on factors like trip purpose, the origin and destination of trips, and traveler sensitivity could be performed to refine these estimates (but fell outside the scope and resources of this study).

Table 6: Per-Event Economic Impacts of Route 7 Segment Closure

Event	Per-Event Cost, Lower-bound AADT (\$2012)	Per-Event Cost, Upper-bound AADT (\$2012)
SLR + 2-year Tidal Storm	\$438,689	\$928,503
SLR + Hurricane Sandy-equivalent Storm	\$26,321,356	\$55,710,202

Next, the economic cost per event was multiplied by the estimated probability of occurrence for each event between 2050 and 2100 (the segment is not currently vulnerable to the 2-year surge). This assessment focused on two events: the 2-year tidal surge (occurring, on average) once every 2-years—an Annual Exceedance Probability of 50%—and a Hurricane Sandy-equivalent event, for which a 1% chance Annual Exceedance Probability was assumed as a proxy (in actuality, Sandy significantly exceeded the estimated 100-year surge, but the probabilities associated with rare events are clouded by

greater than the surrounding areas’ 100-year BFE, for the purpose of the economic analysis, the return period of a Hurricane Sandy-equivalent storm was assumed to be 100 years.

¹⁴ Census.gov, New York-Northern New Jersey-Long Island, NY-NJ-PA Metro Area, <http://www.census.gov/prod/2013pubs/acsbr12-02.pdf>

¹⁵ Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, US DOT, June 2014, <http://www.dot.gov/sites/dot.gov/files/docs/USDOT%20VOT%20Guidance%202014.pdf>

¹⁶ An Analysis of the Operational Costs of Trucking: A 2013 Update, American Transportation Research Group, September 2013, <http://truckexec.typepad.com/files/atri-operational-costs-of-trucking-2013-final.pdf>

¹⁷National Highway Transportation Survey, U.S. DOT, 2009, http://nhts.ornl.gov/tables09/fatcat/2009/avo_TRPTRANS_WHYTRP1S.html

¹⁸ This assumes that, if travelers know that a given route is closed, a portion will develop alternate schedules or workarounds to avoid the delay.

significant uncertainty). The estimated *yearly* costs associated with each event were derived by multiplying the 2-year tidal surge disruption cost by 50%, and the Sandy-equivalent surge by 1% (i.e., in any given year there is a 1% chance of the event occurring).

To derive the expected costs over the forecast horizon (again, 2050 to 2100), the 2012 annual event costs were multiplied by a compounded annual background growth rate (ABGR) of 0.9% from 2012 to 2050 to derive the 2050 value of costs. The ABGR is based on the expected annual growth in traffic for the corridor.¹⁹ Similarly, in the years following 2050, the economic costs were assumed to increase by 0.9% per year due to the expected growth in traffic.

A non-constant discount rate was applied based on research by IEA, Inc.²⁰, which indicates that a decreasing discount rate should be applied when calculating environmental benefits in the far-distant future. Based on this research, the analysis assumed a 3% real discount rate from 2010 through 2034, 2% for 2035-2084, and 1% for 2085-2100.

The economic impacts estimated in this analysis are the aggregate of all costs for each year between 2050 and 2100 for both the 2-year tidal surge and the Sandy-equivalent event. The cumulative estimated impacts for each event are summarized for the lower and upper bound scenarios (low and high AADT and AADTT) in Table 7.

Table 7: Cumulative Economic Impacts of Route 7 Segment Closure

Event	Cumulative Economic Impacts (2050-2100), Lower bound AADT	Cumulative Economic Impacts (2050-2100), Upper bound AADT
SLR + 2-year Tidal Storm (discounted 2012 dollars)	\$7.73 Million	\$16.36 Million
SLR + Hurricane Sandy-Equivalent Storm (discounted 2012 dollars)	\$9.30 Million	\$19.64 Million

Note: All estimates have been rounded to the nearest \$10,000, and are in units of discounted 2012 dollars

5.3 EFFECT ON DISADVANTAGED POPULATIONS

NJ Route 7 provides important access between Jersey City and the Town of Kearny as well Jersey City and the Town of Harrison. These towns contain pockets of disadvantaged residents. For example, approximately 10% of Kearny’s population and 17% of Harrison’s population is below the poverty line²¹. There are two block groups in the Western part of Kearny and one block group in the Northern part of Harrison in which over 35% of the population is below the poverty line²². While there are alternative roadway routes and transit routes available connecting Jersey City to the Towns of Kearny and Harrison, closure of the Route 7 segment could potentially increase travel costs and delay provision of support or emergency services to these communities. However, there are no bus routes on NJ Route 7, and little

¹⁹ Concept Development Report, NJ Route 7, MP 1.70-3.80, Drainage Improvements, Town of Kearny, Hudson County”, prepared by McCormick Taylor for New Jersey Department of Transportation (NJDOT), Dated September 2012

²⁰ Discount Rates for Environmental Benefits Occurring in the Far-Distant Future, Independent Economic Advisors, February 2009, <http://www.iearesearch.com/papers/discounting.pdf>

²¹ U.S. Census, 2008 - 2012

²² U.S. Census, 2007 - 2011

concrete evidence to suggest that disruption of the study segment will disproportionately impact disadvantaged populations.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

This section presents adaptation strategies to address projected inundation under the 2100 mid-range SLR + 2-year tidal surge scenario, associated with a projected water level of approximately 9 feet NAVD88²³. Given that the installation of sheeting was already studied in the Concept Development Report, the team elected not to analyze this option. Another potential option-- armoring of the roadway embankment and shoulder—was ruled out because overwashing and/or settlement were not identified as risks of principal concern. The selected option, analyzed below, was to raise the profile of low-lying stretches of the Route 7 segment and build a seawall to protect stretches that cannot be raised due to clearance issues (see Section 5.1).

6.1 RAISE ROUTE 7 PROFILE AND CONSTRUCT A SEA WALL

This strategy proposes raising the profile of certain stretches of Route 7 and building a sea wall to protect those stretches which cannot be raised, primarily due to vertical clearance restrictions, with the shared objective of mitigating the impacts of coastal flooding events of 9 feet NAVD88-- the projected elevation of the 2100 mid-range SLR and 2-year tidal surge scenario—or less.

Near the southern boundary of the Route 7 segment, there are stretches of about 600 feet on the northbound and southbound sides (Stretch 2 and Stretch 3, respectively, highlighted in yellow in Figure 4) at an elevation below 9.0 feet NAVD88. Both directions have an approximate pavement width of 40 feet. There is an additional stretch of about 500 feet on the southbound side at the northern boundary of the Route 7 segment, also below 9.0 feet NAVD88 (See Stretch 1 highlighted in yellow in Figure 4).

This option includes raising the Route 7 profile at these stretches to a minimum of 9 feet NAVD88 to mitigate the disruption-related impacts of inundation. The range of current study segment elevations is shown in Figure 4. Stretch 1, with a minimum elevation of 6.4 feet NAVD88, would need to be raised by up to 2.6 feet. Similarly, Stretches 2 and 3 have minimum elevations of 7.5 feet NAVD88 and 7.9 feet NAVD88 respectively, and would have to be raised by up to 1.5 feet and 1.1 feet.

Near the southern boundary of the Route 7 segment, a 300 foot stretch on the northbound side (highlighted in blue in Figure 4) passes under CR 659. The minimum required vertical clearance for a new structure is 16.5 feet, according to NJDOT Design Standards. For an existing structure that doesn't meet the minimum vertical clearance standard, the requirement is to maintain the existing vertical clearance. The NJ Route 7 Concept Development Report on Drainage Improvements identifies that three out of the four Route 7 underpass structures in that section (0910155, E109.02 and 0910152) have sub-standard vertical clearances. This indicates that the CR 659 overpass may also have a substandard vertical clearance, especially considering the approximately 40-year age of this structure. Raising this stretch of Route 7 is not likely to be a suitable option.

In light of this constraint, a traditional concrete seawall could be installed in the vicinity of this stretch of Route 7. This stretch currently has a minimum elevation of 8 feet NAVD88. The seawall, therefore, should have a top elevation of at least 10 feet NAVD88 to block tidal surge flow onto the roadway (which includes a freeboard of 1 foot required for the design of the seawall as per guidance in the NJDOT Bridges and Structures Design Manual). This means that the height of the seawall will be 2 feet, or more.

²³ Based on the vulnerability analysis, it was determined that the 2050 mid-estimate SLR and 2-year tidal storm scenario (approximately 7 feet NAVD88) does not pose a significant risk and therefore likely does not warrant adaptation.

New or reconstructed storm drains and/or outfalls might be necessary to accommodate resulting changes to flows. Pump stations might also be required where gravity flow conditions cannot be achieved. It is estimated that two new or reconstructed drainage systems and two 25-horsepower pumps would be needed. Additional right-of-way and/or easement will likely be needed in order to raise the roadway, install the seawall, and construct storm drains, outfalls, and pump stations. The seawall could also be designed and constructed to provide a foundation for potential augmentation in the future—either in response to increasing rates of sea level rise or to protect against storms of greater magnitude, should risk tolerances shift.

As noted previously, this adaptation strategy is not configured to protect against more extreme tidal storms. Projected inundation under the 2100 high-range SLR + Hurricane Sandy-equivalent storm scenario is 17.3 feet NAVD88. The study segment is, on average, 7 - 10 feet below this elevation, except for the portion where Route 7 passes over the railroad.

Figure 4: Proposed locations for elevating the Route 7 profile and installing a seawall



Source: Google Maps, 2014

6.1.1 ECONOMIC ANALYSIS

This strategy could potentially prevent adverse impacts on mobility and the economy due to chronic disruptions to the roadway as a result of SLR and storm surge, which would likely otherwise occur in the absence of the strategy by mid century and beyond. As shown in Table 7, the estimated cumulative economic costs of SLR and 2-year tidal surge from 2050 to 2100 are \$7.73 million and \$16.36 million (discounted 2012 dollars) for the lower and upper AADT/AADTT scenarios, respectively. The project team estimates that implementation of the selected strategy would prevent these disruption costs²⁴.

²⁴ It should be noted that the economic analysis does not include the prevented cost of future major repairs or deterioration, which could potentially be significant.

6.1.2 ENVIRONMENTAL ANALYSIS

This strategy may have potential impacts on air quality, soil quality, and habitat. In order to evaluate the environmental impacts of this strategy in detail, site specific analyses would be needed. These analyses may include architectural and cultural resource studies, Green Acres²⁵ and Section 4(f) consultation, air and noise studies, wetland fill mitigation studies, and hazardous waste mitigation studies. The study area is in the jurisdiction of the NJ Meadowlands Commission, and the wetlands within the NJ Meadowlands are under the jurisdiction of the U.S. Army Corps of Engineers. Examples of permits that may be required include:

- Army Corps of Engineers: Jurisdictional Determination, Nationwide or Individual Permit
- NJDEP Section 401 Water Quality Certification
- Hudson Essex Passaic County Conservation District: Soil Erosion & Sediment Control Plan Certification
- NJDEP Waterfront Development Permit

6.1.3 EQUITY ANALYSIS

This strategy could potentially prevent adverse equity-related impacts from disruptions to the roadway, which would likely otherwise occur in the absence of the strategy. NJ Route 7 provides access between Jersey City and the Towns of Kearny and Harrison. As discussed in Section 5.3, there are pockets of disadvantaged communities located in this region. The closure of the Route 7 segment could potentially increase travel costs and restrict provision of support or emergency services for disadvantaged communities. The implementation of this strategy could prevent these impacts on disadvantaged communities.

6.1.4 COST ANALYSIS

Table 8 and Table 9 show the cost components associated with this adaptation strategy. The cost estimates in Table 8 include the cost of a seawall and its associated infrastructure, whereas the estimates in Table 9 do not include these costs.

Table 8: Cost Estimates Including Seawall and Associated Infrastructure

Cost Component	Cost (\$)
Cost of seawall (900 SF* @ \$250/SF)	\$225,000
Cost of 2 new (or reconstructed) drainage systems	\$600,000
Cost of other drainage / stormwater treatment items	\$750,000
Cost of pump stations (each pump station is equipped with two 25 horsepower pumps for each outfall for the two new (or reconstructed) drainage systems (2 pump stations @ \$1.5M each)	\$3,000,000
Cost of raising profile/pavement	\$3,500,000
Cost of Rights-of-Way	\$500,000
Cost of handling contaminated soil	\$400,000
<i>Soft cost (including traffic, MPT, lighting, lump sum items, construction engineering, utility relocation, ROW, and contingencies)</i>	\$6,825,000
Total cost estimate	\$15.8 Million

Note: The cost is estimated using NJDOT's preliminary construction cost estimate spreadsheet in conjunction with the latest NJDOT Construction Cost Estimating Guide.

²⁵ Green Acres is a NJ Department of Environmental Protection program focusing on conserving open space and providing recreational activities in the state. <<http://www.nj.gov/dep/greenacres/>>

* The estimate of 900 square feet is a product of height (3 feet) times length (300 feet). The seawall width is typically standard and proprietary, and therefore does not impact the cost calculation.

Table 9: Cost Estimates Not Including Seawall and Associated Infrastructure

Cost Component	Cost (\$)
Cost of two new (or reconstructed) drainage systems	\$600,000
Cost of other drainage / stormwater treatment items	\$750,000
Cost of raising profile/pavement	\$3,500,000
Cost of Rights-of-Way	\$500,000
Cost of handling contaminated soil	\$400,000
<i>Soft cost (including traffic, MPT, lighting, lump sum items, construction engineering, utility relocation, ROW, and contingencies)</i>	\$3,550,000
Total cost estimate	\$9.3 Million

Note: The cost is estimated using NJDOT's preliminary construction cost estimate spreadsheet in conjunction with the latest NJDOT Construction Cost Estimating Guide.

6.1.5 TIMING FOR IMPLEMENTATION

As previously stated, the study segment is not expected to require adaptation (associated with the 2-year tidal surge) through mid century. The selected adaptation strategy is intended to mitigate flooding associated with the end-of-century, mid-range SLR + 2-year tidal surge scenario. Therefore, implementation could occur *after* 2050 unless SLR projections are revised upward, risk tolerances shift to favor mitigation of more significant surge events, and/or a significant reconstruction occurs toward the middle of the century into which adaptation can be integrated cost effectively.

For the low portions of the roadway that could incur limited inundation under the 2050 high-range scenario (see discussion in Section 3.2), NJDOT could address them prior to mid-century. This could entail implementing some components of the adaptation strategy during the next reconstruction of this segment (i.e., phased implementation).

After funding has been procured, it is estimated that the design and permitting process will take approximately 5 years. This estimate includes the time needed for conceptual, preliminary, and final design, as well as permitting (including funding procurement, the process could take up to a decade). Once design and permitting is complete, construction could take approximately 3 years from notice to proceed to final site clearance. These time frames compare favorably to the estimated 4.5 years that would be required for routine replacement of the roadway without any additional adaptation measures, assuming funding is already in place (this timeframe would be expedited in an emergency situation). NJDOT could continue to monitor climate projections periodically, incorporate the strategy into its capital planning program, and seek funding around mid-century.

7. CONCLUSION

This assessment identified potential coastal inundation vulnerabilities of a segment of NJ Route 7 associated with mid- and end-of-century time horizons. The study segment is not likely to be impacted by 2-year tidal surges with projected SLR (mid-range) by 2050, but it is likely vulnerable to all other SLR and storm surge scenarios identified in Table 4. This assessment proposes adaptation strategies to mitigate coastal flooding associated with the mid-range SLR and 2-year tidal surge under the end-of-century time horizon (2100). A 2-year tidal surge was selected in order to maintain consistency with ongoing

adaptation planning efforts in adjacent areas. The proposed adaptation strategies will not be adequate to mitigate the impacts more extreme tidal storms or greater sea level rise—a limitation recognized by all involved agencies during the scoping of this assessment.

To address mid-range SLR and 2-year tidal storms by 2100, the following adaptation strategies were selected for analysis from among a broader list of potential options:

- Raise the profile of certain stretches of the Route 7 segment, and
- Build a seawall to protect stretches that cannot be raised due to vertical clearance restrictions.

Given that the study segment is not likely to be impacted by the combination of SLR and 2-year storm surge until mid-century, immediate action may not be necessary. However, this strategy could be reassessed periodically as, for example, SLR projections are refined, risk tolerances shift, and/or broader projects emerge into which these adaptation strategies could be cost-effectively integrated.



Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

Port Jersey South Engineering Informed Adaptation Assessment

PANYNJ PORT JERSEY MARINE TERMINAL, PENINSULA AT BAYONNE HARBOR, BAYONNE, NJ

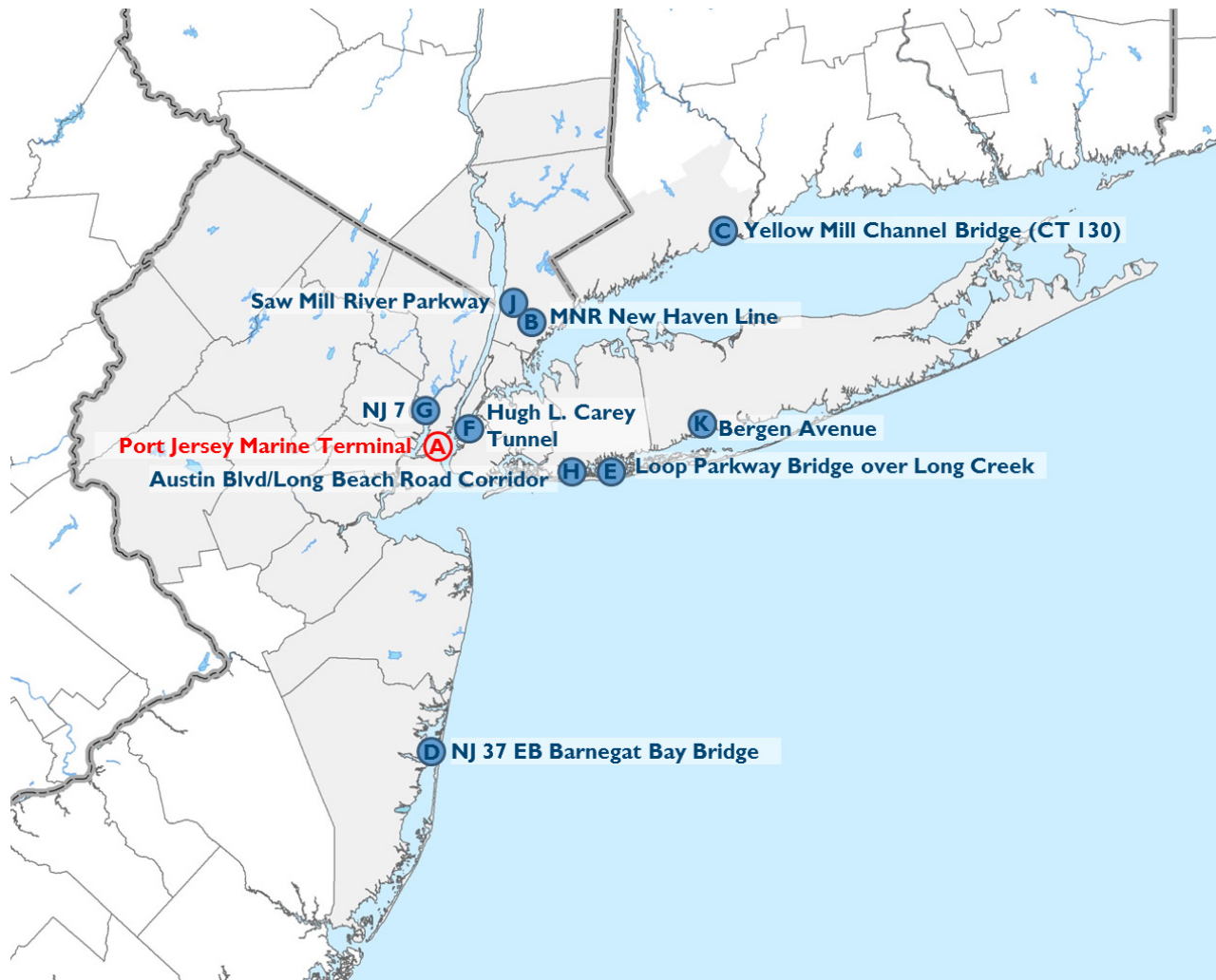
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched an initiative to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Port Jersey Marine Terminal is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the Port Jersey Marine Terminal study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for 10 FHWA Study Areas (Port Jersey Marine Terminal in Red)



2. FACILITY DESCRIPTION

The Port Jersey Marine Terminal is located at the southeastern corner of the City of Bayonne, New Jersey, and is managed by the Port Authority of New York and New Jersey (PANYNJ). This assessment examines the Peninsula at Bayonne Harbor (identified by the red dotted line in Figure 2), on which one of the arms of the Port Jersey Marine Terminal is located. PANYNJ owns approximately 120 acres of land on this Peninsula. PANYNJ leases some of its land to commercial tenants such as Royal Caribbean International and Bayonne Dry Dock & Repair Corporation, and uses the rest for port operations. Other stakeholders operating on the Peninsula include the U.S. Coast Guard, Ports America, and residential developments located on the inland side of the Peninsula (e.g., Alexan CityView Apartments).

Figure 2: The Peninsula at Bayonne Harbor, Bayonne, NJ



Source: Google Maps, 2015

PANYNJ identified sea level rise (SLR) and storm surge as the primary climate stressors of concern for this site. In particular, recent extreme storm events like Hurricane Sandy have highlighted existing vulnerabilities of the Peninsula’s electrical components. Hurricane Sandy resulted in an estimated 3-4 feet of flooding at the Peninsula, damaging the majority of electrical/power components and necessitating their repair or replacement.

In light of these vulnerabilities to coastal inundation, PANYNJ selected the Peninsula’s electrical infrastructure as the focus of this assessment. PANYNJ has operational control over various types of electrical infrastructure such as switchgear, circuit breakers, transformers, and feeder lines, which are housed in various buildings on the Peninsula. Figure 3 shows a satellite view of the buildings containing the switchgear and circuit breakers (gray labels), as well as examples of the Port’s commercial tenants served by the electrical infrastructure (orange labels). The overall condition of the electrical components at the Peninsula can be categorized as poor (See Table 1 and Section 4.1 for more details on age, lifespan and condition).

Figure 3: Locations of Port-owned Buildings and Commercial Tenants on the Peninsula at Bayonne Harbor



Note: Gray labels indicate buildings containing switchgear and circuit breakers. Orange labels indicate commercial tenants.
Source: Google Maps (basemap) and PANYNJ.

Table 1: Facility details

Category	Details
Facility Type	Port Terminal
Facility Component	Electrical Components (Switchgear and Circuit Breakers)
Estimated Age (Lifespan)	The Port is approximately 75 years old and the age of the electrical components ranges from 30 to 40 years. The typical lifespan of switchgear and circuit breakers is approximately 20 years if it does not undergo periodic rehabilitation. With maintenance, the lifespan can exceed 20 years.
Estimated condition	Poor (This ranking was provided by PANYNJ. It applies to the condition of the electrical components at the Port, particularly those components that have not been replaced since being damaged by Hurricane Sandy).
Use	The Peninsula serves various Port activities and other industrial, office, cruise, and residential activities.

Source: Port Authority of New York and New Jersey

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

The Peninsula has not experienced flooding during high tides, as the average ground floor elevation of the buildings on the Peninsula is approximately 7.2 feet NAVD88¹, and the Mean Higher High Water (MHHW) elevation is 2.2 feet NAVD88. However, the average ground floor elevation of the buildings (including those housing electrical equipment) is well below the 100-year flood elevation of 13 feet NAVD88 at the Peninsula.

