





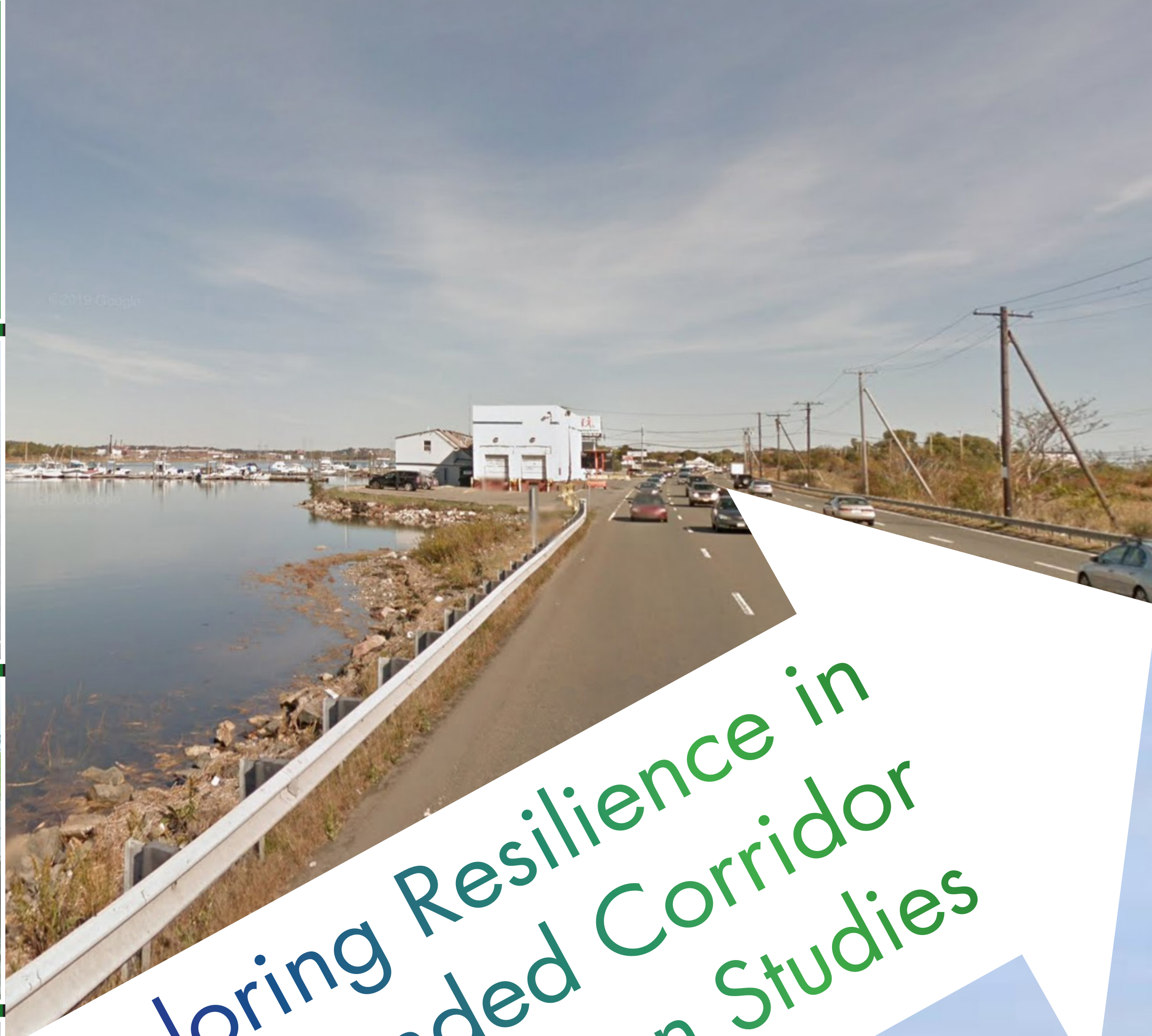

Exploring Resilience in MPO-Funded Corridor and Intersection Studies

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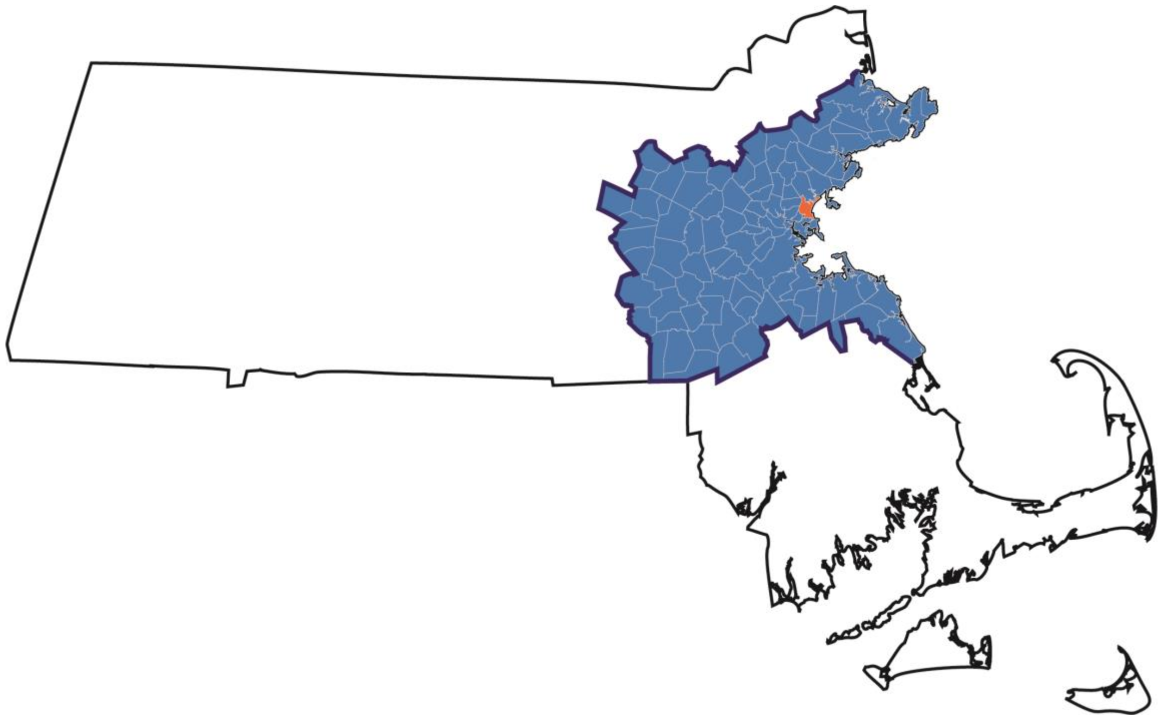

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Abstract

Incorporating resiliency into transportation infrastructure has become an increasingly important priority in Massachusetts as climate change effects have intensified and become more visible. Making the transportation system resilient is a growing challenge and addressing the issue is a statewide priority. Programs currently in place and ongoing at state agencies and municipalities are addressing climate change impacts. In addition, municipalities in the Boston region have completed vulnerability assessments and have action-oriented resiliency and hazard mitigation plans for protecting vulnerable assets.

The Boston Region Metropolitan Planning Organization (MPO) has also played a part in resiliency planning for the transportation system. The MPO recognized the issue of climate change in its long-range transportation plans over the past decade. In the current plan, *Destination 2040*, the MPO stated its goal of regularly considering climate change vulnerability and risk and adaptation strategies in transportation decision-making at system and project levels. This MPO-funded study explored ways to incorporate resilience into the MPO's discrete and recurring studies and how to increase the MPO staff's knowledge and experience to enable them to provide technical assistance to communities seeking to address climate change challenges.

In this study, MPO staff researched literature on resilience, conducted a community survey, and identified a roadway segment for a pilot study. The community survey facilitated understanding of how municipalities in the Boston region are using resilience practices in their planning and engineering, and the challenges they face in making transportation assets more resilient to climate change impacts.

A segment of Route 1A in the City of Revere was selected for the pilot study. Route 1A is in natural low-lying area and close to the flood pathways of the Pines River estuary to the north and the Chelsea Creek estuary to the south. The corridor is highly vulnerable to flooding resulting from high tides, coastal storm surge, and rain storms, and to inundation from sea level rise. These hazards are expected to worsen in the future.

The Route 1A corridor offered MPO staff the experience of incorporating resilience into corridor and intersection studies, as staff became familiar with the relevant data sources, methodologies, adaptation strategies, and knowledge of best practices. The Route 1A study also provided the Massachusetts Department of Transportation and the City of Revere with an assessment of vulnerabilities of the corridor and adaption measures to consider.

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ES 1 PRIORITIZING RESILIENCY IN MASSACHUSETTS

Addressing the issue of climate change impacts is a growing challenge and a statewide priority. In 2016, the Massachusetts Executive Order No. 569 called for establishing an integrated climate change strategy for the Commonwealth. The order has facilitated work at state agencies and municipalities to address climate change impacts. The State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) has outlined specific actions and strategies to manage the risks of natural hazards and climate change, and has established the Resilient Massachusetts Action Team (RMAT) to help implement the SHMCAP's objectives. Progress has been made on the SHMCAP's 108 action items at several state agencies although some items have much longer timelines than others.

At the municipal level, programs and action grants have been established that help municipalities to complete vulnerability assessments and have action-oriented resiliency plans for protecting vulnerable assets in their communities. The Municipal Vulnerability Preparedness (MVP) Program provides funding for communities to develop action-oriented resiliency plans and implement priority projects. Additionally, local Hazard Mitigation Plans (HMPs) represent municipalities' commitments to address potential hazards and allocate resources to mitigation activities.

The Boston Region Metropolitan Planning Organization (MPO) recognized the issue of climate change in its Long-Range Transportation Plans (LRTPs) over the past decade. In the current LRTP, *Destination 2040*, the MPO emphasized the need to plan for resiliency in the transportation system to protect investments. For several years, the MPO has considered climate change resilience when evaluating projects to be funded through the Transportation Improvement Program (TIP). Now the MPO is exploring ways to incorporate climate change resiliency in decision-making at project levels. This study focused on approaches to incorporate resilience into corridor and intersection studies and provide technical assistance to communities seeking to address climate change challenges. The study also aimed to increase the MPO staff's knowledge and experience with climate resiliency planning.

ES 2 COMMUNITY SURVEY

To learn more about resilience practices currently being used within the Boston region, staff conducted a survey of all cities and towns in the region that sought information on the impact of climate change on transportation, climate resiliency planning for transportation assets, resilience practices and challenges, and the MPO's transportation resilience activities.

The key takeaways from the survey were as follows:

- Stormwater flooding and snow and ice storms are major hazards for many municipalities; and roads, bridges, and culverts are the major transportation assets vulnerable to these climate hazards.
- Municipalities face multiple hazards and are taking multiple approaches to address transportation resiliency. The MVP, HMP, and Climate Improvement Program (CIP) are the main tools for addressing resilience.
- Municipalities expressed strong support for the actions the MPO has taken to improve the regional transportation system such as considering climate change and resilience in developing the LRTP and in TIP project evaluation criteria.
- Municipalities support the idea of having MPO staff provide technical assistance to communities, such as guidance on updating design standards for projects based on climate projections, and conducting studies.

ES 3 DATA SOURCES

Conducting vulnerability assessments and identifying adaptation options require various types of data on assets, climate, land use, and socio-economic and demographic data. Therefore, data sources for current and future climate conditions will be instrumental to the MPO staff's effort to incorporate resilience into corridor and intersection studies. The RMAT team is coordinating an effort to standardize data sources for vulnerability assessments. In addition, the team is developing standards for incorporating consistent climate projection data in project analyses and guidelines for best practices for incorporating climate resilience during the planning, design, and implementation of projects. Additional efforts include the development of tools to enable users to quantify benefits of resilient projects.

Presently, the Massachusetts Department of Transportation's (MassDOT) geoDOT website provides data on transportation assets. The Massachusetts Coast Flood Risk Model (MC-FRM) is the state's standard for assessing coastal assets, and it provides probability-based outcomes that can be effectively used to assess vulnerabilities, prioritize planning, and test various adaptation and engineering options. Models for inland flooding are currently being developed for assessing inland assets. Thus, ample resources (data, models, and tools) currently exist to help MPO staff to conduct vulnerability assessments and incorporate resilience into MPO-funded corridor and intersection studies.

ES 4 ADAPTATION OPTIONS

Several adaptation options are available to municipalities for addressing climate change impacts. The most popular options identified in the SHMCAP, local HMPs, and MVP reports are as follows:

- Nature-based solutions, such as saltwater marsh restoration and other measures, created by human design, engineering, and construction that imitate natural features, such as coir rolls and sills that prevent erosion
- Structural solutions, such as resizing culverts, adding rock revetments, and elevating assets
- Policy-based solutions, long-range planning tools that help guide development within communities to address climate change impacts, such as comprehensive plans and regulatory and non-regulatory policies

ES 5 ROUTE 1A RESILIENCE PILOT STUDY

The objectives of the pilot study were twofold: (1) work with MassDOT and the City of Revere to identify problems and develop recommendations to make Route 1A resilient, and (2) provide MPO staff with knowledge and ideas of how to use available resources effectively to incorporate resilience into corridor and intersection studies and help municipalities seeking to address transportation resilience. MPO staff selected Route 1A for the pilot study because portions of it are in natural low-lying areas with elevations no greater than 10 feet above sea level (surveyed relative to the North American Vertical Datum of 1988) and close to the flood pathways of the Pines River estuary to the north and the Chelsea Creek estuary to the south.

The corridor is highly vulnerable to flooding resulting from high tides, storm surge, and rain storms, and inundation from sea level rise, all hazards that are expected to worsen in the future. In the past, flooding and overtopping of Route 1A led to closure of the roadway for repair that lasted for two or more days. The roadway passes through the Rumney Marsh Reservation, a coastal saltwater marsh and wetland and home to a variety of wildlife. This marsh has been undergoing a restoration to preserve the natural resources and control flooding. An initial assessment of the corridor indicated that some culverts have failed or were completely obstructed, and the tidegates were not functioning well because of stuck or missing top floats that control openings and closings of the tidegates.[1]

[1] A tidegate is usually mounted to a culvert on the tidal side. In the event of a storm surge, the tidegate will close and latch automatically and will resume normal water control when the tide returns to normal cycles and levels. The intent of a self-regulating tidegate is to allow for tidal flushing of saltwater marshes during normal tidal cycle, while providing flood protection for upland areas.

The evaluation of vulnerabilities was based on the MC-FRM flood risk probabilities and depth of flooding for four scenarios—representing conditions in the present day, 2030, 2050, and 2070. The flood risk maps show areas vulnerable to flooding based on different combinations of estimates for sea level rise, heights of storm surge and tides, and wave action. The northern segment of Route 1A (from Revere Street to Mills Avenue) is the most highly exposed to climate hazards. The southern segment of Route 1A (from Butler Circle to the Boston city line) is exposed to flooding but not as seriously as the northern segment.

Options for managing climate change impacts on Route 1A include the following:

- **Do nothing and manage retreat–**This option is not recommended because the loss of Route 1A would adversely impact transportation for Revere and other North Shore communities, as the parallel roads, including Route 107, and the MBTA Newburyport/Rockport commuter rail line also have similar flooding issues. Hence, diversion routes would add tens of miles and cause significant delay to motorists.

- **Nature-based solutions—**This option presents effective low-cost alternatives that blend in with the natural environment. MPO staff recommend implementing nature-based solutions for the northern segment of Route 1A to complement restorations efforts of the Rumney Marsh Reservation. When maintained regularly, nature-based measures can provide near-term benefits and long-term benefits when combined with appropriate structural solutions.

- **Floodgate strategy—**This option consists of a floodgate on the mouth of Saugus River with nine gated openings that are tied to 3.1 miles of shorefront improvements along the Lynn Harbor, Point of Pines, and Revere Beach Reservation. The project has received renewed interest and taken on a regional approach to address climate change and rising sea level by providing high level coastal protection for five communities: Everett, Lynn, Malden, Revere, and Saugus.

- **Flood control and protection measures (assess and resize culverts)—**The culverts under Route 1A are 50 years old (installed in 1972) and may be inadequate (undersized) to handle projected sea level rise, storm surges, and heavy precipitation. MPO staff recommend conducting a drainage assessment of the hydraulic and hydrologic capacities of the culverts and self-regulating tidegates to identify any necessary short-term repairs and gather data for planning to replace the existing culverts with larger ones. The improvements would help increase tidal water exchange to saltwater marshes and protect Route 1A from floods and washouts.

- **Flood control and protection measures (upgrade stormwater pump stations)—**There are four pump stations located in the corridor in the low-lying areas, owned and maintained by the City of Revere. Staff recommend conducting a detailed assessment of stormwater pump stations using projected climate data. Such analysis would help to determine overall functionality of the pump stations and necessary upgrades for increasing pumping capacity, identify where drainage outfalls could be relocated, and determine if new stormwater pump stations are necessary for long-term flood protection of vulnerable areas.

- **Flood control and protection measures (construct stormwater controls)—**Stormwater controls such as detention and retention basins and constructed wetlands hold stormwater during intense storms to reduce peak storm runoff rates, settle particles, and decrease flood damage. Detention basin systems may include pump stations to increase efficiency and further reduce the frequency of flooding. MPO staff recommend implementing best management practices for stormwater control for the southern segment of Route 1A.

- **Flood control and protection measures (elevate assets)—**Elevating assets on the northern segment of Route 1A is recommended as a long-term solution. The northern segment would be highly exposed to rising sea level and storm surges beginning in 2030 and these conditions are expected to continue to worsen thereafter. There are limited properties abutting the roadway in the segment, which minimizes the impact that a higher roadway elevation may have on neighborhoods, such as by creating drainage problems and potentially funneling damaging water into homes.

- **Hybrid solutions—**This option combines nature-based and structural solutions to protect infrastructure assets exposed to medium and high wave energy. Hybrid solutions are appropriate and recommended for the northern segment of Route 1A because of its location near the Rumney Marsh Reservation and its high exposure to sea level rise and storm surge. This segment would be inundated the most, according to the flood probability and depth maps, and would need structural solutions (revetments, bulkheads, and roadway elevation) to complement the nature-based solutions.

- **Adaptive and modular solutions—**Adaptive and modular solutions are highly recommended for the northern segment of Route 1A. These solutions involve a collection of policies, nature-based measures, and structural measures to reduce flood risk. This approach provides flexibility among policies and measures to enable transitions from one measure to another over time to account for uncertainty in future projections and to spread costs over time. For example, instead of designing for 2070 or 2100 planning horizon, an adaptive or modular approach could design for a 2050 planning horizon and integrate flexibility to add-on future improvements depending on monitoring results.

ES 6 RECOMMENDATIONS TO THE BOSTON REGION MPO

Resources in terms of data and climate prediction models are available to MPO staff to incorporate resilience in corridor and intersection planning studies. The community survey results indicated support for incorporating resilience into MPO studies. MPO staff could do this with current MPO-funded corridor studies by reviewing the corridors for climate change impacts and incorporating nature-based (green infrastructure) solutions and low-impact development techniques into the improvement concepts.

Also, MPO staff can provide technical assistance on climate resiliency planning to municipalities seeking to combat climate-related challenges. The community survey indicated that municipal staff strongly support the idea of MPO staff providing this technical assistance.

MPO staff could meet this need by collaborating with staff of the Metropolitan Area Planning Council (MAPC) to provide communities with a better understanding of flood risks and adaptation options available to them, and by reviewing and coordinating roadway studies identified in their MVP planning reports and guiding municipalities toward applying for MVP action grants or TIP funding. Any projects that would be candidates for TIP funding would be subject to the MPO's TIP project evaluation criteria.

The MPO continues to consider climate change and resilience when developing the LRTP and revising TIP project evaluation criteria. The survey indicated strong support for these MPO actions.

ES 7 LESSONS LEARNED AND NEXT STEPS

During this study, MPO staff gained knowledge and ideas about how to incorporate climate resiliency planning in corridor and intersection studies. The Route 1A pilot study provided staff with the opportunity to put that knowledge and experience into practice.

Many of the relevant data sources, methodology, and steps in vulnerability assessments were identified. The MC-FRM, for example, was very useful in the Route 1A study. The flood risk probabilities and depth of flooding enabled staff to identify areas where the roadway may be most vulnerable to climate hazards. By being able to target these areas, MassDOT may be able to proactively focus improvement efforts on locations within the corridor that are best suited for protecting assets and natural resources. The RMAT evaluation tool, currently being developed, will be another useful source of information, when ready.

The pilot study resulted in cost-effective strategies for protecting and preserving the Route 1A corridor. The issues, recommendations, and opportunities identified in the study should lead to a regional coordination and interagency participation to advance the recommendations into projects.

Chapter 1—Introduction

1.1 OVERVIEW

Incorporating resiliency into transportation infrastructure has become an increasingly important priority in the Commonwealth of Massachusetts as climate change effects have intensified. Making the transportation system resilient is a growing challenge and addressing the issue is a statewide priority. Massachusetts Executive Order No. 569 called for establishing an integrated climate change strategy for the Commonwealth.[2] As a result of that order, programs are currently in place and ongoing at state agencies to address climate change impacts and support municipalities' resiliency planning. All municipalities in the Boston region have completed vulnerability assessments in their communities and have action-oriented resiliency and hazard mitigation plans for protecting vulnerable assets in their communities.

The Boston Region MPO has recognized the issue of climate change in its past and current long-range transportation plans. The current plan, *Destination 2040*, emphasized the need to plan for resiliency in the transportation system to protect transportation investments. The MPO's goal is to incorporate regular consideration of climate change vulnerability and risk and adaptation strategies in transportation decision-making at system and project levels.

The Boston Region Metropolitan Planning Organization (MPO) has contributed to this resiliency planning. The MPO conducts the federally required metropolitan transportation planning process for the Boston region and works cooperatively to allocate federal and state transportation funds to programs and projects that improve roadway, transit, bicycle, and pedestrian infrastructure. As part of the work, the MPO has been gathering information on climate change and its effects on transportation infrastructure since 2007 and has produced several papers on greenhouse gas reduction strategies and effectiveness.

Many elements of the transportation infrastructure designed to function under historical climate conditions are aging and vulnerable to future climate and weather hazards, such as coastal and inland flooding and extreme heat. Making them resilient to these hazards would protect assets and investments, which could allow for lower maintenance costs, fewer service disruptions, increased safety, system preservation, and economic vitality.

[2] Commonwealth of Massachusetts, "Executive Order No. 569: Establishing an Integrated Climate Change Strategy for the Commonwealth" (September 2016).

Now, the MPO is exploring how to incorporate climate change vulnerability and adaptation measures into transportation decision-making at both the system and project level and how to help municipalities seeking to address extreme weather effects and other climate-related challenges. This MPO-funded study explored ways to incorporate resilience into MPO-funded discrete and recurring studies, how the MPO can help to improve the resilience of the regional transportation system, and how the MPO can focus its technical assistance to communities seeking to address climate change challenges. MPO staff identified best practices, and the lessons learned in the study have provided staff with more knowledge and ideas about how to incorporate resilience into corridor and intersection studies.

This report includes a review of the climate change adaption efforts in Massachusetts, an inventory of available data and models for conducting vulnerability and adaptation assessments, and an analysis of a community survey conducted to identify community needs and efforts addressing climate change impacts. The report also includes results of a pilot study *Route 1A Resilience in Revere*, which allowed MPO staff to work with MassDOT and City of Revere to incorporate resilience into the corridor using existing data and climate projection models. The final chapter presents recommendations to the MPO board about incorporating resilience in corridor and intersection studies and focus areas for technical assistance to member communities. The report has appendices including comments about the study, the survey questionnaire, information about the selection of the study location, and preliminary exposure and criticality ratings.

Chapter 2—Climate Change Resiliency Efforts

This chapter provides a brief summary of the climate change resiliency efforts in Massachusetts, including a focus on adaptation measures and climate resiliency planning efforts in the transportation sector at the state and municipal level.

2.1 CLIMATE CHANGE

As climate change progresses, the Boston region is likely to experience the increasing effects of natural hazards, such as sea level rise, extreme precipitation, and extreme heat and heat waves. These hazards will likely affect transportation systems in the region by flooding roads, bridges, tunnels, and transit stations; creating public transit service disruptions due to power outages; and affecting passenger safety and discomfort on transit due to extreme heat.

Preventing the impacts climate change causes involves applying two types of measures: mitigation and adaptation. In recent years, adaptation techniques have gained immense traction as a viable solution to shield vulnerable communities and critical assets from impacts of climate change. Adaptation measures also complement mitigation measures thus producing an effective hybrid approach.

> Mitigation measures are those actions taken to reduce and curb greenhouse gas emissions, while adaptation measures are based on reducing vulnerability to the effects of climate change. Mitigation, therefore, attends to the causes of climate change, while adaptation addresses its impacts.