SLR and storm surge were selected for further analysis based on conversations between the project team, PANYNJ, and FHWA. Projections for SLR were compiled by the project team based on data from the New York City Panel on Climate Change (NPCC, 2015), as suggested by PANYNJ. Mid-estimate (25th to 75th percentile) and high-estimate (90th percentile) SLR scenarios were considered in this assessment for the mid-century time horizon (2050s). The SLR estimates corresponding with the 25th and 75th percentile are 11 to 21 inches respectively. Based on guidance from PANYNJ, the threshold adopted in this assessment was the mid-point projection of 16 inches, or 1.3 feet. The 90th percentile SLR projection is 2.5 feet. These projections for SLR are shown in Table 2, and are relative to a baseline period of 2000-2004.

Table 2: Sea Level Rise Projections, 2050

Stressor Type	Scenario	Magnitude
Sea Level Rise	NPCC Middle Estimate (mid-point of 25 th to 75 th percentile)	1.3 feet
	NPCC High Estimate (90 th percentile)	2.5 feet

Source: New York Panel on Climate Change, 2015. <http://onlinelibrary.wiley.com/doi/10.1111/nyas.12593/epdf>

To account for storm surge, the one percent (annual) chance flood elevation (the “100-year flood”) was considered. According to FEMA’s Preliminary Flood Insurance Rate Maps (PFIRMs, 2014), the 100-year Base Flood Elevation (BFE, stillwater + wave heights) at the Peninsula is 13 feet NAVD88 (see Figure 4). With the addition of the middle estimate SLR for mid century, the total Water Surface Elevation (WSEL) considered in this analysis is 14.3 feet NAVD88² (i.e., 1.3 feet SLR + 13 feet BFE).

Table 3: Tidal Flood Elevations Examined To Account for Storm Surge

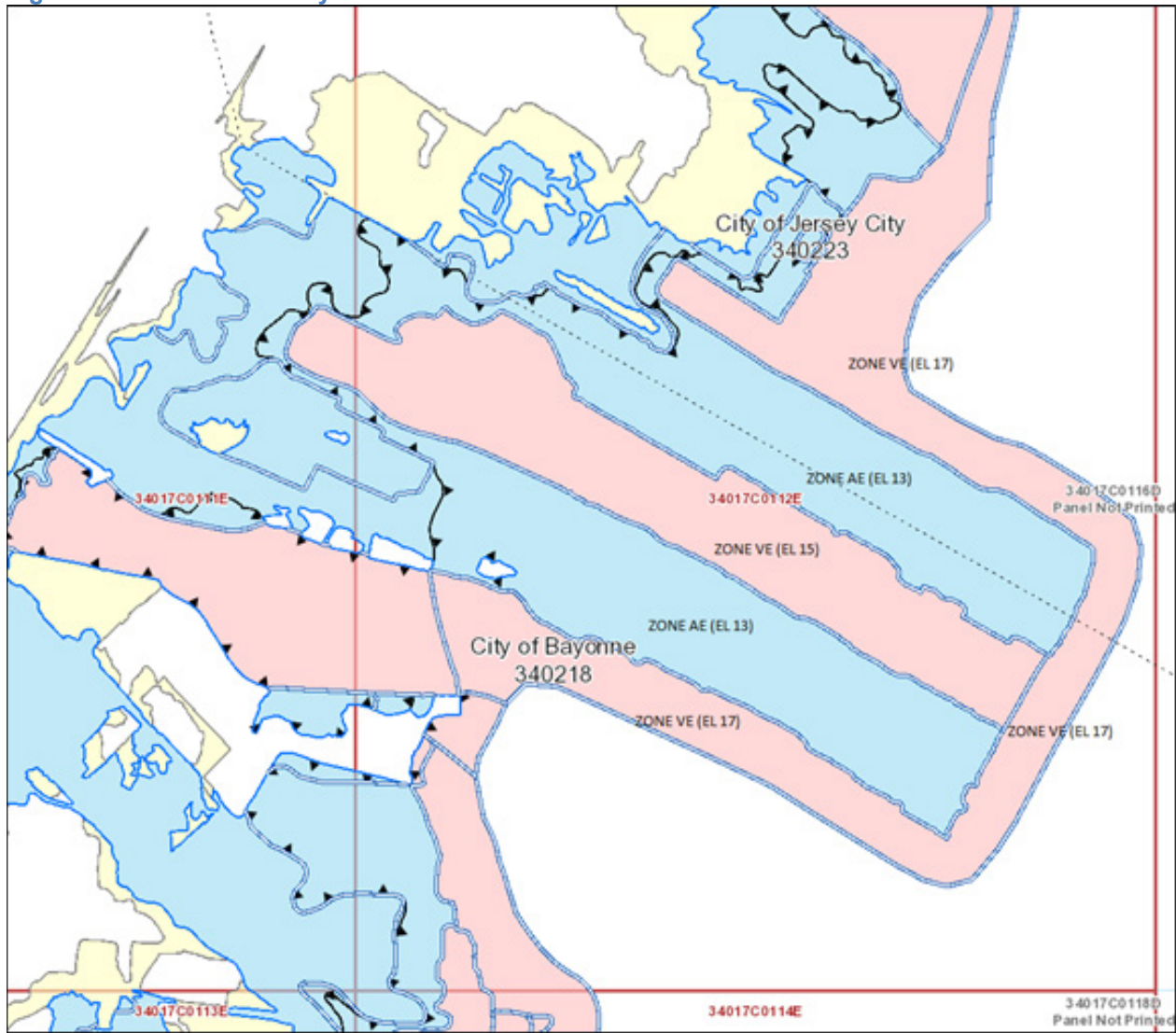
Stressor Type	Options	Elevation (feet NAVD88)
100-year Flood	100-year FEMA PFIRM BFE at Peninsula	13

Source: FEMA Region II Coastal Analysis and Mapping, Preliminary Flood Insurance Rate Map (PFIRM) Data for Hudson County, 2014 <<http://www.region2coastal.com/view-flood-maps-data/view-preliminary-flood-map-data/>>

¹ Based on background information received from PANYNJ, the average ground floor elevation of facilities on the Peninsula is assumed to be 10 feet above the mean low water level. Based on a site survey drawing of the Peninsula, the mean low water level is at an elevation of -2.8 feet NAVD88. Therefore, the ground floor elevation is expressed as 7.2 feet NAVD88 (= -2.8 feet NAVD88 + 10 feet).

² Not including freeboard, which is considered subsequently.

Figure 4: FEMA Preliminary FIRM for the Peninsula



Source: FEMA Region II Coastal Analysis and Mapping, Preliminary Flood Insurance Rate Map (FIRM) Data for Hudson County, 2014 <<http://www.region2coastal.com/view-flood-maps-data/view-preliminary-flood-map-data/>>

Table 4 shows the projected WSEL when mid-century SLR (based on NPCC data) is added to the FEMA 100-year flood elevation.

Table 4: Projected Elevations for 100-year Flood Events Combined with SLR, 2050s

Elevation Scenario	With Mid-estimate (Mid-point of 25 th to 75 th Percentile) SLR Scenario (feet NAVD88)	With High-estimate (90 th Percentile) SLR Scenario (feet NAVD88)
100-year FEMA PFIRM BFE at Peninsula	14.3	15.5

Source: FEMA

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

This site is vulnerable to flooding from 100-year flood events. Hurricane Sandy, which exceeded the 100-year flood event in magnitude, resulted in 3-4 feet of flooding at the site, damaging the majority of electrical/power components that support various operations.

By mid-century, the Peninsula's likelihood of exposure to storm surge is expected to increase due to rising sea levels³. If exposed, the site could be sensitive to the following potential modes of failure:

- **Service Disruption:** Much of Peninsula is likely to be inundated by over 5 feet during a mid-century, 100-year flood event, and therefore rendered inaccessible. During Hurricane Sandy, most of the Peninsula was flooded by 3-4 feet (based on observations). It is likely that a more frequent flooding event (e.g., a 2% annual chance [50-year] event) could also cause inundation at the site. Overtopping and inundation are highly likely to disrupt activities at the site. Disruption from a significant storm event, like Hurricane Sandy, can last for multiple months. For example, PANYNJ's administration building (Building 51) at the Peninsula was closed for approximately 5 months after Hurricane Sandy. PANYNJ estimates that the average time for port tenants to restore normal operations after a storm similar to Hurricane Sandy could be approximately 30 to 120 days.
- **Physical Damage:** Inundation and storm surge can damage electrical/power infrastructure in various ways. Moisture and debris that is not readily visible can cause internal damage to equipment and compromise the integrity of electrical insulation. Electrical distribution equipment contains protective components within assemblies such as panel boards and switchboards, which is critical to the safe operation of distribution circuits. The ability of panel boards and switchboards to protect these circuits can be adversely affected by exposure to corrosive minerals and particles present in salt water during inundation. The corrosive impact can continue well after flood waters recede. Storm surge can also damage the surface or foundations on which equipment is located.
- **Premature Deterioration:** Inundation and storm surge can significantly reduce the lifespan of the electrical materials and fixed equipment and increase the likelihood of failure and required replacement frequency. Hurricane Sandy caused irreparable damage to the equipment at the Peninsula. The typical lifespan of switchgear is approximately 20 years assuming no periodic maintenance is performed. If maintenance is performed, the lifespan can exceed 20 years. Some of the electrical equipment serving the Peninsula was last replaced in 1985 (approximately 30 years old), while other equipment is even older. Since Hurricane Sandy, some equipment has been replaced. A replacement schedule for the remaining equipment was not available at the time of writing.

Table 5 provides estimates of the replacement cost and recovery time required to restore services at the site after a flooding event similar to Hurricane Sandy.

³ The strongest storms in the Atlantic Basin may also increase in the future (NPCC, 2015).

Table 5: Replacement Cost, and Recovery Time for Project Site

Time and Cost	Magnitude
Estimated Replacement Cost	\$40,000,000 (This value is for all the electrical equipment on the Peninsula. The replacement cost of the switchgear and circuit breakers, which are the focus of this assessment, is shown in Section 6)
Estimated Recovery Time	6 to 12 months to fully replace all electrical equipment on the Peninsula.

Source: Port Authority Marine Terminal managed by the Port Authority of New York and New Jersey

4.2 ADAPTIVE CAPACITY ANALYSIS

The adaptive capacity of the electrical components at the site is limited. Short-term flood protection measures for the electrical components were implemented by PANYNJ after Hurricane Sandy. These measures include the replacement of cables affected by saltwater damage, the addition of stop-logs around facilities, the addition of flood barrier walls (e.g., those manufactured by HESCO) around substations, and the installation of a new sump pump. The Western Substation was recently replaced and two new weatherproof switchgears were installed. The Eastern Substation is also being renovated. However, in the absence of a more comprehensive long-term solution (e.g., raising the equipment at the site), the adaptive capacity of the electrical components is likely to remain low in the face of extreme events like Hurricane Sandy.

Activities on the Peninsula that rely on electrical infrastructure also exhibit low adaptive capacity. Based on PANYNJ estimates, it would take approximately 30 to 120 days for businesses to resume normal operations in the aftermath of a significant coastal flooding event. Immediately after an event, as a short term solution, businesses may be able to operate under limited conditions if they have generators. Some generators are equipped with automatic transfer switches and, when the main power supply is cut off, are able to start supplying power to buildings within fifteen to thirty seconds of the outage. In general, generators can run 24 hours a day, 7 days a week as long as the appropriate oil level is maintained in the generator engine. However, for power outages of greater than two (2) days, the unit's oil would need to be tracked for consumption.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of the Peninsula's main access road would restrict access to facilities on the Peninsula (such as Coast Guard and Ports America). However, given the coastal location of the Peninsula, it is not anticipated that disruption to assets onsite would adversely impact regional road-based mobility.

5.2 EFFECT ON REGIONAL ECONOMY

In light of the minimal expected impacts to regional mobility as a result of disruption at the Peninsula, there is no evidence to indicate that closure of Peninsula will significantly impact the regional economy. However, the regional economic impacts pertaining to business activities are highly dependent on the redevelopment of the Peninsula. As detailed information is not currently available on the nature of the development at the Peninsula, regional economic impacts pertaining to business activities at the Peninsula have not been evaluated in this assessment.

5.3 EFFECT ON DISADVANTAGED POPULATIONS

Impacts to the Peninsula are not anticipated to disproportionately impact disadvantaged populations, given the location of the Peninsula, and the nature of the economic activities which are supported by Peninsula.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

A number of adaptation strategies were considered to protect the electrical components at the Peninsula. One option considered in the early stages of this assessment involved raising the entire peninsula instead of focusing on asset-specific interventions. However, this option was ruled out until more is known about the anticipated redevelopment of the Peninsula—a long-term prospect. To address shorter-term needs, the adaptation strategies proposed in this assessment focus on asset-specific, engineered solutions such as raising the electrical components, replacing currently damaged or vulnerable components with more resilient alternatives, and enhancing weatherproofing features. Together, these options offer a promising combination of risk mitigation, shorter-term implementation feasibility, and cost-effectiveness.

6.1 RAISE ELECTRICAL EQUIPMENT

This strategy proposes that all electrical components in Buildings 61-D, 44-C, and 108 be elevated on a platform, based on the SLR projections and 100-year flood elevations described in Section 3. These buildings are all single-floor buildings, and the dimensions of the buildings allow for raising equipment on top of a platform without having to build a second floor. It is recommended that all the electrical systems and equipment be raised to an elevation above the 100-year Base Flood Elevation (BFE) + SLR projected for mid-century + Freeboard. FEMA defines freeboard as “a factor of safety usually expressed in feet above a flood level for purposes of floodplain management”. Freeboard tends to compensate for the many unknown factors that could contribute to flood heights greater than the design flood, such as wave action.

Considering the mid-point of the 25th and 75th percentile SLR projections by mid-century and FEMA PFIRM BFEs from 100-year flood events, this option involves raising all equipment to a minimum elevation of 15.3 feet NAVD88. Table 6 below depicts how this elevation was derived. A complementary composite elevation based on the high-estimate (90th percentile) SLR projection is also included (16.5 feet NAVD88). Figure 5 shows an illustration of the elevation to which equipment can be raised.

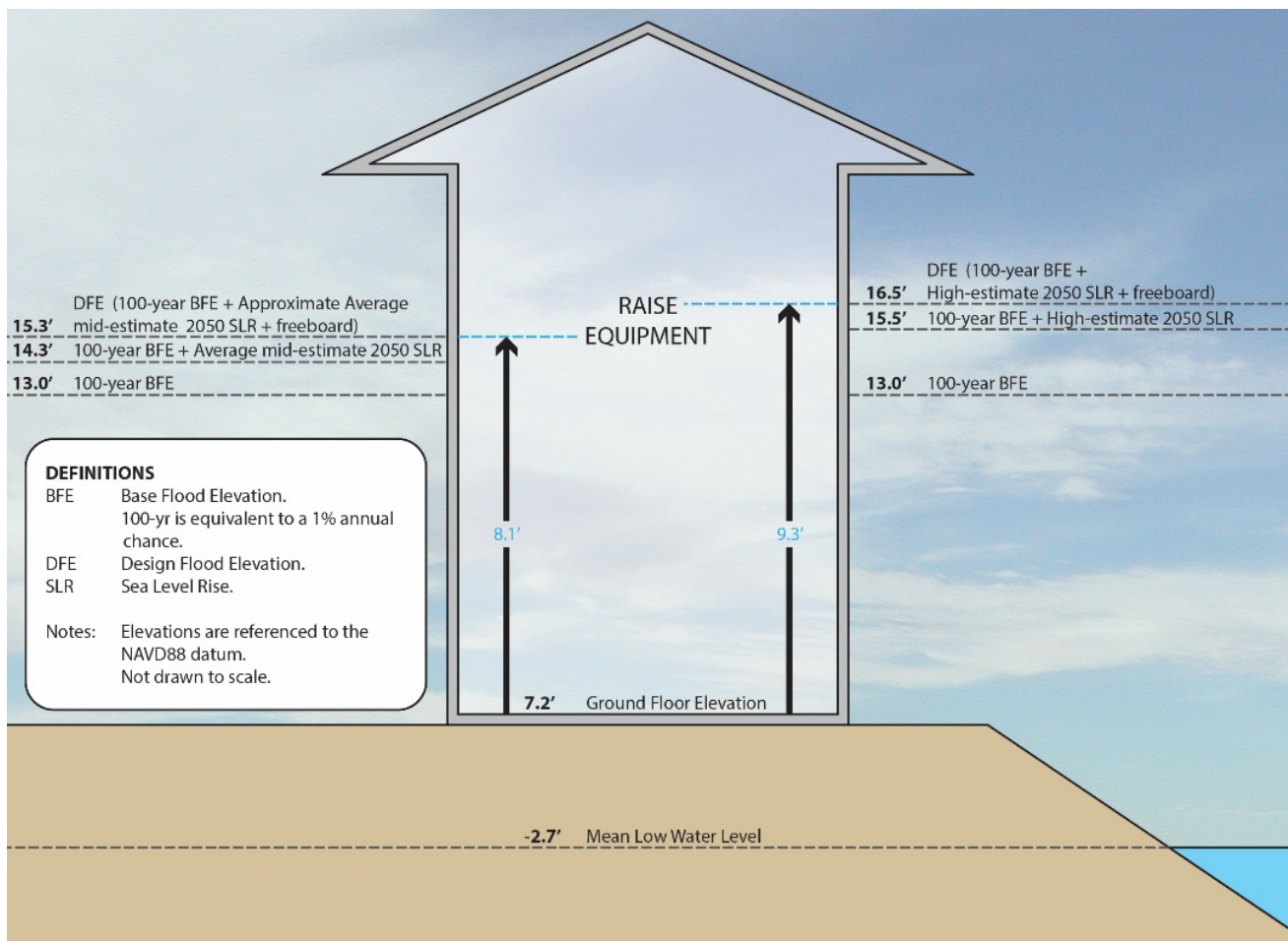
In January 2015, independent of this assessment, PANYNJ issued Climate Resilience design guidelines. See the attached Annex A for further information on design flood elevations derived from this guidance.

Table 6: Options for Minimum Recommended Elevations to Which Equipment Can Be Raised

Recommended Elevation	= BFE* (ft. NAVD88)	+SLR (ft.)	+Freeboard (ft.)	= Result (ft. NAVD88)
Mid-estimate (Approximate Mid-point of 25th to 75th Percentile) SLR Scenario	13.0 ¹	+1.3 ^A	+1.0	= 15.3
High-estimate (90th Percentile) SLR Scenario (feet NAVD88)	13.0 ¹	+2.5 ^B	+1.0	= 16.5

¹ Base Flood Elevation for 100-year flood based on FEMA PFIRM (2013)
^A 2050 NPCC 25th-75th percentile approximate mid-point (16 inches or 1.3 feet)
^B 2050 NPCC 90th percentile (30 inches or 2.5 feet)

Figure 5: Schematic for Raised Equipment in Buildings (All Elevations NAVD88)



Source: AECOM, 2014
 Note: Based on PANYNJ guidance, ground floor elevation is 7.2 feet NAVD88.

6.1.1 ECONOMIC ANALYSIS

The regional economic impacts of implementing this strategy are highly dependent on the redevelopment of the Peninsula. As detailed information is not currently available on the nature of the development at the Peninsula, regional economic impacts of implementing this strategy have not been evaluated.

6.1.2 ENVIRONMENTAL ANALYSIS

No significant environmental impacts are anticipated as a result of implementing this strategy.

6.1.3 COST ANALYSIS

Table 7 provides an estimate of the cost of installation of a platform on which sensitive equipment can be placed in Buildings 108, 44-C, and 61-D. The total cost (last column) is for a platform height of approximately 8 to 10 feet (costs will vary only minimally within this range). To protect equipment from mid-estimate SLR and 100-year flood elevations, the height of the platform would be 8.1 feet (starting from the floor elevation of 7.2 feet NAVD88 and elevating to 15.3 feet NAVD88). To protect equipment from high-estimate SLR and 100-year flood elevations, the height of the platform would be 9.3 feet (7.2 feet NAVD88 to 16.5 feet NAVD88).

Table 7: Cost estimates for raising equipment

Building	Raised Platform Length and Width Dimensions (feet)	Existing Floor Elevation (Feet NAVD88)	Additional Required Height (Feet)	Platform Surface Area (Square Feet)	Cost per Square Foot (\$/Square Foot)	Connection and other Costs (%)	Contingency Costs (%)	Total Cost (\$)
108	53'L x 17'W	7.2	8.1 to 9.3	~1000	\$65	30%	20%	\$100K
44-C	29'L x 17'W	7.2	8.1 to 9.3	~500	\$65	30%	20%	\$50K
61-D	20'L x 17'W	7.2	8.1 to 9.3	~350	\$65	30%	20%	\$35K

Source: AECOM, 2014

6.1.4 TIMING FOR IMPLEMENTATION

This strategy can be implemented in the short-to-medium term, as it is intended to address mid-century SLR and 100-year flood elevations. For currently damaged equipment, the implementation of this strategy can coincide with scheduled replacement. For new equipment, this strategy would apply immediately.

6.2 REPLACE DAMAGED EQUIPMENT AND PROVIDE WEATHERPROOF HOUSING FOR ELECTRICAL EQUIPMENT

This strategy involves replacing the existing electrical components that have been identified as damaged from Hurricane Sandy with more resilient equipment and providing weatherproof housing.

Replacement of Equipment

The damaged switchgear and associated components could be replaced with gas-insulated switchgear (GIS), which offers higher reliability and safety, and has lower maintenance costs as opposed to conventional equipment⁴. The medium-voltage gas insulated vacuum circuit breaker switchgear assembly can be type 8DA10 (single-bus) or 8DB10 (double-bus).. This gas-insulated switchgear has an encapsulated design and is ideal for installation sites that are subject to dust, vermin, salt, or contaminated atmospheres. The 8DA10 type can be 1/5th the size of conventional air insulated switchgears, which results in savings in space and building costs.

⁴ Based on a quote from Siemens (July 2015), the cost of gas insulated switchgear is approximately \$100,000 per circuit, compared to approximately \$35,000 per circuit for conventional switchgear.

No maintenance is required for the first 10,000 operations of the circuit breaker (or 1,000 operations on the three-position switch or for up to ten years). The three-position switch is built into the switchgear and allows the circuit to be opened, closed or grounded on the load side. Switches are used to interrupt any short-circuits or overload currents that may occur on the network. The vacuum interrupter has an expected life of 10,000 or 30,000 operations, depending on its rating.

Vacuum switching technology and a digital protection system allow for the high-voltage elements to be isolated from environmental conditions and provide for a low-maintenance operation since it is contained within a hermetically-sealed pressure system in a corrosion-resistant aluminum alloy vessel.

The component enclosure for the switchgear is NEMA 4X, which is a specific rating for a type of enclosure from the National Electrical Manufacturers Association that is constructed for both indoor and outdoor use and also provides protection to personnel from hazardous parts of the equipment, such as live or electrified parts. This enclosure type protects the equipment inside the enclosure against ingress of solid foreign objects (such as windblown dust) and water (rain, sleet, snow, splashing water, and hose directed water), and also from corrosion. This enclosure type can also be resistant to the external formation of ice on the enclosure.

Weatherproof Housing:

In addition to replacing the damaged switchgear with more robust switchgear inside NEMA 4x enclosures, this strategy also considers placing the switchgear inside electrical houses. Electrical houses (also known as E-houses) are a method to keep electrical equipment in a weatherproof setting. E-houses are walk-in metal enclosures specifically built to protect critical electrical equipment. E-houses are constructed using a welded I-beam base, providing a solid foundation for internally mounted components, and allowing for either slab or raised platform installation (consistent with the strategy recommended in Section 5.1).

6.2.1 ECONOMIC ANALYSIS

The regional economic impacts of implementing this strategy are highly dependent on the redevelopment of the Peninsula. As detailed information is not currently available on the nature of the development at the Peninsula, regional economic impacts of implementing this strategy have not been evaluated in this assessment.

6.2.2 ENVIRONMENTAL ANALYSIS

No significant environmental impacts are anticipated as a result of implementing this strategy.

6.2.3 COST ANALYSIS

Table 9 shows the estimated costs for the replacement of the switchgear and associated equipment components, as well as the cost of installing E-houses for the equipment inside the buildings. There are many options that can affect the price of the overall electrical systems. The costs below are for hardware and E-houses only. Installation, start-up, training, shipping, raised platform and stair costs, among other services, are not included in the estimates below.

Table 8: Replacement Costs for Electrical Components at the Project Site

Name	# of Switchgear Sections	GIS* only	E-house** only	GIS + E-house
61D West	4	\$400,000	\$36,000	\$436,000
Building 108	15	\$1,500,000	\$132,000	\$1,632,000
Building 44C	7	\$700,000	\$62,000	\$762,000
Total	26	\$2,600,000	\$230,000	\$2,830,000

*GIS = Gas Insulated Switchgear

**E-House = Electrical House

Source: Siemens, 2015

6.2.4 TIMING FOR IMPLEMENTATION

This strategy can be implemented in the short-to-medium term, as it is intended to address mid-century SLR and 100-year flood elevations. For currently damaged equipment, the implementation of this strategy can coincide with scheduled replacement of key equipment. For new equipment, this strategy would apply immediately.

The estimated timeline for the replacement of all switchgear and associated components, as well as the installation of E-houses by the manufacturer, is approximately 40 weeks. This timeframe only includes shipping, assembly, construction and testing of the new equipment at the site and does not include permitting, site development or the building of structural components such as raised platforms for equipment elevation.

7. CONCLUSION

This assessment identified the existing and potential future vulnerabilities of critical electrical infrastructure on the Peninsula at Bayonne Harbor to projected SLR and 100-year flood events by mid-century. To address these vulnerabilities, the following adaptation strategy options are considered:

- **Strategy 1:** Raising the equipment to an elevation above the projected elevation from a combination of SLR and 100-year flood events
- **Strategy 2:** Replacing equipment that is currently damaged and/or vulnerable with more robust equipment, including additional weatherproofing features.

Of these two options, Strategy 1 is likely to be the most effective in protecting electrical equipment from SLR and storm surge. Strategy 2 can be implemented in conjunction with Strategy 1 as an added measure of resilience, as much of the electrical equipment at the Peninsula is already scheduled for replacement due to the damage it suffered from Hurricane Sandy. There are numerous advantages to pursuing these strategies in tandem. The GIS equipment has higher reliability and safety, and has lower maintenance costs than conventional equipment. The NEMA 4x enclosure (with GIS equipment) provides greater protection to personnel from live or electrified equipment parts while protecting the equipment itself from dust, water, and corrosion, and mitigating the external formation of ice.

Annex A

Based on the PANYNJ Climate Resilience Guidelines⁵ (issued 1/22/2015), the following table shows the recommended design flood elevation for raising electrical equipment (relative to the grade elevation of the facility under consideration). A Benefit/Cost Analysis for this design flood elevation would be performed to determine if the elevation of the equipment provides a positive return on investment.

The SLR assumption is based on the asset’s life expectancy. Both mid-century (2050s) and end-of-century (2080s) values are shown. Additionally, power distribution facilities (electrical substations, switch houses) are considered critical assets by PANYNJ, for which an additional 2 feet of freeboard is required (the core assessment, which preceded these guidelines, used 1 foot of freeboard—hence the approximately one foot differential for 2021-2050).

Table 9: PANYNJ Climate Resilience Guidelines

Asset Life Expectancy	AE/VE 100-Year Base Flood Elevation	Critical Asset Freeboard	SLR Adjustment	Final Flood Protection Elevation
2021-2050	13'	2'	1.33'	16.33'
2051-2080	13'	2'	2.33'	17.33'

⁵ <http://www.panynj.gov/business-opportunities/pdf/discipline-guidelines/climate-resilience.pdf>



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT-

Saw Mill River Parkway Engineering Informed Adaptation Assessment

SAW MILL RIVER PARKWAY, DOBBS FERRY, NY

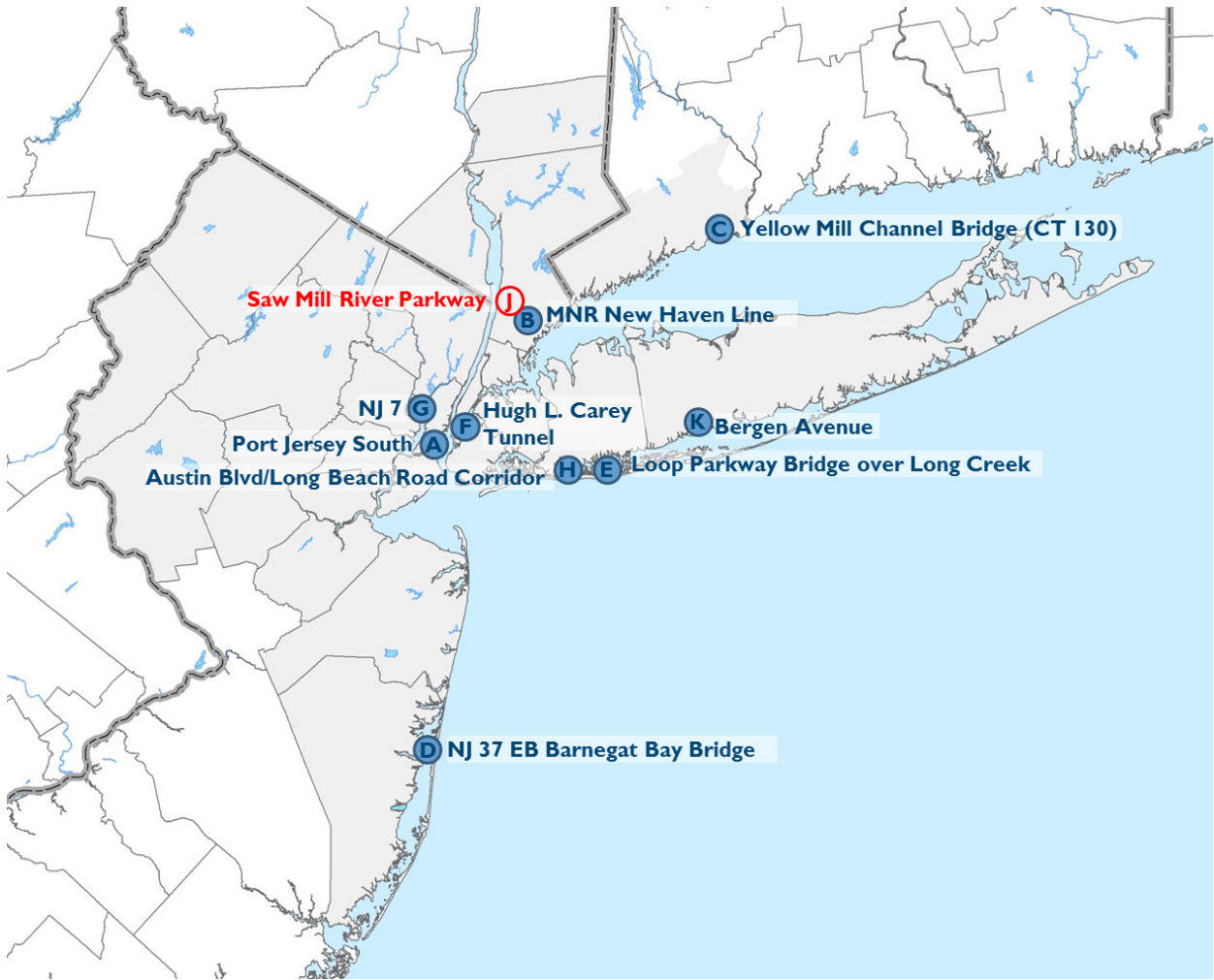
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut (region to climate change and extreme weather events). FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene, and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Saw Mill River Parkway Corridor is one of ten transportation facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas, with the Saw Mill River Parkway study area highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities

Figure 1: Context Map for Ten FHWA Study Areas (Saw Mill River Parkway in Red)



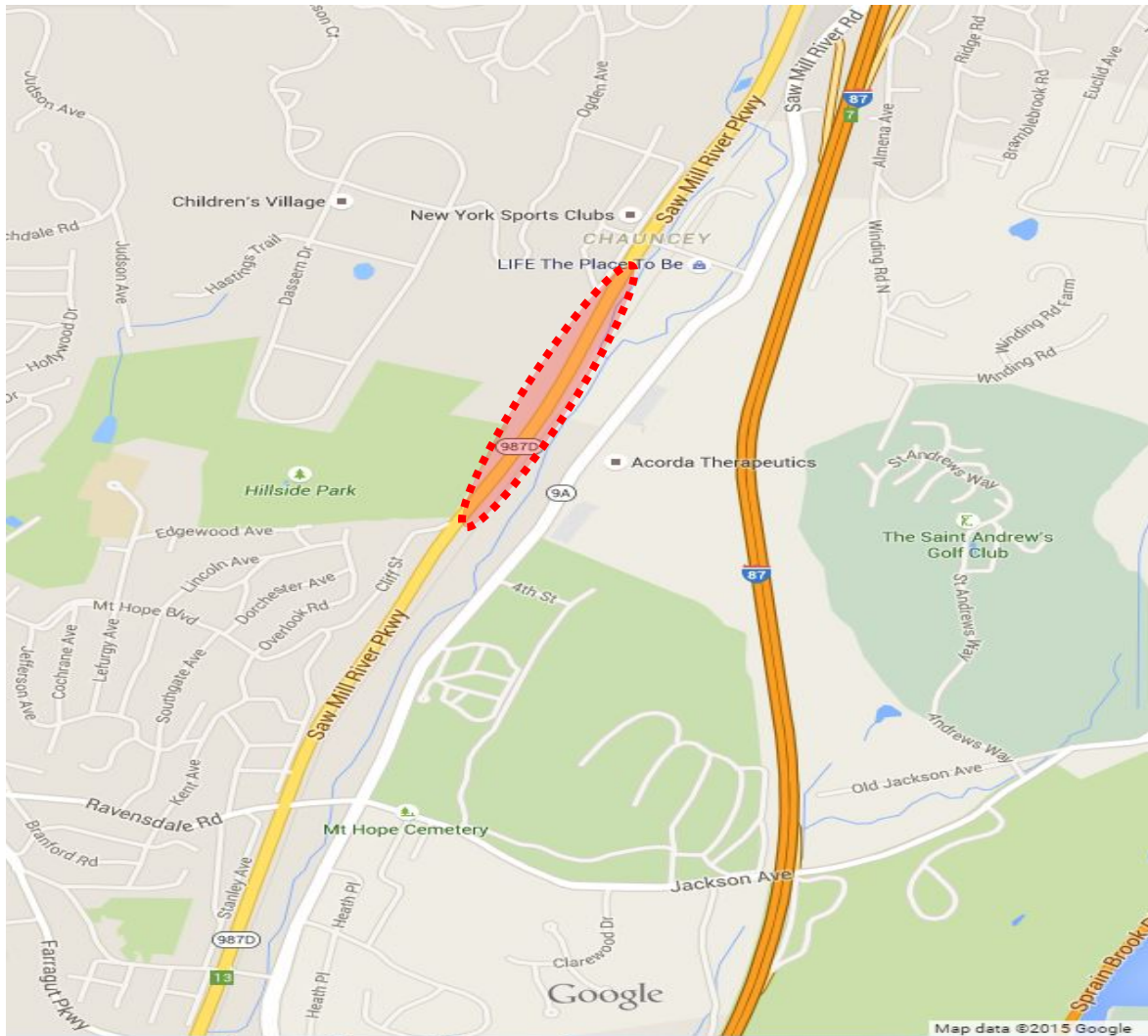
2. FACILITY DESCRIPTION

The Saw Mill River Parkway was built in the 1930s and is under the jurisdiction of the New York State Department of Transportation (NYSDOT). The Parkway extends for 29 miles through Westchester County, New York, beginning at the border of Westchester County and the Bronx as a continuation of the Henry Hudson Parkway, and terminating at an interchange with Interstate 684 and New York State Route 35. It is a north-south Parkway supporting two lanes of traffic in each direction divided by a median barrier. The curbed Parkway has a total of 22 feet of pavement with a 4-foot wide median and no shoulders. The Saw Mill River flows north to south and is immediately adjacent to the Parkway.

Several segments of the Parkway currently experience flooding during precipitation events of various return periods. The segment of the Parkway that experiences the most critical flooding is in Pleasantville, and this segment is currently being reconstructed to address it. The second most flood-prone segment is directly south of Lawrence Street, identified as segment MP201.2 – MP201.4¹ (See Figure 2). This segment experiences flooding during moderate to heavy rainstorms due to the inadequate capacity of its drainage system to divert rainwater, and also due to additional floodwater overflows from the adjacent Saw Mill River. For example, the segment was closed to traffic six times for 2-5 hours in 2011 and 5 times in 2010 due to a few inches flooding. During Hurricane Irene, the Parkway was closed for 24 hours due to 12 inches of flooding. This segment was chosen by NYSDOT for further analysis in this assessment. Since flooding conditions are similar throughout the Parkway, adaptation strategies developed for this segment could be applied to other segments as well.

¹ MP stands for milepost.

Figure 2: Parkway Segment South of Lawrence Street, between Markers MP201.2 and MP201.4



Source: Google Maps, 2015

2.1 CAUSES OF RIVERINE FLOODING AT THE SAW MILL RIVER PARKWAY:

With the Saw Mill River, as with other rivers, there are various factors that exacerbate the physical limitations of the river channel, thus contributing to flooding of the Saw Mill River Parkway.

Intense Rainfall Events: During a storm event, precipitation and storm water runoff increase the volume, as well as peak flows in the Saw Mill River. Intense rainfall events above a threshold storm intensity, duration and frequency (specific to the location) raise the water surface elevation above its capacity to remain confined within the river channel.

Inadequate Storage Capacity: The geometry of the Saw Mill River's channel creates a finite area for conveyance above the water surface elevation; therefore, there will be flooding in the river's floodplain when the channel's conveyance capacity is exceeded.

Watershed Characteristics: The complexity of the Saw Mill River's watershed varies by location and plays a role in triggering riverine flooding events. The ground cover/development (e.g., pervious grass or impervious pavement), average basin slope, basin response time (time of concentration²), and availability of flood storage in the watershed affect the amount of storm water runoff reaching the river. The Saw Mill River watershed is located within a highly urbanized area in Westchester County with limited available storage in lakes and swamps. This limits infiltration capacity during storms and generates greater runoff volumes. Further, the relatively high basin slope and narrow valley-shaped watershed reduces the basin response time during small intense storms as well as larger storms, resulting in flooding in the watershed.

The flooding of the Saw Mill River is primarily due to inadequate channel conveyance capacity and lack of storage in the watershed. Other contributing factors are described below.

Lack of Channel Maintenance: Lack of maintenance of the Saw Mill River channel allows build-up of debris. This debris can influence the shape of the river bed. Debris and the shape of the river bed are both primary providers of flow resistance. When the debris restricts the river's flow, water is no longer effectively conveyed in the channel. With further buildup of debris and/or an increased volume of water in the channel due to a storm event, the river will backup and overflow its banks. While a quantitative estimate of the frequency of channel maintenance is not available, this frequency is believed to be low.

Undersized Roadway Bridges: The presence of bridges and culverts affect the Saw Mill River's normal course.³ Inadequate bridge openings and undersized culverts restrict the river's flow. A bridge with an inadequate opening height above a riverbed can become inundated when the water elevation rises due to a storm event. Undersized culverts can create a bottleneck, restricting the river's flow, resulting in flooding when the water cannot pass through the culvert and is diverted. A culvert is undersized, from a hydraulic engineering perspective, when the calculated peak discharge at the culvert is greater than its capacity. According to Chapter 8 of the NYSDOT Highway Design Manual, culvert crossings at interstates and other freeways are expected to accommodate a 50 year design flood without exceeding the design criteria. The original waterway opening under a bridge may become inadequate over time as a result of changing drainage patterns and land use conditions in the watershed.

According to the FEMA Flood Insurance Study for Westchester County (2007), a significant amount of storage and routing occurs at locations of undersized bridges/culverts in the Saw Mill River floodplain.

² Time of concentration is a concept used to measure the response of a watershed to a rain event, defined as the time needed for water to flow from the most remote point in a watershed to the watershed outlet.

³ There are likely over a hundred bridges on the river. An exact estimate of the number of undersized bridges is not readily available, but can be determined by examining the profiles of each segment of the river.

Cumulatively, these floodplain storage locations lead to the reduction of peak discharges significantly in downstream reaches. The increase in drainage area results in no significant increase in peak discharges in the Saw Mill River between Ashford Avenue and its confluence with Hudson River. For example, the 1 percent annual chance (100-Year) peak discharge in Saw Mill River at Ashford Avenue is 1,967 cubic feet per second for 20.4 square miles of drainage area, which is approximately 20% lower than a peak discharge of 2,344 cubic feet per second at the Woodland Lake outlet, which is upstream of Ashford Avenue and accommodates 19.7 square miles of drainage area. This reduction in discharge is a direct result of flood storage/routing in the floodplain upstream of Ashford Avenue.

The build-up of debris at bridge and culvert openings further constricts the river's flow. When the debris is cleared, the chance of flooding is decreased. See Figures 3 through 5 of two box culverts along the Saw Mill River in the town of Greenburg, south of Lawrence Street. These pictures illustrate the importance of maintenance to remove debris from clogged bridge and culvert openings to prevent flooding during future storm events. By removing the obstruction and clearing the opening, the river is able to flow freely through the culvert. During a later storm event, the water surface elevation rises, but there is no flooding.

Figure 3: Debris blocking/clogging one of two box culverts on the South County Trailway, adjacent to the Saw Mill River Parkway south of Lawrence Street



Source: NYSDOT, January 2012

Figure 4: Culverts after debris removal



Source: NYSDOT, March 2012

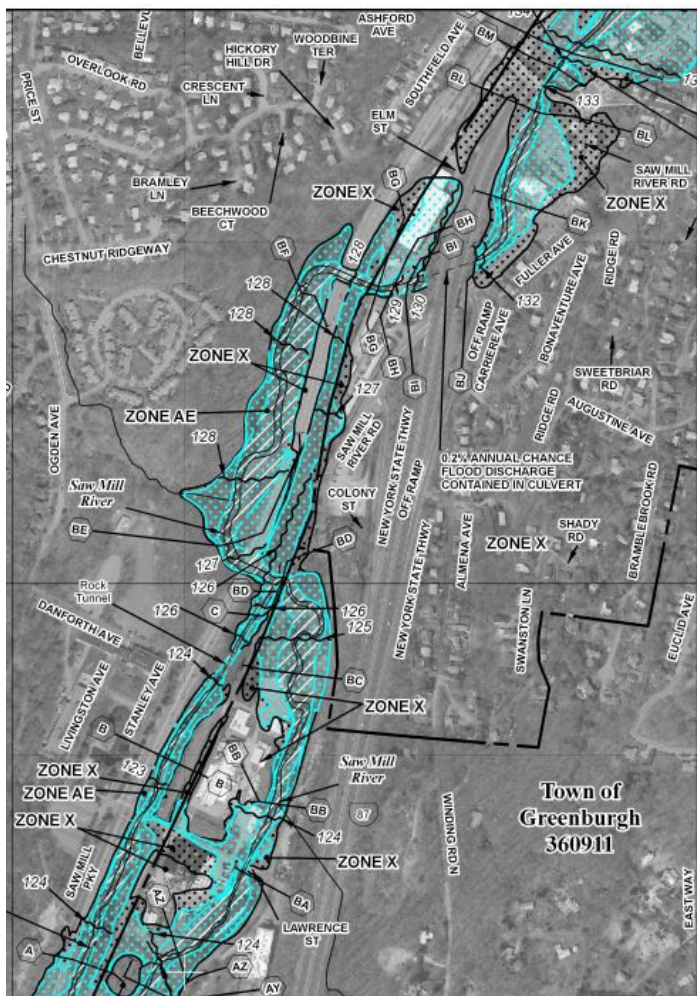
Figure 5: Culverts after later storm event



Source: NYSDOT (image taken after March 2012; exact date unknown)

Parkway Orientation in Floodplain: Finally, the location and elevation of the Saw Mill River Parkway in a floodplain is a major indicator of the likelihood of its flooding. If the roadway's elevation is below a storm's flood elevation, it will flood. FEMA Flood Insurance Studies and Maps are a public source for flood hazard information and indicate an area's flood risk. FEMA Flood Insurance Rate Maps (FIRMs) utilize statistical information, such as data for river flow, storm tides, hydrologic/hydraulic analyses, and rainfall and topographic surveys to determine flood risk. These maps indicate various flood conditions, highlighting Special Flood Hazard Areas subject to inundation by the 100-Year flood, also known as the base flood. See Figure 6 for the FIRM covering the area along the Saw Mill River Parkway in the vicinity of Lawrence Street. The map identifies the areas at risk for flooding. Water surface elevations for the 10-, 50-, 100-, and 500-year floods are also available in FEMA Flood Insurance Studies.

Figure 6: Flood Insurance Rate Map at the Saw Mill River



Source: FEMA Flood Map Service, Effective Date September 28, 2007

All of the events/conditions discussed above can independently lead to a river overtopping its banks; however, when combined, result in a greater degree of riverine flooding.

This assessment examines the drainage system of the selected Parkway segment, but it does not address the contribution of overflows from the Saw Mill River to flooding at the Parkway. Such an analysis is outside the scope of this project. The 0.2 mile segment of the Saw Mill River Parkway being analyzed in this assessment is a very small portion of a large corridor, and a riverine analysis needs to be performed at a watershed scale.

The Saw Mill River Parkway provides vital connectivity to the region. It serves as a commuter route to Hudson River villages, Yonkers, and Manhattan, and as a reverse commute route to Tarrytown, White Plains and other destinations in the vicinity, including recreational destinations. The Parkway has an Annual Average Daily Traffic (AADT) of 55,129.⁴ It is also an evacuation route for the Indian Point Nuclear Power Plant located in northern Westchester County, which makes it a critical route from a safety perspective. Trucks are not permitted on the Parkway.

Table 1 provides details on the age, condition, and use of the Parkway segment’s drainage system.

Table 1: Facility details

Category	Details
Facility Type	Roadway Segment
Facility Component	Drainage System
Estimated Age (Lifespan)	75 years (This estimate applies to the drainage system)
Estimated condition	Poor (This rating applies to the drainage and is based on its lack of maintenance and limited capacity)
Use / Ridership	55,129 AADT, AADTT Not Applicable

Source: NYSDOT Region 8

⁴ Source: NYSDOT Region 8

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

The Parkway segment evaluated in this assessment is located in a floodplain and currently experiences flooding during moderate to heavy rainstorms. The entire Parkway corridor is projected to face an increase in the frequency and magnitude of precipitation events of different return periods in the future. For this reason, precipitation was selected as the climate stressor to review as part of this assessment. Specific projections for the frequency and magnitude of precipitation events were analyzed based on conversations with NYSDOT.

3.1 FREQUENCY OF EXTREME PRECIPITATION EVENTS

The specific scenarios for projected changes to the frequency of extreme precipitation events were selected by NYSDOT based on a report developed by the New York State Energy Research and Development Authority (NYSERDA) entitled *Climate Change in New York State* (ClimAID, 2014).⁵ The frequency of precipitation events of different return periods in the Parkway corridor is projected to increase over time. Looking at the high estimate projections of precipitation events, the annual average number of days with over 1 inch of rainfall is projected to increase from 13 (baseline years 2000-2004) to 17 by 2050 and 18 by 2080⁶. The average annual number of days with over 2 inches of rainfall is projected to increase from 3 (baseline years 2000-2004) to 5 by both 2050 and 2080. Looking at the middle estimate projections, the annual average number of days with over 1 inch of rainfall is projected to increase to 14-16 by 2050 and 15-17 by 2080. The average annual number of days with over 2 inches of rainfall is projected to increase to 4 by 2050 and 4-5 by 2080. See Table 2 for a summary of these projections.