Mitigation measures that can reduce emissions include the following:

- Energy efficiency practices
- Expansion of renewable energy sources
- Electrification of industrial processes
- Efficient transportation modes: electric public transport, bicycle and pedestrian, and shared cars

Adaptation measures that increase resiliency to climate change include the following:

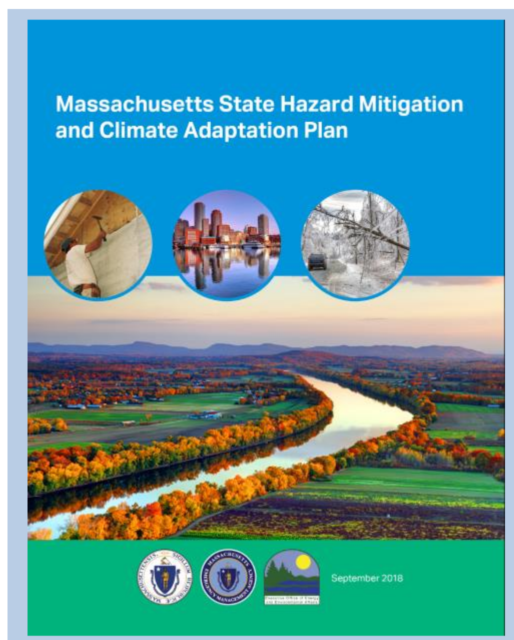
- Securing facility locations and infrastructure
- Landscape restoration and reforestation (nature-based solutions)
- Preventive and precautionary measures: evacuation plans and policies

2.2 CLIMATE RESILIENCY PLANNING IN MASSACHUSETTS

There are several ongoing programs to address climate resilience in Massachusetts. The State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) outlines specific actions and strategies to manage the risks of natural hazards and climate change, and reduce the future costs of rebuilding.[3] The Municipal Vulnerability Preparedness (MVP) Program provides funding for communities to develop action-oriented resiliency plans, such as vulnerability assessments, and implement priority projects. In addition, the local Hazard Mitigation Plan (HMP) establishes a coordinated process to reduce potential losses from future disasters. Additional statewide efforts included the formation of the Resilient Massachusetts Action Team (RMAT), a task force that helps implement the SHMCAP's objectives.

2.3 STATE HAZARD MITIGATION AND CLIMATE ADAPTATION PLAN

The State Hazard Mitigation and Climate Adaptation Plan for the Commonwealth was adopted on September 17, 2018. The SHMCAP satisfies Executive Order No. 569 and provides a framework for each state executive office to assess its agencies' vulnerability to climate change and extreme weather events and to develop policies and programs aimed at climate resiliency planning. This statewide climate adaptation plan is the approved mitigation plan that enables the Commonwealth to receive federal funding for mitigation and adaptation efforts.[4]



One hundred eight actions emerged from the SHMCAP, complete with timelines and agency responsibilities. Progress has been made on the SHMCAP's 108 action items, although some items have much longer timelines than others. For example, the Massachusetts Department of Transportation (MassDOT) is incrementally updating its project design guidelines, which will include incorporating new climate resiliency standards. Appendix B includes MassDOT's resilience programs from the SHMCAP.

[3] Commonwealth of Massachusetts. *Massachusetts State Hazard Mitigation and Climate Adaptation Plan,* (September 2018).
[4] United States Code, *Sec. 322. Mitigation Planning (42 U.S.C. 5165), Robert T. Stafford Disaster Relief and Emergency Assistance Act* (1988).

The purpose of the SHMCAP is to identify risks and vulnerabilities associated with natural disasters and climate change, and to develop long-term strategies for protecting people and property. The plan was developed through coordination with state and federal agencies and local mitigation planning. The Massachusetts Emergency Management Agency (MEMA) updates and submits the state's hazard mitigation plan every five years to the Federal Emergency Management Agency (FEMA) for approval.

The State Hazard Mitigation and Climate Adaptation Plan for the Commonwealth provides the framework for each executive office to assess its agencies' vulnerability to climate change and extreme weather events, and to identify adaptation options. One hundred eight actions emerged from the SHMCAP, complete with timelines and agency responsibilities.

Fourteen climate hazards facing the Commonwealth were assessed in the SHMCAP—inland flooding, coastal flooding, coastal erosion, severe winter storms, hurricanes/tropical storms, extreme temperatures, drought, wildfire, landslides, tsunamis, invasive species, tornados, earthquakes, and other severe weather events (such as high winds). The Resilient Massachusetts Action Team (RMAT) has been established to advance priority actions from the SHMCAP. RMAT has assembled a multidisciplinary team from multiple agencies and researchers to develop standards, guidelines, and capital planning tools for supporting climate resilience projects in the state.

2.4 LOCAL HAZARD MITIGATION PLANS

The Robert T. Stafford Disaster Relief and Emergency Assistance Act provides hazard mitigation funding to municipalities that develop a hazard mitigation plan (HMP) that meets specified criteria. [5] These funds are typically administered by FEMA.[6] The local HMP must be developed with an open public involvement process, the planning process must be

The local hazard mitigation plan has three elements. Municipal planners must first identify their communities' hazards, risks, and vulnerabilities. Then, they must clearly describe mitigation activities and planned actions to reduce losses from the hazards. Finally, they must establish a strategy to implement those actions. Of the 97 communities in the Boston region, 78 have hazard mitigation plans and eight communities are currently developing one.

[5] United States Code, *Sec. 322. Mitigation Planning (42 U.S.C. 5165), Robert T. Stafford Disaster Relief and Emergency Assistance Act* (1988).

[6] The Federal Disaster Mitigation Act of 2000 requires all municipalities that wish to be eligible to receive FEMA funding for hazard mitigation grants to adopt a local multi-hazard mitigation plan and update this plan in five-year intervals.

documented, and the maintenance process must be integrated with other municipal planning efforts.

The HMP represents a municipality's commitment to address potential hazards by allocating resources to mitigation activities. The HMP also informs state leaders of technical assistance and prioritization of project funding.[7] The state is required to provide technical assistance and training to local governments to assist them in applying for hazard mitigation grants and in developing local mitigation plans.

2.5 MUNICIPAL VULNERABILITY PREPAREDNESS PROGRAM

The Municipal Vulnerability Preparedness Program is one example of technical assistance offered by the Commonwealth. This community-led program addresses social equity, assets and liabilities, and informs coordinated statewide efforts, such as the SHMCAP. All 97 communities in the MPO region are designated MVP communities.

The Massachusetts Executive Office of Energy and Environmental Affairs (EEA) initiated the Commonwealth's MVP grant program in 2017 to help communities plan and take action toward becoming more resilient to the impacts of climate change.[8] The MVP program is one example of technical assistance offered by the Commonwealth. Municipalities use MVP funding to determine top hazards and vulnerabilities, develop priorities and recommendations, produce HMPs, conduct workshops and public listening sessions, and generate final deliverables and reports. Once a community receives MVP designation, it can apply for additional funding (such as MVP Action Grants) to pursue projects identified in the MVP Planning Grant process.

The MVP Program has been very successful since it began in 2017. As of September 2020, 89 percent of the Commonwealth, or 312 communities, are "MVP Designated" communities. The grant program has awarded more than $44 million statewide. The focus areas for the MVP Action Grants include nature-based storm-damage protection, drought mitigation, water quality and infiltration techniques, infrastructure and technology solutions to reduce vulnerability to

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[7] Code of Federal Regulations. *Title 44- Emergency Management and Assistance, Part 201-Mitigation Planning* (Washington, DC: October 2013), 364-374.

[8] The MVP grant program provides support for cities and towns in Massachusetts to begin the process of planning for climate change resiliency and implementing priority projects. The state awards funding to communities to complete vulnerability assessments and develop action-oriented resiliency plans. Communities that complete the MVP program become certified as an MVP community and are eligible for MVP Action Grants and other opportunities.

extreme heat and poor air quality, and nature-based solutions to reduce vulnerability to climate change impacts, such as ecological restoration and habitat management.

Municipalities are eligible for MVP Action Grant funding for the following project types:

- Planning assessments and regulatory updates
- Nature-based solutions for ecological and public health
- Resilient redesigns and retrofits for critical facilities and infrastructure

Key Indicators from MVP Planning Grant Reports
Top hazards: freshwater flooding; severe winter storms; extreme temperatures
Top vulnerabilities: vulnerable populations; roadways; stormwater management
Top priorities: regulations, zoning and policy; data and maps; emergency management and preparedness

Source: Massachusetts Executive Office of Energy and Environmental Affairs.

2.6 COMPARING PLANS: MVP PROGRAM AND LOCAL HMP

The MVP Program deliverables and the HMP share many qualities as regards process development and content. Both require a dedicated project team and a public engagement component, and both use climate science and local knowledge to identify vulnerable assets and determine risk and liabilities. The MVP Program is not associated with federal disaster mitigation funding. A local HMP is a federal requirement for receiving federal disaster mitigation funding.

MVP reports are typically less technical than HMPs. The MVP Program generally focuses on climate change and allows for some flexibility in developing action items. Action items are based on community members' perceptions, which may not reflect climate projections or the hazard's actual implications. Municipal HMPs account for past and current hazards that triggered federal remedial funding, unlike most MVP Program reports.

A municipality can use an MVP Planning Grant to produce a combined MVP and HMP document, or update an outdated HMP, to streamline the process that satisfies both EEA and MEMA requirements. A municipality does not need an HMP to receive MVP designation.

2.7 RESILIENCE AND ADAPTATION MEASURES

Communities can adopt a variety of adaptation measures to build resilient communities and respond to climate change. Given the natural, ecological, socio-economic, land use, and infrastructure conditions particular to each community, a combination of measures must be employed to build resilient transportation systems. The most common types of adaptation solutions in the SHMCAP, local

HMPs, and MVP reports are nature-based, structural, and policy-based measures.

2.7.1 Nature-Based Measures (Green Infrastructure)

Nature-based solutions can provide protection for infrastructure and natural resources for decades before more costly structural adaptation measures (walls, bulkheads, and revetments) would be required.[9] Numerous resources are available from the Federal Highway Administration (FHWA) and the Massachusetts Office of Coastal Zone Management (CZM) to guide engineers and planners and many more resources are in development.

Listed below are the most common nature-based solutions:

- Shade trees help lower temperature by providing shade and mitigate stormwater flows through evapotranspiration.
- Living shorelines are an alternative to bank and shoreline stabilization measures that use natural and organic materials that complement the natural shoreline characteristics while providing suitable habitat for local species.[10]
- Permeable and porous pavements and vegetative buffers and islands in large parking areas filter stormwater and reduce runoff.
- Green stormwater infrastructure incorporates vegetated features including rain gardens, constructed wetlands. And green stormwater practices are designed to allow stormwater to infiltrate into the ground, evaporate into the air, or transpire from vegetation, or temporarily store stormwater runoff. These options provide other benefits, including mitigation of the urban heat island effect, habitat creation, and water and air quality benefits.[11]
- Vegetated berms are compacted earthen levees constructed parallel to the shoreline that act as barriers to flooding.

> Nature-based solutions mimic characteristics of natural features but are created by human design, engineering, and construction. They can be less costly than engineering solutions. They enhance quality of life and provide habitat for local species. Federal and state agencies view these green infrastructure options as preferred adaptation measures.

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[9] Choate, et al., *Synthesis of Approaches for Addressing Resilience in Project Development,* Federal Highway Administration, United States Department of Transportation, (July 2017), 55.

[10] Federal Highway Administration, *Living Shoreline along Coastal Roadways Exposed to Sea Level Rise: Shore Road in Brookhaven, New York*, (September 2016), 21.

[11] City of Boston and Boston Planning & Development Agency, *Coastal Flood Resilience Design Guidelines,* (September 2019).

- Blue belts divert stormwater away from buildings and important facilities to low-lying areas or detention basins by gravity-based drainage systems.[12]

2.7.2 Structural Measures (Engineering or Gray Infrastructure)

Structural measures to make the transportation system more resilient are engineered solutions, often called gray infrastructure improvements. Examples of these measures are listed below:

- Rebuilding undersized culverts and widening bridge openings
- Rock revetments (sloping structures, usually rocks) for protecting embankments for coastal roads against erosion caused by wave action, storm surge, and currents
- Levees, storm surge barriers, seawalls, bulkhead, groins, flood-proofing techniques, and detached breakwaters
- Elevation of assets (roadway, bridge, structures, and utilities) above the projected flood elevation or relocation of existing vulnerable critical assets outside of high-risk areas

When making structural changes to infrastructure, such as culverts and bridges, it is important to take an approach that considers the condition of downstream infrastructure and avoids increasing the vulnerability of undersized assets and less prepared communities.[13]

2.7.3 Policy-Based Measures

Policy-based measures are long-range planning tools applicable both at state and local levels for incorporating climate resiliency into planning efforts. Often these are comprehensive plans and regulatory and non-regulatory policies to help guide development within communities in order to address climate change impacts.

Comprehensive plans can include the following activities:

- Developing emergency action plans for specific hazards
- Incorporating resiliency into planning efforts, including in comprehensive master plans, capital planning processes, and plans for open space, harbors, hazard mitigation, floodplain management, stormwater management, and Complete Streets
- Implementing flood warning systems and monitoring specific hazard conditions

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[12] City of Boston and Boston Planning & Development Agency, *Coastal Flood Resilience Design Guidelines,* (September 2019).

[13] Choate, et al., *Synthesis of Approaches for Addressing Resilience in Project Development,* Federal Highway Administration, United States Department of Transportation, (July 2017), 58.

Regulatory tools include the following:

- State and federal regulatory compliance
- Land use regulations
- Design flood elevation at or above base flood elevation
- Design guidelines (for example, to require the elevation of foundations in new construction or to locate critical systems to upper level floors)
- Stormwater management practices (for example, to encouraging the use of porous pavement and vegetative buffers and islands in large parking areas)
- Flood resilience zoning overlay districts
- Zoning restrictions to limit, prohibit and/or regulate development in hazard areas

Non-regulatory tools include the following:

- Buy-outs and transfer of development rights
- Rolling easements and conservation easements
- Land acquisition for proposed conservation and preservation
- Stormwater fees
- Impact fees imposed upon developers and/or property owners to fund public hazard mitigation projects or payments that mitigate the impacts of new development
- Incentives or disincentives for hazard mitigation measures (for example, special tax assessments to discourage builders from constructing in hazardous areas)

2.8 TRANSPORTATION RESILIENCE AND THE BOSTON REGION MPO

As the climate resiliency planning field continues to evolve within Massachusetts, cities and towns in the Boston region can take advantage of existing resources while new ones are being developed. With the adoption of the MPO's long-range transportation plan (LRTP), *Destination 2040*, in August 2019, the MPO strengthened its resolve to focus on making the transportation system more resilient. During selection of the investment programs in the LRTP, the MPO decided that resiliency should be integrated into all its investment programs:

- Major Infrastructure Program

- Complete Street Program
- Bicycle and Pedestrian Connections Program
- Intersection Improvements Program
- Transit Modernization Program
- Community Connections Program

Each year, when reviewing projects to receive funding through the MPO's Transportation Improvement Program (TIP), the MPO considers whether project designs will help to make a more resilient transportation system.

During the development of *Destination 2040*, the MPO revisited its vision, goals, and objectives and put more emphasis on creating a resilient transportation system. Since the adoption of *Destination 2040*, the MPO has revised its project selection criteria for both its LRTP and Transportation Improvement Program (TIP), the MPO's five-year capital plan, to strengthen its resiliency criteria.

In addition, the MPO is monitoring ongoing work at the local, state, and federal levels for up-to-date climate data, policies, and programs. Within the Boston region, municipalities are taking a collaborative approach. For example, the Minuteman Advisory Group on Interlocal Coordination (MAGIC) released its *Climate Change Resilience Plan: Vulnerability Assessment & Response Strategies*, which addresses climate change from a regional perspective.

Also, the FHWA Order 5520, which established the FHWA's policy on climate change resiliency and preparedness, is encouraging MPOs to develop, prioritize, implement, and evaluate risk-based and cost-effective strategies to minimize climate impacts and protect critical infrastructure using the best available science, technology, and information.[14]

[14] Federal Highway Administration, "FHWA Order 5520: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events," (December 2014), 1-6.

Chapter 3—Data Sources and Models for Analysis

Vulnerability and adaptation assessments require various types of data on transportation assets, climate, land use, socio-economics, and demographics. This chapter focuses on the datasets, models for climate projection data, and relevant sources. The objective is to inform the MPO of any challenges in obtaining the necessary data for assessing resilience in MPO corridor and intersection studies. Climate data come from a variety of sources including state and federal agencies, local governments, and MPOs. Climate data require professional interpretation. For best practices, a multidisciplinary team is usually convened to determine the scope of data collection and integration. In Massachusetts, the RMAT team is coordinating this effort to help identify all existing data and manage data collection efforts and to ensure that agencies are all using the same data for analyses.

3.1 VUNERABILITY ASSESSMENT DATA

Data required for vulnerability assessments come from multiple sources. For transportation data, MassDOT's geoDOT website provides a platform that gives MassDOT and its partners the ability to share geographic information systems (GIS) data and track data on many of the transportation assets in the Commonwealth. These assets include roads and highways, pedestrian walkways and bikeways, railways, ports, ferries, bridges, culverts, and bus stations and bus stops. The geoDOT portal has web-based GIS tools that allow for display of various datasets simultaneously. The MPO staff houses models for projecting traffic and ridership data.

> Vulnerability assessment and adaptation solutions require data and information on transportation assets, land use, transportation equity, demographics, and socio-economic variables. MassDOT's geoDOT website provides a platform for sharing and tracking transportation assets. The MPO and MAPC track data on land use, population, socio-economic variables, and critical facilities.

Land use, demographic, and socio-economic data are available at MAPC. Land use data include zoning, regulations, and ecosystems. Demographic and socio-economic data include population, income, vulnerable populations, and other transportation equity indicators.

3.2 CLIMATE DATA

Vulnerability assessments require climate data to establish the projected future climate conditions to which assets would be exposed and to set planning horizons. Historical data and projections for changes in temperature, precipitation, sea level rise, and storm surge all factor into these assessments. The objectives and scope of the assessment and the type of asset usually determine the climate data to collect and the planning horizon.

3.2.1 State Data Resources

Massachusetts is leading the nation on climate change and adaptation efforts. Since Executive Order No. 569 and the release of the SHMCAP, state agencies have been coordinating efforts to address climate change impacts. Some of these efforts are focused on establishment of data resources, standardizing climate resilience design standards, modeling for climate data projections, and gathering the necessary data and information to support the monitoring and management of assets and systems.

CZM is the lead policy, planning, and technical assistance agency on coastal and ocean issues within the EEA and implements the state's coastal program under the federal Coastal Zone Management Act. CZM has a wealth of information on coastal management and resilience. CZM has developed the sea level rise and coastal flooding viewer for the Commonwealth. The tool maps areas of potential inundation under various sea level rise and worst-case hurricane surge scenarios and areas located within the FEMA coastal flood zones.

Massachusetts Coast Flood Risk Model

The Massachusetts Coast Flood Risk Model (MC-FRM) is the state's standard for assessing coastal assets. This model derived from the Boston Harbor Flood Risk Model (BH-FRM), which was developed to determine inundation risk and flood pathways affecting the Central Artery Tunnel and to simulate the dynamic nature of flooding in the City of Boston. The BH-FRM was an advanced model that simulated the effects of tides, storm surge, wind, waves, wave setup, river discharge, sea level rise, and future climate change scenarios. The model, now called the MC-FRM, was expanded to cover the entire Massachusetts coast and islands. The MC-FRM supports assessment of vulnerability and risks for coastal communities outside of the Boston Harbor area.

> The MC-FRM is the state's standard for assessing vulnerability and risk to coastal assets. The MC-FRM produces storm surge, flood, and sea level rise information for the present day and horizon years of 2030, 2050, 2070, and 2100.

The MC-FRM produces storm surge, flood, and sea level rise information for short-, medium-, and long-term risks for projecting to horizons such as 10, 30, and 50 years from the present. The probability-based results can be effectively used to assess vulnerabilities and prioritize planning and to test various adaptation and engineering options. Model outputs—including tidal benchmarks, base flood elevation (BFE), wave heights, duration of flooding, design flood velocity, wave forces, and scour or erosion—can be requested from the MC-FRM for various planning horizons and exceedance probabilities (the probability of a flood event being equaled or exceeded each year).

Climate projections based on scenarios ensure that the assessment is considering a range of possible futures rather than relying on any one single climate scenario. In addition, the RMAT teams are developing standards for consistent climate projection data to use in projects analyses, guidelines for best practices to incorporate climate resilience into projects through the planning and design phases to implementation, and tools enabling users to quantify benefits of resilient projects.

3.2.2 Federal Data Resources

Climate data and models for projections are also available at federal agencies that make them available to states, MPOs, and local governments. Federal agencies, such as the National Oceanic and Atmospheric Administration (NOAA), FEMA, United States Geological Survey (USGS), and United States Army Corp of Engineers (USACE) have several datasets and tools for displaying climate data. Because climate models and projections are complex and constantly evolving as new methods, variables, and high-quality data becomes available, federal and state agencies and research institutions are collaborating to develop models and tools for use across the country.

> Federal and state agencies' efforts and collaborations have made available climate and environmental data, models, tools for assessing vulnerability and planning for resilience. NOAA, FEMA, USGS, and USACE are some of the agencies that provide climate data and models for sea level rise, storm and wave surge, stormwater and river discharge, precipitation, and extreme heat conditions.

Sea Level Rise and Storm Surge

NOAA's sea level rise data provides a preliminary look at coastal areas likely to be inundated at high tide by various levels of sea level rise. The information includes vulnerability and risk maps that can be used to examine the impacts of different sea level rise scenarios, as well as to learn about impacts to locations.

In addition, NOAA's National Weather Service produces estimates of storm surge heights and flooding vulnerability that helps to evaluate the risk of storm surge in hurricane-prone coastal areas along the East and Gulf Coasts of the United States and Puerto Rico.

Stormwater Flooding, Extreme Precipitation, and Heat

FEMA produces flood insurance rate maps (FIRMs) that show flood hazard zones applicable to a community. The information from the maps are used to better understand flood risk and type of flooding, and for assessing vulnerability. The maps depict flood levels associated with one percent chance of annual flood risk (the 100-year storm) and 0.2 percent chance of annual flood risk (the 500-year storm).

NOAA's Atlas 14, Volume10, contains precipitation frequency estimates for the northeast United States. The maps provide estimates of temporal distribution of heavy precipitation and annual exceedance probabilities (AEP). The precipitation data are used for managing stormwater, redefining floodplains, and making design decisions to increase the useful life of infrastructure and protect communities and water resources from unnecessary risk.

USGS provides data on how streamflow and floodplains may be affected as a result of changing precipitation patterns, sea level rise, and storm surges. Many other sources of climate information on natural hazards, health of ecosystems and the environment, and the impacts of climate and land-use change are available from USGS.

Chapter 4—Survey

This chapter provides an insight into the climate change impacts and transportation resiliency planning in the Boston region. The MPO staff conducted a survey of municipalities in the region to learn more about the resilience practices they are currently using. The participants were identified through several sources—the MPO's contact database and contacts listed in MVP and HMP reports. All 97 cities and towns in the Boston Region MPO's planning area were asked to complete the survey.

Participants were given four weeks to complete the survey. Extensive efforts were made to increase survey participation through identification of alternative contacts within those communities where we did not reach the original contact. In addition, two email reminders were sent to participants to complete the survey: one midway from the deadline and one close to deadline.

Nineteen municipalities participated in the survey, a completion rate of approximately 20 percent. Figure 1 shows the cities and towns that completed the survey. They represent communities with varying climate hazards, transportation network components, and adaptive capacities.

> The survey was developed to better understand how municipalities in the Boston region are using resilience practices in their planning and engineering, and the challenges these municipalities face in making transportation assets more resilient to climate change impacts. Nineteen municipalities participated in the survey, a completion rate of approximately 20 percent.

4.1 SURVEY RESULTS

The survey began by asking information about the municipality and the respondent's area of expertise. Participants from each municipality worked in the planning, public works, environmental, or engineering departments. Next, the respondents were asked 10 questions categorized into three sections:

1) The impact of climate change on transportation
2) Climate resiliency planning for the transportation assets
3) Transportation resilience and the MPO

See Appendix C for the questionnaire.