Table 2: Projections for Frequency of Extreme Precipitation events

	Days with more than 1 inch of rainfall			Days with more than 2 inches of rainfall		
	Baseline	2050	2080	Baseline	2050	2080
(High estimate – 90th percentile)	13	17	18	3	5	5
(Middle estimate – 25th to 75th percentile)	13	14 to 16	15 to 17	3	4	4 to 5

Source: ClimAID, 2014.

⁵ Horton, R., D. Bader, C. Rosenzweig, A. DeGaetano, and W. Solecki. 2014. *Climate Change in New York State: Updating the 2011 ClimAID Climate Risk Information*. New York State Energy Research and Development Authority (NYSERDA), Albany, New York.

⁶ Data on precipitation events is not available for 2100, which is why data projected for 2080 is being used instead.

3.2 MAGNITUDE OF PRECIPITATION EVENTS

The magnitude of precipitation events in the Parkway corridor is also likely to increase based on projections developed by the Northeast Regional Climate Center (NRCC) at Cornell University for the Dobbs Ferry, NY location. These projections have been developed for NYSERDA in partnership with NYSDOT. The projections are generated from two types of model simulations: the North American Regional Climate Change Assessment Program (NARCCAP) simulation and the Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulation. The NARCCAP and CMIP5 simulations are based on the A2 and RCP-8.5⁷ future global greenhouse gas (GHG) emissions scenarios, respectively. Both these scenarios represent conditions under which global GHG emissions continue to increase over the course of the century, reflecting only modest improvements in technology and energy efficiency, and a lack of proactive climate policies.

NRCC provided the projected percent change in the magnitude of precipitation over a duration of 24 hours for precipitation events of various return periods for the mid-century (2040-2069) horizon. See Table 3 for a summary of these projections for 10- and 50-year return periods for the Dobbs Ferry, NY location. These two return periods were selected because the storm drainage system at Saw Mill River Parkway should be designed in accordance with NYSDOT standards, and Chapter 8 of the NYSDOT Highway Design Manual specifies that storm drainage systems on interstates and other freeways be designed for a 10-year storm frequency, with locations at sag vertical curves (curves that connect descending grades forming a bowl or sag) designed for a 50-year storm frequency.

Table 3: Mean Percent Change in Precipitation over 24 Hours from 10-year and 50-year Rainstorms, Dobbs Ferry, NY

Precipitation event Return Period	NARCCAP Simulation (2040-2069)	CMIP5 Simulation (2040-2069)
10-Year Return Period	+15.49%	+15.78%
50-Year Return Period	+14.16%	+15.28%

Source: Northeast Regional Climate Center, Cornell University.

Note: Data on end-of-century projections can be requested from the Northeast Regional Climate Center.

In discussions with NYSDOT, it was agreed to take a low risk-tolerance (conservative) approach and focus on the high estimate (90th percentile) projections for precipitation events in this assessment. Furthermore, the Highway Drainage Section (Chapter 8) of the NYSDOT Highway Design Manual specifies that highway storm drain systems shall have a design life and anticipated service life equal to 70 years. Based on the anticipated service life of storm drain systems, it is proposed by the project team that end-of-century precipitation projections be considered in proposed improvements to the existing drainage system at the Saw Mill River Parkway segment.

⁷ RCP stands for Representative Concentration Pathways

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

The segment of the Saw Mill River Parkway being evaluated in this assessment currently experiences flooding during moderate to heavy rainstorms. As stated in previous sections, this flooding is due to the inadequate capacity of its drainage system to divert rainwater, and also due to additional floodwater overflows from the adjacent Saw Mill River. The frequency and magnitude of precipitation events impacting the Parkway segment are projected to increase. Given this current and projected exposure to precipitation events, the segment is and will be sensitive to the following potential modes of failure:

1. **Overtopping/Inundation:** In the past, moderate to heavy rainstorms have flooded the Saw Mill River Parkway with a few inches of water, shutting down the Parkway in both directions for approximately 2 to 5 hours. For example, this segment of Parkway was closed to traffic six times in 2010 and five times in 2011 due to flooding. In each event, both northbound and southbound traffic had to be detoured. More frequent and intense rainstorms could result in the Parkway's closure more often and for longer periods of time.
2. **Physical/Structural/Foundational Damage:** The Parkway segment itself is approximately 75 years old and considered to be in good to fair condition; however, prolonged saturation from flooding can deteriorate segment materials. Currently, damage above the segment's sub-base is minimal due to the slow rise and fall of flood waters. However, future flooding may damage the segment's surface or foundations, thereby increasing maintenance requirements, reducing the lifespan of the surface materials, increasing the likelihood of failure, and leading to disruptions until repaired or stabilized.
3. **Drainage Failure:** Based on historical observations, the Parkway segment's drainage system is unable to handle moderate to heavy rainstorms due to inadequate capacity. The lack of maintenance to the existing drainage system is further affecting its efficiency. This system will need to be updated to accommodate more frequent and intense rainstorms in the future.

Table 4 provides estimates of the full replacement cost of this 0.2 mile Parkway segment and the recovery time required to restore services at the Parkway after a flooding event.

Table 4: Replacement Cost and Recovery Time for Parkway Segment

Cost and Time	Magnitude
Estimated Replacement Cost	\$1,500,000
Estimated Recovery Time	2-5 hours (moderate to heavy rainstorms); 24 hours (severe storms/hurricanes, e.g., Hurricane Irene)

Source: Estimates of the replacement cost and recovery time were provided by NYSDOT Region 8.

4.2 ADAPTIVE CAPACITY ANALYSIS

The transportation network that includes the Saw Mill River Parkway exhibits some degree of adaptive capacity. Two alternate highway routes – the New York State Thruway (I-87) and the Sprain Brook Parkway – run parallel to the Saw Mill River Parkway and can accommodate longer-distance trips in the corridor when the Saw Mill River Parkway is closed. Furthermore, the Sprain Brook Parkway does not flood to the same degree as the Saw Mill River Parkway, and only experiences closures during 50-year

storms (or stronger).⁸ Metro North Railroad's Hudson Line and Harlem Line can also accommodate north-south trips, although the Hudson Line is in a location prone to coastal as well as inland flooding. Local roads including Saw Mill River Road (New York State Route 9A) and U.S. 9 (Broadway) can accommodate local traffic handled by the Saw Mill River Parkway, although Saw Mill River Road, which runs adjacent to the Parkway, is often affected by the same flooding that affects the Parkway.

During closures of the Saw Mill River Parkway, detour time and additional cost are incurred by motorists, who would need to drive an additional distance via the parallel routes. The estimated detour distance and delay time as a result of disruption to the Parkway segment are approximately 3 miles and 9 minutes respectively.⁹ See Section 5.2 for an analysis of the economic impacts of this detour distance and delay time.

⁸ Source: NYSDOT Region 8

⁹ Mileage and time estimates are based on Google Maps. The time of the detour is 5 minutes without traffic; however, due to the storm events and additional traffic on the alternate route, a time penalty of 80 percent was applied to arrive at the estimate detour time of 9 minutes per auto.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Closure of the Parkway would affect commuter traffic as it serves as a commuter route to Hudson River villages, Yonkers and Manhattan and as a reverse commute route to Tarrytown, White Plains and other destinations in the vicinity. This stretch of Parkway also serves local trips between the river towns in Westchester County and unincorporated areas in the Town of Greenburgh. Trucks are not permitted on the Saw Mill River Parkway; therefore, road closures would not affect the movement of goods. It is important to note that the Saw Mill River Parkway is one of the evacuation routes for the Indian Point Nuclear Power Plant, and therefore it is an extremely critical route from a safety perspective, which means that its closure could have significant safety repercussions.¹⁰

5.2 EFFECT ON REGIONAL ECONOMY

Closure of the Parkway would result in additional travel time and vehicle operating costs for people who use it to travel to work, for on-the-clock business trips, and for personal trips. These costs can have broader impacts on the regional economy. This analysis estimates the per-event economic costs of Parkway closure from two types of weather events: moderate to heavy rainstorms (assuming 3.5-hours of road closure)¹¹ and severe storms/hurricanes (assuming 24 hours of closure).¹² The economic costs include travel time costs and vehicle operating costs.

As a first step in this analysis, the 2012 AADT (55,129¹³) was utilized to calculate the total traffic impacted over the duration of the closure for each event. For a moderate to heavy rainstorm event, AADT was divided by 24 hours to derive an hourly traffic count and was subsequently multiplied by the 3.5-hour closure. Although an overnight closure would have orders of magnitude less impact than a morning or evening peak commute period closure, this analysis is presented for illustrative purposes. For a hurricane/severe flooding event, the full AADT was used because the closure was assumed to last 24 hours. Truck traffic is not permitted on this portion of the Saw Mill River Parkway; therefore AADTT is not applicable to this analysis.

The delay imposed by a detour due to each event was assumed to be approximately 9 minutes with traffic (equivalent to 3 miles)¹⁴, assuming the use of I-287 West, I-87 South, and the Cross County Parkway West in the southbound direction and the same route in reverse in the northbound direction.¹⁵

The travel time costs were derived from the hourly New York-Northern New Jersey-Long Island, NY-NJ-PA Metropolitan Statistical Area (MSA) median household income (\$30.76 per hour in 2012 dollars).¹⁶

¹⁰ Westchester County, Indian Point Emergency Guide, 2013-2014, http://www.safesecurevital.com/uploads/Westchester_English.PDF

¹¹ See Table 4. Analysis assumes that a moderate to heavy rainstorm event would close the road for 2 to 5 hours, or an average of 3.5 hours, due to flooding. The time of recovery/duration of disruption depends on the extent of the rainfall amount and the ability of the drainage system to handle the volume. However, for the purposes of this analysis, an average of closure of 3.5 hours is applied.

¹² See Table 4. Analysis assumes that a hurricane/severe flooding event would close the road for 24 hours, as it did with Hurricane Irene.

¹³ See Table 1.

¹⁴ Mileage and time estimates are based on Google Maps. The time of the detour is 5 minutes without traffic; however, due to the storm events and additional traffic on the alternate route, a time penalty of 80 percent was applied to arrive at the estimate detour time of 9 minutes per auto.

¹⁵ Mileage and time estimates are based on Google Maps. The time of the detour is 5 minutes without traffic; however, due to the storm events and additional traffic on the alternate route, a time penalty of 80 percent was applied to arrive at the estimate detour time of 9 minutes per auto.

¹⁶ Census.gov, New York-Northern New Jersey-Long Island, NY-NJ-PA Metro Area, <http://www.census.gov/prod/2013pubs/acsbr12-02.pdf>

The analysis conservatively assumed that automobile travel is composed entirely of personal or commutes trips; therefore, the value of time is 50 percent (\$15.38 per hour or \$0.26 per minute) of the hourly median household income for the region, based on USDOT guidance.¹⁷ The per-minute cost for total traffic impacted for both types of events was then multiplied by the number of minutes per delay to capture to economic cost for all vehicles impacted for the length of the delay. The automobile occupancy was assumed to be 1.55 persons per vehicle (USDOT).¹⁸

To determine the vehicle operating costs incurred per event, the estimated total additional miles travelled by vehicles impacted by the detour were multiplied with vehicle operating cost per mile traveled for both moderate to heavy rainstorm events and severe/hurricane events to derive the cost per additional vehicle mile traveled for all traffic. The vehicle operating cost per additional vehicle mile traveled includes the cost of gas, maintenance, tires, and half of depreciation, and amounts to \$0.32 per mile (in 2012 dollars)¹⁹. It was assumed that the additional distance travelled (in miles) due to the detour is 3 miles per vehicle.²⁰

For both moderate to heavy rainstorm events and severe storms/hurricanes, not every traveler was assumed to be affected by an event. There are a number of transit alternatives including Metro-North Railroad and the Bee-Line Westchester Bus System that provide direct service to Yonkers, Scarsdale, the Bronx, and Manhattan.²¹ Assumptions were made that 90 percent of travelers would be affected by the moderate to heavy rainstorm event and incur a cost, because transit mode share is already very high for the origin-destination pairs served by bus and rail services, and the majority of those who choose to drive are assumed to attempt the trip during these moderate to heavy rainstorm events.

For severe storms/hurricanes, only 40 percent were assumed to be affected and incur a cost, because the severity of these events is more predictable, and the duration of a closure is longer such that travelers can develop alternate plans (such as telecommuting) to avoid the hazard. Therefore both the economic travel time and vehicle operating costs per event were multiplied by 90 percent for moderate to heavy rainstorm events and by 40 percent for severe storms/hurricanes. The balance of travelers was assumed to be able to avoid the hazard with minimal costs due to telecommuting, availability of transit, etc. In a more detailed study, additional research would be performed or purchased to better understand trip purpose, the origin and destination of trips, how sensitive travelers are to changes in traffic patterns, and how diverted traffic could, in turn, cause delays on alternate routes and modes.

After going through these calculations, the per-event cost of moderate to heavy rainstorms was estimated at \$33,016 (\$2012) and that of severe storms/hurricanes was estimated at \$78,853 (\$2012). This analysis does not estimate the annualized economic costs (based on the frequency of these events) or the cumulative discounted costs over the mid- and end-of-century time horizons. See Table 5 for a summary of the per-event travel time costs and vehicle operating costs.

¹⁷ Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, US DOT, June 2014, <http://www.dot.gov/sites/dot.gov/files/docs/USDOT%20VOT%20Guidance%202014.pdf>

¹⁸ National Household Travel Survey, U.S. DOT, 2009, http://nhts.ornl.gov/tables09/fatcat/2009/avo_TRPTRANS_WHYTRP1S.html

¹⁹ AAA; Your driving Costs, 2013

²⁰ It is likely that some share of vehicles that would normally travel on this segment of the Saw Mill River Parkway would not use the assumed detour route and could have a shorter or longer detour. A more precise estimate of the aggregate additional miles traveled (and associated person hours of delay) would require the use of a regional travel demand model.

²¹ Westchester County, Bee-Line System Map, <http://transportation.westchestergov.com/images/stories/pdfs/2014SysMapEng.pdf>

Table 5: Per-Event Economic Impacts for Flood Events

	Travel Time Costs (\$2012)	Vehicle Operating Costs (\$2012)	Total Costs (\$2012)
Moderate to heavy Rainstorm	\$25,874	\$7,142	\$33,016
Severe storm / Hurricane	\$78,853	\$21,765	\$100,618

5.3 EFFECT ON DISADVANTAGED POPULATIONS

The Parkway serves several jurisdictions between Yonkers (in the south) and White Plains (in the north); including some with more than 10 percent of the population below the poverty line (See Table 6 for a list of jurisdictions served by the Parkway along with statistics on their poverty levels).

Table 6: Poverty Statistics in Jurisdictions served by the Saw Mill River Parkway

Location	Percentage of the population below poverty level (%)
Yonkers	15.6
Dobbs Ferry Village	3.9
Elmsford Village	13.5
Hastings-on-Hudson Village	4.2
Irvington village	6.3
Mount Kisco Village	11.7
Pleasantville Village	1.5
Bedford Hills CDP	12.3
Hawthorne	4.3
Katonah	12.3
Thornwood	5.6

Source: U.S. Census 2008-2012

For disadvantaged populations with access to personal vehicle, the impacts of closure to the Parkway may be higher, as closure will result in additional time delays and costs. There are 17 block groups in the southern part of the City of Yonkers west of the Parkway in which between 23 and 38 percent of the population is below the poverty level. Furthermore, there are 11 block groups in the same vicinity in which between 38 and 58 percent of the population is below the poverty level. These block groups are located south of the Parkway segment evaluated in this assessment, and closure of the segment could impact reverse-commuters in these areas going north towards Tarrytown and White Plains, assuming they use the Parkway. However, closure would not impact commuters in these areas going south towards New York City.

Similarly, there is one block group in the southwestern part of Elmsford Village immediately east of the Parkway in which approximately 30 percent of the population is below the poverty level. This block group is located north of Parkway segment evaluated in this assessment, and commuters in this block group

going south towards New York City would be impacted if the segment is closed, assuming they use the Parkway.

Lastly, there is one block group in the southern part of Bedford Hills immediately east of the Parkway in which approximately 35 percent of the population is below the poverty level. This block group is located north of Parkway segment evaluated in this assessment, and commuters in this block group going south towards New York City could also be impacted if the segment is closed, assuming they use the Parkway.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

Strategies at three levels can be taken to manage and mitigate the impacts of riverine flooding on roadway facilities:

- Watershed-level (discussed in Section 6.1),
- Facility-level (Section 6.2), and
- Systemic updates to design guidelines (Section 6.3).

In this assessment, three specific adaptation strategies are reviewed using the criteria laid out in the engineering informed adaptation assessment process tested in this research effort:

- Installing asphalt ditches to improve drainage;
- Installing green infrastructure such as bioswales; and
- Adjusting design guidelines.

6.1 WATERSHED-LEVEL STRATEGIES

6.1.1 DEVELOPMENT OF A WATERSHED MASTER PLAN:

A Watershed Master Plan can be utilized to recognize issues with water conveyance within the Saw Mill River watershed and recommend strategies for flood mitigation. The first step in the watershed planning process is to identify areas of concern and key stakeholders, and set end-goals for improvements.

Next, data collection, including field surveys, are needed to analyze the causes and sources of flooding to be controlled. Detailed hydrologic and hydraulic models need to be developed as part of the data collection and analysis process. A hydrologic model will simulate the conversion of rainfall into surface runoff. The results of the model include inflow hydrographs that define inflow to the Saw Mill River at a particular location. These inflow hydrographs (supplemented by information collected in the field) are used as inputs for the hydraulic model to examine how the movement of the water is affected by natural characteristics of the river (e.g., topography, vegetation) and structures (e.g., bridges and culverts). The hydraulic model provides water surface elevations that can locate areas of flooding for particular storm events.

Next, a risk assessment has to be conducted to identify the broader consequences of flooding in the watershed, after which preliminary strategy alternatives are proposed based on previously set end-goals. The hydrologic and hydraulic model results will inform possible floodplain management alternatives for the watershed. For the Saw Mill River, the outcomes of such a planning process would be prioritized strategies to address storage capacity and structural improvements for the bridges and culverts (see Facility-Level Strategies below for more detail).

Once the strategies are finalized in the Master Plan, an implementation program can be designed, which would include an implementation schedule, a monitoring component, and technical and financial assistance needed to implement the Plan. As a next step after the development of the Master Plan, detailed design/feasibility studies for each proposed strategy including a cost benefit analysis could be conducted. Once the Master Plan is implemented, progress can be monitored and appropriate adjustments made. Westchester County has initiated a few watershed management plans in its jurisdiction which encourage green infrastructure and storage options, but this has not been proposed in plans for the Saw Mill River.

6.1.2 ENHANCEMENT OF FLOOD STORAGE CAPABILITIES

Another feasible strategy at the watershed level is to construct temporary floodwater storage facilities in the watershed to collect storm water and slowly release it at a controlled rate to prevent flooding and erosion downstream. A detention or retention basin can be utilized for this purpose, the main difference being whether or not it has a permanent pool of water, similar to a pond. The water level in the basin is set by the low flow orifice, typically part of a metal or concrete structure called a riser. With a detention basin, the orifice level is at the bottom of the basin, and therefore all the water is eventually drained from the basin and it remains dry between storms. The riser for a retention basin has an orifice at a higher elevation so that it retains a permanent pool of water. The elevation of the orifice in the riser is selected to release small amounts of water as needed to maintain the desired water level. It should be noted that while a detention or retention basin would be appropriate to mitigate the flows of local drainage entering the Saw Mill River, it may not be an adequate solution to mitigating flows during moderate or high intensity storms, which typically require significantly larger storage ponds. However, a review of the effective FEMA Flood Insurance Study and watershed patterns indicates that there is low potential to enhance existing storage capacity in ponds and swamps along the Saw Mill River and its major tributaries.

6.2 FACILITY-LEVEL STRATEGIES

6.2.1 RAISING OR RELOCATING THE ROADWAY

At the facility-level, one option is to raise the elevation of the roadway above flood elevations. While an expensive option, it would effectively remove roadway infrastructure from the floodplain, specifically downstream of Lawrence Street where the water surface elevations during specific storm events go over the bridge elevations, and flooding concerns are among the most significant along the different segments of the roadway.

Raising the roadway is an effective flood mitigation strategy; however, there are a number of considerations, including temporary and long term impacts to the surrounding areas. During construction, traffic would be disrupted as detours re-route motorists to the New York State Thruway, parallel parkways, and local roads.

In addition to raising the Saw Mill River Parkway, all access points to the roadway would need to be reconstructed to meet the parkway's new elevation. Bridges would need to be raised to maintain required vertical clearances and culverts would need to be enlarged. Existing utilities would need to be evaluated and possibly relocated or raised along with the roadway. These implications increase the cost associated with this strategy.

6.2.2 IMPROVEMENTS TO NETWORK-LEVEL ADAPTIVE CAPACITY

A second set of alternatives assumes that NYSDOT chooses not to raise or relocate the roadway (e.g., for environmental or historic preservation reasons) and instead pursues two complementary approaches. First, it would be assumed and accepted that the Saw Mill River Parkway would flood periodically. The most vulnerable river crossings and nearby segments of roadway would be made resilient to overtopping (short of raising the roadway), and embankments and other geotechnical structures in the area of flooding would be made resilient to erosion.

The second part of this strategy assumes that NYSDOT and the New York State Thruway Authority would make capital and operational improvements on alternative routes to accommodate detour traffic on days when the Saw Mill River is closed to traffic due to flooding. For example, northbound traffic historically has detoured to the Cross County Parkway at Exit 4 and then traveled east on the Cross County Parkway and north on the New York State Thruway to re-enter the Saw Mill River Parkway via Thruway Exit 8. Note that there is an opportunity to re-enter the Saw Mill River Parkway northbound at

Exit 7A, but often the section of the Parkway in Elmsford is closed to flooding when the section that is the focus of this analysis is flooded. US 9 (Broadway) is another detour route to the west, although it has significantly less excess capacity.

NYS DOT and the New York State Thruway Authority could install Variable Message Signs, make improvements to ramps and interchanges (particularly the Saw Mill River Parkway/Cross County and Cross County/Thruway interchanges), allow shoulder use, waive tolls at the Ardsley Plaza (or increase them, if demand management is a goal), retime signals on US 9 and connecting routes, coordinate with the New York Metropolitan Transportation Authority (MTA) and Bee Line Bus to encourage use of the Metro-North Railroad (e.g., via free shuttles to Metro-North stations), and use other measures to accommodate flows of people and freight on days when the Saw Mill is closed due to flooding.

6.2.3 DRAINAGE IMPROVEMENTS

Alternatives to raising or relocating the roadway include:

- Replacing undersized culverts with larger ones;
- Installing asphalt ditches to improve drainage;
- Installing green infrastructure such as bioswales; and
- More frequent maintenance of these structures to prevent debris accumulation.

These alternatives will help to improve river conveyance. The identification of appropriate strategies can be informed by a facility-level risk assessment using the effective FEMA Flood Insurance Study Profiles for the Saw Mill River. The Flood Profiles can help with the identification of undersized culverts, channel obstructions and abrupt changes in flood elevation, all of which can cause flooding at specific locations.

Appendices A.1 and A.2 shows the Saw Mill River's Flood Profiles in the vicinity of Dobbs Ferry, NY, highlighting factors that contribute to flooding. Flood Profiles illustrate the water surface elevation for various storm events with culvert and bridge crossings plotted along the river profile. Bridges are indicated with an "I" shaped symbol to represent the distance from the bridge's lowest structural component to the top of the roadway. Inadequate bridge openings for a storm event can be identified where the flood elevation is above the bottom of the bridge, causing floodwaters to pond upstream of the crossing. The flood elevation relative to the top of roadway elevation will indicate if the roadway will be inundated with water.

Undersized culverts can be identified where there is a back-up of floodwaters upstream. If all of the floodwater can flow through a culvert or under a bridge without backing up, the river profile would not have an appreciable change at that location.

The storm drainage system on the Saw Mill River Parkway uses a design that was commonly used for roadways of the same era, but is not commonly used in the new construction of roadways today. The design of the Parkway's drainage system utilizes curb openings to drain water to unpaved, grass shoulders behind the Parkway's 4-inch mountable curb. Due to maintenance challenges, compounded with the Parkway's flat longitudinal slope (grade or incline), these grass ditches are not effectively carrying the water away from the Parkway. The existing ditches could to be reshaped to facilitate the flow of stormwater. When the grass is overgrown and the ground is saturated from heavy rain, the ground's infiltration rate decreases. The curb openings get blocked with debris and the rainwater ponds, flooding the Parkway. An existing curb opening on the Saw Mill River Parkway in need of maintenance is shown in Figure 7.

Figure 7: Overgrown grass and debris at a curb opening on Saw Mill River Parkway



Source: Google maps

6.2.3.1 ASPHALT DITCHES

This adaptation strategy proposes that asphalt paved ditches replace the unpaved shoulders to more effectively move stormwater away from the Parkway (See Figure 8). At this location, natural ditches cannot take the rainwater off the Parkway fast enough during moderate to heavy rainstorms. Asphalt paved ditches increase the velocity and capacity of the ditch. The lack of maintenance for the existing grass ditches and build-up of debris at the curb openings has become a major problem, both of which would be improved with paved ditches (which generally require less maintenance).

In addition to providing paved ditches, due to the projected increase in the frequency and magnitude of precipitation events of various return periods, this adaptation strategy also proposes additional curb openings to get the water off the Parkway and into the ditches faster.

A cross roadway drainage system should be constructed to carry water from the roadside ditches to the adjacent Saw Mill River to be discharged. Cross roadway drainage pipes will carry the stormwater accumulating in the roadside ditches to discharge in the Saw Mill River to avoid overtopping the ditch and flooding the Parkway. Since the topography of the Parkway is flat, the ditches and pipes of the drainage system will be flat. If the minimum velocity recommended for prevention of sediment deposition cannot be achieved in the pipes (3 feet per second), they will not be self-cleaning, requiring maintenance to remove the build-up of debris. This proposed adaptation strategy is the same for both 2050 and 2080 scenarios. There will be a difference in the design specifications for the two scenarios (e.g., in terms of number of inlets, width of ditch etc.) but the rainfall intensity patterns indicate that an exponential change in the design is unlikely. These specifications can be determined once calculations for a conceptual design have been carried out.

According to Chapter 8 of the NYSDOT Highway Design Manual, highway storm drain systems should have a design life and anticipated service life equal to 70 years. Therefore, a conservative (low-risk) approach points to the 2080 horizon as the optimal planning scenario for future improvements to the existing drainage system along the Saw Mill River Parkway.

Figure 8: An example paved ditch to convey stormwater to an outfall location



Source: [Google maps](#)

Asphalt paved ditches have little potential for erosion, thereby reducing maintenance required for surrounding areas as compared to the existing vegetated ditches, which require more frequent maintenance (e.g., mowing and periodic cleaning). However, they do require periodic crack sealing and must be kept clean of sediment and debris to avoid becoming a vegetated ditch. Central maintenance specifications will not need to be updated to implement this design recommendation.

Economic Analysis

This strategy could potentially prevent adverse impacts on mobility and the economy from disruptions to the Parkway, which would otherwise occur during moderate to heavy rainstorms. If this strategy were to be implemented, the per-event avoided costs from moderate to heavy rainstorms are as follows:

	Travel Time Costs (\$2012)	Vehicle Operating Costs (\$2012)	Total Costs (\$2012)
Moderate to heavy Rainstorm	\$25,874	\$7,142	\$33,016

Considering these per-event costs of moderate to heavy rainstorms impacting the Parkway segment, and the annual frequency of these storms, the cumulative avoided costs as a result of implementing this strategy are significant when compared with the estimated costs of implementing this strategy, which are less than \$1 Million, as discussed in detail in Section 6.1.4. Thus, it can be concluded that the economic benefits (i.e., avoided costs) of this strategy considerably outweigh the net present value of costs of implementing this strategy.

Environmental Analysis

The proposed drainage system with asphalt ditches could have an environmental impact at the outlet, depending on where the system discharges. The system must meet stormwater quality regulations, and coordination would be required with the New York State Department of Environmental Conservation to obtain the necessary water quality certification. Pollutants can enter the ditch along with stormwater;

therefore, the water would need to be treated before it can be discharged into the Saw Mill River. The proposed drainage system would need a stormwater quality treatment device. It should be noted that in theory, the existing drainage system at the Parkway has an inherent pollutant removal ability (fewer pollutants enter the Saw Mill River because a portion of the stormwater infiltrates into the ground while in the grass ditches before discharging to the river). However, this ability is likely hampered due to the lack of maintenance at the site. When the grass is overgrown and the ground is saturated from heavy rain, the ground's infiltration rate decreases. Therefore, it is concluded that the existing drainage system is not likely to provide significant pollutant removal benefits compared to the proposed system.

The proposed drainage system would also need to meet other stormwater management requirements related to the volume of discharge. The proposed system will increase the paved (impervious) area, thereby increasing the volume of discharge into the river.

In addition, it should be noted that land along the Parkway (adjacent to the vegetated ditches) is designated as parkland and is under the jurisdiction of the New York's State Historic Preservation Office (SHPO). According to SHPO's Environmental Review Program, projects adjacent to NY State parkland should coordinate with the Environmental Management Bureau for approval.

Equity Analysis

This strategy could potentially prevent adverse equity-related impacts from disruptions to the Parkway (see Section 5.3), which would otherwise occur. In the absence of this strategy, a detour route must be used by disadvantaged populations when the Parkway is closed due to flooding. As a result of the implementation of this strategy, the mobility of disadvantaged populations would not be disrupted.

Cost Analysis

The cost analysis for this strategy is based on a high planning-level design and only includes capital costs. If this strategy moves forward to the concept design phase, a more refined cost analysis would need to be conducted in parallel with a more detailed drainage needs assessment based on the specific conveyance needs associated with rainfall intensities for a 10-year design storm. Additionally, it is recommended that future assessments include a lifecycle cost analysis to enable a more complete comparison of no action and adaptation alternatives. For this high planning-level design, there was assumed to be no difference in cost for solutions designed for the 2050 or 2080 scenarios.

The cost analysis for this strategy estimates that it will cost approximately \$800,000 to construct the recommended drainage design improvements utilizing asphalt paved ditches along the 0.2 mile segment of the Parkway (See Table 7). This total cost includes \$350,000 of construction costs.

Table 7: Cost Analysis for Asphalt Ditches

Cost Component	Cost (\$)
Construction Costs:	
- Excavation: 788 CY x \$45/CY = \$35,460	
- Drainage Inlets: 6 inlets x \$4,000/inlet = \$24,000	
- Roadway Crossing Pipes: 3 pipes x 55'/pipe x \$110/ft. =18,150	
- Asphalt for paved gutters: 8,008 CF x 0.075 Ton/CF x \$200/Ton = \$120,120	
- Pavement Restoration at Pipe Crossings:	
CLSM: 260 CY x \$240/CY = \$62,400	
Asphalt: 195 CF x 0.075 Ton/CF x \$200/Ton = \$3,000	
- Restore Curb, Guiderail, Median at Pipe Crossings:	
Curb: 60 LF x \$55/LF = \$3,300	
Guiderail: 30 LF x \$46/LF = \$1,380	
Median: 3 CY x \$1,150/CY = \$3,450	
- Oil-Water Separator: 1 EA x \$40,000/EA	
- 10% Contingency = \$31,126	
Total Construction Cost (Rounded)	\$350,000
Survey Stake-Out (2% of total construction cost)	\$7,000
Engineering Cost (13% of total construction cost)	\$45,500
Escalation (4% for 5 Years)	\$80,500
Maintenance and Protection of Traffic (MPT)	\$300,000
Total Cost (Rounded)	\$800,000

Source: The construction costs were calculated with unit prices based on the New York State Department of Transportation Pay Item Catalog (PIC), which includes regional and statewide average awarded price history as soon as a project has been awarded.

Timing for Implementation

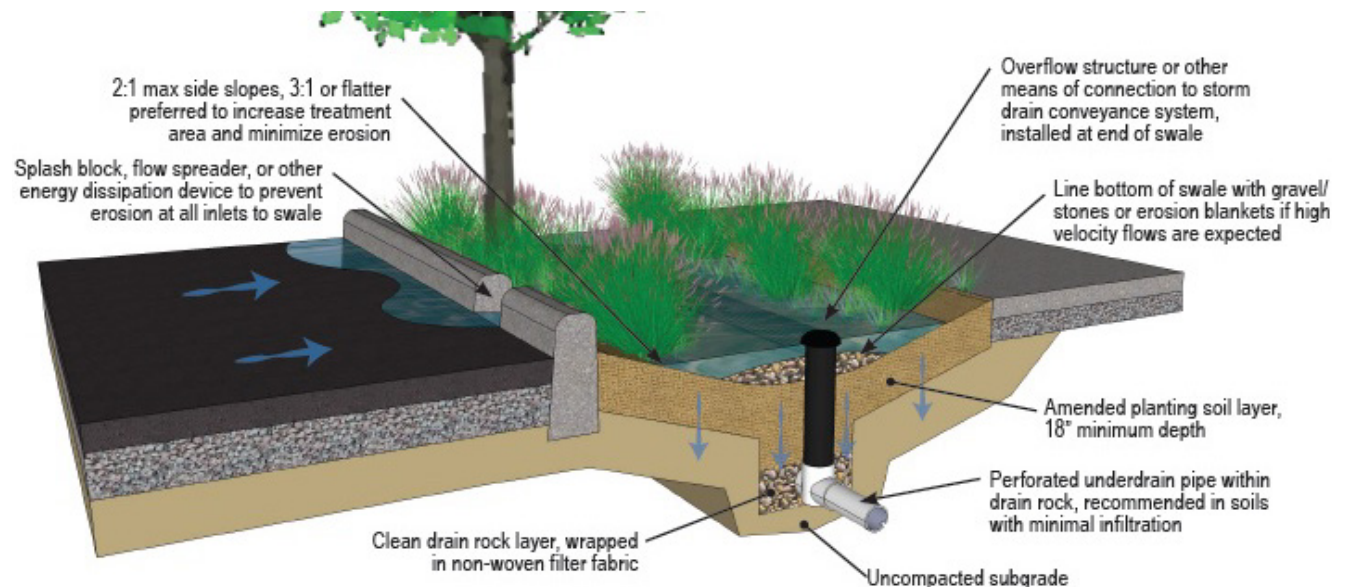
It is estimated that construction of the asphalt ditches would take approximately six months; however, the design process and permit application process must take place prior to construction and could take several years depending on the agency’s ability to find the funding, and carry out the design process. The estimated time for the implementation of this strategy from design and permitting to construction is approximately five years.

6.2.3.2 IMPROVEMENTS TO DRAINAGE VIA GREEN INFRASTRUCTURE (BIOSWALES)

This adaptation strategy is an alternative to the adaptation strategy on asphalt ditches described above. This strategy recommends that instead of asphalt ditches, bioswales replace the existing unpaved shoulders to move stormwater away from the Parkway. A bioswale is an engineered vegetated system that uses specific soil and plant configurations to infiltrate stormwater runoff and remove sediments and other pollutants while still providing flow conveyance. This system can provide the same flow capacity as an asphalt swale for flood events, while also providing ancillary benefits such as attenuating the peak flow through infiltration and storage in the soil, providing an aesthetic amenity, and improving water quality in downstream receiving waters. If a roadway’s longitudinal slopes are not steep enough to maintain the desired flow velocities for debris removal, a bioswale may work in conjunction with asphalt ditches in series, or an underdrain system may be installed as shown in Figure 9. Additional features such as forebays and check dams with bypasses can be installed to manage trash and debris without compromising flow capacities. Bioswales generally have higher capital costs and require more

maintenance than asphalt ditches as they need to be cleared of debris and periodically landscaped. However, however the multiple benefits often provide an adequate return on investment if funds are available (see Section 5.2.2 for more details on the environmental benefits of this strategy). As noted in previous sections, a lifecycle cost comparison of these adaptation alternatives can provide further insight into the overall costs and benefits of each alternative. Design calculations need to be done to make sure this option is effective enough to solve the drainage issue.

Figure 9: A technical detail of an engineered bioswale used to convey, infiltrate and treat stormwater



Source: AECOM, 2014

Economic Analysis

This strategy could potentially prevent adverse impacts on mobility and the economy from disruptions to the Parkway, which would otherwise occur during moderate to heavy rainstorms. It is assumed that this strategy can prevent the same adverse mobility-related and economic impacts, as the ones that can potentially be prevented by the strategy which proposes improvements to the drainage system via asphalt ditches.

As part of the additional analysis required to evaluate this green infrastructure alternative, the monetized benefits associated with the potential for reduced stormwater treatment costs and improved water quality could be considered to determine if the additional benefits would exceed the additional lifecycle costs of the investment.

Considering the per-event costs of moderate to heavy rainstorms impacting the Parkway segment, and the annual frequency of these storms, the cumulative avoided costs as a result of implementing this strategy are significant when compared with the estimated costs of implementing this strategy, which are approximately \$1.7 Million, as discussed in detail in Section 6.2.4. Thus, it can be concluded that the economic benefits (i.e., avoided costs) of this strategy considerably outweigh the net present value of costs of implementing this strategy.

Environmental Analysis

The drainage system proposed in this strategy would have a lower environmental impact at the outlet compared to conventional systems, as stormwater runoff pollutants would be treated through bioswales, which would remove sediments, reduce nutrient loading and attenuate peak flow conditions from small storms, therefore reducing erosion at the outfalls. The proposed drainage system would not need stormwater quality treatment devices prior to discharging to the Saw Mill River.

The proposed drainage system would also meet stormwater management requirements as the proposed design does not increase the amount of paved (impervious) area, which means the volume of water being discharged is either the same or less than the volume being discharged under current conditions.

It should be noted that land along the Parkway (adjacent to the vegetated ditches) is designated as parkland and is under the jurisdiction of the New York's State Historic Preservation Office (SHPO). According to SHPO's Environmental Review Program, projects adjacent to NY State parkland should coordinate with the Environmental Management Bureau for approval.

Equity Analysis

This strategy could potentially prevent adverse equity-related impacts from disruptions to the Parkway (see Section 5.3), which would otherwise occur. In the absence of this strategy, a detour route must be used by disadvantaged populations when the Parkway is closed due to flooding. As a result of the implementation of this strategy, the mobility of disadvantaged populations would not be disrupted.

Cost Analysis

The cost analysis for this strategy is based on a high planning-level design and only includes capital costs. If this strategy moves forward to the concept design phase, a more refined cost analysis would need to be conducted in parallel with a more detailed drainage needs assessment based on the specific conveyance needs associated with rainfall intensities for a 10-year design storm. Additionally, it is recommended that future assessments include a lifecycle cost analysis to enable a more complete comparison of no action and adaptation alternatives. For this high planning-level design, there was assumed to be no difference in cost for solutions designed for the 2050 or 2080 scenarios.

The bulk of the costs for this strategy are associated with the static elements of the construction (inlets, excavation, trenching, etc.). The costs that would change due to higher rainfall intensity for this relatively small tributary area would be capacity-related (i.e. pipe sizes, width of ditch, underdrain.) These incremental cost increases would most likely be insignificant relative to the static costs. The cost of pipes of various sizes is generally linear until certain size thresholds are met, and given the projected increase in rainfall intensity, it is not expected that these thresholds will be crossed.

It will cost approximately \$1.7 Million²² to construct the recommended drainage design improvements utilizing bioswales along the 0.2 mile Parkway segment (See Table 8). This total cost includes approximately \$790,000 of construction costs.

²² A conservative approach has been applied in estimating this cost.

Table 8: Cost Analysis for Bioswale

Cost Component	Cost (\$)
Construction Costs:	
- Drainage Inlets = \$24,000	
- Roadway Crossing Pipes = \$18,150	
- Bioswale Const. based on LF (SF bid cost) = 792,000	
- Pavement Restoration at Pipe Crossings = \$65,400	
- Restore Curb, Guiderail, Median at Pipe Crossings = \$8,130	
- 10% Contingency = \$90,768	\$1,000,000
Total Construction Cost (Rounded)	
Survey Stake-Out (2% of total construction cost)	\$20,000
Engineering Cost (13% of total construction cost)	\$130,000
Escalation (4% for 5 Years)	\$217,000
Maintenance and Protection of Traffic (MPT)	\$300,000
Total Cost (Rounded)	\$1.7 Million

Source: The construction costs were calculated with unit prices based on the New York State Department of Transportation Pay Item Catalog (PIC), which includes regional and statewide average awarded price history as soon as a project has been awarded.

Timing for Implementation

It is estimated that construction of the asphalt ditches would take approximately six months; however, the design process and permit application process must take place prior to construction and could take several years depending on the agency’s ability to find the funding, and carry out the design process. The estimated time for the implementation of this strategy from design and permitting to construction is approximately five years.

6.3 UPDATED DESIGN GUIDELINES

Recognizing that the entire Parkway as well as other similar roadways in Westchester County may be vulnerable to an increase in the frequency and magnitude of precipitation events of various return periods in the future, this assessment also proposes that drainage design guidelines be updated to account for the projected changes to extreme precipitation patterns. These guidelines can be applied to all new construction and updates to existing drainage systems on State- and locally-maintained roadways in Westchester County.

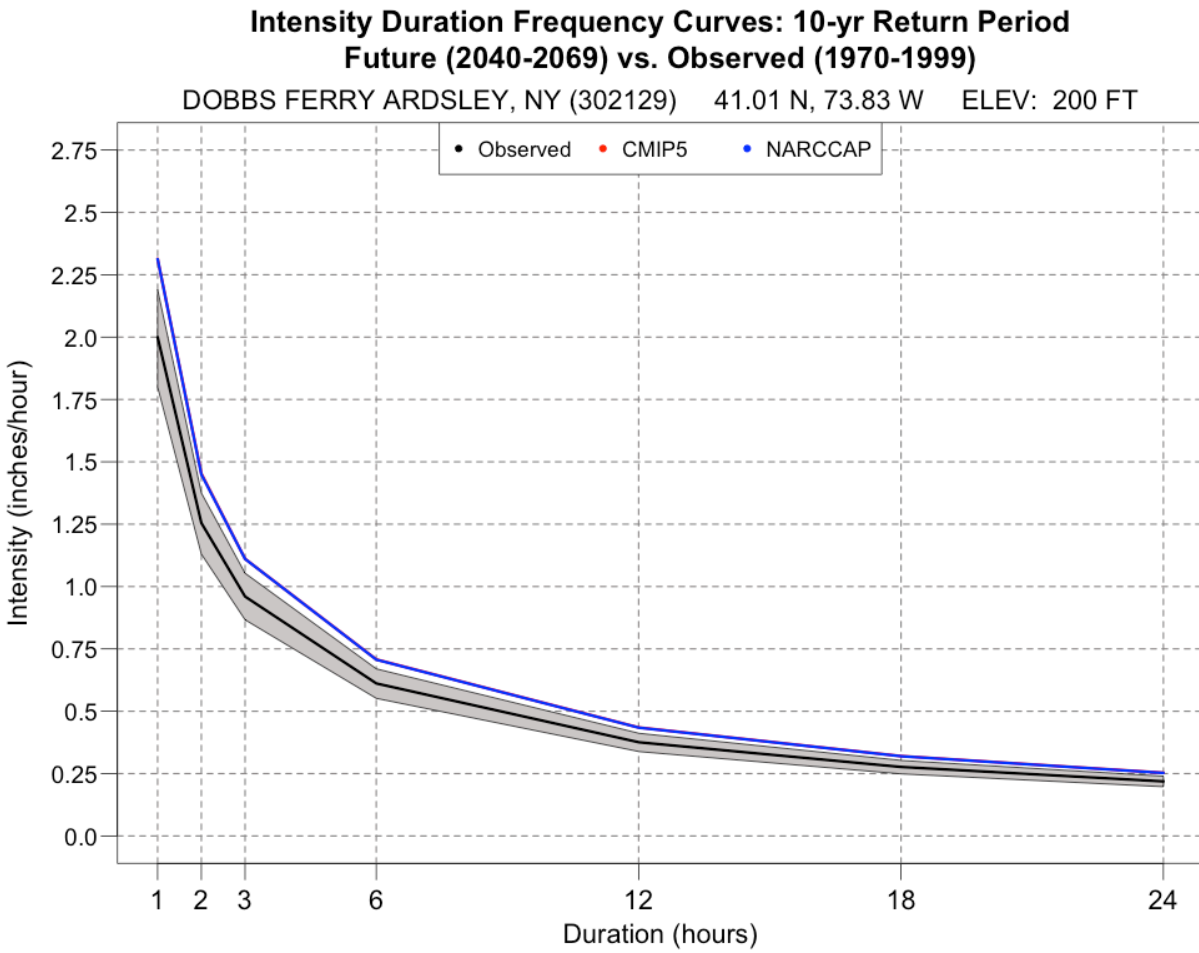
Chapter 8 of the NYSDOT Highway Design Manual specifies that highway storm drain systems should have a design life and anticipated service life equal to 70 years. Therefore, a conservative (low-risk) approach would be to update current design guidelines to reflect end-of-century projections.

The proposed updates to the drainage design guidelines would most likely increase the number of drainage structures needed at a particular location in comparison with the number of existing structures. The maintenance requirements would be the same as existing requirements; however, there would be more structures to clean and maintain.

To inform updates to design guidelines, an updated Intensity Duration Frequency (IDF) curve can be used to reflect the increase in annual precipitation projected for mid-century or end-of-century. Chapter 8 of the NYSDOT Highway Design Manual specifies that storm drainage systems on interstates and other freeways be designed for a 10-year storm frequency, with locations at sag vertical curves designed for a 50-year storm frequency. By using an updated IDF curve, 10- and 50-year design storms, as specified in the current Highway Design Manual, can continue to be used to provide an adequate number of drainage structures to accommodate end-of-century projections.

As mentioned in Section 2, the NRCC at Cornell University has developed projections for the increase in the magnitude and frequency of precipitation events at the Dobbs Ferry, NY location, using NARCCAP and CMIP5 simulations. As part of this work, the NRCC has developed updated IDF curves for events of various return periods. These IDF curves can be used to inform the process of updating drainage design guidelines. See Figure 10 and Figure 11 for the IDF curves for precipitation events of 10- and 50-year return periods. Sub-hourly rainfall intensities would need to be extrapolated from the future IDF curves according to best engineering judgement.