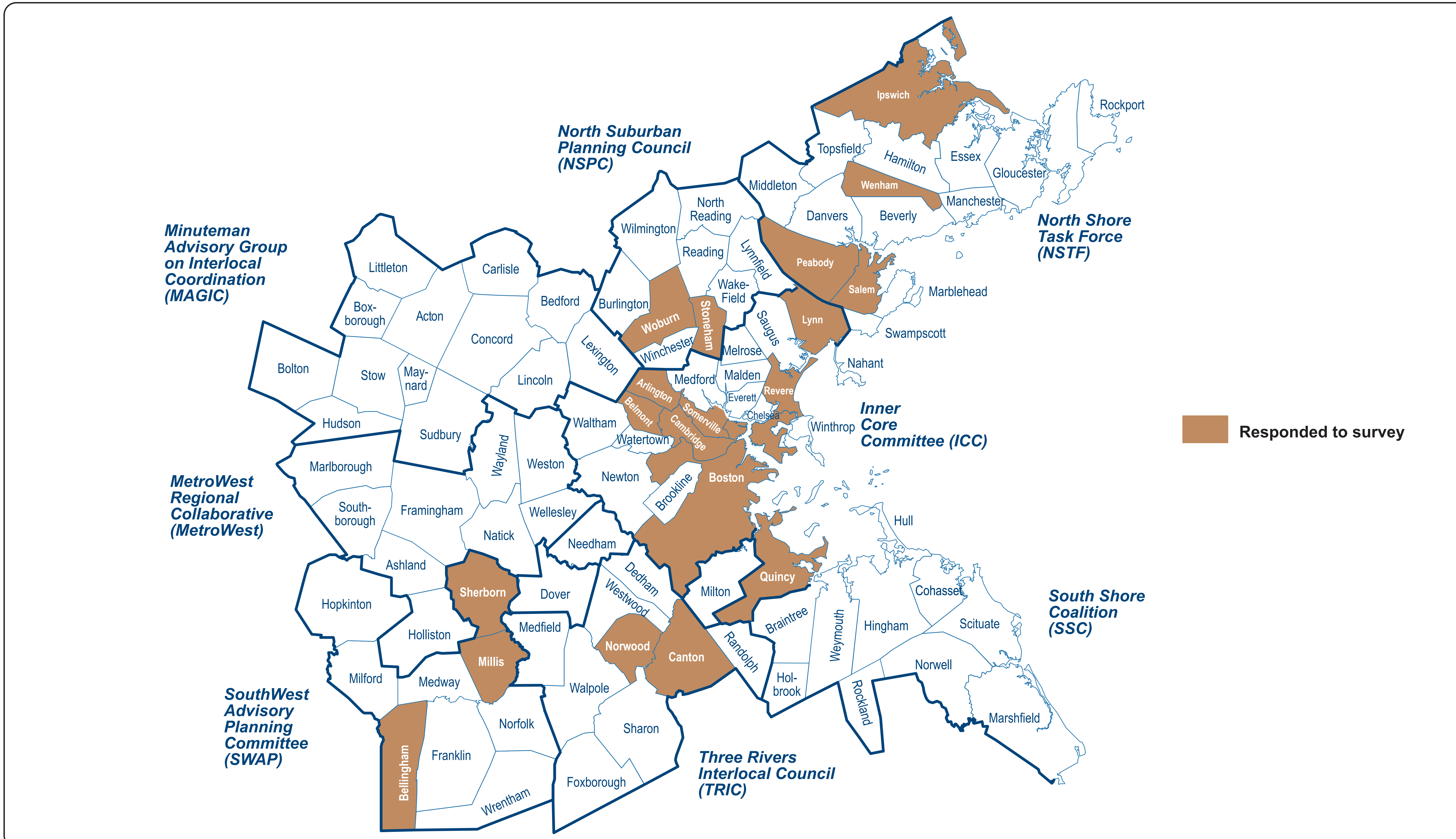

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FIGURE 1
Survey Respondents

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Figures 2 through 9 show the results for each question. The following are takeaways from survey:

- Stormwater flooding and snow/ice are major hazards for many municipalities.
- Roads, bridges, and culverts are the major transportation assets vulnerable to climate hazards.
- Municipalities are taking multiple approaches to addressing transportation resiliency.
- The MVP, HMP, and CIP are the main tools for addressing resilience.
- Stormwater flooding is a major concern identified in both MVP and HMP reports.
- Stormwater management solutions and field inventories of culverts and bridges are the top recommendations to improve transportation resilience.
- Municipalities employ a wide range of policy measures to make the transportation system resilient to climate change.
- There is a demonstrated need and opportunity for the MPO to help improve the resilience of the regional transportation system (provide technical assistance and incorporate resilience into studies).

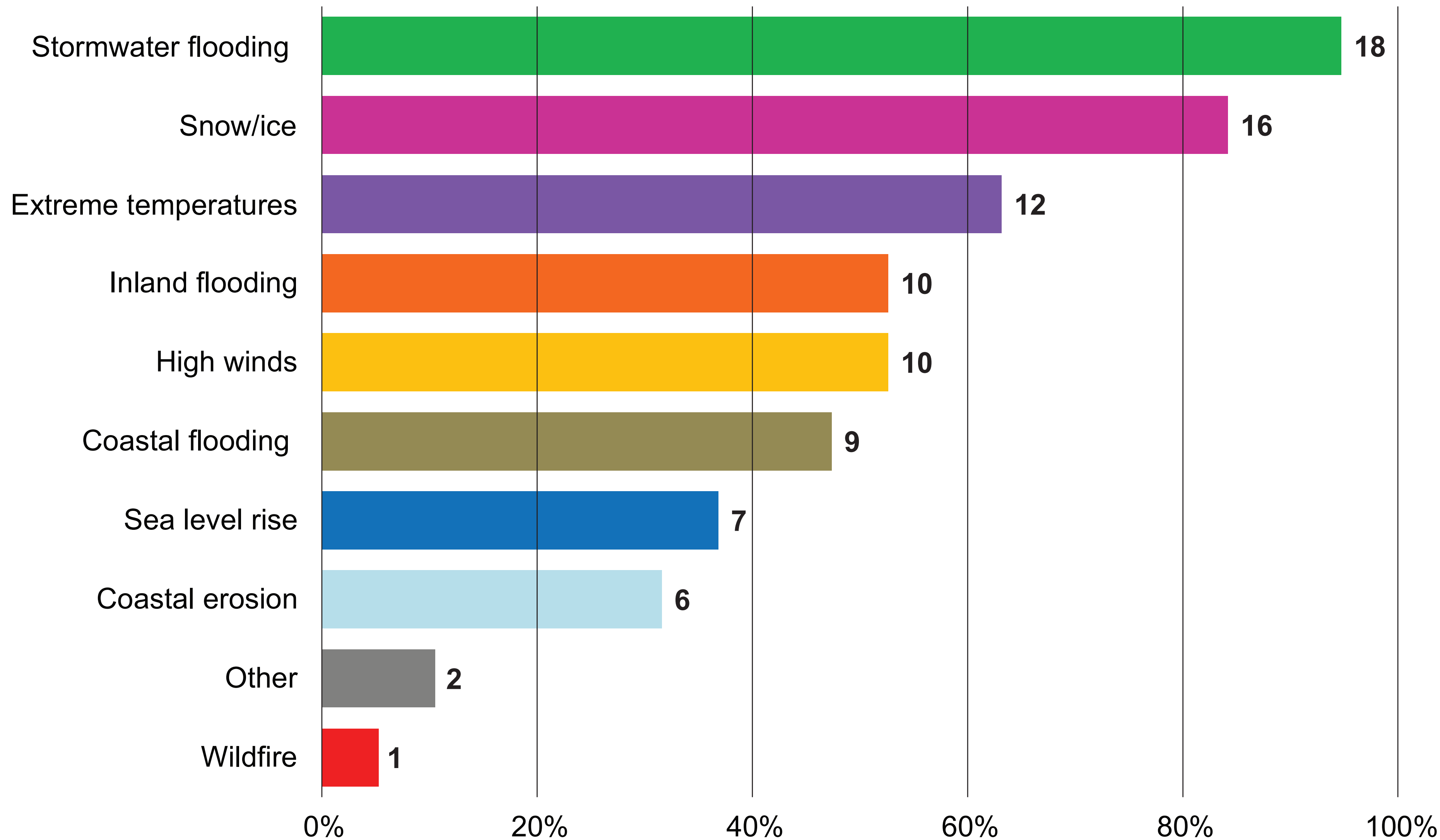

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FIGURE 2
Hazards and Stressors

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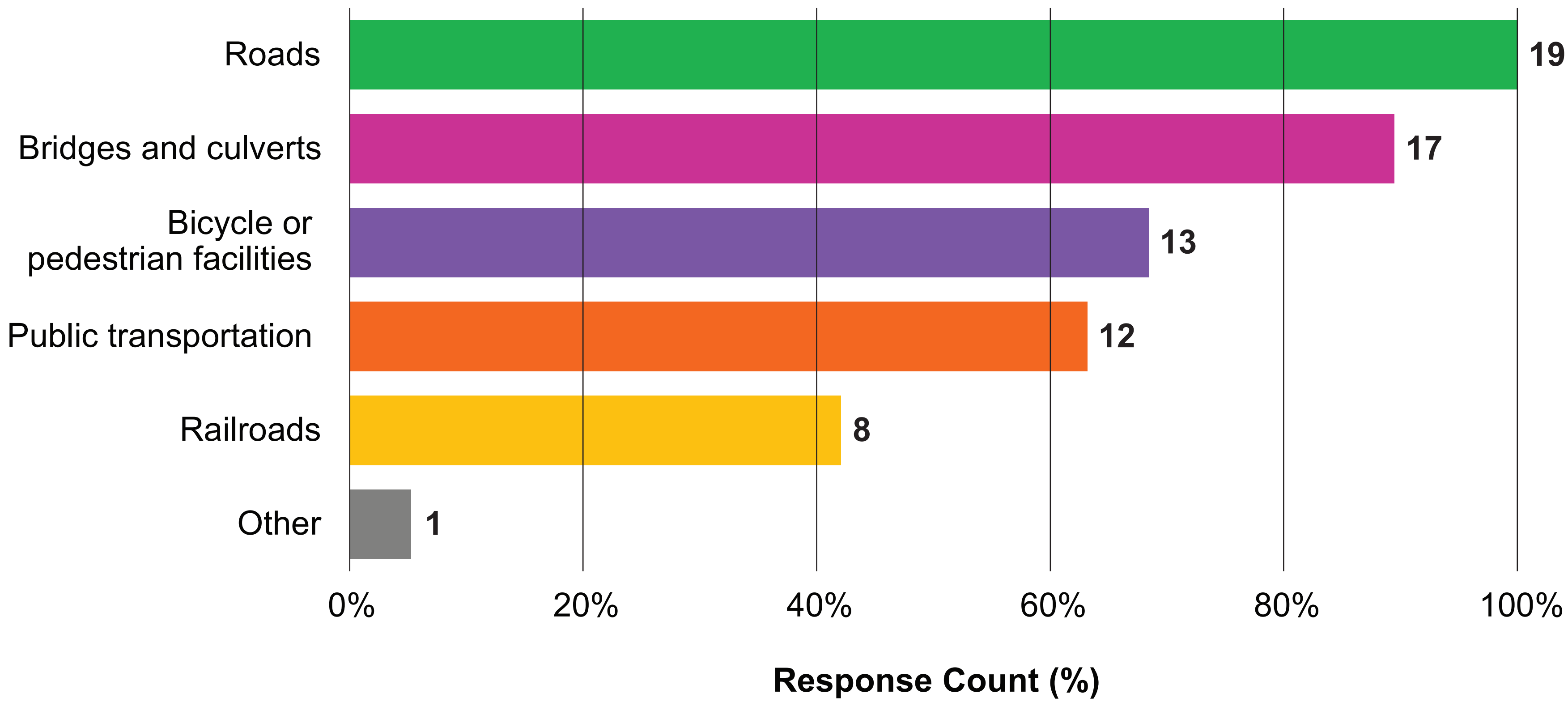

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FIGURE 3
Transportation Assets Vulnerable to Climate Hazards

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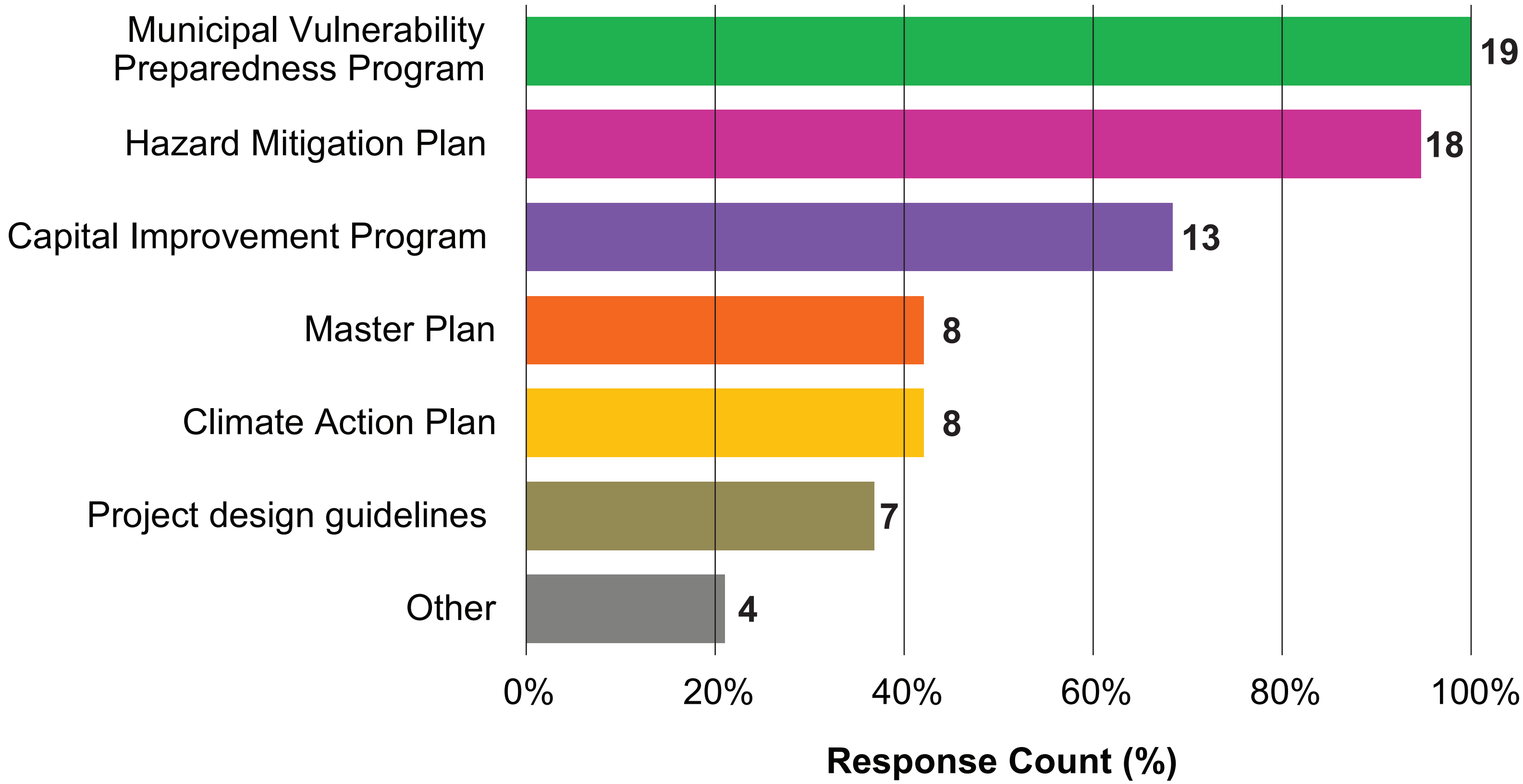

FIGURE 4
Transportation Resilience Tools

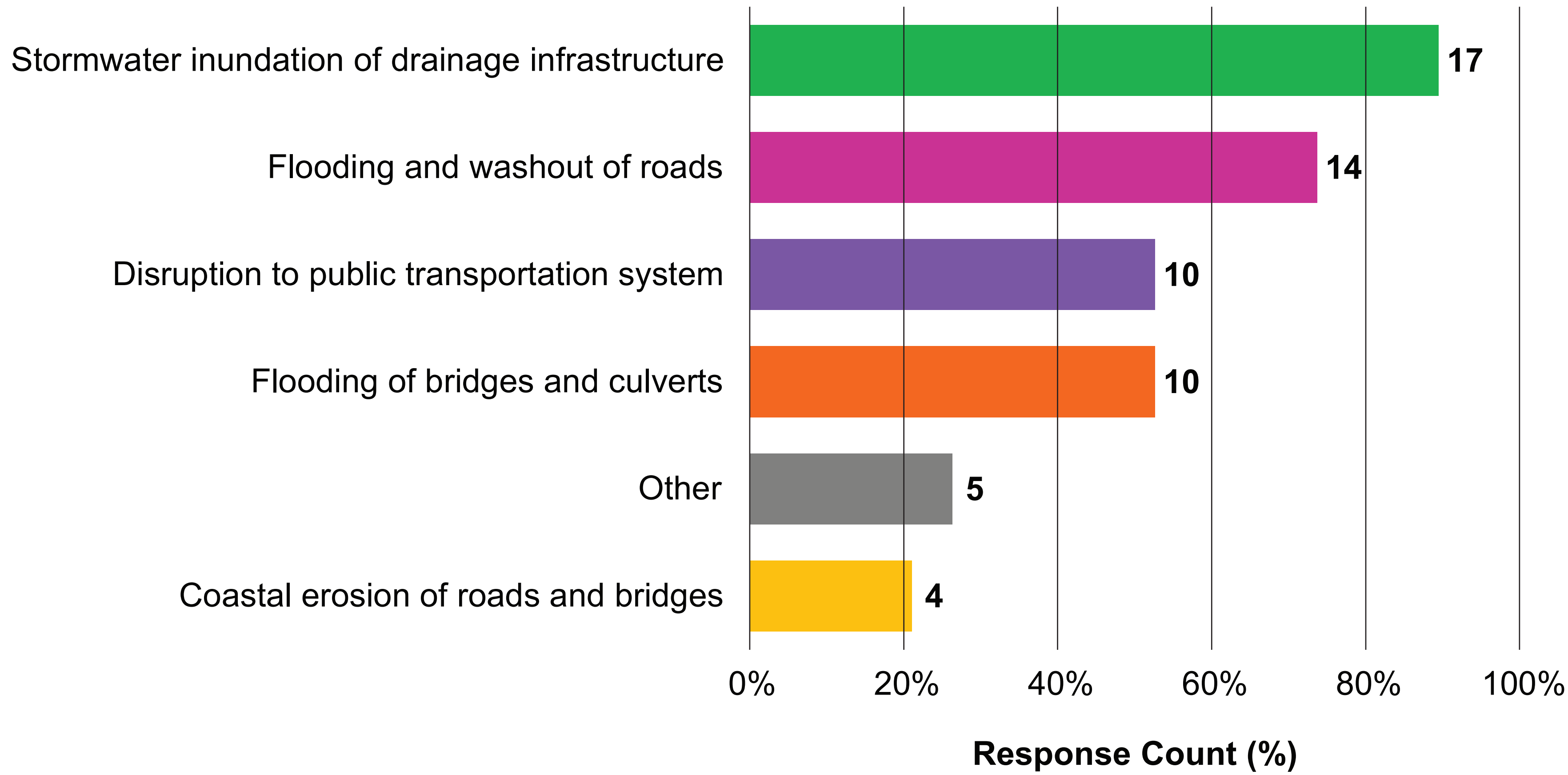

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FIGURE 5
Climate Change Impacts of Greatest Concern to Transportation Assets

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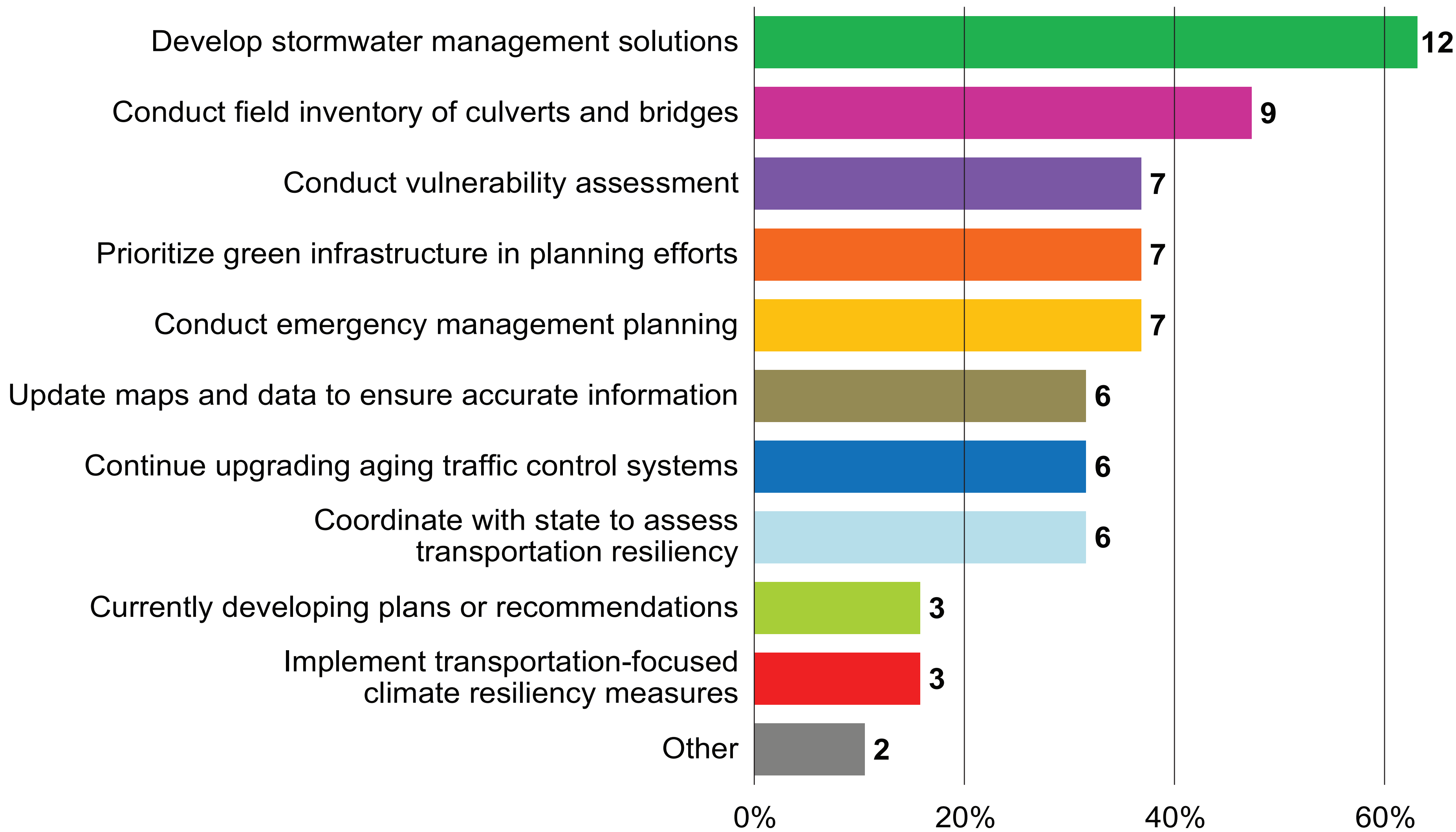

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FIGURE 6
Top Recommendations to Improve Transportation Resilience

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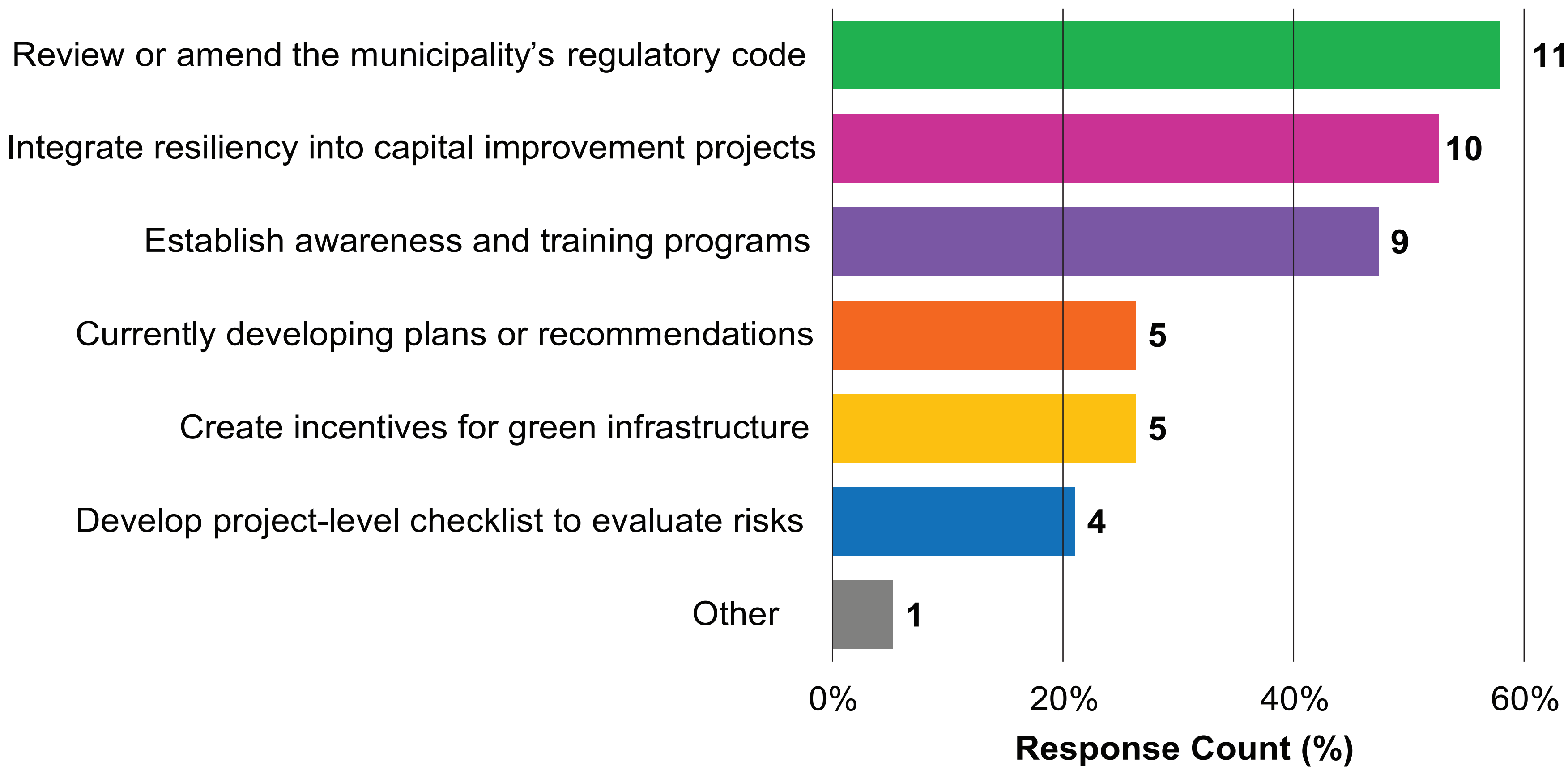

FIGURE 7
Policy Measures and Action Plans to Make Transportation System Resilient