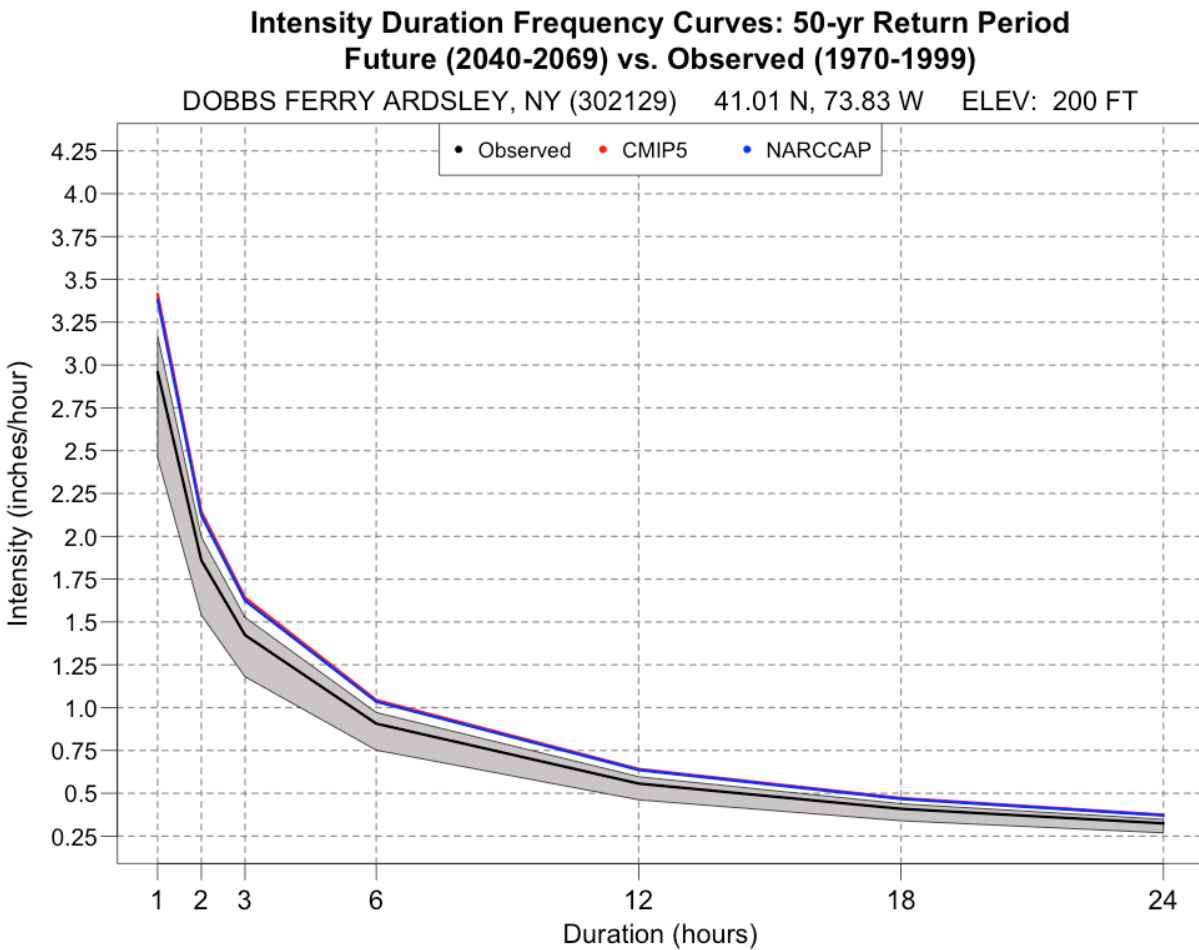
Figure 10: Historical and Future IDF Curve for 10-Year Return Period



Source: Northeast Regional Climate Center, Cornell University

Note: The gray shaded region on the figures indicates the 90th percent confidence interval of the historical rainfall intensities.

Figure 11: Historical and Future IDF Curve for 50-Year Return Period



Source: Northeast Regional Climate Center, Cornell University

Note: The gray shaded region on the figures indicates the 90th percent confidence interval of the historical rainfall intensities.

Economic Analysis

Given that this strategy recommends modifying drainage design guidelines, this strategy is only applicable to future drainage systems or existing systems subject to significant modification. While this strategy can lead to enhanced drainage systems in the future, it is assumed in this analysis, that this strategy will not have direct economic, environmental, or equity-related impacts on the Parkway. However, it should be noted that this strategy can potentially influence physical drainage improvement strategies in the future, which would result in broader economic, environmental, or equity-related impacts.

Environmental Analysis

Not applicable (See Section 5.3.1)

Equity Analysis

Not applicable (See Section 5.3.1)

Cost Analysis

The cost of updating design guidelines is assumed to be approximately \$500,000.²³ This cost includes the cost of conducting a background study and following other NYSDOT procedures for updating design guidelines.

Timing for Implementation

Preliminary research to inform the implementation of this strategy can be initiated in the near term (0 – 3 years), by building upon existing research. The entire Saw Mill River Parkway currently experiences regular flooding during precipitation events of various return periods. Climate projections indicate an increase in the frequency and magnitude of these precipitation events, and are likely to impact other similar roadways in the County and State. Updates to drainage design guidelines could be considered in the short term, particularly if major capital improvements to drainage systems in the state are planned in the near future.

7. CONCLUSION

This assessment identified existing and projected vulnerabilities of a 0.2 mile segment of the Saw Mill River Parkway to moderate to heavy rainstorms. The Parkway segment experiences flooding due to the inadequate capacity of its drainage system to divert rainwater, and also due to additional floodwater overflows from the adjacent Saw Mill River.

There are numerous considerations when evaluating alternatives to mitigate flooding. Prior to selecting an alternative, it is important to analyze impacts to both upstream and downstream floodplains. For example, when there is a blockage in the river, water is not effectively transported and is stored upstream of the blockage, resulting in reduced downstream flows. When the blockage is cleared, the downstream flows will increase, possibly causing flooding issues. In this case, instead of fixing the problem, the issue is moved downstream and will need to be resolved at a different location.

Once the optimal alternative is selected, potential challenges remain. State and Federal permits are required when working within floodplains. Proposed changes within the Saw Mill River floodplain would require a Floodplain Evaluation Report to be prepared and submitted to NYSDOT. A New York State Department of Environmental Conservation (NYSDEC)/US Army Corps of Engineers (USACE) Joint Application Form for a wetland permit must be approved. A NYSDEC Protection of Waters Permit for disturbance (temporary or permanent) to the bed or banks of a stream is required. The proposed project must also be submitted to FEMA and upon review, FEMA may issue a Conditional Letter of Map Revision (CLOMR)²⁴ and/or Letter of Map Revision (LOMR)²⁵. With possible environmental, wetland and stream impacts, the selected flooding mitigation alternative must meet State, Federal and County requirements. Lead time must be factored into the project schedule for the permitting process to be completed prior to construction.

²³ This amount was estimated by the project team under the assumption that NYSDOT may need to conduct studies prior to initiating the process of updating design guidelines, and then following the process.

²⁴ “A Conditional Letter of Map Revision (CLOMR) is FEMA’s comment on a proposed project that would, upon construction, affect the hydrologic or hydraulic characteristics of a flooding source and thus result in the modification of the existing regulatory floodway, the effective Base Flood Elevations (BFEs), or the Special Flood Hazard Area (SFHA). The letter does not revise an effective NFIP map, it indicates whether the project, if built as proposed, would be recognized by FEMA.” (www.fema.gov).

²⁵ “A Letter of Map Revision (LOMR) is FEMA’s modification to an effective Flood Insurance Rate Map (FIRM), or Flood Boundary and Floodway Map (FBFM), or both.” (www.fema.gov).

A watershed can be large; therefore, the proposed improvement (if at the watershed scale) may affect multiple towns. Public outreach and coordination will need to be performed and all towns will be involved in the decision making process. Stakeholders should be engaged at the beginning of the project's planning process. Without stakeholder involvement, critical information regarding the project may be missed and once obtained, may require rework, adding to the cost of the project and delaying its advancement. Another task to be completed at the beginning of the project is land acquisition. A combination of public and private land may need to be acquired for the project. This process can be further complicated with impacts to historic and cultural resources. New York's State Historic Preservation Office (SHPO) helps to identify and preserve historic, archeological, and cultural resources. If applicable, SHPO's role in the project review process would be to ensure that the impacts to eligible properties are considered and avoided or mitigated during the project planning process.

This assessment highlights the key causes of riverine flooding and corresponding flood mitigation solutions for the Saw Mill River Parkway corridor. Causes of flooding include intense precipitation events, inadequate storage capacity in the Saw Mill River channel, characteristics unique to the Saw Mill River watershed, lack of maintenance of the channel, undersized roadway bridges across the channel, and development trends in the river floodplain, such as the location and elevation of the Saw Mill River Parkway.

This analysis proposes solutions at the watershed and facility scales, as well as updates to design guidelines, to address the causes of flooding. Watershed-scale solutions include the development of a watershed master plan and enhancement of flood storage capacity. Facility scale solutions include structural improvements to the roadway, improvements to network level adaptive capacity, and drainage system improvements coupled with regular maintenance to remove debris.



U.S. Department of Transportation
Federal Highway Administration

Post-Hurricane Sandy Transportation Resilience Study of NY, NJ, and CT –

Yellow Mill Channel Bridge Engineering Informed Adaptation Assessment

YELLOW MILL DRAWBRIDGE, (CT 130 OVER YELLOW MILL CHANNEL), BRIDGEPORT, CT

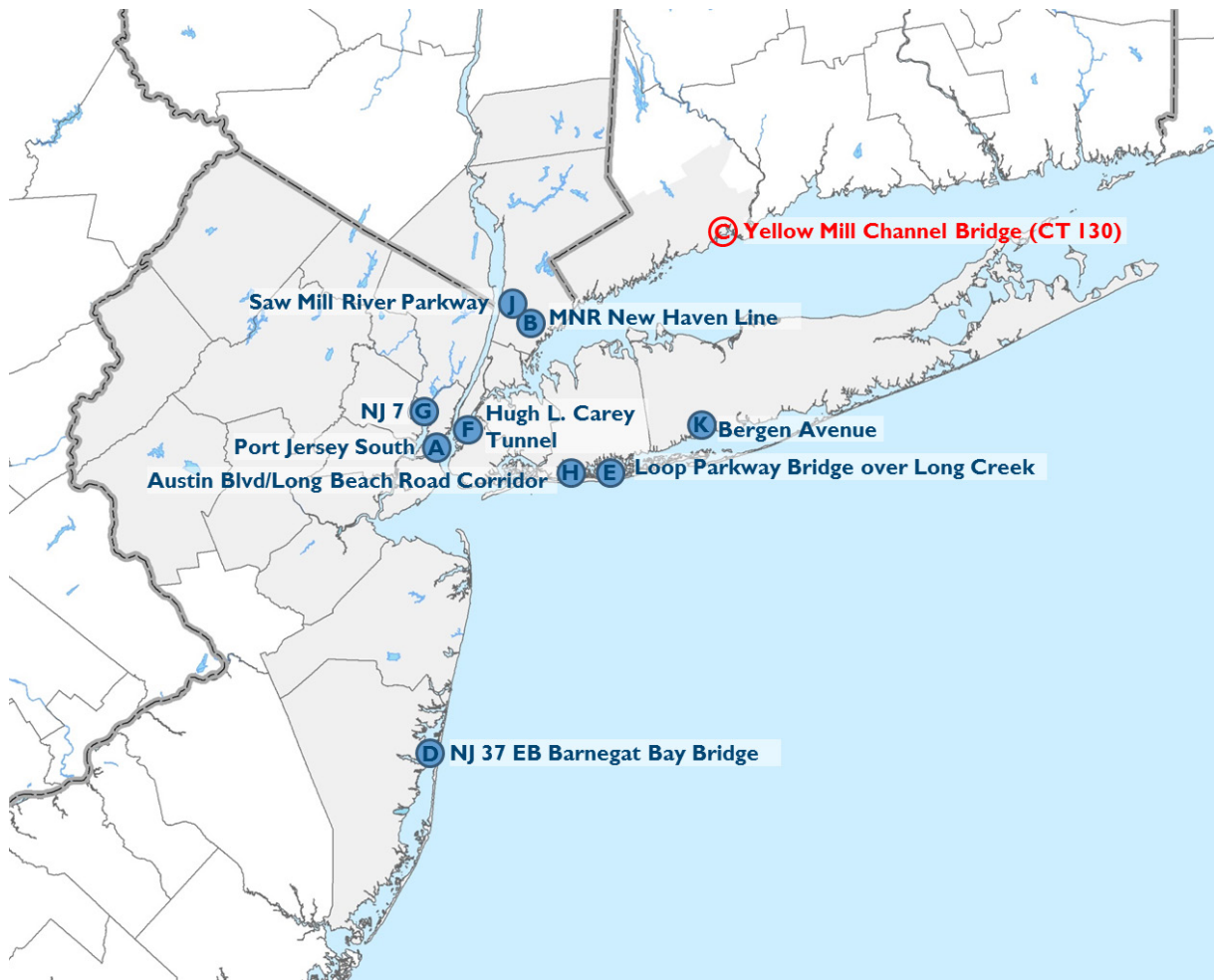
1. INTRODUCTION

In late 2013, the Federal Highway Administration (FHWA) launched a study to improve the resilience of the transportation system in the New York-New Jersey-Connecticut region to climate change and extreme weather events. FHWA partnered with State Departments of Transportation and local transportation agencies to understand the lessons learned from Hurricanes Sandy and Irene and develop feasible, cost-effective strategies to address the vulnerabilities of transportation assets to the projected impacts of climate change.

The Yellow Mill Drawbridge on Connecticut Route 130 (CT 130) is one of ten facilities selected for an engineering-informed adaptation assessment. See Figure 1 for a context map of all 10 study areas. The CT 130 study area is highlighted in red.

In this early stage of transportation engineering study and analysis related to extreme weather events and climate, sharing lessons learned is a proven way to expand a transportation agency's ability to address these risks. However, it is important for practitioners to remember that every facility and location is unique. The engineering informed adaptation assessments conducted for the Post-Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT, focus on specific facilities in specific locations, and each of the assessments acknowledges and accounts for the local aspects of the assets. In addition, these engineering informed assessments were conducted as part of a research study with limited resources and, in many cases, additional study and analysis would be required to fully assess the set of options for addressing the vulnerabilities identified through the assessment. Practitioners should exercise care in applying the lessons learned directly to these and any other facilities.

Figure 1: Context Map for Ten FHWA Study Areas (Yellow Mill Drawbridge on CT 130 in Red)



2. FACILITY DESCRIPTION

The Yellow Mill Drawbridge over Yellow Mill Channel is owned and maintained by the Connecticut Department of Transportation (CTDOT). The bridge is a part of Connecticut Route 130 (CT 130), which runs from the Town of Fairfield, CT in the west to the Town of Stratford, CT in the east. The bridge is a twin double-leaf bascule bridge and was built in 1926. The bridge spans a navigable waterway and carries two lanes of traffic in each direction along CT 130 (Stratford Avenue) (see Figure 2 and Figure 3).

Recent storms (including Hurricane Sandy and Hurricane Irene) flooded the bridge's mechanical pits and damaged the electrical and mechanical equipment. Given its past exposure to storm events, and anticipated exposure to future sea level rise (SLR) and storm surge, an assessment of potential climate change vulnerabilities and risks was performed. This assessment focuses on the mechanical pits and electrical rooms of the bridge.

The overall facility (including components such as the bridge structure, pits, and piers) is nearly 90 years old and was rehabilitated in 1998. It is a four-span bridge comprising a steel girder-floor beam-stringer double-leaf bascule main span and pre-stressed concrete box beam approach spans composite with a

reinforced concrete deck. The main span is made of four mechanically independent leaves. Each leaf supports two lanes of vehicular traffic, a breakdown lane, and a sidewalk adjacent to the roadway. The superstructure is supported by reinforced concrete and stone masonry abutments and piers. The curb-to-curb roadway width is 60 feet, and the overall length of the bridge is 340 feet.

Mechanical equipment is housed in mechanical pits located within each pier on the bridge. The span drive operating machinery for each bascule leaf is mounted on the movable leaf below the roadway level. Each of the four (4) leaves has its own (identical) span drive machinery, which consists of a main motor, an auxiliary drive, a machinery brake, and tail lock machinery.¹ The machinery systems for each of the four leaves are fully independent.

The bridge has two facility and equipment rooms (electrical rooms) located on the southeast and southwest sides of the bridge. These rooms contain the electrical power and control equipment to operate the bascule leaves. The southwest electrical room also contains a standby 150-kilowatt (kW) generator. Pedestrian access to the electrical rooms is at deck level; however, there is a lower level on which the generator is located. As part of the rehabilitation in 1998, the superstructure, mechanical sub-systems, and electrical sub-systems were replaced.² The bridge superstructure, the mechanical equipment, and the electrical equipment each have a current rating of 'fair' and the substructure has a current rating of 'satisfactory' as per the CTDOT bridge rating system.

The mean higher-high water (MHHW) elevation at the nearby Bridgeport, CT tide gauge is 3.48 feet NAVD88.³ The bridge's low steel elevation is 13.72 feet NAVD88. Based on these elevations, the project team estimates that the bridge has a closed maximum vertical clearance of approximately 10.2⁴ feet above MHHW where the bascule leaves meet.⁵ The approximate deck elevation at the piers is 17.98 feet NAVD88⁶ and the entry point into the mechanical pits is at an approximate elevation of 5.51 feet NAVD88.⁷ The lower-level (generator-level) elevation is approximately 9.50 feet NAVD88.⁸

The Yellow Mill Drawbridge has an Annual Average Daily Traffic (AADT) of approximately 16,000 and an Annual Average Daily Truck Traffic (AADTT) of nearly 500 (3% of AADT). The bridge rises to provide water-based access to and from the Yellow Mill Channel. The waterway is traversed mostly by recreational vessels, including sail boats, cruisers, and pleasure boats, but also periodically by harbor master and local police boats. The Bridgeport Harbor Management Plan⁹ (2006) cites O&G Industries as a water-dependent use, but multiple inquiries produced no confirmation of current commercial traffic through this passageway. The channel provides direct access to local marine support services and boat slips located to the north.

During the summer months, the bridge is opened up to 4 times per week (an average of 48 times from May through August, the peak season). The bridge operator towers are currently unmanned, so vessels are required to request a remote-raising of the bridge at least 24 hours in advance. In the future, the

¹ The main motors are 40 horsepower, 900 revolutions per minute (RPM) wound rotor type AC induction motors. Speed control of each main drive motor is accomplished via a thyristor drive system. Auxiliary power is obtained from 2-speed electric gear motor rated 7.5 horsepower at 900 RPM and 15 horsepower at 1800 RPM. Span breaking for each leaf is provided by two brakes of the electro-hydraulic thruster power-release, spring-set drum type, with one on the drive shaft and one on an extension shaft. Source: Bridge No. 03637 - 2013 Routine Mechanical Bridge Inspection Report.

² Bridge No. 03637 - 2013 Routine Bridge Inspection Report.

³ <http://tidesandcurrents.noaa.gov/datums.html?id=8467150>.

⁴ For additional reference, NOAA Chart 12369, panel 6, indicates a vertical clearance of 11 feet.

⁵ According to the National Bridge Inventory, the **minimum** vertical clearance is approximately 4.9 feet, although the applicable datum from which this measurement extends is not specified.

⁶ Rehabilitation of Stratford Avenue Bridge over Yellow Mill Channel dated 1994, Sheet No. S28 of S70

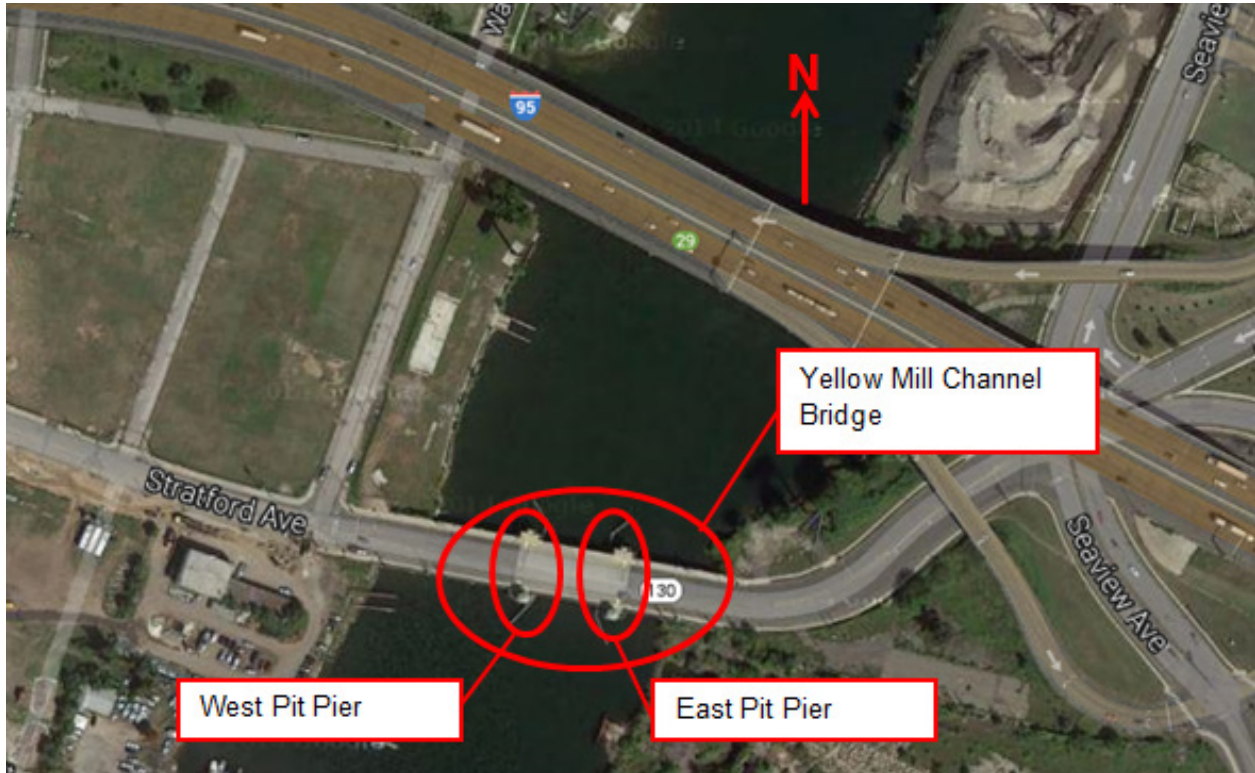
⁷ Rehabilitation of Stratford Avenue Bridge over Yellow Mill Channel dated 1994, Sheet No. S27 of S70

⁸ Rehabilitation of Stratford Avenue Bridge over Yellow Mill Channel dated 1994, Sheet No. A9 of A11

⁹ <http://www.bridgeportct.gov/filestorage/89019/89753/95286/103729/TheHarborManagementPlanDecember2009.pdf>

bridge may be manned 24 hours/day¹⁰ due to the Steelpointe Harbor Development project, a proposed 2.8 million square foot mixed-use waterfront development located near the bridge, which includes a new marina.¹¹ Although current vessel traffic is believed to be primarily recreational, the U.S. Coast Guard has a strong desire to keep the bridge operational at all times.¹⁰

Figure 2: Yellow Mill Drawbridge Location Map

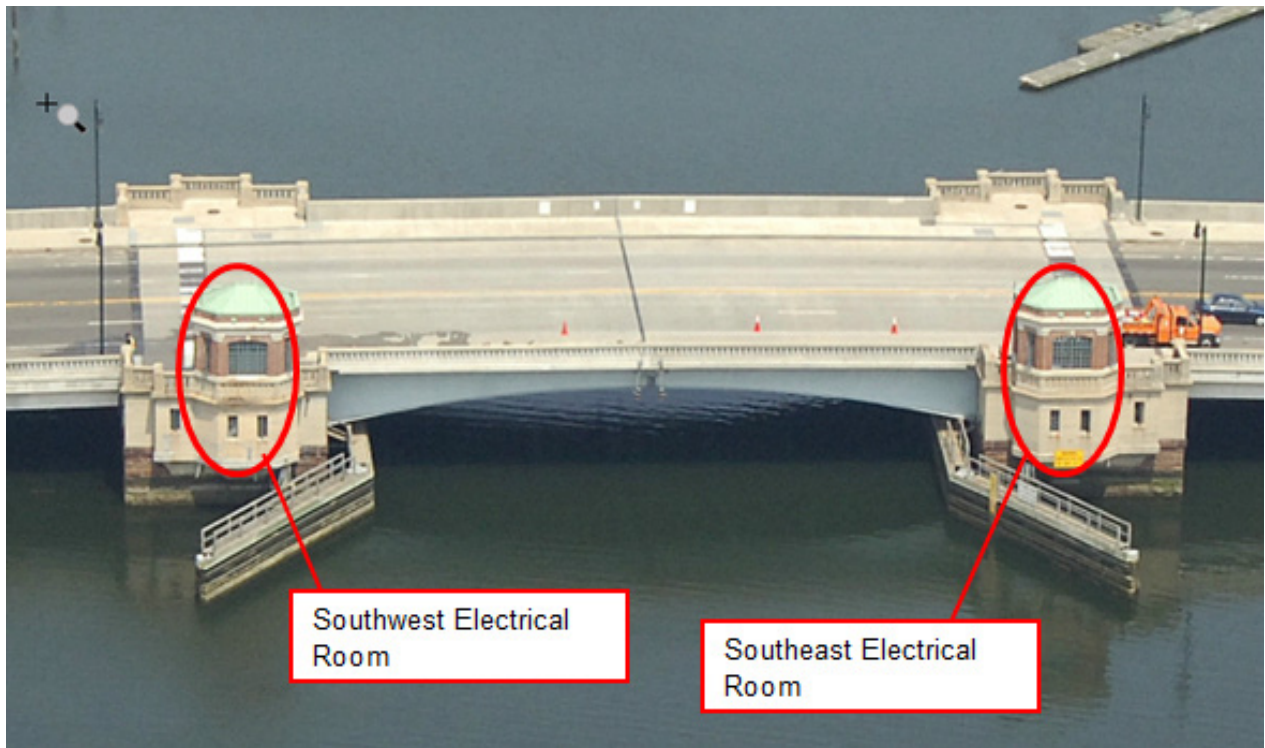


Source: Google Maps <<http://www.maps.google.com>>

¹⁰ Connecticut Department of Transportation, telephone conversation, 5/9/14.

¹¹ The current project plan situates the new marina to the Bridgeport Harbor side of the bridge, however, which presumably would not require additional bridge openings.

Figure 3: Yellow Mill Drawbridge (Looking North)



Source: Marinas.com http://marinas.com/view/bridge/198_Pequonnock_River_Bridge_Bridgeport_CT_United_States

Table 1 provides details on the age, lifespan, condition, and current use of the Yellow Mill Drawbridge.

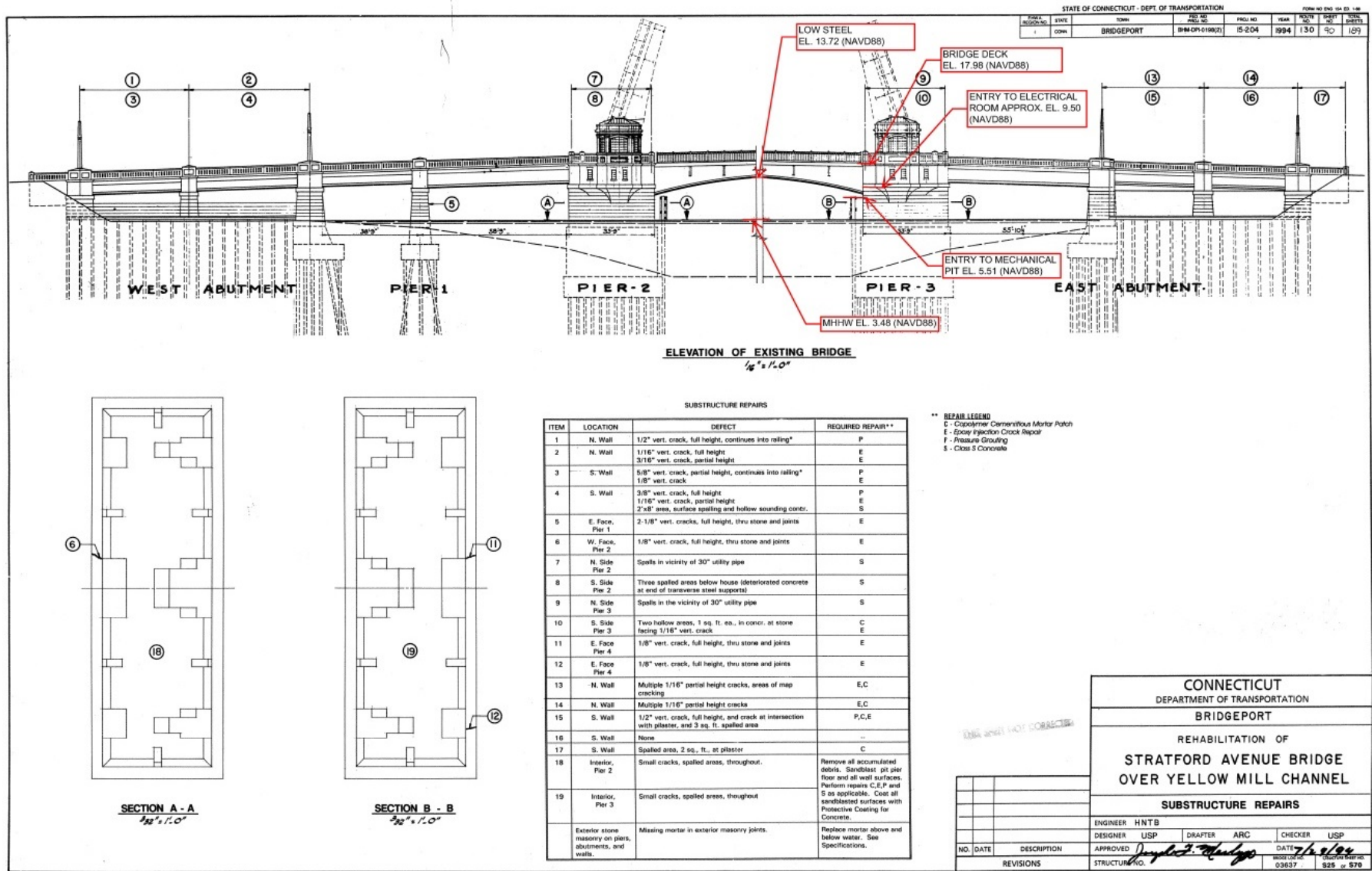
Table 1: Yellow Mill Drawbridge Facility details

Category	Details
Facility Type	Bridge
Facility Component	Electrical and Mechanical Equipment
Estimated Age (Lifespan)	Bridge: Built in 1926. Estimated remaining lifespan: 25 years. Mechanical equipment: 16 Years, Rehabilitated in 1998 Electrical equipment: 16 Years, Rehabilitated in 1998
Estimated condition	Deck: Fair Superstructure: Fair Substructure: Satisfactory Channel & Channel Protection: Satisfactory Mechanical Systems: Fair Electrical Power and Control Installation: Fair
Use / Ridership	16,000 Annual Average Daily Traffic with 500 Trucks (3% of AADT) Average of 12 bridge openings/month from May-August*

Sources: Yellow Mill Drawbridge Routine Inspection Report dated 11/26/2013, Routine Mechanical Inspection Report dated 12/23/13 and Routine Electrical Inspection Report dated 12/23/13.

* Source: CTDOT, based on data from 2013-2015 (as of July). Openings typically diminish in the off season.

Figure 4: Schematic of Yellow Mill Drawbridge with Elevation of Components



Source: Connecticut Department of Transportation, 1992, AECOM, 2015

3. CURRENT AND FUTURE CLIMATE STRESSOR EXPOSURE

Recent storms (including Hurricane Sandy and Hurricane Irene) flooded the Yellow Mill Drawbridge's mechanical pits, damaging the electrical and mechanical equipment. Therefore, Sea Level Rise (SLR) and storm surge were selected for further analysis. Based on guidance from CTDOT, it was agreed that a mid-century (2050s) SLR scenario would be most appropriate for examining risks to the bridge, and that both mid-estimate and high-estimate values for SLR would be considered (0.77 feet and 1.72 feet, respectively (see Table 2). To account for storm surge, it was agreed that the Highest Observed Water Level (HOWL) from Hurricane Sandy (9.2 feet NAVD88) would be considered (see Table 3).¹²

Table 4 shows the combined water elevations when mid-century SLR is added to a Superstorm Sandy-equivalent storm surge elevation. Given the entry elevation of the mechanical pits (5.51 feet NAVD88) and the lower-level (generator-level) elevation of the electrical rooms (approximately 9.50 feet NAVD88), these bridge components are estimated to be susceptible to inundation from all aforementioned combinations of SLR and storm surge.

Table 5 and Figure 6 show the bridge components of principal interest and their respective elevations compared to the projected storm surge and SLR combinations.

Table 2: Sea Level Rise Projections (2050)

Mid-estimate SLR (feet)	High-estimate SLR (feet)
0.77	1.72

Source: USACE Sea Level Rise Curve Calculator, referenced to the NOAA Bridgeport, CT tide gauge.

¹² The HOWL (registered during Hurricane Sandy) was evaluated based on CTDOT's guidance. For additional perspective on flood elevations at the Yellow Mill Drawbridge site, the FEMA 100-year Base Flood Elevation (BFE) at the site is 14 feet NAVD88. The BFE was not evaluated in this assessment.

Table 3: Highest Observed Water Level (Storm Surge proxy)

Tidal Storm Type	Elevation (feet NAVD88)
HOWL during Hurricane Sandy	9.20

Source: NOAA tide gauge 8467150 at Bridgeport, CT.

Table 4: HOWL Combined with Sea Level Rise, 2050s

Tidal Storm Type	Elevation (feet NAVD88)	Analysis Year and Scenario
SLR + HOWL during Hurricane Sandy	9.97	2050s mid-estimate
	10.92	2050s high-estimate

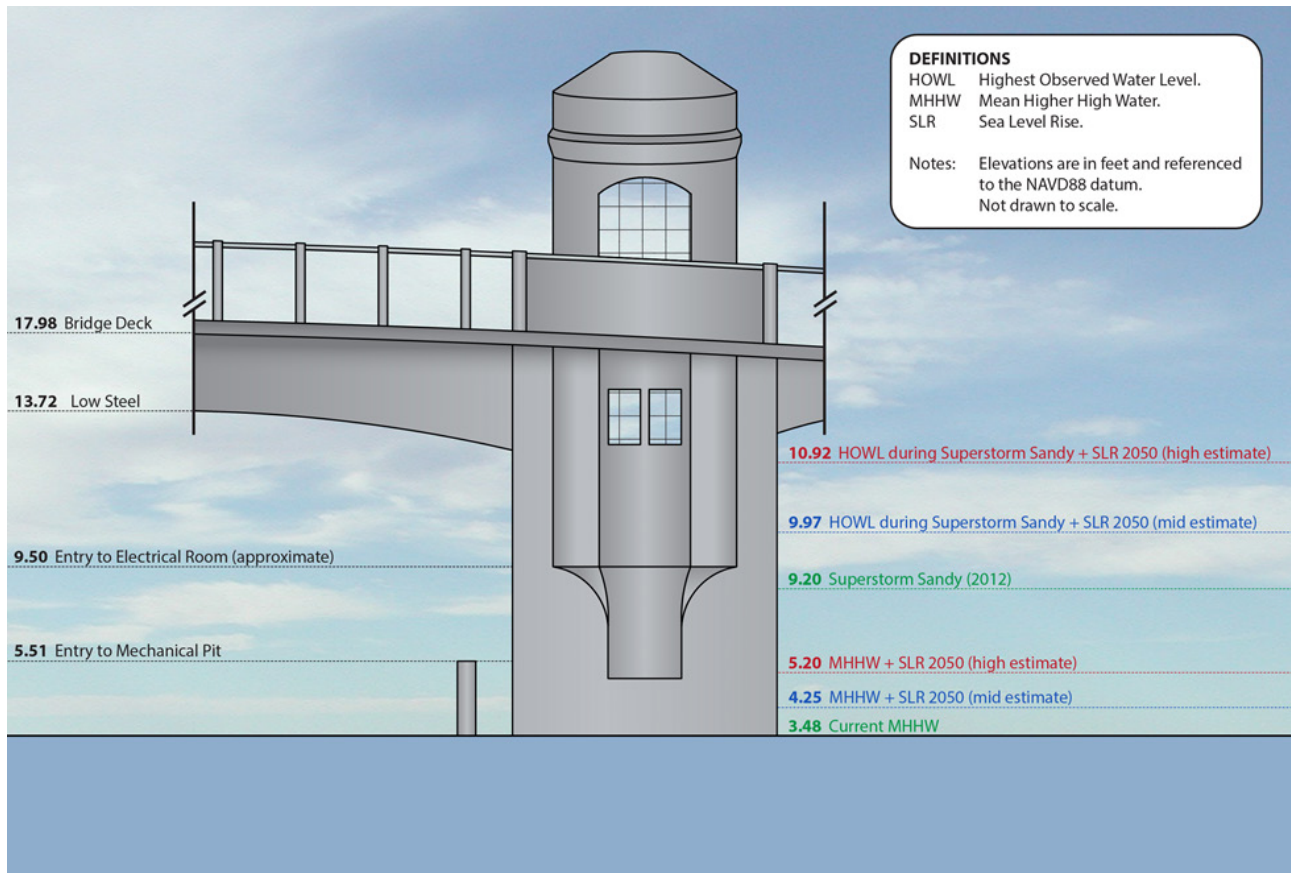
Source: USACE, and NOAA

Table 5: Yellow Mill Drawbridge Components vs. Projected Water Levels

Asset Component	Elevation (feet NAVD88)	Tidal datum, Analysis Year and Scenario	Elevation (feet NAVD88)
Bridge Deck	17.98	HOWL during Hurricane Sandy with SLR 2050 (high estimate)	10.92
Low Steel of Bridge	13.72		
Entry to Electrical Rooms	9.50 (approx.)	HOWL during Hurricane Sandy with SLR 2050 (mid estimate)	9.97
Entry to Mechanical Pits	5.51	Hurricane Sandy (2012)	9.20
		MHHW with SLR 2050 (high estimate)	5.20
		MHHW with SLR 2050 (mid estimate)	4.25
		Current MHHW (2014)	3.48

Source: USACE, NOAA, and AECOM 2015

Figure 5: Elevation of Yellow Mill Drawbridge Components Compared to Tidal Datums/SLR



Source: AECOM, 2015.

4. VULNERABILITY ASSESSMENT

4.1 SENSITIVITY ANALYSIS

The Yellow Mill Drawbridge is currently susceptible to flooding from tidal storms, a risk projected to increase in the future as sea levels rise. As a result, the bridge could be sensitive to the following potential modes of failure:

- Inundation of Mechanical Pits:** During recent storms (including Hurricane Sandy and Hurricane Irene), the mechanical pits of the bridge flooded, which caused damage to span drive machinery that operates the movable bridge.¹³ Equipment in the pits such as limit switches, junction boxes, wiring, et cetera had to be replaced after both storm events. The HOWL during Hurricane Sandy at a nearby tide gauge in Bridgeport, CT was 9.20 feet NAVD88, whereas the entry points to the mechanical pits are at 5.51 feet NAVD88. The bridge has sump pumps meant for leaks which were not sufficient to manage the volume of water from these tidal storm events. There is long-term concern with maintaining the functionality of the mechanical systems during tidal storms. After Hurricane Sandy, some of the equipment in the mechanical pits was functional after the water was pumped out, but periodic inundation from tidal storms may damage the equipment in the future. Given that the mechanical pits are already well below the HOWL, it is expected that these vulnerabilities will worsen as the century progresses due to sea level rise.
- Inundation of Electrical Rooms:** During recent storms (including Hurricane Sandy and Hurricane Irene), the water level was within inches of entering the electrical rooms. The electrical equipment is

¹³ Connecticut Department of Transportation, telephone conversation, 5/9/14.

housed below deck level at each pier. The doors and windows to the electrical rooms are sealed, but not watertight (i.e., they can withstand splashing water but not inundation). If water had entered the electrical rooms, there would have been significantly more damage. The electrical rooms contain the automatic transfer switches and motor control centers which are fed from the main utility service. In addition, the bridge is provided with a standby generator located in the west equipment house a floor below the roadway level. If inundation exceeds the lower-floor elevation of approximately 9.50 feet NAVD88, salt water could potentially enter the electrical room, either through the floor or through a hatch which connects the electrical room to the mechanical pits. The electrical rooms are projected to be susceptible to all considered combinations of SLR and HOWL. It is a critical priority to maintain the functionality of the electrical systems during future storms.¹³

- **Service Disruption:** Flooding of the mechanical pits and electrical equipment can disrupt marine traffic, as the bridge is locked in the closed position in anticipation of major storm events. In recent storms (including Hurricane Sandy and Hurricane Irene), the bridge remained in the closed position for approximately five days after the storm.¹⁴ Although marine traffic is believed to be primarily recreational, the U.S. Coast Guard has a strong desire to keep the bridge operational at all times. Marine vehicles exceeding the closed vertical clearance cannot pass under the bridge if it is not operational.
- **Structural Damage:** Structural components of the bridge are estimated to be minimally vulnerable to damage from waterborne debris. There has been no physical damage to the actual mechanical pits due to storm surge in the past, though there has been damage to the equipment inside the pits as detailed above. There is no evidence that the bridge will be more susceptible to structural damage in the future.
- **Premature Deterioration:** The bridge mechanical and electrical equipment was replaced as part of the bridge rehabilitation in 1998. Although the equipment is currently in fair condition, equipment condition deteriorates with age and with exposure to the elements. Inundation as a result of storm surge may increase the likelihood of failure, increase maintenance requirements, and reduce the lifespan of the equipment due to salt water corrosion, the impacts of which typically become more noticeable after repeated flooding events.

Table 6 provides estimates of the replacement cost of critical bridge components and of the recovery time required to restore full operation to the Yellow Mill Drawbridge after a major flooding event. Based on recent events (Hurricane Sandy and Hurricane Irene), it is likely to take approximately seven days to pump flood water from the mechanical pits using temporary pumps and complete clean-up activities. The condition of the mechanical and electrical systems may then be assessed. If the equipment is damaged beyond repair and requires full replacement, it may take up to six months for full restoration of operations.

Table 6: Est. Recovery Cost and Recovery Time for Yellow Mill Drawbridge

Time and Cost	Magnitude
Estimated Recovery Cost	\$1.8 Million
Estimated Recovery Time	7 days to 6 months

Source of Replacement Cost and Recovery time: CTDOT and AECOM, 2014¹⁵.

¹⁴ Connecticut Department of Transportation, telephone conversation, 5/9/14.

¹⁵ The estimated replacement costs were provided by CTDOT based on replacement costs incurred at a similar bridge in CT, which sustained slightly more damage than the Yellow Mill Drawbridge. The minimum estimated recovery time of 7 days is based on recovery times from recent storms (Hurricane Sandy and Hurricane Irene). If equipment is damaged beyond repair, a timeframe of 6 months is estimated for the removal and installation of the new equipment.

4.2 ADAPTIVE CAPACITY ANALYSIS

CT 130 (Stratford Ave) is part of a local transportation network that exhibits significant potential adaptive capacity. According to the National Bridge Inventory (2012), CT 130 facilitates an Annual Average Daily Traffic volume of 16,000 (as opposed to 149,800 on the parallel I-95 bridge over Yellow Mill Channel) and is not an evacuation route. There are existing alternative roadway routes, particularly I-95 and U.S. Route 1, which provide ample redundancy, although those roadways were not evaluated as part of this assessment.

However, there is no alternative entry point into the Yellow Mill Channel for marine traffic. The drawbridge sits at the mouth of the Channel, and all marine traffic accessing the Channel must pass through. Vessels with air drafts exceeding the recommended navigational clearance require the drawspan to open to facilitate passage.¹⁶ The Yellow Mill Channel is home to marine support services, primarily for recreational craft. Commercial barges have traversed this waterway in the past, but present commercial use could not be confirmed.¹⁷ Nonetheless, the U.S. Coast Guard has a strong desire and legal obligation to keep the bridge operational at all times. During the summer months, the bridge is opened up to 4 times per week, according to CTDOT.

Following both Hurricane Sandy and Hurricane Irene, the bridge remained in the closed position for approximately five days. During this time, access to the Channel was unavailable for vessels exceeding the vertical clearance requirements. Should more comprehensive repairs or even replacement of essential electrical and mechanical equipment be required in the future, the duration of closure could be weeks or months.

¹⁶ According to 33 CFR 117.225, the drawspan “must open on signal if at least 24-hours notice is given.”

¹⁷ Connecticut Department of Transportation, telephone conversation, 5/9/14.

5. CONSEQUENCE ANALYSIS

5.1 EFFECT ON REGIONAL MOBILITY

Based on past observations and future projections of storm surge, no significant disruption to vehicular traffic is anticipated due to bridge failure during a coastal flooding event, as the bridge is locked in the down position in preparation for a major storm event.¹⁸ In the instance that vehicular traffic cannot access the bridge, Interstate 95 and U.S. Route 1 provide alternative routes; Interstate 95 crosses Yellow Mill Channel less than 500 feet to the north, but at a significantly greater elevation (about 40 feet of navigational clearance cited by NBI), and U.S. Route 1 passes the Channel approximately ½ mile north—well inland. However, these detours would increase travel times and potentially delay provision of support or emergency services. The estimated length of these detours is approximately 1 mile.¹⁹ When the bridge is not mechanically operational, the local marine support services offered on Yellow Mill Channel cannot be accessed by vessels exceeding the closed vertical clearance.²⁰

5.2 EFFECT ON REGIONAL ECONOMY

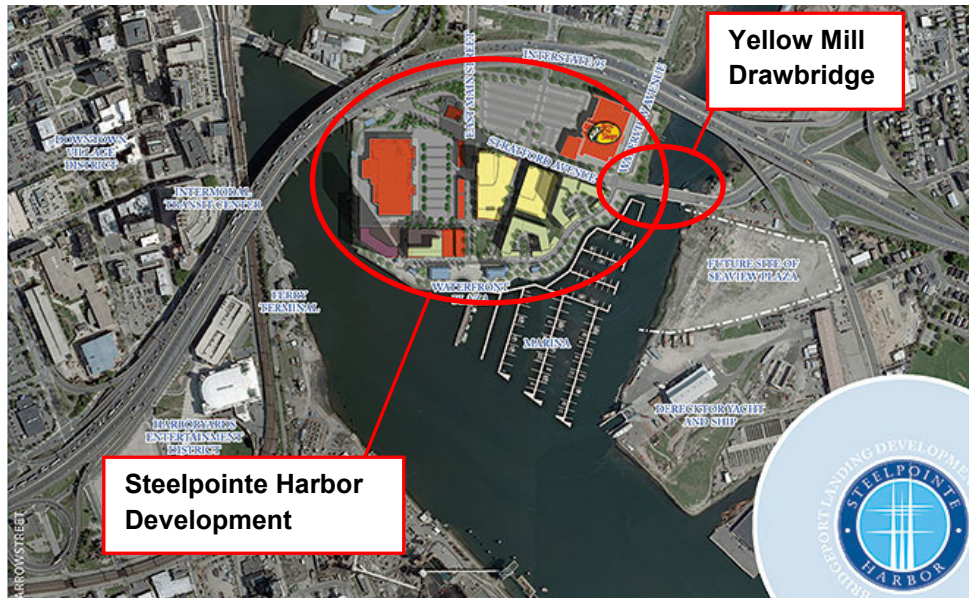
In addition to providing access to and from downtown Bridgeport currently, in the future the bridge will also provide vehicular access to the Steelpointe Harbor development, a proposed 2.8 million square foot mixed-use waterfront development to be located less than a quarter mile to the west of the bridge (see Figure 6). When complete, the development is expected to significantly increase the number of vehicles crossing over the bridge. Although unlikely, a complete bridge closure to vehicles could affect the economic activity associated with this development. With regard to vessel traffic, loss of access to local marine support services would have adverse effects on the local recreational boating community and associated economy.