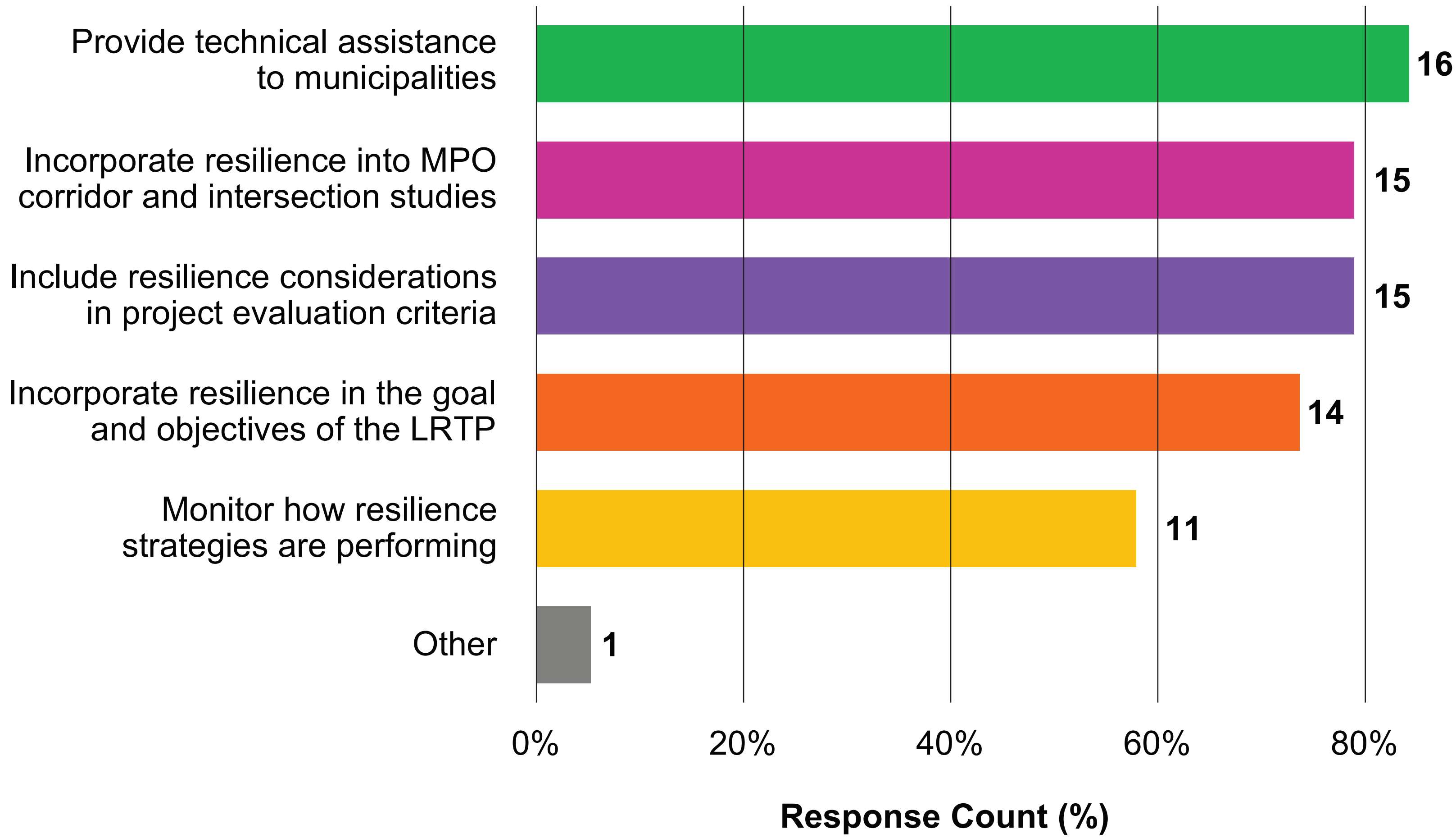

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FIGURE 8
Actions to Improve Resilience of the Regional Transportation System

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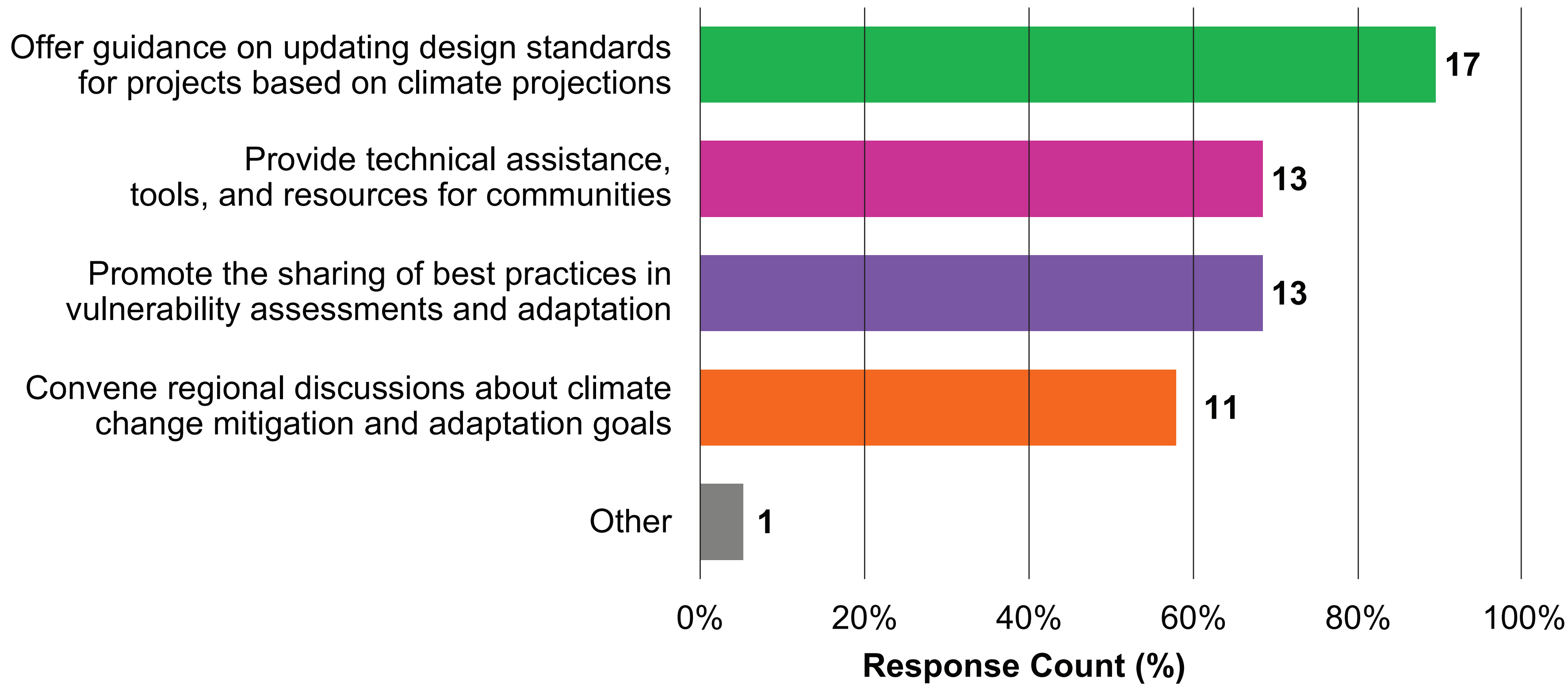

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FIGURE 9
Types of Technical Assistance to Municipalities

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Chapter 5—Revere Route 1A Resilience

5.1 PROBLEM AND CONTEXT

The purpose of the pilot study was twofold: (1) to work with MassDOT and the City of Revere to identify problems and develop recommendations to make Route 1A resilient and protect natural resources, and (2) to provide MPO staff with ideas of how to use available resources effectively to incorporate resilience into MPO-funded corridor and intersection studies and help municipalities seeking to address transportation resilience.

The Route 1A traverses natural low-lying areas with elevations around 10 feet above sea level (surveyed relative to the North American Vertical Datum of 1988 [NAVD 88]) and is close to the flood pathways of the Pines River estuary to the north and the Chelsea Creek estuary to the south. The corridor is highly vulnerable to flooding resulting from high tides, storm surge, and rain storms, and inundation from sea level rise, all hazards that are expected to worsen in the future. In the past, serious flooding and overtopping led to closures of the roadway for repair that lasted for two or more days. Route 1A passes through the Rumney Marsh Reservation, a coastal saltwater marsh and wetland, and home to a variety of wildlife. The marsh has been undergoing a restoration to preserve the natural resources and control flooding.

5.2 SELECTION OF THE STUDY LOCATION

Route 1A in Revere was selected as the location for a pilot study after a review of other hazard-prone corridors in the Boston region. The selection process consisted of three steps:

1. MPO staff gathered and assembled vulnerable corridors from the MVP and HMP reports.
2. MPO staff evaluated the corridors considering transportation equity, multimodal significance, regional significance, planned and programmed projects, and action items in the MVP and HMP reports. MPO staff identified 12 corridors as candidates for study. (See Appendix D.)
3. MPO staff reviewed climate data and models required for assessing the corridors. For coastal flooding risks, the MC-FRM is available for use in assessments, however models for inland flooding are currently being developed.

The focus on coastal flooding narrowed the selection further to six corridors. Route 1A in Revere was selected because it is particularly vulnerable to flooding. The MassDOT Office of Transportation Planning is in the midst of the procurement process for a Route 1A East Boston Corridor Study. The local study area is anticipated to encompass the land segment west of Route 1A, as well as Route 1A from Chelsea Street/Saratoga Street to Bell Circle in Revere. The regional study area is expected to include East Boston, Revere, Lynn, Chelsea, and Winthrop. In addition, MassDOT Project 608396, *Bridge Reconstruction, Route 1A over Saugus River, substructure and superstructure investigation and necessary repairs/reconstruction,* is in the preliminary design stage. MassDOT is currently studying final structure options and coordinating with the United States Coast Guard and City entities at each end, in Revere and Lynn. MassDOT and the City of Revere have expressed support for the pilot study.

5.3 PROJECT AREA DESCRIPTION

Route 1A is critical to the regional transportation system. It is an evacuation route and it provides access to residential, educational, recreational, commercial, and industrial areas. Residents of North Shore communities use this roadway to connect to Boston and Logan Airport and to access the Blue Line at the MBTA's Wonderland Station in Revere. Classified as a principal arterial, Route 1A is part of the National Highway System (NHS) and it is federal-aid eligible. Traffic volumes vary along the corridor, from approximately 62,000 vehicles per day at the Boston and Revere city line to approximately 40,000 vehicles at the Lynn and Revere city line.

Figure 10 shows the study limits on the four-mile, four-lane highway between the Boston and Lynn city lines. This section of highway is open to all vehicles, has partial access control, and is a designated state truck route. The speed limits vary from 30 miles per hour (mph) at the busy segments to 50 mph in the less busy, unsettled areas. Figure 11 shows pictures of the roadway at several locations. MassDOT has jurisdiction of the road, which was recently transferred from the Department of Conservation and Recreation (DCR).

5.3.1 Asset Characterization

The assets on Route 1A were characterized to document their conditions and interdependencies. Table 1 presents the various assets in the corridor. Data on their locations and conditions were obtained from MassDOT's geoDOT platform and the MPO's data resources. Although, transportation assets are the focus of the study, the roadway coexists with natural resources and other facilities. Figure 12 shows the locations of the transportation assets: bridges, culverts, tidegates, and traffic signals.

Table 1
Route 1A Asset Category, Type, and Subtype

Asset Category	Infrastructure	Natural resources
Asset Type	Transportation	Coastal resource area
Asset Subtype	Road	Coastal wetland
	Bridge	Land exposed to tidal action
	Culverts	Saltwater marsh
	Tidegates	Estuarine open water
	Bus stops	

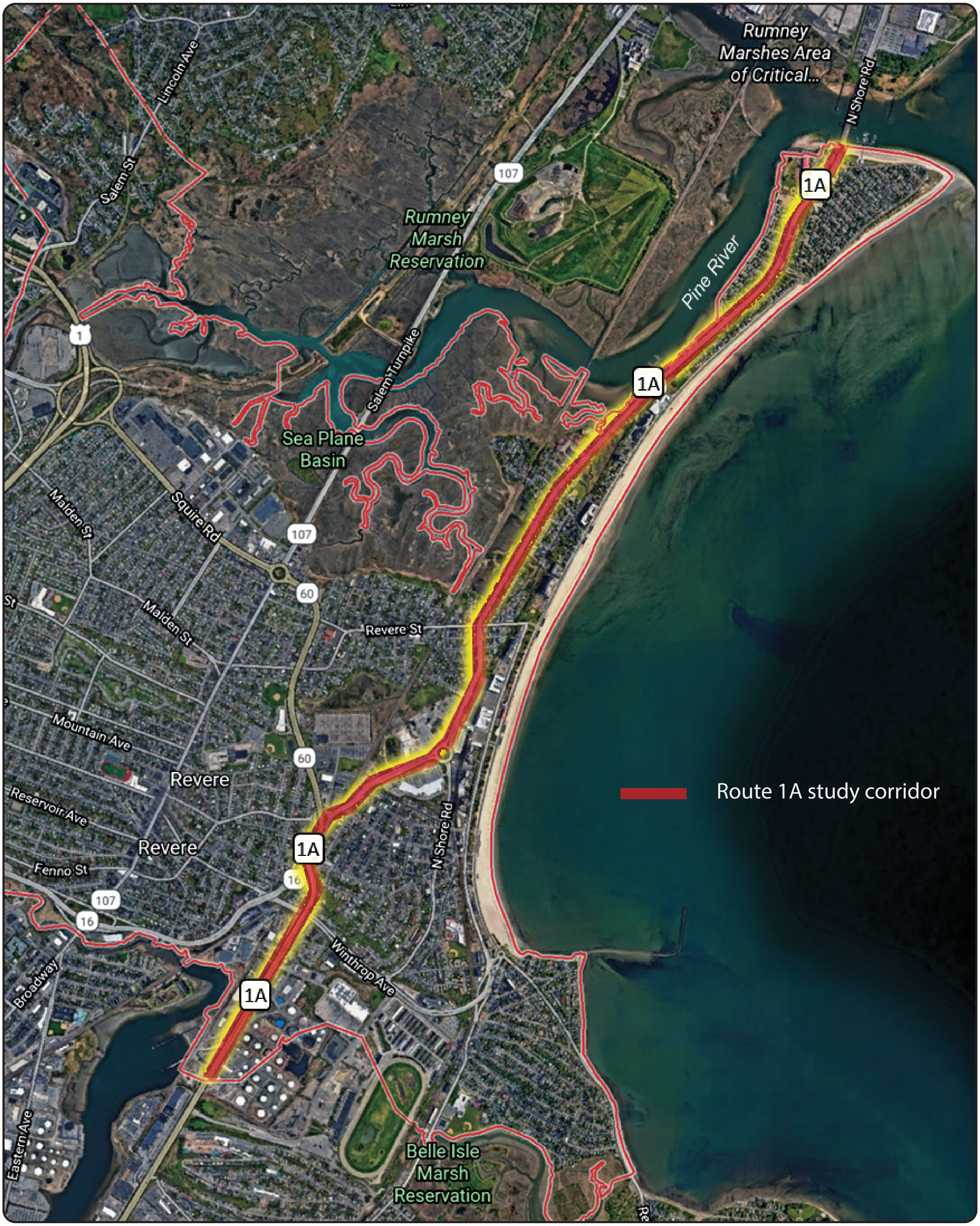

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FIGURE 10
Study Corridor

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Route 1A at Mills Avenue


Route 1A south of the Marina


Route 1A at the Marina
(east side of the roadway)


Route 1A north of Revere Street


Route 1A at Rick's Auto Collision


Route 1A near Mills Avenue
(east side of the roadway)


Route 1A at the MBTA Wonderland Station


Route 1A at the oil and gas storage tanks
near the Boston city line

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FIGURE 11
Existing Conditions

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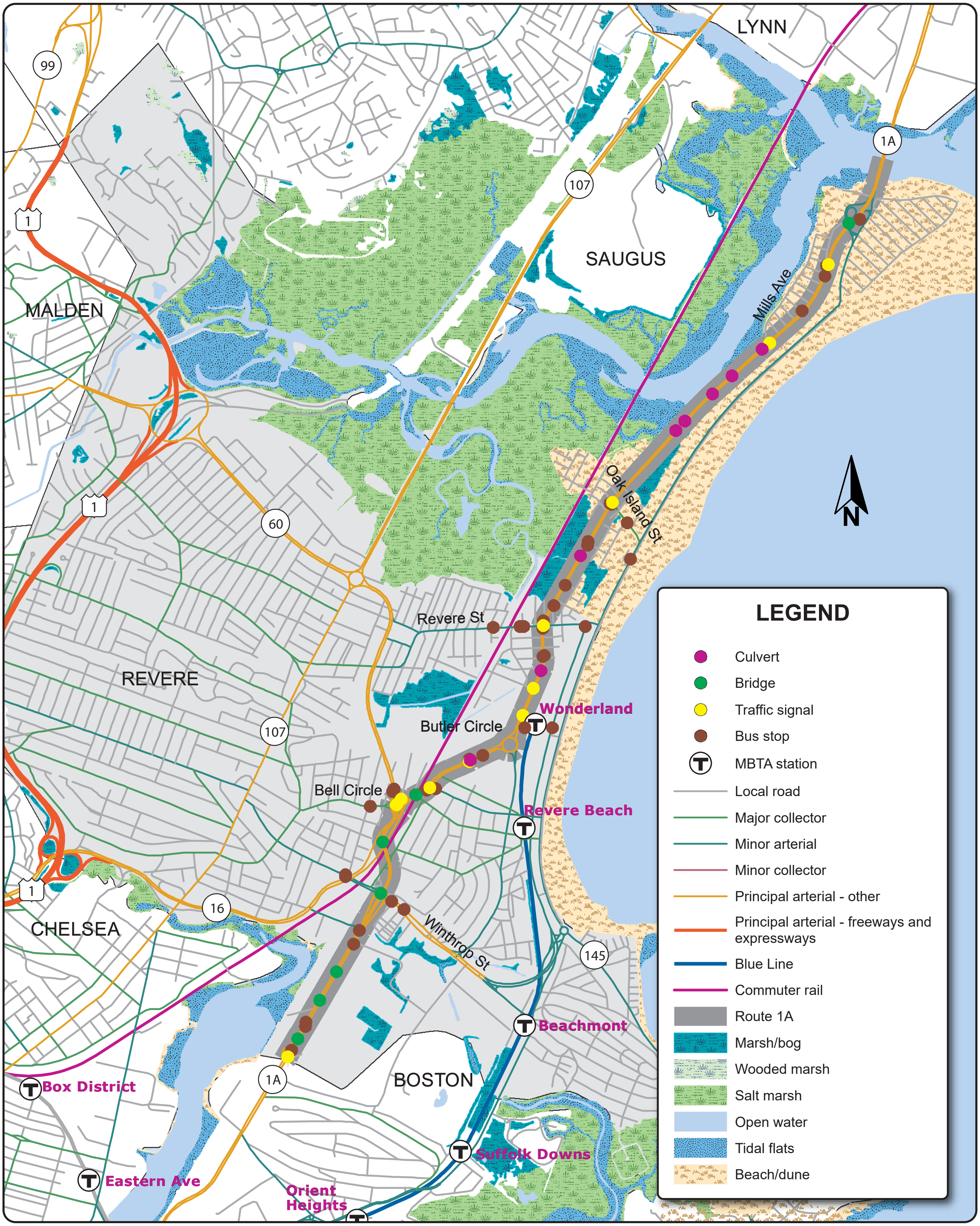

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FIGURE 12
Transportation and Natural Resources Assets

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Bridges

There are seven bridges within the study limits, all under MassDOT's jurisdiction. Most of the bridges are located on the southern segment of the corridor, where they carry Route 1A over railroad, road, tunnels, and floodplains. The bridges were built between 1932 and 1934 and were reconditioned between 1975 and 1977. In the latest inspections in 2018, the superstructures, substructures, and decks received ratings between 5 and 7, which is fair condition.[15] All of the bridges are open to traffic and none of them are structurally deficient.

Culverts

There are nine culverts located in the study limits, most of them under Route 1A in the northern segment of the corridor. The culverts were installed in 1970 and last inspected in 2016. The seven culverts in the northern segment are connected by a ditch system that drains and feeds into the tidal saltwater marsh and brackish wetland area located between Revere Beach Reservation and Route 1A, north of Island Street. Another culvert under Route 1A is at the Eastern County ditch (located between Revere Street and Oak Island Street) and discharges to Diamond Creek. Existing culverts at the north of Revere have self-regulating tidegates, but some of them are not functioning well due to debris, missing top floats, crushed culvert outlets, or missing grated vault covers, or they are completely obstructed.

Tidegates

There are seven self-regulating tidegates, all located in the northern segment of the corridor and integrated with the culvert-ditch drainage system. Drainage system inadequacies have been reported. These inadequacies result from overgrowth in ditches, debris obstructions in trash racks, and obstructions that leave flappers stuck in a half open position. The concern is that significant adverse impacts to the saltwater marshes would occur if malfunctioning tidegates restrict saltwater to the marshes.

Presently, some of the most vulnerable locations on Route 1A are protected by rock revetments and drainage systems of ditches, culverts, and self-regulating tidegates. On site visits, MPO staff found that some of rock revetments require enhancements. Assessments by the US Environmental Protection Agency and the City of Revere's engineering staff indicate that some culverts have failed because they are undersize or completely obstructed and the tidegates are not functioning well because of stuck or missing top floats.

[15] If the lowest rating for a bridge (superstructure, substructure, and deck) is at least seven, the bridge is classified as in good condition; a rating of five or six is fair; and a rating of four or less is poor.

Traffic Signals, Signs, and Supports

There are 11 traffic signals in the corridor and all are operating well. All traffic signals are at intersections where vehicular or pedestrian traffic intersect with Route 1A. No information was available about the structural capacity of the signals and whether the poles and signal sections meet current MassDOT standards. In addition, there are signs and supports guiding motorists, bicyclists, and pedestrians through the corridor.

Transit Assets

Three MBTA bus routes (Routes 439, 441, 442, and 450) operate on Route 1A, connecting to Wonderland Station in Revere, Central Square in Lynn, Logan Airport, and Boston. The bus routes have 21 bus stops on Route 1A in Revere. The MBTA's Blue Line rapid transit service has its terminal at Wonderland Station; both the station and the parking lots are accessed from Route 1A. The Newburyport/Rockport commuter rail line passes under Route 1A at two locations near Bell Circle.

Critical Facilities

There are several critical facilities in the corridor, including police and fire stations, storm and wastewater pump stations, and schools. Figure 13 shows the locations and types of facilities. The pump station at Eastern County ditch headwall at the Boston and Maine (B&M) railroad tracks discharges to Diamond Creek. Flooding from storms can wreak havoc on these facilities and the gradual rise of sea levels also threatens to inundate critical facilities in the coming decades.

Natural Resources

Rumney Marsh is a saltwater marsh and wetland that is home to a variety of wildlife. Figure 13 shows the location and extent of Rumney Marsh. Located in Revere and Saugus, it encompasses approximately 2,274 acres and has been identified by the Massachusetts Secretary of Energy and Environmental Affairs as an Area of Critical Environmental Concern due to its quality, uniqueness, and significance that need to be preserved. The United States Fish and Wildlife Service characterized Rumney Marsh as "one of the most biologically significant estuaries in Massachusetts north of Boston."

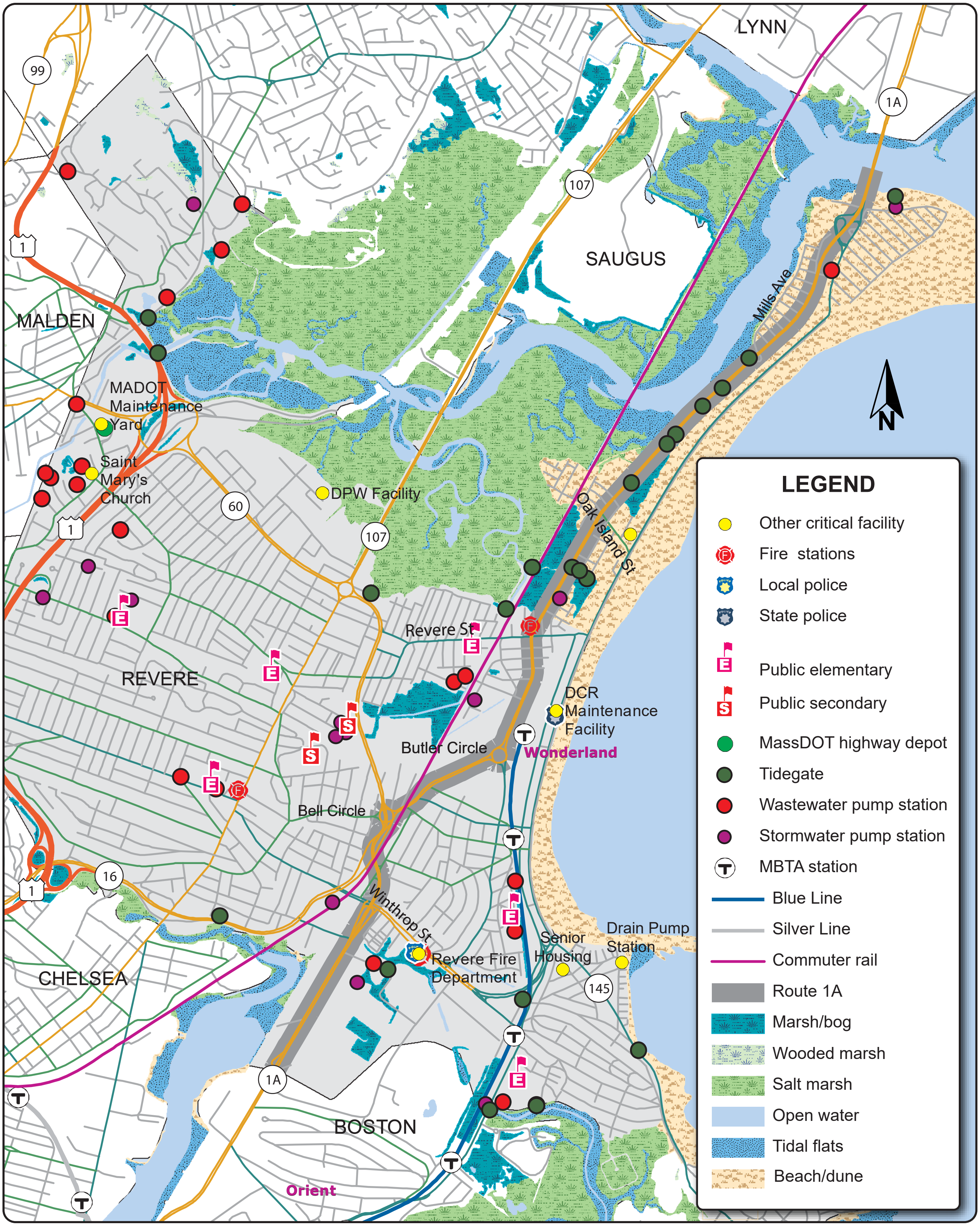

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FIGURE 13
Critical Facilities

Exploring Resilience in MPO-Funded Corridor and Intersection Studies

5.4 INITIAL ASSESSMENT

The initial assessment of Route 1A involved using readily available data and information to gain a general understanding about the challenges that flooding and sea level rise may present in the future. Tools from NOAA, FEMA, and CZM, such as sea level rise viewer, flood maps, and precipitation charts, were used to screen the corridor for vulnerabilities. The initial assessment also involved rating the asset's exposure to climate hazards. Because the Route 1A corridor is vulnerable to several climate hazards, a focus of the study was to target areas that are most vulnerable and focus the development of adaptation measures to these areas.

5.4.1 Sea Level Rise, Storm Surge, Tides, and Waves

With rising sea levels, flooding of natural low-lying areas along the Route 1A corridor is expected to occur due to more frequent tidal and storm surge inundation and stormwater flooding. Damage to infrastructure, natural resources, and facilities, including properties and neighborhoods, may occur as tidal and wave energy increases. Figure 14 shows probabilistic projections of how much and how quickly future mean sea level is likely to rise under two emission scenarios, RCP4.5 and RCP8.5.[16] These RCPs represent the intermediate and worst-case scenarios, respectively.

> By 2050, the sea level could rise between 1.3 to 4.0 feet, and between 2.3 to 5.5 feet by 2070 depending on how successful we are in reducing greenhouse gas emissions.

The CZM/NOAA sea level rise viewer was selected to review the impacts along the corridor of a three-foot sea level rise. The results show near- and medium-term flooding problems in the Route 1A corridor, especially for the segment of Route 1A north of Revere Street, which is in a low-lying area, on the flood pathways of the Pines River, and directly exposed to storm surges.

[16] These representative concentration pathways (RCPS) are potential trajectories of greenhouse gas concentrations set by the Intergovernmental Panel on Climate Change for climate modeling and research.

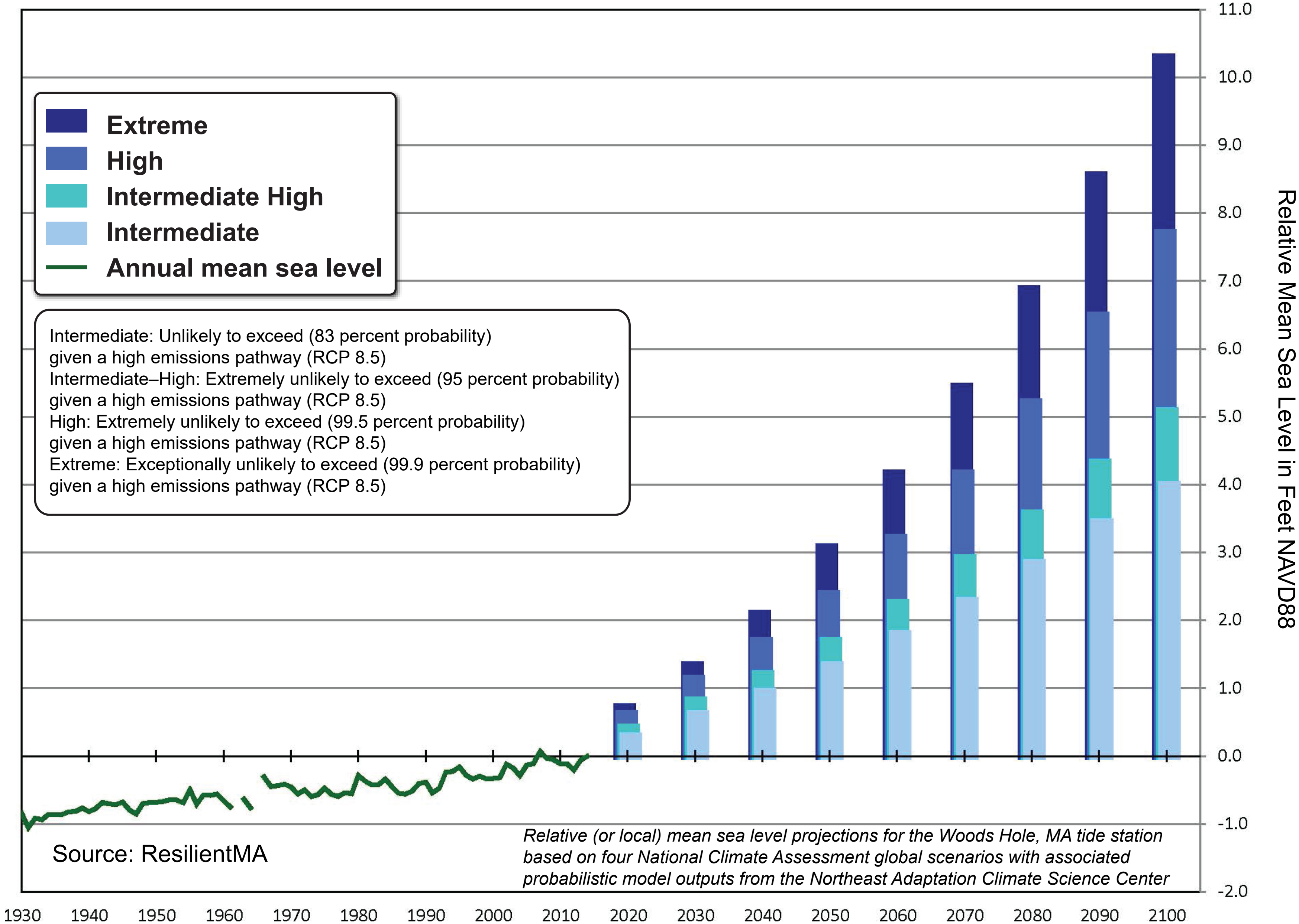

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FIGURE 14
Relative Annual Mean Sea Level and Future Scenarios

Exploring Resilience in MPO-Funded Corridor and Intersection Studies

5.4.2 Extreme Precipitation

Climate change is projected to produce more intense rain storms. Extreme precipitation may result in stormwater flooding, which could disrupt traffic, overtop or wash out roadways, damage undersized culverts, and overtop bridges. Table 2 shows estimated 50th percentile values for projected change in precipitation greater than two inches, precipitation greater than four inches, and total precipitation for two emission scenarios, RCP4.5 and RCP8.5.

Projections indicate that total annual precipitation would increase by three inches by 2050 and four inches by 2070. Also, the number of days with more than two inches of precipitation would increase in the future.

Table 2
Annual Projected Change in Precipitation

Precipitation Parameter	Baseline	Emission Scenario	2030s	2050s	2070s	2090s
Precipitation more than 2 inches	1.10 days	High RCP8.5	+0.27	+0.34	+0.48	+0.59
Precipitation more than 2 inches	1.10 days	Medium RCP4.5	+0.18	+0.30	+0.30	+0.23
Precipitation more than 4 inches	0.07 days	High RCP8.5	+0.06	+0.05	+0.05	+0.07
Precipitation more than 4 inches	0.07 days	Medium RCP4.5	+0.06	+0.07	+0.05	+0.05
Total precipitation	45.31 inches	High RCP8.5	+2.46	+2.97	+3.82	+4.01
Total precipitation	45.31 inches	Medium RCP4.5	+1.54	+3.16	+2.58	+4.11

Source: ResilientMA.

Figure 15 shows the parts of Route 1A that are vulnerable to flooding in a 100-year and 500-year storm. There is a one percent chance annually of a 100-year storm and a 0.2 percent chance of a 500-year.

5.4.3 Extreme Heat

Higher temperatures can cause pavement to soften and expand. This can create rutting and potholes, particularly in high-traffic areas, and stress bridge joints. Generally, extreme heat is more than 90 degrees Fahrenheit and a heat wave is three or more consecutive days of these temperatures. Table 3 shows the likely

By 2050, days with temperatures greater than 90 degrees could increase by 13 to 20 days and by 16 to 35 days by 2070. Also, annual maximum temperature could increase by three to five degrees by 2050 and four to seven degrees by 2070.

annual average change in temperature for two emissions scenarios used in this study.

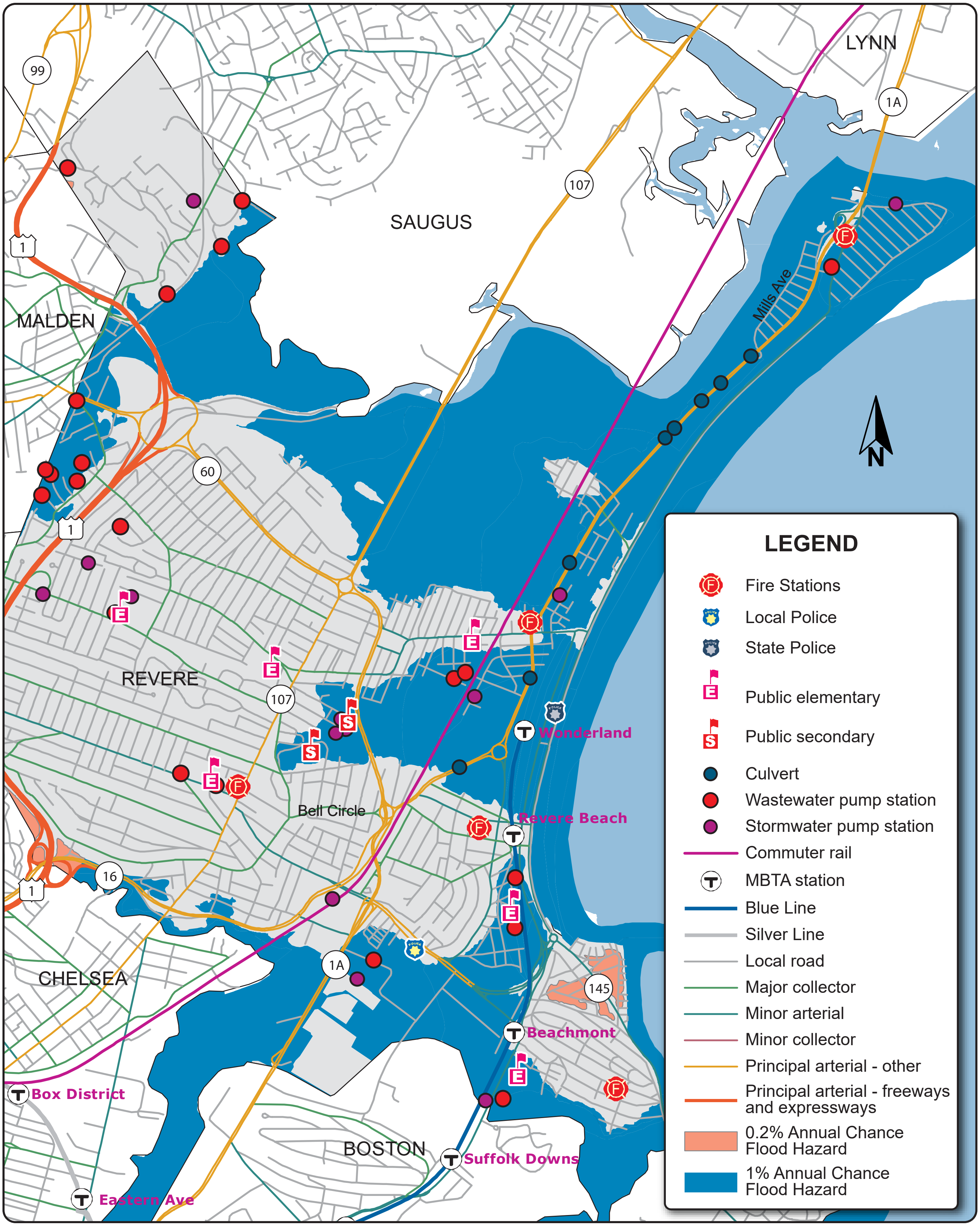

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FIGURE 15
FEMA National Flood Hazard Layer for Revere

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Table 3
Projected Annual Average Change in Temperature

Temperature Parameter	Baseline (Days)	Emission Scenario	2030s	2050s	2070s	2090s
Days hotter than 90º F	7.69	High RCP8.5	+10.74	+20.53	+35.22	+48.54
Days hotter than 90º F	7.69	Medium RCP4.5	+8.51	+13.82	+15.50	+17.84
Days hotter than 95º F	0.88	High RCP8.5	+3.22	+7.01	+15.53	+25.32
Days hotter than 95º F	0.88	Medium RCP4.5	+2.24	+4.10	+4.73	+5.95
Maximum temperatures	59.15	High RCP8.5	+3.38	+5.15	+7.16	+9.12
Maximum temperatures	59.15	Medium RCP4.5	+2.60	+3.76	+4.31	+4.76

Source: ResilientMA.

5.5 POTENTIAL RISK OF ASSETS

Exposure and criticality analyses provide an understanding of an asset's potential vulnerability and the consequences of losing that asset for informed decision-making. Three types of assessments are conducted in these analyses:

- Threat assessment—What is the likelihood of the identified hazard?
- Consequence assessment—What happens if the hazard occurs? Will there be road closures, traffic diversions, or impacts on emergency and evacuation capabilities? What are the expected losses and economic impacts? Will the hazard result in deaths, loss of property, or business closures, for example?
- Vulnerability assessment—What are the asset's vulnerabilities that would allow a hazard to result in expected condequences? These factors could be the height of a bridge, scouring at the base of a bridge, undersized culverts, tidegate problems, or the elevation of a roadway.

5.5.1 Exposure Rating

The entire Route 1A corridor is exposed to climate hazards. Spreadsheets developed by RMAT were used in screening, scoring, and rating Route 1A's exposure to climate hazards. Table 4 presents the exposure rating, which indicates that Route 1A is highly exposed sea level rise, storm surge, extreme precipitation, and extreme heat. Appendix E includes the RMAT worksheets used for the exposure screening.

Table 4
Preliminary Exposure Rating

Climate Parameter	Exposure Rating
Sea level rise /storm surge	High exposure
Extreme precipitation—riverine	High exposure
Extreme precipitation—urban	High exposure
Extreme heat	High exposure

Source: Central Transportation Planning Staff.

5.5.2 Criticality Rating

The criticality rating for Route 1A and its surrounding natural resources was based on questions about scope, time, and severity developed by the RMAT for screening infrastructure and natural resources assets. The scope of this study did not allow for an assessment of individual transportation assets, such as bridges, culverts, tidegates, and bus stops. In addition, the natural resources in the corridor, including saltwater marshes, land subject to tidal action, estuarine open water, and coastal wetlands, were not assessed individually. Detailed criticality studies of the specific assets are appropriate in functional design reports and conditional assessment reports.

Table 5 presents the criticality ratings for the transportation infrastucture and natural resources along Route 1A. Based on the screening and scoring, Route 1A and surrounding natural resources assets were rated as medium. The criticality worksheets with the scores are included in Appendix E.

Table 5
Preliminary Criticality

Asset	Criticality
Route 1A	Medium
Natural resources	Medium

Source: Central Transportation Planning Staff.

5.5.3 Risk Rating

Table 6 is a risk matrix. It combines the exposure and criticality ratings in Table 4 and Table 5 into a risk rating. For example a high exposure rating and a medium criticality rating results in a high risk rating. Table 7 presents the asset risk rating for Route 1A. Based on the matrix, Route 1A assets (Section 5.5.1) are rated high risk—highly vulnerable to sea level rise and storm surge, extreme precipitation, and extreme heat.

Table 6
Matrix of Risk Rating

Criticality	Not Exposed	Low Exposure	Moderate Exposure	High Exposure
High	Low Risk	Moderate Risk	High Risk	High Risk
Medium	Low Risk	Low Risk	Moderate Risk	High Risk
Low	Low Risk	Low Risk	Moderate Risk	Moderate Risk

Source: ResilientMA.

Table 7
Asset Risk Rating for Route 1A

Climate Parameter	Exposure Rating	Risk Rating Infrastructure	Risk Rating Natural Resources
Sea Level Rise/Storm Surge	High	High	High
Extreme Precipitation (Riverine)	High	High	High
Extreme Precipitation (Urban)	High	High	High
Extreme Heat	High	High	High

Source: Central Transportation Planning Staff.

5.6 DETAILED VULNERABILITY ASSESSMENTS

Evaluation of vulnerabilities and resilience of the Route 1A involved evaluating flood probabilities and depth of flooding for four scenarios—present-day, 2030, 2050, and 2070. These criteria were assessed using MC-FRM's probability-based maps.

5.6.1 Risk Maps

Figures 16 through 19 show the flood risk probability maps for present day, 2030, 2050, and 2070 planning horizons. Figures 20 through 23 show the one percent flood depth maps for the same planning scenarios. Risk mapping shows areas vulnerable to flooding from different combinations of sea level rise, storm surge, tides, and waves and provide flood information that can be used to inform adaptation plans to better protect assets. Risk mapping also strengthens the ability to make informed decisions about reducing risk. The maps show significant flooding in the near- and medium-term that require actions to protect assets.

5.6.2 Focus Segments

Based on the risk maps, the Route 1A corridor was divided into two segments (northern and southern) based on similarities and consistencies in physical conditions such as geography, dominant land use, and road elevations. The purpose of the division was to prioritize improvements and allow resources to be focused on the most vulnerable segment. Also, improvements suggested for each segment are influenced by the characteristics in the segment.

5.6.3 Northern Segment (Revere Street to the Point of Pines)

The northern segment extends from Revere Street to the Point of Pines. In this segment, approximately two miles long, Route 1A is in a natural low-lying area about eight to nine feet above sea level (NAVD 88). The roadway is close to the banks and flood pathways of the Pines River estuary and is highly vulnerable to flooding resulting from high tides, storm surge, and rain storms, and inundation from sea level rise. In the past, serious flooding and overtopping of the roadway led to closure of the road for repair that lasted for two or more days. Rock revetments have been installed where the roadway is directly adjacent to the riverbank. The northern segment also passes through the Rumney Marsh Reservation, a coastal saltwater marsh and wetland and home to a variety of wildlife. The land use is mixed, primarily residential with some commercial areas in the vicinity of Oak Island Street.

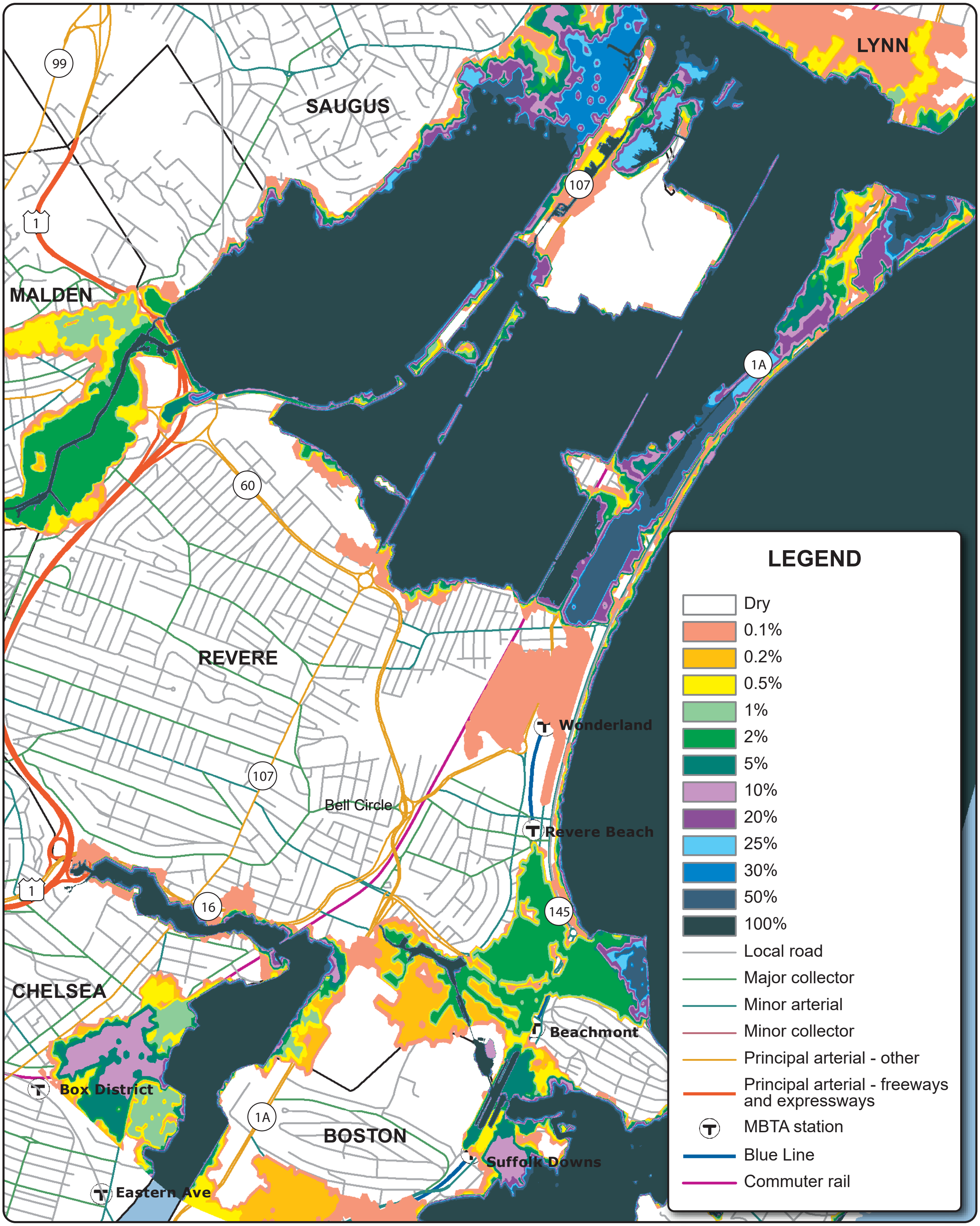

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FIGURE 16
Present-Day Flood Probabilities

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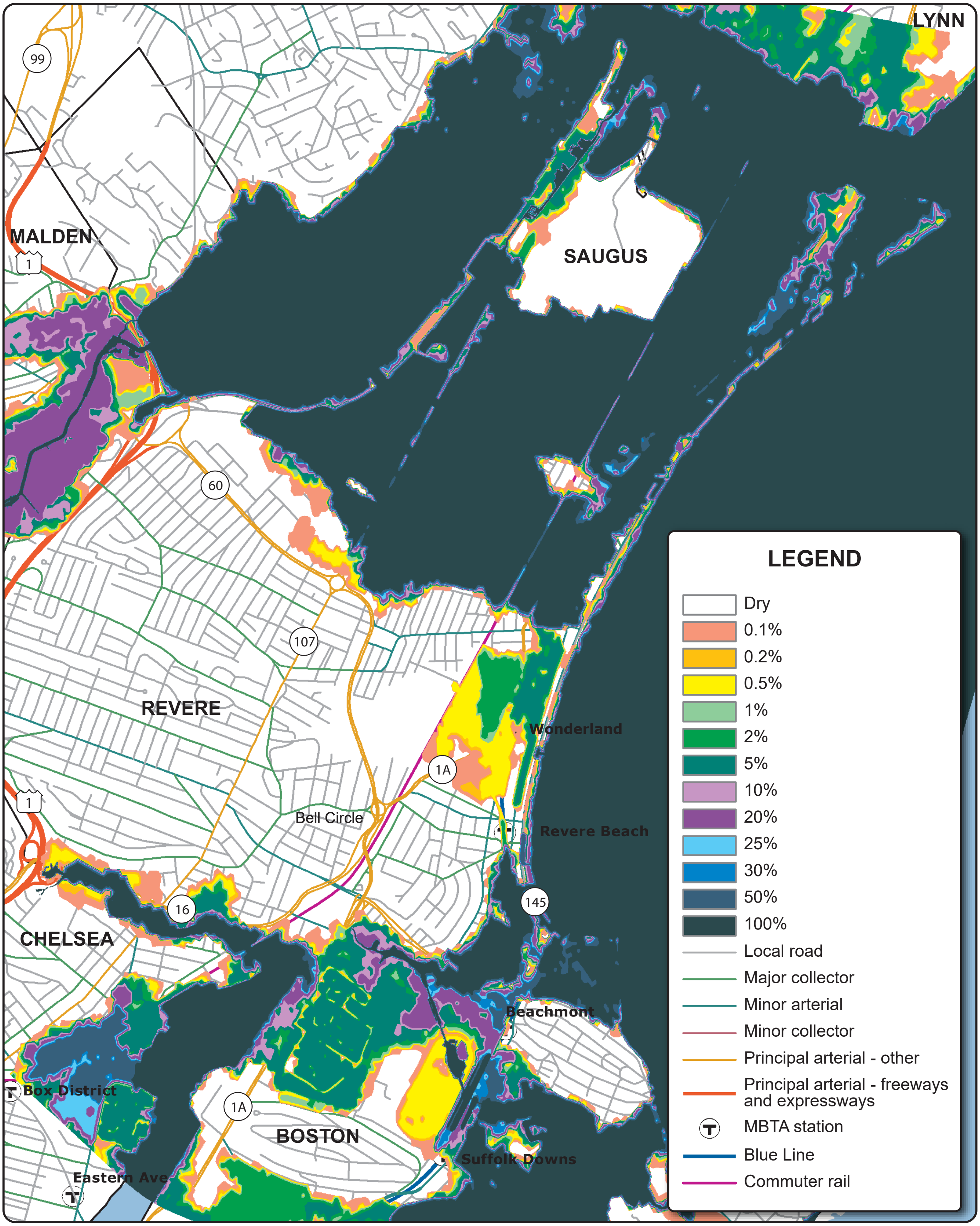