¹⁸ Even though the bridge would remain in the closed position, it is possible that traffic may be temporarily restricted during and after a storm event due to the need to remove debris, inspect bridge components, and/or pump water out of mechanical pits and electrical rooms.

¹⁹ Bridge No. 03637 - 2013 Routine Bridge Inspection Report.

²⁰ Rehabilitation of Stratford Avenue Bridge over Yellow Mill Channel dated 1994, Sheet No. S1 of S70.

Figure 6: Steelpointe Harbor Mixed-Use Development



Source: <http://www.bldsteelpointe.com/the-steelpointe-project>

5.3 EFFECT ON DISADVANTAGED POPULATIONS

The Yellow Mill Channel Bridge is located near pockets of disadvantaged communities in the greater Bridgeport region. Approximately 24 percent of Bridgeport's population lives below the poverty line.²¹ In the area immediately west of the bridge, approximately 33 percent of the population is below the poverty line.²² CT 130 serves three bus routes (the County Link Route, Route 10, and Route 13) of the Greater Bridgeport Transit Authority, each of which could divert to an alternative route if the bridge were closed to vehicular traffic. However, given that a bridge closure in the down position would likely only disrupt marine traffic—most or all of which is recreational—failure of the mechanical and electrical equipment is not likely to have a disproportionately higher impact on disadvantaged populations.

6. DEVELOPMENT AND SELECTION OF ADAPTATION STRATEGIES

Toward the completion of this assessment, a reported \$2.625 million grant²³ was allocated to CTDOT for a project to improve the resilience of the Yellow Mill Channel Drawbridge. As of the first quarter of 2015, design development was underway.²⁴ To avoid hampering an active design development process, the study team developed a range of generic, conceptual strategies that *might* be appropriate for further consideration in similar circumstances. Illustratively, an agency faced with comparable issues could explore a range of adaptation strategies including:

- Continued operations and maintenance (O&M) activities, including scheduled maintenance of electrical and mechanical equipment and replacement of equipment on normal cycles. From a lifecycle cost perspective, regular O&M may compare favorably with strategies associated with

²¹ U.S. Census, 2008 – 2012.

²² <http://www.city-data.com/poverty/poverty-Bridgeport-Connecticut.html>.

²³ As part of the second tranche of Community Development Block Grant-Disaster Recovery funds allocated to the State of Connecticut for Hurricane Sandy recovery from the U.S. Department of Housing and Urban Development.

²⁴ http://www.ct.gov/doh/lib/doh/sandy_relief_docs/qpr_download_3-31-15.pdf.

large capital costs. Also, if there were a bridge replacement or major rehabilitation project in the planning or project development pipeline, regular or even reduced O&M may be the best use of resources, as long as acceptable safety and performance are maintained;

- Moderate investments to prevent inundation of the electrical and mechanical equipment, either by protecting the existing mechanical pits and electrical rooms in place or raising the equipment to a higher elevation; or
- Major investments, including, but not limited to, replacement of the bridge with a high-level span. This tack could be appropriate if, for instance, the land adjacent to Yellow Mill Channel were targeted for significant maritime-oriented development (either commercial or recreational) that required reliable and uninterrupted access and egress for marine traffic and/or if the bridge were expected to carry significantly larger traffic volumes (thus creating more significant disruptions each time the bridge is opened).

An agency's tolerance for risk is also a factor in selecting an adaptation strategy. An agency that has a low tolerance for risk may not find the uncertain prospect of undergoing multiple failure/recovery cycles to be acceptable—and opt for early replacement. An agency with higher risk tolerance may opt for moderate risk mitigation investments or just continue with standard O&M activities.

7. CONCLUSION

This assessment identified existing and potential future vulnerabilities of critical mechanical and electrical equipment of the Yellow Mill Drawbridge to coastal storm events by mid-century. Enabled by a HUD grant, CTDOT has begun design development to enhance the resilience of the bridge, so specific risk mitigation strategies were not developed as part of this assessment. Under similar circumstances (e.g., moveable bridges vulnerable to flooding/water intrusion), an agency could explore a continuum of potential risk mitigation alternatives, ranging from standard operations and maintenance activities to component-specific repairs and replacements to complete replacement of the bridge. For Yellow Mill Drawbridge, the appropriate alternative(s) will be determined as part of the ongoing design development process.

F Resources

This appendix is a compilation of the resources that were used to inform the technical work on this research effort. While this is not a comprehensive list of reports and data sources, the following websites contain a wealth of information that may be of use to practitioners undertaking a climate vulnerability and risk assessment.

Federal and National Resources

National Oceanic and Atmospheric Administration's climate.gov is a source of timely and authoritative scientific data and information about climate. The goals of climate.gov are to promote public understanding of climate science and climate-related events, to make data products and services easy to access and use, to provide climate-related support to the private sector and the Nation's economy, and to serve people making climate-related decisions with tools and resources that help them answer specific questions.

NOAA's Climate.gov groups information into three categories designed to serve different audiences:

- **News & Features** is a popular-style magazine for the science-interested public covering topics in climate science, adaptation, and mitigation.
- **Maps & Data** is a gateway to reusable climate maps and datasets that document various climate conditions. The section aims to serve officials and professionals who need climate data to inform their decisions or compile a climate adaptation report.
 - NOAA has a **Sea Level Rise Map Viewer** that illustrates the scale of potential coastal flooding after varying amounts of sea level rise. Users can simulate inundation associated with one to six feet of sea level rise at various scales along the contiguous United States coast.
 - NOAA's **National Water Model** provides information on observed and forecast stream flow.
- **Teaching Climate** offers learning activities and curriculum materials, multi-media resources, and professional development opportunities for formal and informal educators who want to incorporate climate science into their work.

Link: www.climate.gov

The U.S. Department of the Interior's **U.S. Geological Survey (USGS) [Climate Research and Development \(Climate R&D\) Program](#)** conducts research to improve understanding of the rates, causes, and consequences of climate and land use change.

Link: https://www2.usgs.gov/climate_landuse/clu_rd/default.asp

The USGS **[StreamStats](#)** Web application incorporates a Geographic Information System (GIS) with an assortment of analytical tools that are useful for a variety of water-resources planning and management purposes, and for engineering and design purposes. StreamStats users can select USGS data-collection station locations shown on a map and obtain previously published information for the stations, including descriptive information, and previously published basin characteristics and streamflow statistics. Currently, StreamStats provides additional tools that allow users to select sites on ungaged streams and do the following:

- Obtain the drainage-basin boundary,
- Compute selected basin characteristics,
- Estimate selected streamflow statistics using regression equations,
- Download a shapefile of the drainage-basin boundary, as well as any computed basin characteristics and flow statistics
- Edit the delineated basin boundary
- Modify the basin characteristics that are used as explanatory variables in the regression equations and get new estimates of streamflow statistics,
- Print the map,
- Measure distances between user-selected points on the map, and
- Obtain plots of the elevation profile between user-selected points on the map.

Link: <https://water.usgs.gov/osw/streamstats/>

The USGS **[Future Flow Explorer for NY](#)** presents the results of an analysis of flood regressions and climate scenarios to explore estimates of future peak flows.

Link: <https://ny.water.usgs.gov/maps/floodfreq-climate/>

The **[Federal Emergency Management Agency \(FEMA\)](#)** offers resources related to climate change, resilience, mitigation, and emergency response.

Link: <https://www.fema.gov/climate-change>

- The [FEMA Flood Map Service Center \(MSC\)](https://msc.fema.gov/portal) is the official public source for flood hazard information produced in support of the National Flood Insurance Program (NFIP). The MSC can be used to find official flood maps, access a range of other flood hazard products, and take advantage of tools for better understanding flood risk. FEMA flood maps are continually updated through a variety of processes.

Link: <https://msc.fema.gov/portal>

The [U.S. Environmental Protection Agency \(EPA\)](https://www.epa.gov) provides resources related to climate science, impacts, mitigation strategies, and adaptation efforts.

- The EPA's [Climate Resilience Evaluation and Awareness Tool \(CREAT\)](https://www.epa.gov/crwu/build-resilience-your-utility) a risk assessment application, which helps agencies and utilities in adapting to extreme weather events through a better understanding of current and long term weather conditions.

Link: <https://www.epa.gov/crwu/build-resilience-your-utility>

- The EPA's [National Stormwater Calculator \(SWC\)](https://www.epa.gov/water-research/national-stormwater-calculator) is a desktop application that estimates the annual amount of rainwater and frequency of runoff from a specific site anywhere in the United States (including Puerto Rico). Estimates are based on local soil conditions, land cover, and historic rainfall records.

Link: <https://www.epa.gov/water-research/national-stormwater-calculator>

- The EPA Report ["Climate Change Indicators in the United States, 2016 \(Fourth Edition\)"](https://www.epa.gov/climate-indicators) reflects information gathered by the EPA in partnership with more than 40 data contributors from various government agencies, academic institutions, and other organizations to compile a key set of indicators related to the causes and effects of climate change. The indicators are published in a hard-copy report and on [EPA's website](https://www.epa.gov/climate-indicators).

Link: <https://www.epa.gov/climate-indicators>

The **Federal Highway Administration (FHWA)** has a number of resources and tools related to resilience and sustainability [on its website](https://www.fhwa.dot.gov/environment/sustainability/resilience/). Link: <https://www.fhwa.dot.gov/environment/sustainability/resilience/>

These include the following:

CMIP Climate Data Processing Tool. This spreadsheet tool processes raw climate model outputs from the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) CMIP3 and CMIP5 databases into relevant statistics for transportation planners, including changes in the frequency of very hot days and extreme precipitation events that may affect transportation infrastructure and services by the middle and end of the century.

Link: <https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/>

Vulnerability Assessment Scoring Tool (VAST). This spreadsheet tool guides the user through conducting a quantitative, indicator-based vulnerability screen. It is intended for agencies assessing how components of their transportation system may be vulnerable to climate stressors.

Link: <https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/>

Virtual Framework for Vulnerability Assessment. This online resource provides a guide to assessing the vulnerability of transportation assets to climate change and extreme weather events. It gives an overview of key steps in conducting vulnerability assessments and uses in-practice examples to demonstrate a variety of ways to gather and process information. The framework is comprised of three key steps: defining study objectives and scope; assessing vulnerability; and incorporating results into decision making.

Link: https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/

[Transportation Engineering Approaches to Climate Resiliency \(TEACR\) Study.](#) The FHWA is conducting a project to evaluate engineering approaches to assessing climate hazards and develop a state of the practice set of solutions and methodologies that project sponsors across the nation can use in developing transportation infrastructure. The TEACR project includes:

- An analysis of gaps and needs in the current state of practice in incorporating climate change considerations into engineering;
- Case studies of a diverse set of transportation assets around the country that include facility-level climate change vulnerability assessments and engineering and economic analysis of potential adaptation options;
- A synthesis of specific recommendations and approaches for engineers to use in designing transportation projects to enhance resiliency to climate change and extreme weather events at both the system and project scales; and
- Development of a new module for the FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework to assist transportation agencies in identifying project specific hazards and developing engineering solutions to improve resiliency.

Link: https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/

The FHWA Office of Bridges and Structures (HIBS), working with the Office of the Natural Environment (HEPN) and the Resource Center, has developed two complementary products that provide technical guidance and methods for assessing the impacts of climate change on infrastructure:

Hydraulic Engineering Circular No. 17 (HEC-17), "[Highways in the River Environment: Extreme Events, Risk and Resilience](#)"

The HEC-17 manual, released in 2016, is a major and significant update that provides technical guidance and methods for assessing the nexus of riverine and transportation as it relates to floods, floodplain policies, extreme events, climate change, risks, and resilience. An important focus is quantifying exposure to extreme flood events considering climate change and other factors.

Specifically, HEC-17 describes and discusses:

- FHWA and other floodplain policies and guidance
- Uncertainty associated with hydrologic models
- Nonstationarity and two drivers: climate change and land use/land cover changes
- Several tools for identifying and adjusting for trends in the historical record
- Techniques for projecting floods
- Global/regional climate models, downscaling techniques, and emissions scenarios
- Risk and resilience and the probabilistic nature of flood events

Link: https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec17_announcement.cfm

Hydraulic Engineering Circular No. 25 (HEC-25) – Volume 2, “[Highways in the Coastal Environment: Assessing Extreme Events](#)”

The HEC-25 manual, released in 2014, provides technical guidance and methods for assessing the vulnerability of coastal transportation facilities to extreme events and climate change. The focus is on quantifying exposure to sea level rise, storm surge, and wave action. It is anticipated that there will be multiple uses for this information, including risk and vulnerability assessments, planning activities, and design procedure guidance.

HEC-25 focuses primarily on appropriate methods for quantifying the exposure of transportation assets to climate stressors. It summarizes the current state of the practice for incorporating climate change and sea level projections into coastal storm surge modeling relevant to the analysis and design of transportation projects including:

- obtaining sea (or lake) level change estimates,
- selecting storm scenarios,
- using coastal surge and wave models, and
- interpreting results.

The HEC-25 manual is a standalone supplement, a “Volume 2,” to the existing, primary FHWA Hydraulic Engineering Circular (HEC) document: “Highways in the Coastal Environment,” HEC- 25 (FHWA 2008). That primary technical manual provides more general, overall guidance for the analysis, planning, design, and operation of highways in the coastal environment.

Link: <https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf>

The U.S. Army Corps of Engineers’ [North Atlantic Coast Comprehensive Study](#) conducted extensive analysis and modeling to address coastal storm and flood risk to vulnerable populations, property, ecosystems, and infrastructure affected by Hurricane Sandy in the United States’ North Atlantic region.

The study is designed to help local communities better understand changing flood risks associated with climate change and to provide tools to help those communities better prepare for future flood risks. It builds on lessons learned from Hurricane Sandy and attempts to bring to bear the latest scientific information available for state, local, and tribal planners.

In addition to the interim and final reports and state-by-state appendices posted on the NACCS website, the study produced the following useful resources:

- A nine-step Coastal Storm Risk Management Framework that can be customized for any coastal watershed;
- A geodatabase that contains vector GIS information from various NACCS geospatial analyses, including results of the Sea Level Affecting Marshes Model (SLAMM) and Sea, Lake and Overland Surges from Hurricanes (SLOSH) model. It also has features used to generate report maps and figures, including

base map features. Raster geospatial products present results of the NACCS exposure analysis (with maps of an exposure index applied to coastal study areas), risk analysis (with maps of a corresponding risk index), future mean sea level inundation mapping, and housing density projections.

Link: <http://www.nad.usace.army.mil/CompStudy/>

here are many national-level clearinghouses of climate data and resources. These two in particular provided information for this study:

The [Infrastructure & Climate Network \(ICNet\)](#) is a network of over 60 academics, students, and practitioners who are dedicated to accelerating climate science and engineering research in the Northeastern United States. The ICNet focuses on climate change and sea level rise impacts and adaptation for sustainable bridges, roads, and transportation networks. The ICNet was established in October 2012 with support from the National Science Foundation.

ICNet includes the following types of resources:

- A research guide with introductory information (such as “The Basics of Climate Change”) and specific methods for understanding and conducting research at the interface of climate change and transportation infrastructure;
- Guidance on choosing climate models;
- Maps of 21 climate indicators that ICNet members identified as relevant to the transportation infrastructure community, with downloadable GIS data;
- A database of reports and other documents related to climate change and infrastructure.

Link: <http://theicnet.org/>

[Georgetown Climate Center Adaptation Clearinghouse](#)

The Adaptation Clearinghouse seeks to assist policymakers, resource managers, academics, and others who are working to help communities adapt to climate change.

Content in the Adaptation Clearinghouse is focused on the resources that help policymakers at all levels of governments reduce or avoid the impacts of climate change to communities in the United States. The Adaptation Clearinghouse tends to focus on climate change impacts that adversely affect people and our built environment.

Content focal areas include the water, coastal, transportation, infrastructure and public health sectors, and adaptation planning, policies, laws, and governance. Resources that fall within these areas receive priority and are the most likely to be published in the Adaptation Clearinghouse.

Link: <http://www.adaptationclearinghouse.org>

State and Local Resources

The remainder of this appendix summarizes examples of state and local sources of information that were used in this study. Although these were produced by state and local organizations, in many cases the information has relevance to the entire study area.

New York City Intergovernmental Panel on Climate Change

In response to climatic change and associated impacts to the city's infrastructure, and in order to support goals outlined in [PlaNYC](#), the City's comprehensive sustainability plan, Mayor Michael Bloomberg convened the New York City Panel on Climate Change (NPCC) in August 2008. The NPCC, which consists of leading climate change and impact scientists, academics, and private sector practitioners, was charged with advising the Mayor and the New York City Climate Change Adaptation Task Force on issues related to climate change and adaptation as it relates to infrastructure. It produced a set of climate projections specific to New York City and the report '[Climate Risk Information](#),' released in 2009.

Following Hurricane Sandy, Mayor Bloomberg convened the second New York City Panel on Climate Change (NPCC2) in January 2013 to provide up-to-date scientific information and analyses on climate risks for to create "[A Stronger, More Resilient New York](#)" plan.

In response to the Mayor's charge to the Panel, the report '[Climate Risk Information 2013 - Observations, Climate Change Projections, and Maps](#)' provides new climate change projections and future coastal flood risk maps for New York City. This climate risk information is designed to inform community rebuilding plans, and help to increase current and future resiliency of communities, and citywide systems and infrastructure to a range of climate risks.

A 2015 update titled "[Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report](#)" presents the work of the New York City Panel on Climate Change from January 2013 to January 2015.

The 2015 report documents recently observed climate trends and climate projections for the New York metropolitan region up to 2100. The report presents new maps that show increasing flood risks due to climate change defined for the 100- and 500-year coastal flood event in the 2020s, 2050s, 2080s and 2100. It compares future coastal flooding simulated by static and dynamic modeling that include the effects of sea level rise.

The report reviews key issues related to climate change and health relevant to the citizens of New York City and sets forth a process for developing a system of indicators and monitoring to track data related to climate change hazards, risks, impacts, and adaptation strategies. Research needs and recommendations for climate resiliency are provided.

The **New York State Energy Research and Development Authority (NYSERDA)**, in partnership with Cornell University and Northeast States for Coordinated Air Use Management (NESCAUM), has developed the [New York State Climate Science Clearinghouse](#), a portal for climate information for New York. The

portal serves as a regional gateway to data and information relevant to climate change adaptation and mitigation across New York State. It provides climate science data and literature and other resources for policy-makers, practitioners, and the public, to support scientifically sound and cost-effective decision making.

Link: <https://www.nyclimatescience.org/>

Responding to Climate Change in New York State (ClimAID)

The ClimAID assessment provides information on climate change impacts and adaptation for eight sectors in New York State: water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, and public health. Observed climate trends and future climate projections were developed for seven regions across the state. Within each of the sectors, climate risks, vulnerabilities, and adaptation strategies are identified. Integrating themes across all of the sectors are equity and environmental justice and economics.

Case studies are used to examine specific vulnerabilities and potential adaptation strategies in each of the eight sectors. These case studies also illustrate the linkages among climate vulnerabilities, risks, and adaptation, and demonstrate specific monitoring needs.

Link: <https://www.nyserda.ny.gov/climaid>

The [New York State Department of Environmental Conservation \(DEC\)](#) maintains resources related to climate change in the following categories:

- Impacts of climate change;
- Mitigation of climate change;
- Adaptation to climate change;
- Community action on climate; and
- Climate change information sources.

Link: <http://www.dec.ny.gov/energy/44992.html>

The [New York State Sea Level Rise Task Force](#) assessed sea-level rise impacts and identified the greatest threats to coastal communities and natural resources:

- Increased frequency and intensity of severe flooding and storm surge damage, not only to communities and infrastructure, but also to critical ecosystems that buffer against floods, protect drinking water and provide habitat for important species;
- Increased erosion of beaches and bluffs;

- Inundation of low-lying areas;
- Saltwater infiltration of surface waters and aquifers;
- Possible compromise of low-lying sewage, wastewater, transportation, communication, and energy infrastructure and systems.

The Sea Level Rise Task Force recommendations are the basis for many of New York's current climate change adaptation policies.

Link: http://www.dec.ny.gov/docs/administration_pdf/slrtrfinalrep.pdf

NYS 2100 Commission was appointed by the Governor after Superstorm Sandy to make recommendations to strengthen and make more resilient the States infrastructure released its preliminary report and recommendations. With support from the Rockefeller Foundation, the Commission developed a report that includes short- and long-term recommendations in the areas of energy, transportation, land use, insurance, and infrastructure financing, as well as cross-cutting recommendations that are common to these sectors.

Link: <http://www.governor.ny.gov/assets/documents/NYS2100.pdf>.

The **Northeast Regional Climate Center** (NRCC) at Cornell University was formed to facilitate and enhance the collection, dissemination and use of climate data and information, as well as to monitor and assess climatic conditions and impacts in the twelve-state, northeastern region of the United States. Its activities are intended to further the economic efficiency and general welfare of public and private institutions and individuals in the region.

The NRCC provides a wealth of resources relevant to this study area, including the following:

- Downscaled Projections of Extreme Rainfall in New York State: Future IDF curves and I downscaled extreme precipitation forecasts
- Precip.net – analysis of annual series vs. partial series. Partial series on precip.net includes more data points

Link: <http://www.nrcc.cornell.edu/>

The **New Jersey Climate Adaptation Alliance** was formed in response to a diverse group of stakeholders who came together on November 29, 2011 at Rutgers University to participate in the conference "Preparing NJ for Climate Change: A Workshop for Decision-Makers."

A changing climate and rising sea levels will have a devastating impact on New Jersey's economy, the health of our residents, the State's natural resources, and the extensive infrastructure system that delivers transportation services, energy and clean water to millions of New Jerseyans. The Alliance will focus on climate change preparedness in key impacted sectors (public health; watersheds, rivers and coastal communities; built infrastructure; agriculture; and natural resources) through:

- Conducting outreach and education of the general public and targeted sectoral leaders;

- Developing recommendations for state and local actions through collaboration with policymakers at the state, federal and local levels;
- Undertaking demonstration and pilot projects in partnership with the private sector, local governments, non-governmental organizations, and others;
- Identifying science, research and data needs; and
- Developing capacity for implementation of preparedness measures and documentation of best practices.

Link: <http://njadapt.rutgers.edu/>

Representative reports produced by members of the Alliance include:

- Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel (which summarizes the deliberations of a Science and Technical Advisory Panel on this topic convened by Rutgers University)
- Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: A Companion Report to the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel Report (which describes how coastal hazard data and coastal climate change impacts are currently being addressed in New Jersey) and
- Integrating Science in Coastal Resilience Planning and Decision Making (which is a high-level summary of the two reports noted above).

Link: <http://njadapt.rutgers.edu/resources/njcaa-reports>

The Connecticut [Office of Energy and Environmental Protection](#) (DEEP) has assembled a collection of resources specific to the State of Connecticut. In support of the Governor's Council on Climate Change, the DEEP, University of Connecticut (UConn), and others have developed publications, conducted research and analysis, and produced materials to support outreach and engagement with stakeholders in Connecticut.

Link: http://www.ct.gov/deep/cwp/view.asp?a=4423&q=521742&deepNav_GID=2121

[Connecticut Institute for Resilience & Climate Adaptation \(CIRCA\)](#) is a partnership of UConn and DEEP that focuses on increasing the resilience and sustainability of communities along Connecticut's coast and inland waterways. These communities' natural, built, and human environments are vulnerable to the growing impacts of climate change.

Link: <http://circa.uconn.edu/>

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