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FIGURE 17
2030 Flood Probabilities

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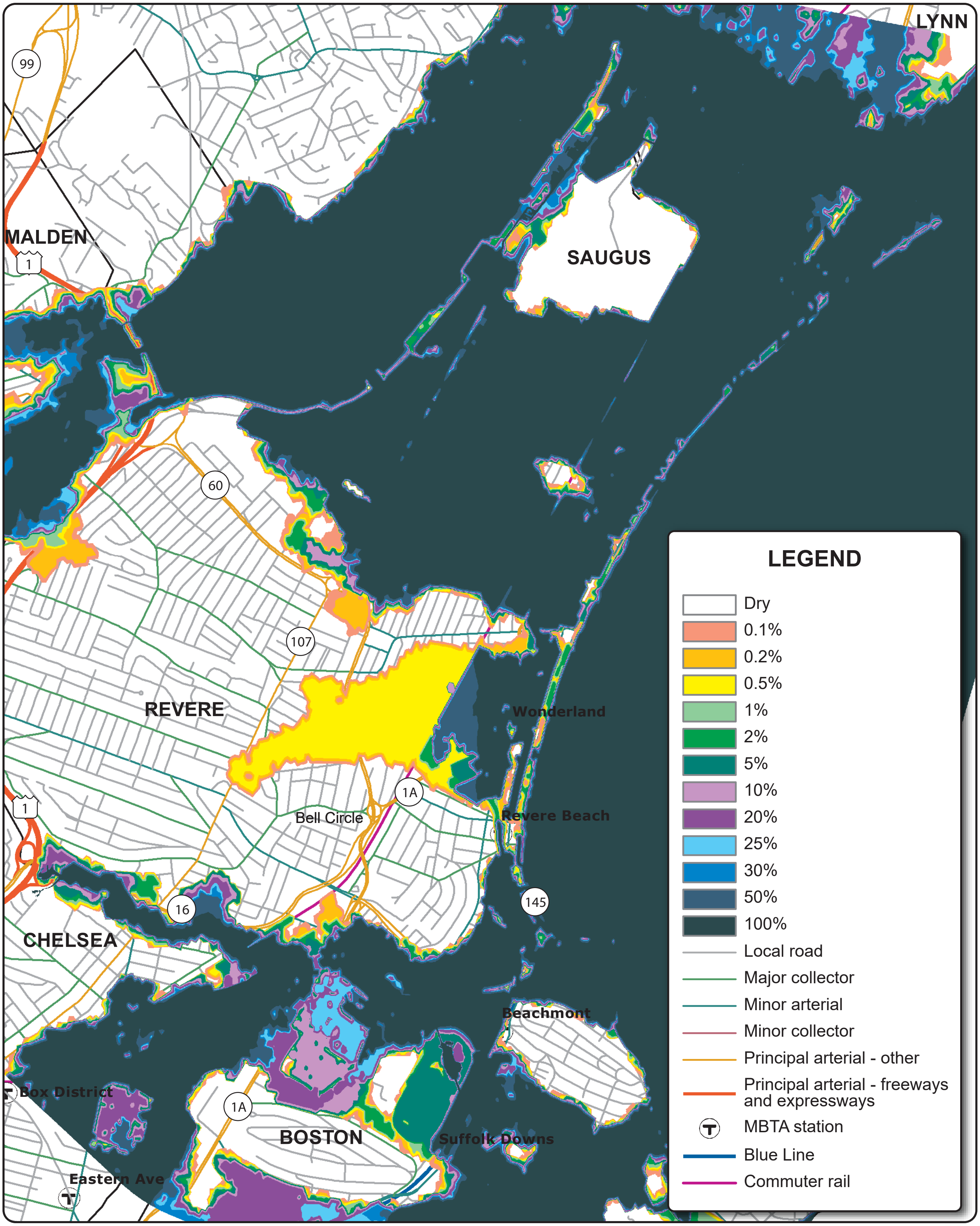

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FIGURE 18
2050 Flood Probabilities

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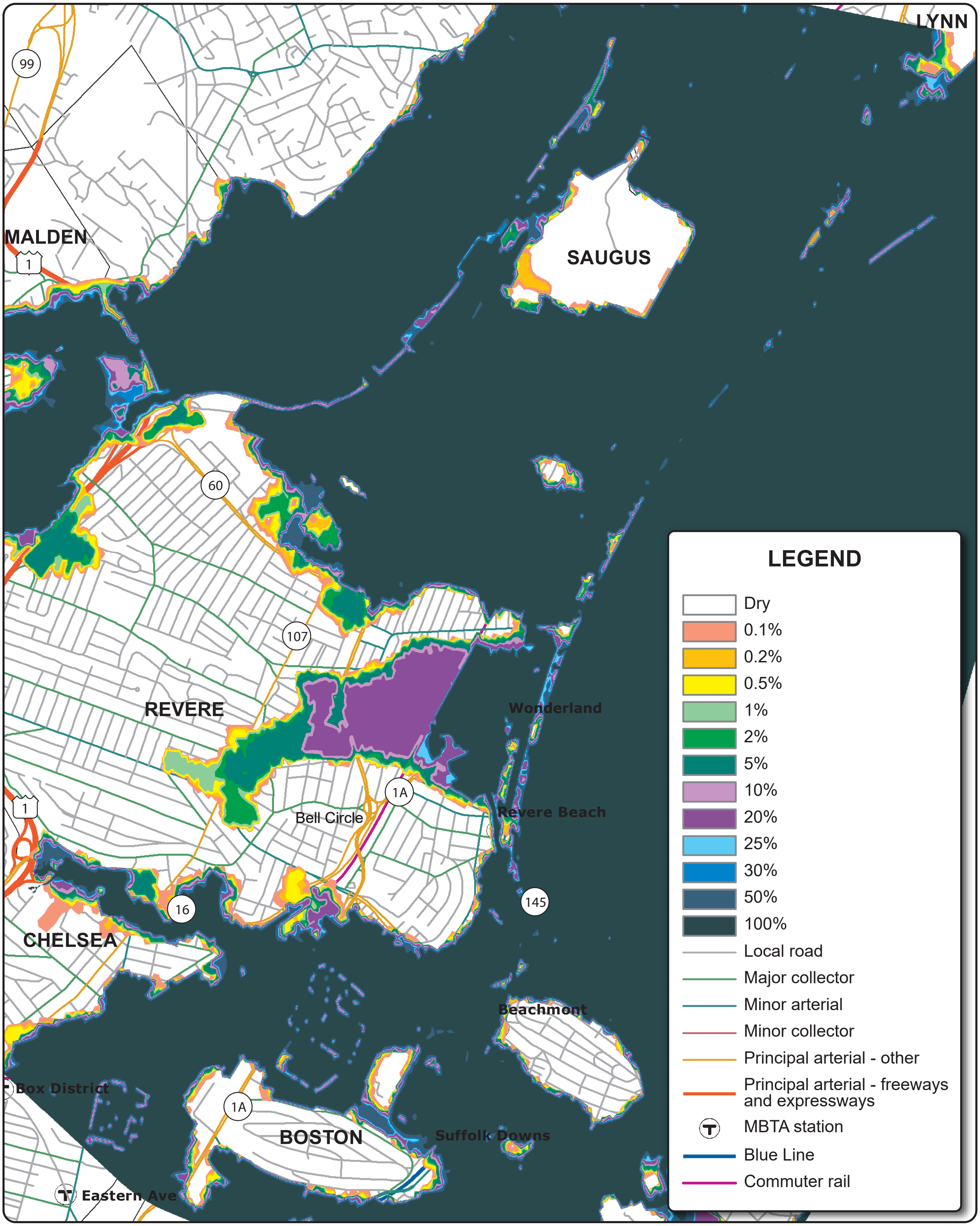

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FIGURE 19
2070 Flood Probabilities

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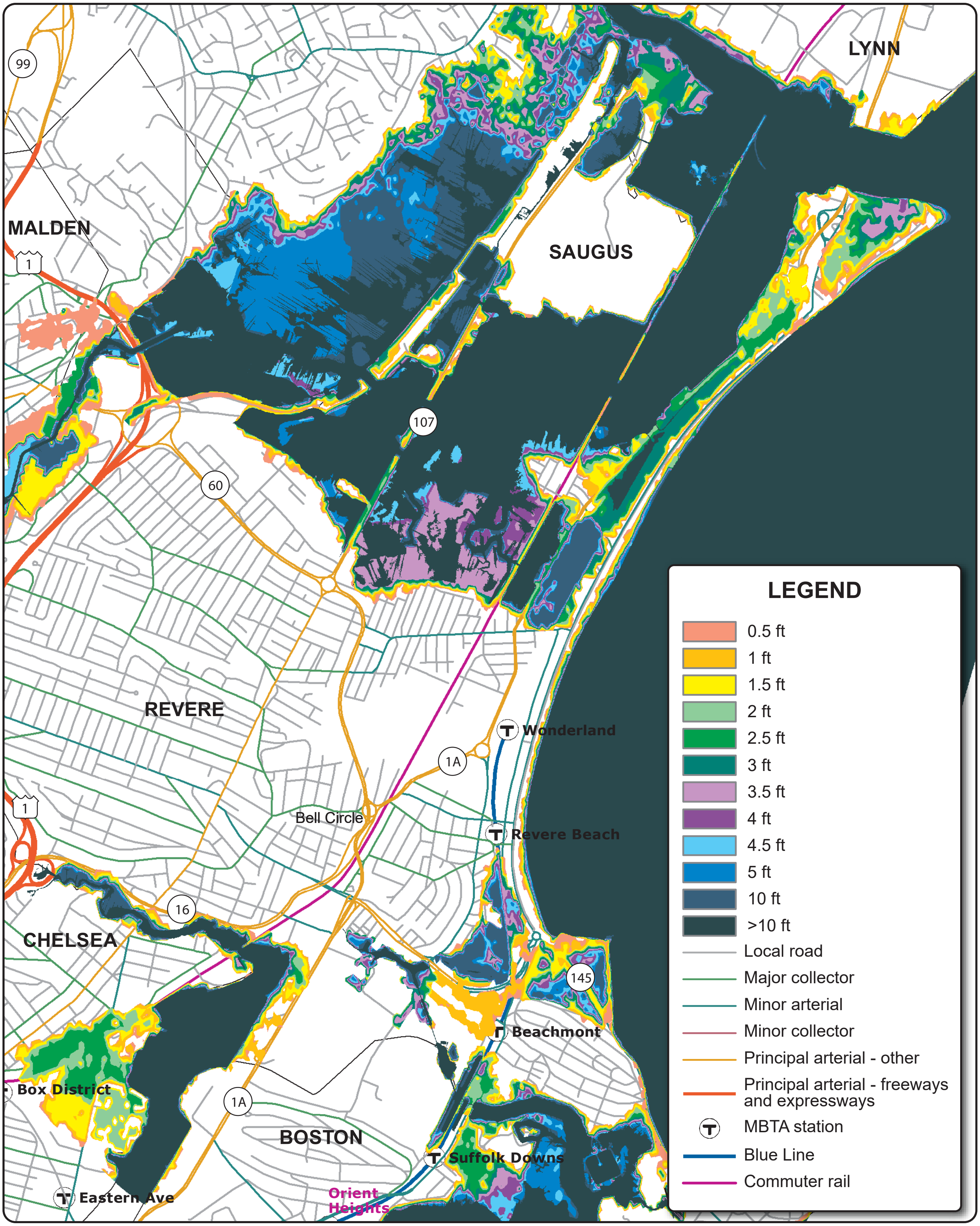

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FIGURE 20
Present-Day Depth of Flooding
(1% Annual Exceedance Probability)

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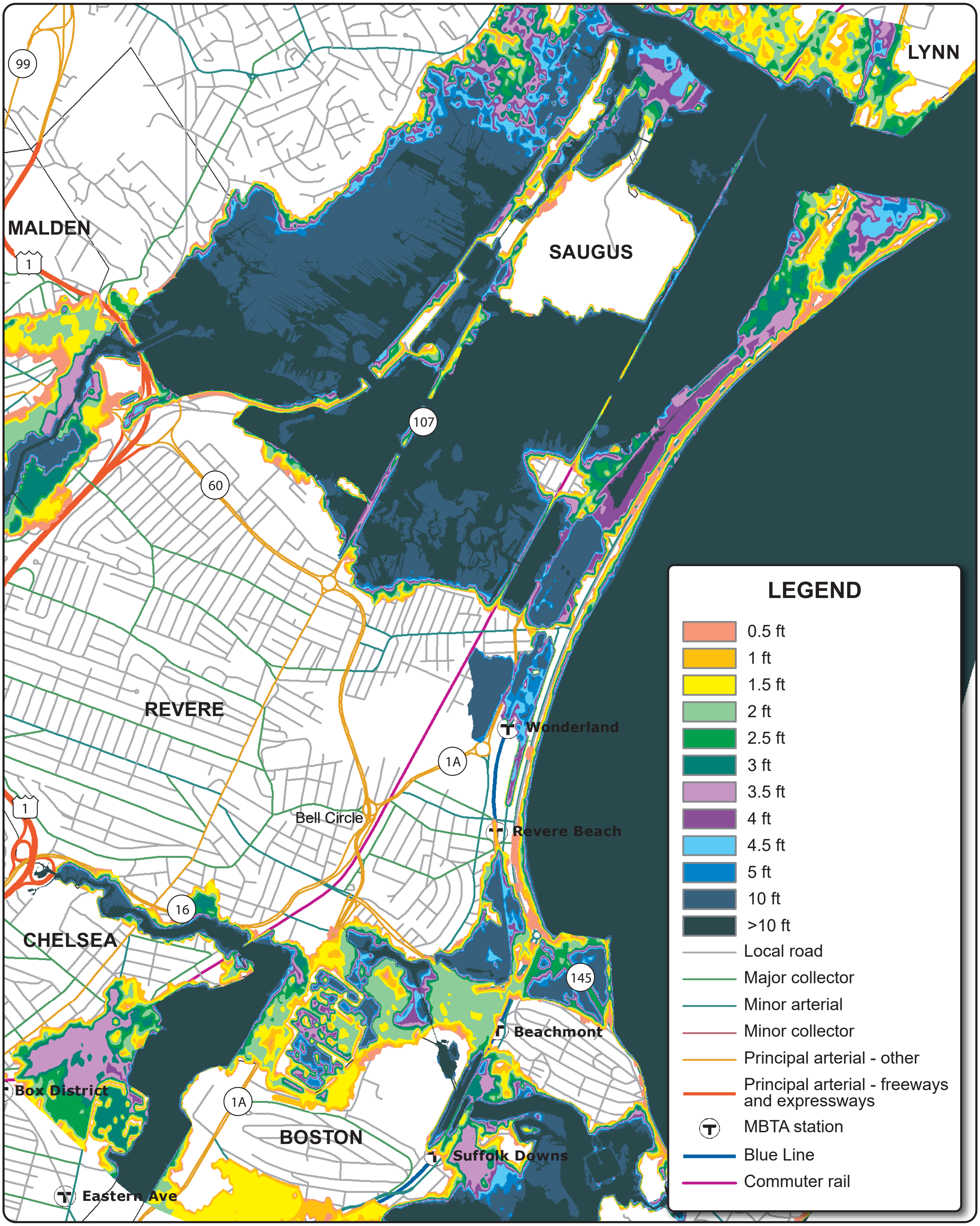

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FIGURE 21
2030 Depth of Flooding
(1% Annual Exceedance Probability)

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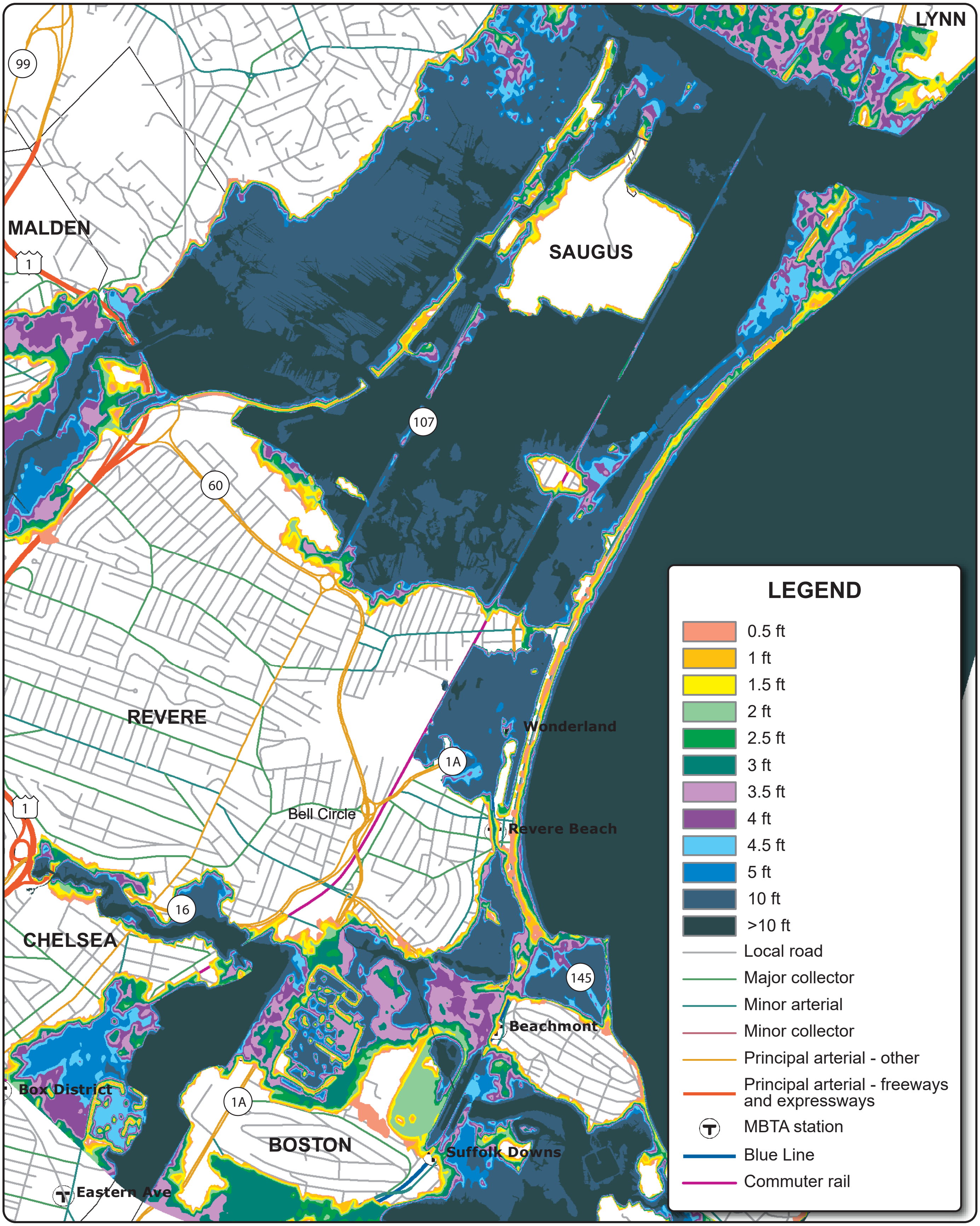

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FIGURE 22
2050 Depth of Flooding
(1% Annual Exceedance Probability)

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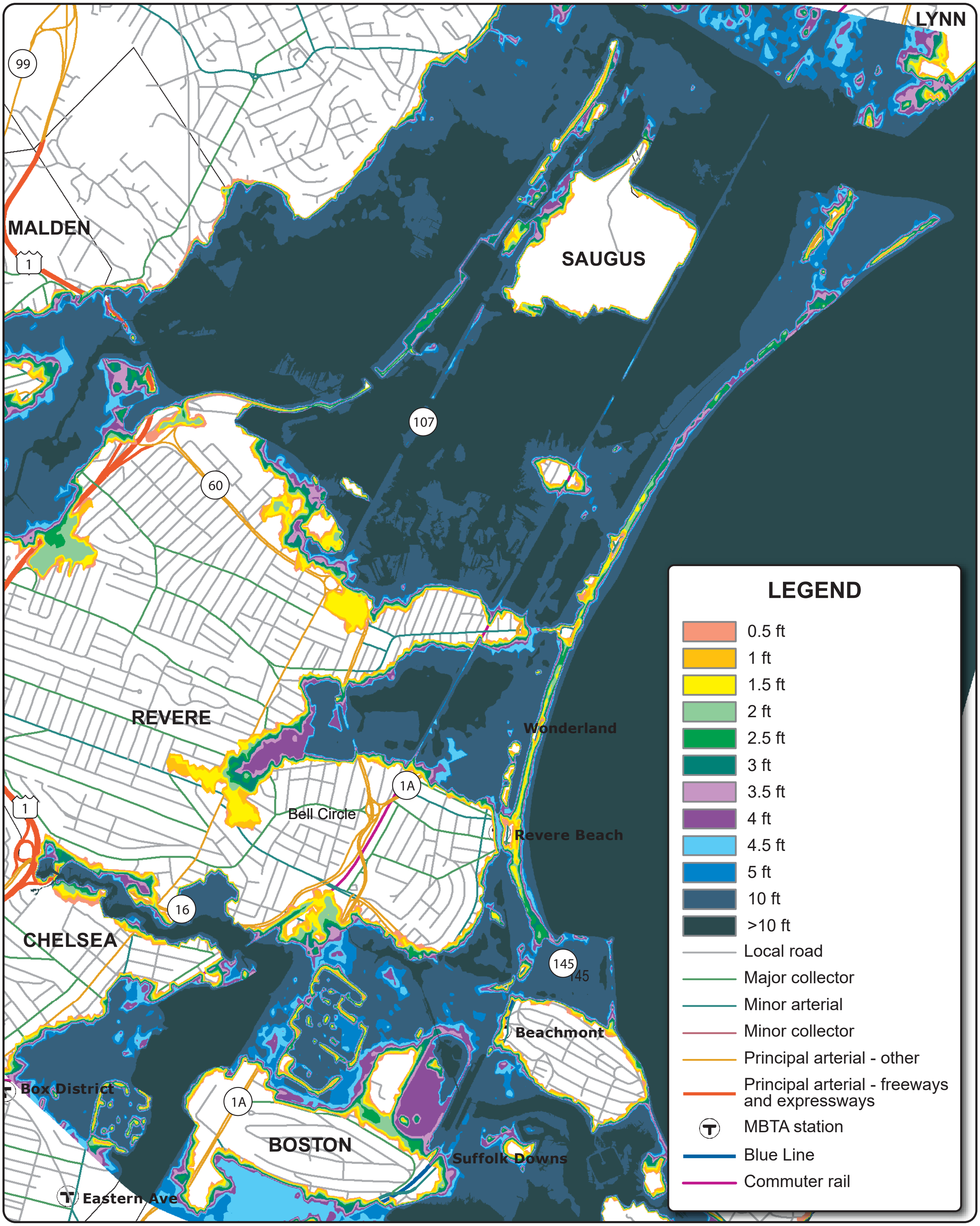

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FIGURE 23
2070 Depth of Flooding
(1% Annual Exceedance Probability)

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Vulnerability

According to the flood probability and depth maps, the northern segment experiences the most significant flooding.

- For present day, there is a 10–20 percent probability that Route 1A would be flooded. The one percent flood depth is estimated at 1.5 feet.
- In 2030, the risk increases to 20–25 percent probability that Route 1A would be flooded. The one percent flood depth is estimated at 2.0–3.5 feet.
- In 2050 and 2070, there is a 100 percent probability that Route 1A would be overtopped at high tide. The one percent flood depth is estimated at 5–10 feet of water.

> The northern segment of Route 1A is the critical segment where resilience efforts should be focused now. The northern segment experiences the most significant flooding currently, and flooding would worsen in 2030 and in subsequent planning horizons. Many of the Route 1A assets in the segment—road, bridges, culverts, tidegates, supports (for signs, signals, gantries), electrical, and bus stops are at risk from flooding.

Consequences

The consequences of losing Route 1A are immense for Revere and many North Shore communities. Route 1A serves regional traffic, passes through communities with transportation equity zones, and serves as an evacuation route. Its loss would be felt immediately after an event as many of the parallel routes (Route 107) and other transportation choices (MBTA commuter rail or rapid transit) face the same flooding issues as Route 1A. Diversion routes would increase trip length, duration, and result in congestion. Economic and social impacts would be high for businesses and transportation equity zones that it serves. As the risk worsens in 2030 and 2050, keeping Route 1A functional would require costly maintenance and repair, unless resilience measures are taken earlier to prevent that from happening.

5.6.4. Southern Segment (Boston city line to Revere Street)

The southern segment of Route 1A extends approximately two miles from the Boston city line to Revere Street. Although this segment is not as vulnerable as the northern segment, there are two natural low-lying areas about eight to ten feet above sea level (NAVD 88):

- South of Route 145 (Winthrop Avenue), where Route 1A is in the flood pathway of the Chelsea Creek estuary
- Between Butler Memorial Circle and Revere Street, the location of the MBTA's Wonderland Station and parking facilities

The dominant land uses in the segment are industrial and commercial, mostly located in the low-lying areas, and residential in the elevated area between the two low-lying areas.

Vulnerability

The southern segment experience far less flooding presently compared to its northern counterpart.

> Although the southern segment is not as critical as the northern segment, by 2050 some resilience efforts would be needed in the segment, especially the in the low-lying areas. The consequences are the same as in the northern segment.

- For the present-day, there is less than one percent probability of Route 1A flooding. The one percent flood depth is zero.
- In 2030, the flood risk increases slightly to 1–2 percent probability of Route 1A flooding. The one percent flood depth is estimated at 1–2 feet in the low-lying areas near the MBTA Wonderland Station and at the oil and gas storage tanks near the Boston city line.
- In 2050, the risk increases significantly to 20–50 percent probability of the Route 1A flooding in the same areas. The one percent flood depth is estimated at 4.5 feet or more.
- In 2070, there is 100 percent probability that many of the low-lying areas will be under water at high tide. The one percent flood depth is estimated at 5–10 feet.

5.7 ADAPTATION STRATEGIES

The cost of replacing or repairing the roadway after a failure would likely be millions of dollars and the economic (and social) impact to the area would be significant. Environmental impacts on natural resources are difficult to assess at this stage. The options for making Route 1A resilient include near-term, medium-term, and long-term improvements of infrastructure and protection of natural resources:

- Do-nothing and manage retreat
- Nature-based solutions
- Saugus River floodgate project
- Flood control and protection measures (resizing culverts)
- Flood control and protection measures (upgrading stormwater pump stations)
- Flood control and protection measures (stormwater controls)
- Flood control and protection measures (elevating assets)

5.7.1 Do Nothing Option and Managed Retreat

The Do-Nothing option is assessed from a planning perspective, focusing on broad consequences as a result of inaction, to bring the issues to attention and to begin stakeholder discussions. Detailed evaluation in terms of economic cost, social, and ecological impacts, are beyond the scope this study.

Location

The Do-Nothing option is not appropriate for the northern segment of Route 1A. However, it might be worth considering for the southern segment, where significant inundation is not expected to occur until 2050.

> Loss of Route 1A would adversely impact transportation for Revere and North Shore communities, as the parallel roads, such as Route 107, and the MBTA Newburyport/Rockport commuter rail also have similar flooding issues. Hence, diversion routes would add tens of miles and cause significant delay to users.

Impact

If the Do-Nothing option is selected, the northern segment would be subjected to frequent inundations beginning in 2030 with frequent overtopping and the roadway would be expensive to maintain. This option would present several problems.

A Do-Nothing option would not benefit current and future investments on Route 1A in the neighboring communities. There are several projects on Route 1A that would not benefit from this option. The General Edwards Drawbridge is one example. The General Edwards Drawbridge is located on Route 1A over the Saugus River in Lynn and Revere. In 2014, MassDOT project #605515 repaired and replaced electrical and mechanical operating machinery of the drawbridge, rehabilitated and made architectural repairs to the operator’s rooms and tower, miscellaneous granite repairs, and various structural steel repairs. The project was completed in 2014 at an estimated cost of $10.3 million.

In 2016, MassDOT Project #608396 was initiated and approved for the reconstruction of General Edwards Drawbridge. The project consists of substructure and superstructure investigation and necessary repairs and reconstruction, which are estimated to cost about $75 million. Currently the project is in preliminary design phase.

The Do-Nothing option would be expected to result in significant economic loss to the state and adverse social impacts on vulnerable populations.

Cost

Although there are no project costs associated with the Do-Nothing option, the economic, social, and transportation costs are very high.

5.7.2 Nature-Based Solutions

Nature-based solutions to coastal highway resilience is growing in popularity because they are effective low-cost alternatives that blend in with the natural environment. They are created by human design, engineered, and constructed to mimic nature. Examples include the restoration of saltwater marshes to minimize the impacts of flooding and edging, coir rolls, berms, and sills to prevent erosion.[17] Restoring marsh areas that have been invaded by Phragmites would help prevent and control flooding by increasing flood storage volume and absorbing some wave energy.[18] Nature-based solutions require experts to identify local marsh species, geological conditions, and drainage systems.

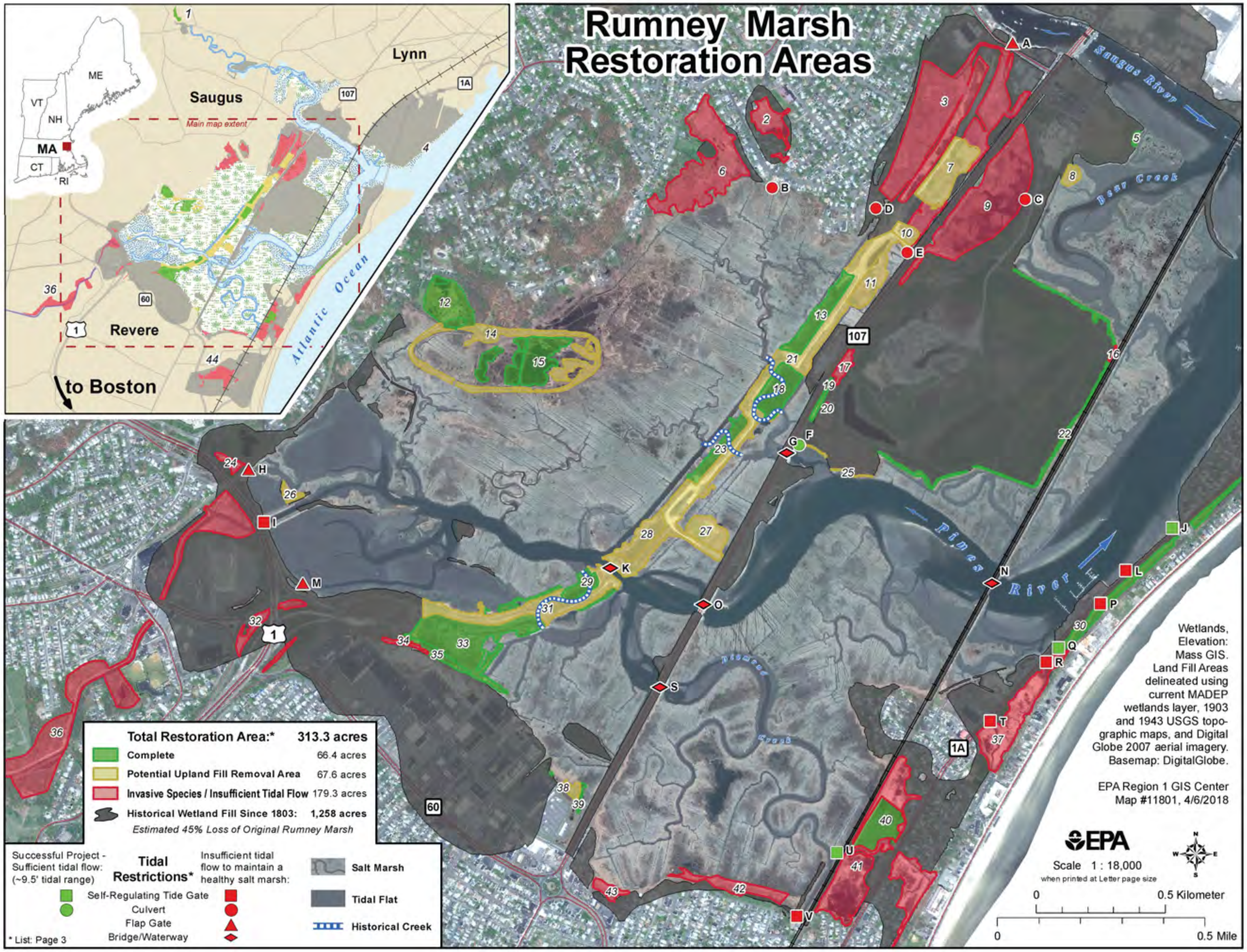
> The City of Revere is already leading efforts to restore the Oak Island Saltwater Marsh, located between the MBTA Newburyport/ Rockport commuter rail line and Route 1A and part of the Rumney Marsh Reservation. The City has already restored 6.6 acres of saltwater marsh in the study area and is working on restoring an additional 7.3 acres.
>
> Phase 2 and 3 of the City's marsh restoration and flood storage efforts will continue on both sides Route 1A between Revere Street and Oak Island Street. The marsh restoration was accomplished through removal of fill and sediment, excavation to create a system of feeder creeks, and reestablishment of saltwater marsh grasses.

Current Restoration Effort

Poor tidal exchange of saltwater to the surrounding marshes has resulted in the growth of invasive Phragmites that have outgrown some saltwater marsh areas, reducing flood water storage, increasing sedimentation, and exacerbating flooding. Figure 24 shows the locations of the saltwater marshes and invasive Phragmites where tidal flows have been restricted in the Rumney Marsh Reservation. Figure 25 shows nature-based solutions for flood and erosion control.

[17] Coir rolls are organic living revetment that provide erosion control and rapid vegetation establishment. They support the growth and development of plants that physically secure the bank or shoreline.

[18] Invasive Phragmites is a perennial, aggressive wetland grass that outcompetes native plants, marshes, and displaces native animals. Invasive Phragmites creates tall, dense stands which degrade wetlands and coastal areas by crowding out native plants and animals, exacerbating flooding, and can create fire hazards from dry plant material.



Credit: United States Environmental Protection Agency, Region 1 GIS Center

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FIGURE 24
Rumney Marsh Restoration Areas

Credit: The Virginia Institute Marine Science

Newly planted marsh with fiber logs allowing plants to establish root system and stabilize shoreline

Credit: Southern Environmental Law Center

Marsh sill to protect salt marshes from erosion. This living shoreline combines a reef to break up wave energy and new marsh vegetation to stabilize and filter sediment.

Credit: The Virginia Association of Soil and Water Conservation

Living shoreline using vegetation in combination with harder shoreline structures (e.g. oyster reefs or rock sills) for added stability to reduce erosion while providing habitat value and enhancing coastal resilience.

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FIGURE 25
Nature-Based Flood and Erosion Control

Location

Nature-based solutions are recommended for the northern segment of Route 1A because it complements restoration efforts of the Rumney Marsh Reservation. When maintained regularly, nature-based solutions can provide medium- to long-term improvement options. On the other hand, nature-based solutions may not be appropriate for the southern segment of Route 1A, as the area is fully built and occupied.

Impacts/Considerations

This option aligns with current restoration efforts for the Rumney Marsh Reservation.

Costs

The costs of nature-based solutions depend on the magnitude of exposure to wave energy. Costs can range from $100 to $200 per linear foot for shorelines exposed to low wave energy, $200 to $500 per linear foot for shorelines exposed to medium energy, and $600 to $1,200 per linear foot for shorelines exposed high energy waves that may require structural measures such as revetments, breakwaters, and bulkheads.

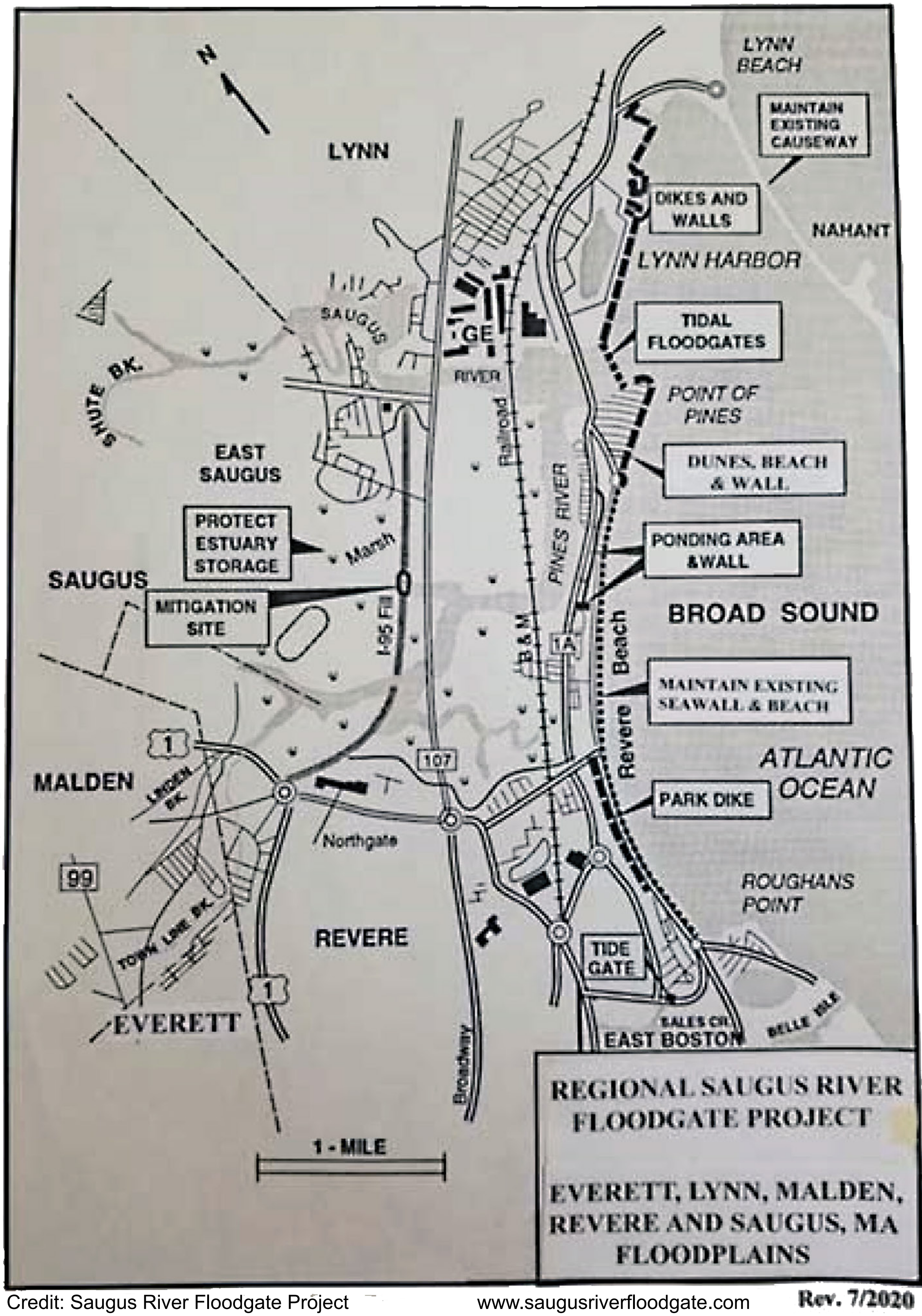
5.7.3 The Saugus River Floodgate Strategy

This strategy is the focus of the Regional Saugus River Floodgate Project, which consists of a floodgate on the mouth of Saugus River with nine gated openings that is tied to 3.1 miles of shorefront improvements along the Lynn Harbor, Point of Pines, and Revere Beach Reservation. The project has received renewed interest and taken on a regional approach to address climate change and rising sea level by providing high level coastal protection for five communities: Everett, Lynn, Malden, Revere, and Saugus. Figure 26 shows the components of project.

The floodgate strategy is expected to protect assets in the region vulnerable to flooding and storm surges—5,000 buildings, 8,000 housing units, 10,000 residents, 20,000 employees, and 40,000 commuters. The project also includes restoration of the Rumney Marsh Reservation, including enhancement and reestablishment of natural tide levels and flushing to 500 acres of the upper estuary and wetlands. This project was initially requested by federal and state agencies and the Town of Saugus. For more information about this project visit *www.saugusriverfloodgate.com.*

Location

The floodgate strategy has a regional project focus that would offer flood protection for five municipalities.



Credit: Saugus River Floodgate Project www.saugusriverfloodgate.com

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FIGURE 26
Saugus River Floodgate Project

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Impacts/Considerations

This project has a broader goal than the Route 1A study as the floodgate and shoreline improvements would protect housing, businesses, transportation infrastructure, and environmental resources. Therefore, MPO staff suggests coordination of resilient measures for Route 1A, bridge repairs, and the reconstruction plan for the General Edwards Drawbridge, and the Regional Saugus River Floodgate Project to ensure integrations and co-benefits.

Costs

The total cost would be $231 million (in 2020 dollars), including purchasing the 1,650-acre estuary for flood water storage and the added cost of restoration of Rumney Marsh.

5.7.4 Assess and Resize Culverts Based on Projected Climate Data

Route 1A is highly exposed to sea level rise, storm surge, and extreme precipitation—all threats that are projected to increase significantly in the future. Recent inspections as part of the Environmental Protection Agency's (EPA) efforts to restore the saltwater marsh in the Rumney Marsh Reservation indicated some of the culverts and tidegates are malfunctioning, crushed, or obstructed with debris.

> Many of the culverts under the Route 1A corridor are almost 50 years old (installed in 1972) and may be inadequate to handle storm surges and heavy rains. Undersized culverts can be overwhelmed leading to overtopping and damage to the roadway and surrounding ecosystem, blocking access to habitat for aquatic organisms, and flooding properties and facilities.

A drainage assessment of the hydraulic and hydrologic capacities of the culverts and tidegates is required. The assessment will determine the necessary short-term repairs and the size of larger replacement culverts in the medium-term to help increase tidal water exchange to saltwater marshes as well as protect Route 1A from floods and washouts. In addition, we recommend that MassDOT maintain regular inspections of the seven self-regulating tidegates to keep them functioning and maintained to ensure flushing of the saltwater marshes.

Location

Assessing and resizing culverts based on projected climate data is recommended for all culverts under Route 1A in the study limits.

Impacts/Considerations

The installation of larger culverts may result in flooding at downstream locations with undersized culverts as larger volumes of water flow through the upstream culverts. While this impact is not anticipated in the Route 1A corridor, downstream flooding is usually addressed through evaluation of the drainage basin.

Costs

The cost of replacing culverts varies and depends on materials, size, and additional components, such as self-regulating tidegates. The cost of replacing a culvert on a principal arterial is generally considered high, costing between $50,000 and $100,000. The implementation timeframe is usually between two and five years.

5.7.5 Upgrade Stormwater Pump Stations

The capacity to collect, convey, and discharge stormwater flows to large bodies of water would be reduced by higher water levels as sea level rises. Drainage outfalls that are below projected water levels for high tides or storm surge should be elevated. These outfall pipes could be fitted with check valves to prevent backups and be pumped rather than gravity drained. There are four pump stations located in the low-lying areas near the Route 1A corridor and many in other parts of Revere. The pump stations are owned and maintained by the City of Revere.

Detailed assessments of stormwater pump stations, considering projected climate data, are required for the corridor's long-term flood protection strategy. Such analysis would help to determine the existing conditions, capacity, and overall functionality of the pump stations, and necessary upgrades to increase pumping capacity, provide emergency power, relocate drainage outfalls, and add new stormwater pump stations to vulnerable areas. Upgrading stormwater pump stations would help prevent areas from flooding and related damage in the future and allow those areas to recover faster from flooding. Additional investment would be necessary for off-site monitoring and control of these facilities.

> Stormwater pumps help to protect areas by pumping away large volumes of water, thereby preventing the occurrence of flooding. With the expected rise in sea level, frequent storm surges, and extreme precipitation, reliability of stormwater pump stations is the key to ensuring that people, homes, roads, bridges, culverts, commercial buildings, and many other facilities are protected when faced with flooding. Reduced discharge capacity and/or failures of pump stations could cause flooding leading to potentially significant consequences.

Locations

Existing stormwater pump stations in the corridor, especially in the northern segment of Route 1A would need assessments. Also, new stormwater pump stations for locations projected to be flooded in the future, especially, in the southern segment of Route 1A, as indicated in the flood risk probabilities maps would need assessment. Figure 27 shows example pump stations.

Impacts/Considerations

Stormwater pumps can protect neighborhoods and assets and allow flood waters to drain more quickly from an area. They are good near-term, medium-term, and long-term investments for both the northern and southern segments of Route 1A.

Cost

The cost of upgrading stormwater pump stations varies greatly and depends on several system components. Upgrading stormwater pump stations is a high-cost, medium-term project with a five-year to 10-year implementation timeframe.

5.7.6 Stormwater Controls

Best practices for stormwater management are designed to reroute stormwater runoff from roadways and other impervious surfaces, minimize the discharge of polluted runoff into local waterways, and control flooding. Pollutants can be removed through vegetative filtering, sedimentation, biological uptake, infiltration into the underlying soil, and nutrient uptake by plants and other aquatic organisms.

Stormwater controls include detention and retention basins, constructed wetlands, biofilters (wet swales and sand filters), and bioretention. (See Figure 28.) These stormwater controls are classified into wet and dry pools. Wet pools are appropriate for larger catchments and have a permanent pool of water, which is replaced with stormwater during storm runoff events. Dry pools systems hold stormwater for short periods of time, especially during intense storms, to reduce peak storm runoff, collect sediment from the flood water, and decrease flood damage. Some stormwater controls, such as detention basin systems, employ medium-sized pump stations to increase efficiency and further reduce the frequency of flooding.

Location

Detention and retention basins are more appropriate for the low-lying areas along the southern segment of Route 1A, though this area is expected to experience far less flooding compared to the northern segment.

Credit: GBA Team

Stormwater pump station

Credit: City of Framingham

Sewer pump station

Credit: Environmental Context Ltd

Stormwater pump station

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FIGURE 27
Example Pump Stations

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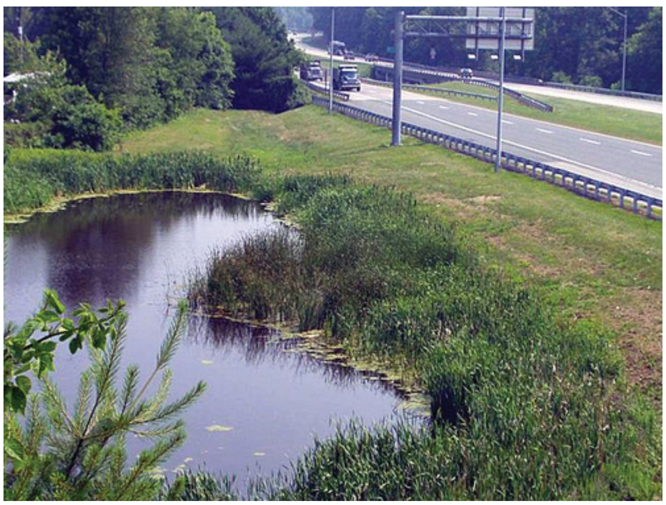
Credit: Maryland Department of Transportation

Stormwater wetlands are large-scale practices that create shallow wetland areas to treat stormwater. They incorporate small permanent pools and/or extended detention storage.



Credit: Maryland Department of Transportation

Wet ponds are permanent pools for stormwater detention. Stormwater runoff is filtered and treated through settling and nutrient uptake by plants and other aquatic organisms.

Credit: El Paso County, Colorado

An extended detention basin is designed to totally drain dry sometime after stormwater runoff ceases. It is an adaptation of a detention basin used for flood control.

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FIGURE 28
Stormwater Management Practices

Costs

The cost of stormwater controls varies by type and size. The cost of highway detention basin systems ranges from $100,000 to $200,000.

5.7.7 Elevate Assets (Raise Roads in Low-Lying Areas)

Based on the flood risk probability and depth maps, Route 1A is already at risk of flooding. Elevating the roadway is one option to consider for ensuring that Route 1A can continue to provide access to vital services and facilities in the future. Figure 29 shows an example of a road raised in response to climate change impacts.

> The decision to protect Route 1A requires an assessment of the roadway's elevation profile and many variables, including sea level rise estimates, protection afforded by existing and projected marshes and rock revetments, present and future transportation needs, and costs for stormwater control infrastructure and measures.
>
> Elevating transportation assets in the area is not limited to Route 1A. The MBTA's Newburyport/Rockport commuter rail line and Route 107, which run through the Rumney Marsh Reservation, are in the same situation.

Locations

The northern segment of Route 1A (Revere Street to Mills Avenue) is the critical segment that could be raised. The area is projected to experience frequent inundations beginning in 2030 and worsening over time. There are limited properties abutting the roadway in this segment, which minimizes the impact a higher roadway elevation would have on neighborhoods by creating drainage problems or potentially funneling damaging water into homes. However, some residents of Riverside and Point of Pines abutting Route 1A would be affected by this option.

Impacts/Considerations

This option would impact residents of Riverside and Point of Pines as a raised road would cause flooding, water pooling, and driveways would be at such a steep slope that they would be inaccessible. Specifically designed to adapt to sea level rise, raised road designs typically include features for collecting, pumping, and treating stormwater that runs off the raised roads. Hence, to prevent raised roads from channelizing stormwater to homes and properties at lower elevations, municipalities often use stormwater pumps, stormwater clearing drains to remove this excess water, and stormwater controls to store, treat, and discharge stormwater.

Miami Beach is raising roads by two feet, at a cost of roughly $2 million per block. The entire project is slated to be completed by 2019.
Credit: City of Miami, Florida: Miami Beach Stormwater Program

Workers raise a street two-to-three feet in Miami Beach, Florida, as part of an effort to get ahead of rising sea levels. The city is barely above sea level.
Credit: City of Miami Beach, Florida

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FIGURE 29
Examples of Roads Being Raised Because of Rising Sea Levels

Exploring Resilience in MPO-Funded Corridor and Intersection Studies

Elevating the roadway, bridges, structures, and utilities above the projected flood elevations would have economic benefits and avoid social and psychological impacts associated with a disruption to or loss of Route 1A, which could result in long commuting times and congestion on limited diversion routes. By incorporating nature-based solutions to complement the elevation project, ecological impacts from construction to the adjacent saltwater marsh, tidal flats, and sanctuaries for fishes and birds would be reduced.

Costs

Roadway reconstruction projects are usually high-cost and long-term projects. The implementation timeframe is usually 10 or more years.

5.8 IMPLEMENTATION STRATEGIES

The adaptation options described above can be combined in several ways to maximize benefits (hybrid solutions) or add on resilience measures over time to reduce costs due the uncertainties in future projections (adaptive and modular solutions).

5.8.1 Hybrid Solution

Nature-based features possess some inherent capacity to reduce storm hazards through reductions in wave height, flood depths and extent, and erosion. These natural systems are most effective at mitigating these hazards under low to moderate intensity events. Revetments and bulkheads are commonly used along with nature-based solutions to protect infrastructure, including coastal roads and bridges threatened by high energy waves.

> For storms with high energy waves threatening a coastal highway, combining nature-based approaches with structural (gray infrastructure) may address some of the shortcomings, while simultaneously enhancing the resilience of both the infrastructure and the ecosystem.

Location

Hybrid solutions are appropriate for the northern segment of Route 1A because of its proximity to the Rumney Marsh Reservation. This segment would be inundated the most, according to the flood probability and depth maps, and would likely require some structural solutions (revetments, bulkheads, and the raising of the roadway) to complement the recommended nature-based solutions.

Impacts/Considerations

While there may be benefits and opportunities for hybrid solutions, it is important to acknowledge the long-term impact of these options as well. Experts in nature-based and coastal structural solutions must be involved to identify options that work together for co-benefits and to avoid damage to the existing ecosystem.

Costs

Nature-based solutions are generally low-cost, while structural solutions are high-cost. By extension, hybrid solutions are high-cost, depending on the options included in the solution, but generally they offer long-term benefits. Table 8 presents relative costs of shoreline stabilization options.

Table 8
Relative Costs of Shoreline Stabilization Options

Technique	Design and Permitting Costs	Construction Costs	Expected Maintenance Frequency[1]	Average Annual Maintenance Costs[2]	Average Annual Mitigation Costs[3]
Artificial dunes and dune nourishment	Low	Low	1–5 years	Low	None
Controlling overland runoff	Low	Low	5–20 years	Low	None
Planting vegetation	Low	Low	1–3 years	Low	None
Bioengineering—coir rolls on coastal banks	Low-Medium	Medium-High	1–3 years	Low-Medium	Low
Bioengineering—natural fiber blankets on coastal banks	Low	Low	1–3 years	Low	None
Sand fencing	Low	Low	3–5 years	Low	None
Beach nourishment	Medium	Low-Medium	5–10 years	Low	Low
Rock revetments—toe protection	High	High	10–20 years	Low	Low- Medium
Rock revetments—full height (up to predicted flood zone elevation)	Very High	Very High	20–25 years	Low	Medium
Seawall	High-Very High	Very High	25–40 years	Low	Medium-High

Note: Construction cost estimates *(average cost per linear foot of shoreline)*: Low: less than $200; Medium: $200-500; High: $500-1,000; Very High: >$1,000.

[1]The frequency of required maintenance is highly dependent on storm severity and frequency and shoreline exposure. See StormSmart Properties fact sheets for details on maximizing longevity.

[2]Estimated annual costs averaged over the life of the project to maintain project components, assuming the project is designed and installed properly

[3]Estimated annual costs averaged over the life of the project to compensate for the technique's adverse effects

Source: Massachusetts Office of Coastal Zone Management.

5.8.2 Adaptive and Modular Solutions

Adaptive and modular solutions involve a collection of policies, nature-based measures, and structural measures to reduce flood risk. The purpose of these solutions is to enable a transition from one measure to another over time to account for uncertainty in future projections. These solutions provide flexibility among policies and measures, thereby spreading costs over time. For example, instead of designing for a 2070/2100 planning horizon, an adaptive/modular approach could use a 2050 planning horizon and integrate flexibility to add-on future improvements depending on monitoring results.

Locations

Adaptive and modular solutions are recommended for the northern segment of Route 1A because of the high cost of structural solutions that would be required to protect the assets. A typical approach is a hybrid solution that starts with nature-based solutions and then, based on monitoring results, adds the options of rock revetments and larger culverts, and then pump stations, and ultimately raising the road if necessary.

> Climate models provide valuable insights about how the climate would respond to rising concentrations of greenhouse gases. However, climate model projections are subject to uncertainty and are still evolving. Hence, it could be prohibitively expensive to prepare for all possible outcomes. Instead, adaptive management approaches are designed for flexibility and facilitating climate resilience throughout the life of infrastructure assets.

Impacts/Considerations

Monitoring is key to the adaptive and modular approach. It informs the decision-making process as to when and where to add on the next measure to enhance resilience. The approach could lead to substantial cost savings and prevent adverse environmental impacts on ecosystems and habitats.

Costs

Depending on monitoring results, adaptive and modular solutions can be low cost if only nature-based solutions are needed, or high cost if structural solutions are needed in the future.

5.9 OPPORTUNITIES

Nature-Based Solutions

Opportunities exist to make Route 1A resilient in a way that benefits the surrounding ecosystem. The City of Revere had already started restoring saltwater marshes to protect the ecosystem habitat and control flooding. Hence, the location of the roadway also provides opportunities to consider effective low-cost coastal highway resilience measures that incorporate nature-based solutions to complement marsh restorations.

Regional Collaboration and Interagency Coordination Effort

There is no reliable alternative to Route 1A if it is flooded. The parallel and closest road, Route 107, also suffers the same issues as Route 1A—both roads are highly exposed to sea level rise, storm surge, and extreme precipitation. The MBTA's Newburyport/Rockport commuter rail is also in the same situation. Hence, building resilience into Route 1A should be considered in the larger context along with the futures of Route 107 and the MBTA commuter rail line. The Regional Saugus River Floodgate Project is an example and presents opportunities for a regional collaboration as well as an interagency and multidiciplinary team to coordinate efforts, optimize capital investments, and protect vulnerable populations and assets.

Adaptive Solutions and Value Creation

Making Route 1A more resilient also presents the opportunity for flexible adaptive solutions to address near-term problems and for adding on future improvements as necessary based on monitoring results. Additional opportunities include new value creation in the surroundings to address environmental and social and equity impacts.

5.10 NEXT STEPS

The next steps in this pilot study are for the MPO staff to work with the City of Revere, MassDOT, MBTA, EPA, CZM, DCR, and other stakeholders to build an interagency collaboration to advance the Route 1A resiliency project. This collaboration will facilitate addressing environmental issues and regulations and optimize investment opportunities by evaluating impacts beyond transportation perspectives. This project also has regional impacts, therefore regional coordination with legislators to build support for the project will be essential.

Chapter 6—Findings and Recommendations

6.1 FINDINGS

The following are the findings from the study:

1. Ample resources (data, models, and tools) currently exist to help MPO staff to conduct and incorporate resilience into MPO-funded corridor and intersection studies.
2. Federal and state agencies' efforts and collaborations have made available climate and environmental data, models, and tools for assessing vulnerability and planning for resilience. NOAA, FEMA, USGS, and USACE are some of the agencies that provide climate data and models for sea level rise, storm surge, stormwater and river discharge, precipitation, and heat.
3. The Massachusetts Coast Flood Risk Model supports the assessment of vulnerability and risks for coastal communities along the entire Massachusetts coast and islands. MPO staff could use the MC-FRM when conducting corridor and intersection studies involving coastal assets.
4. An inland (riverine) flooding model is currently being developed (expected to be completed in 2023) that could be used for corridor and intersection studies.
5. Inland and coastal flooding are major threats for municipalities, according to their MVP and HMP reports. Roads, bridges, and culverts are the vulnerable transportation assets and could be the focus of technical assistance.
6. The MVP, HMP, and CIP are the main tools for addressing resilience in municipalities. MPO staff have summarized the identified problems and recommended actions for each municipality and the list will be consulted regularly whenever a study is initiated.
7. Municipalities are taking multiple approaches to addressing transportation resiliency—a combination of regulatory, nature-based solutions, and structural and engineering solutions.
8. Stormwater management solutions and a field inventory of culverts and bridges are the top recommendations to improve transportation resilience in municipalities.
9. MassDOT and MAPC provide access to valuable data and information on climate change and resilience. MPO staff should continue to collaborate with these agencies in future MPO resilience activities.
10. The RMAT tool can be used in MPO resilience activities when it is available in early 2021 as scheduled.

6.2 RECOMMENDATIONS

1. MPO staff have the resources to incorporate resilience in corridor and intersection planning studies. Resources, including data from climate prediction models, are available to the MPO staff. Also, communities in the region that responded to staff's survey expressed strong support for incorporating resilience into MPO-funded corridor and intersection studies.

2. MPO staff could provide technical assistance to municipalities seeking to combat climate-related challenges by sharing best practices. Staff could begin with coastal communities and use the MC-FRM to provide a better understanding of flood risk level and adaptation options available to these communities. When the inland flood model becomes available, staff could provide this assistance to inland communities. The MPO staff's community survey indicated strong support for technical assistance.

3. The MPO staff continues to consider climate change and resilience when developing the LRTP and evaluating projects to receive funding through the TIP to improve the regional transportation system. The survey also indicated strong support for these MPO actions.

4. The MPO staff can coordinate studies with the MVP Program and guide project proponents toward applying for both MVP Action Grants and TIP funding. MPO staff also could work with municipalities to identify transportation-related resilience items from the MVP Program that could be funded through the TIP. Any projects that would be candidates for TIP funding would be subject to the TIP evaluation criteria.

5. This Route 1A Resilience Study provided MPO staff with several opportunities—knowledge and experience in transportation resilience. Staff can now use this information as part of its MPO outreach programs to promote transportation resilience in the Boston Region MPO area.

Appendix A

Comments

Comment 1. Route 1A Elevation: There is reference in the draft report to the possible elevation of sections of Route 1A, specifically those sections that do not abut residential neighborhoods. How does this option affect the section of Route 1A adjacent to the Riverside and Point of Pines neighborhoods? And how does one transition from the different roadway elevations in residential vs. non-residential sections of the roadway?

Response: MPO staff expanded the recommendation for possible elevation of Route 1A to include the impacts of extending this option to the segment adjacent to Riverside and Point of Pines neighborhoods and how impacts of transitioning from different elevations could be addressed.

Comment 2. Purple Line Tracks: As noted above, among potential strategies referenced in the draft report is the elevation of certain sections of Route 1A. There is no reference in the XS to the possible elevation of the MBTA railroad tracks. Could/should that also be considered?

Response: MPO staff expanded the recommendation for possible elevation of Route 1A to also consider elevation of the MBTA commuter rail tracks.

Comment 3. General Edwards Bridge Replacement: I did not see any reference in the draft report XS to this structure and its replacement, nor to how the design of the replacement bridge could be done in such a way as to enhance climate resiliency in the Route 1A corridor. Unless I missed this reference and discussion, it would be conspicuous by its absence.

Response: MPO staff agrees with this comment and have included the MassDOT project to investigate and make necessary repairs/reconstruction of the substructure and superstructure of the General Edwards Drawbridge in the report. In addition, MPO staff recommended design work and considerations for enhancing resiliency in the Route 1A corridor.

Comment 4. The Seagate Strategy: This option relates to both the Route 1A and possibly the new General Edwards Bridge design. Again, unless I missed this reference and discussion, it would be conspicuous by its absence.

Response: MPO staff agrees with this comment and have added the Saugus River Floodgate Project as one of the comprehensive options to address climate change impacts and resiliency on a regional scale for multiple assets.

Comment 5. SELF Regulation Tide Gates: Ensure the 7 self-regulating tide gates along this corridor are functioning and maintained.

Response: MPO staff emphasized the need to ensuring that the seven self-regulating tidegates in the corridor have regular inspections, maintained, and functioning well.

Comment 6. Marsh Restoration: Continuation of Phase 2 and 3 of marsh restoration and flood storage efforts on both sides of Route 1A between Revere St. and Oak Island.

Response: MPO staff highlighted in the report continuation of Phase 2 and 3 of marsh restoration and flood storage.

Comment 7. Culverts: Additional culvert under Route 1A at the Eastern County ditch.

Response: MPO staff added this culvert to the report

Comment 8. Pump Station: Pump station at the Eastern County ditch headwall at the B&M tracks discharging to Diamond Creek.

Response: MPO staff added more text to describe this pump station.

Appendix B

MassDOT and MBTA SHMCAP Action Items

State Hazard Mitigation and Climate Adaptation Plan (SHMCAP)

The State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) for the Commonwealth was adopted on September 17, 2018, in fulfillment of Governor Baker's Executive Order 569 on climate change.

Transportation focused MassDOT and MBTA

Strategies	Action Descriptions
MassDOT - Expand and improve the Boston Harbor Flood Risk Model to create the Massachusetts Coastal Flood Risk Model	Create improved sea level rise and storm surge scenarios for the present tidal epoch, 2030, 2050, 2070/2100; create northern and southern model grids; consider future shoreline changes; correct CZM/MassGIS shoreline mapping; assess the storm surge vulnerability of the coastal transportation network; and make data available to state agencies, coastal communities, and other interested stakeholders.
MassDOT – Incorporate climate resiliency into capital planning activates	Establish awareness and training to incorporate climate change impacts into project design, and Operations and Maintenance. Impacts of current state and federal regulation impacts, policy, standard operating procedures, design guides will be assessed.
MassDOT – Pilot Deerfield Watershed Stream Crossing Resilience Project	This project will produce GIS layers and a web viewer ranking the vulnerability of culverts and wildlife to climate change. The final report will document the methods used in the project. Next steps will include an evaluation of how to transfer the methods to the remaining watersheds in Massachusetts.
MassDOT – Incremental Development of Resiliency-Oriented Design Guidelines	MassDOT will work towards incrementally updating design standards across all Divisions for projects including roads, bridges, tunnels, and support facilities using the Massachusetts climate change projections.
MassDOT – State-wide Transportation Asset Vulnerability Assessment (inland flooding)	The study aims to provide a better understanding of which MassDOT's assets (infrastructure) are most likely to be at risk due to future inland flooding by utilizing the latest climate model results, suitable hydrologic and hydraulic tools, geospatial analysis and scenario planning methods. The potential impact of extreme heat on

	transportation assets and operations is also investigated qualitatively. The study has delivered a prototype methodology for mapping out future climate-related inland flood plains at U8 watershed level and for assessing assets' vulnerability to extreme flood events. The study will eventually generate a prioritized list of assets for resilience actions.
MBTA – Incorporate climate resiliency into capital planning activities	The MBTA's Strategic Plan and Focus 40 goals explicitly address climate resiliency as a key priority for the MBTA. The overarching capital planning program will continue incorporating climate resiliency as a factor in project-level decision-making. All ongoing and new capital projects will mandate consideration of current and future extreme weather and incremental climate change related risks into design and construction of each project.
MBTA – Complete system-wide vulnerability assessment.	Continue assessing vulnerability of MBTA systems, operations, and assets. Blue Line vulnerability assessment has been completed. Drilldown assessments of critical assets on Blue Line in-progress. Piecemeal approach will continue in FY 2019 with assessments of Red Line, Power and Communications Systems, and portions of Commuter Rail. Additional assessments and resiliency measures will occur from FY2020-onward.
MassDOT – Utilize the Boston Harbor Flood Risk Model and data from the vulnerability assessments to identify current and future high risk areas and strengthen emergency management with local, state and federal agencies.	MassDOT and the Federal Highway Administration co funded a pilot project to assess the vulnerabilities of the Central Artery tunnel system in Boston to coastal storm surge for present day, 2030, and 2070. This project created the Boston Harbor Flood Risk Model (BHFRM) and includes the effects of nor'easters, hurricanes and sea level rise. The goal of the action is encourage the use of BH-FRM data by state and local entities and begin to inform resiliency related projects.
MassDOT – Assess the feasibility of recommendations from the Commission on the Future of Transportation in the Commonwealth	With Executive Order 579: Establishing the Commission on the Future of Transportation in Commonwealth, Governor Baker wanted to investigate 5 areas of interest one of which is Climate and Resiliency. This topic area includes greenhouse gas emission reduction, and what investments will

	be needed to make transportation infrastructure more resilient for the 2020-2040 timeframe. The Commission's report and recommendations are due to the Governor by December 1, 2018.
MassDOT – Capture and document institutional knowledge on vulnerabilities from staff using the Mapping Our Vulnerable Infrastructure Tool (MOVIT)	MOVIT Tool that contains data obtained from the institutional knowledge of maintenance engineers (and anyone else with pertinent knowledge) and data from the vulnerability assessments. This initiative will provide vulnerable asset data collected from districts to be used for project review and prioritization. This information will be stored in MOVIT or other databases as developed.
MassDOT – Coordinate with state and federal agencies to evaluate environmental regulation and permitting processes to address current roadblocks in climate change	Establish a regulatory working group to explore the expansion of Surface Transportation Uniform Relocation Assistance Act regarding exemptions and minor modifications.
MassDOT – Develop climate change adaptation design guidance and provide resources and training for project managers and design teams on bridge and culvert design interaction with emerging fluvial geomorphology practices	MassDOT is developing a fluvial geomorphology based "Rivers & Roads" training program that will be initially offered to staff, including environmental analysts, project managers, bridge and hydraulic engineers, and construction and maintenance personnel. The training will eventually be offered to local government and the private consulting and construction sectors. The program will include three tiers that will increase in complexity.
MassDOT – Incorporate climate change adaptation into the MassDOT Highway Division Transportation Asset Management Plan and coordinate Asset Management across divisions and partner agencies	Conduct an asset management pilot project on the vulnerability of culvert and bridge assets. This information will be stored in MAPIT and will give an alert to proponent to coordinate with Hydraulics, Bridge, and Environmental departments.
MassDOT – Incorporate resiliency review items into the Early Environmental Coordination Checklist	Revise the Environmental Early Coordination Checklist to include resiliency review items.
MassDOT – Leverage permit granting authority and ability to influence M.G.L. Section 61 findings and mitigation	Developers are required to evaluate a project's impacts on transportation through a Transportation Impact Analysis and to include mitigation, as necessary, in the form of highway, transit, pedestrian and bicycle accommodations. After the project is build, the proponent must submit a monitoring report. Example: ENCORE BOSTON HARBOR provided $7.5 million to improve the transit system and ensure multimodal accommodations are effective in mitigating

	new trip generation. Planning is working on getting MassBike, Walk Boston and developers at the same time to evaluate performance and identify ways to enhance the transit system.
MassDOT – Require a holistic evaluation of all vulnerability, environmental, transportation and social data sets in the earliest project planning phases	Understanding a broad range of constraints and sensitive resources early in project planning ensures resilient infrastructure and helps avoid permitting issues later in the project development process. This initiative will also reduce the need to retrofit infrastructure for adaptation measures post-construction. MassDOT will vet and compile data sources including vulnerability data and leverage project planning tools such as MassDOT Project Intake Tool or MAPIT. MAPIT is a web-based GIS and project development tool that brings together transportation, safety, environmental, and vulnerability data to help arrive at the most context sensitive design.

Appendix C

Survey Questionnaire

Exploring Resilience in MPO-Funded Corridor and Intersection Studies

Planning to make the transportation system resilient to the effects of climate change has become a statewide and regional priority and will become more important in the coming years. The Boston Region Metropolitan Planning Organization (MPO)—a cooperative body of local, state, and federal entities, representing 97 municipalities, that decides how to allocate federal transportation funding for transportation projects and studies in the Boston region—has recognized the importance of addressing this issue in its Long-Range Transportation Plan, *Destination 2040*. The MPO's goal is to incorporate consideration of climate change vulnerability and adaptation strategies in transportation decision-making at both the system and project level across the region.

The MPO staff is exploring how to incorporate resilience in MPO-funded corridor and intersection studies. As part of this research, the MPO staff is reaching out to municipalities to better identify problems related to climate change, determine the best practices for conducting vulnerability assessments and planning, and generate ideas for adapting to climate change impacts.

This research will help MPO staff identify best practices and provide assistance to municipalities seeking to address extreme weather, flooding, and other climate-related challenges. Staff will incorporate the findings of this research into MPO-supported discrete studies, recurring studies, and technical assistance programs. To learn more about MPO-supported studies, visit www.ctps.org/publications.

Please take this short survey to help the MPO staff gather information about critical transportation assets and resilience planning in the Boston region. The survey takes about five minutes to complete.

Full Name:

Job Title:

Municipality:

Email:

Section One: The Impact of Climate Change on Transportation

1. What hazards and stressors affect transportation assets in your municipality? (Check all that apply.)
    - Stormwater flooding (heavy rainfall)
    - Inundation from sea level rise
    - Coastal flooding (coastal storms or storm surge)
    - Coastal erosion
    - Inland flooding
    - Heat (extreme temperatures)
    - Snow/ice
    - High winds
    - Wildfire

- Other (Please specify.)

2. What are the critical transportation assets vulnerable to climate hazards in your municipality? (Check all that apply.)
    - Roads
    - Bridges and culverts
    - Trails, bicycle or pedestrian facilities
    - Railroads
    - Public transportation (bus, subway, commuter rail, or ferry)
    - Other (Please specify.)

3. How is transportation resilience being addressed by your municipality? (Check all that apply.)
    - Municipal Vulnerability Preparedness (MVP) grant program
    - Hazard Mitigation Plan (HMP), which allows the community to apply for FEMA funding
    - Master Plan, which includes transportation resilience as a goal or objective for the municipality
    - Climate Action Plan, a collection of policies that will benefit the environment, transportation, and economy
    - Capital Improvement Program or planning process, which considers resilience in the project development and planning process
    - Project design guidelines and other local regulations that require permeable materials for new projects, zoning restrictions on new construction in coastal and flood zones, or other resiliency measures
    - Other (Please specify.)

Section Two: Climate Resiliency Planning in the Transportation Sector

4. If your municipality has developed a MVP program report, Climate Action Plan, and/or HMP, what climate change impacts have been identified as of greatest concern to transportation assets? (Check all that apply.)
    - Coastal erosion and degradation of roads and bridges
    - Flooding and washout of roads and trails
    - Flooding and scouring of bridges and culverts
    - Disruption to public transportation system (as a result of power outages, extreme heat, or buckling of pavement, for example)
    - Stormwater runoff inundation of drainage infrastructure
    - Other (Please specify.)

5. In the last ten years, did your municipality's Capital Improvement Program contain projects that would make transportation assets resilient to climate hazards? (Check only one.)
    - Yes (Please describe the projects.)

- No
- Do not know
- Other (Please specify.)

6. What are the top recommendations to improve transportation resilience in your municipality (based on MVP program reports, HMPs, or Climate Action Plans)? (Check all that apply.)
    - Conduct a vulnerability or risk assessment of an intersection, roadway, or subregional road network to assess impacts and identify potential mitigation measures of applicable climate hazards
    - Conduct a field inventory of culverts and bridges to rank and prioritize projects for increased resiliency (by resizing, replacing, or elevating infrastructure)
    - Prioritize or implement green infrastructure and nature-based solutions into transportation planning efforts
    - Assess drainage infrastructure to develop stormwater management solutions to reduce road flooding
    - Update maps and data to ensure that residents and businesses have the most accurate information regarding risks and the need for potential mitigation strategies
    - Conduct robust transportation resiliency planning to ensure that routes for access and egress are maintained during hazard events (including evacuation routes, emergency access routes, and routes vital for emergency support and mobilization functions)
    - Coordinate with state agencies to assess resiliency of the transportation system with particular focus on minimizing susceptibility to climate hazards and ensuring continued operations
    - Continue upgrading aging traffic control systems with more energy efficient and resilient options, such as low voltage LED lights with back-up power supply to maintain normal traffic flow operations during power outages
    - Implement transportation-focused climate resiliency policy measures
    - Not applicable, or currently developing plans or recommendations
    - Other (Please specify.)

7. Are transportation security and emergency access included in your municipality's plan to make the transportation system resilient? Examples include planning or designating evacuation routes, alternative evacuation routes, and emergency access routes to critical facilities (such as schools, hospitals, and fire and police stations). (Check only one.)
    - Yes (Please describe how these are addressed in the plans.)
    - No
    - Do not know

8. What policy measures or action plans are incorporated in the MVP program reports, HMP, or Climate Action Plans to make the transportation system more resilient to climate hazards in your municipality? (Check all that apply.)

- Integrate resiliency measures into capital improvement projects, operations and maintenance, and planning activities
- Review or amend the municipality's regulatory code for resiliency-focused improvements (such as coordinated stormwater management and land use zoning regulations)
- Establish awareness and training programs to increase knowledge of and familiarity with climate change and resilience
- Create incentives for green infrastructure, nature-based solutions, and engineering-based solutions
- Develop a project-level checklist to evaluate facility risks and vulnerability due to climate change at the time funding is programmed
- Not applicable, or currently developing plans or recommendations
- Other (Please specify.)

Section 3: Transportation Resilience and the MPO

9. How can the Boston Region MPO help to improve the resilience of the regional transportation system? (Check all that apply.)
    - Provide technical assistance to municipalities on climate change resiliency planning for transportation assets and infrastructure
    - Incorporate resilience into MPO-supported corridor and intersection studies
    - Incorporate resilience in the goals, objectives, and needs assessments to guide the development of the MPO's next Long-Range Transportation Plan
    - Include resilience considerations in project evaluation criteria, which are frequently related to performance measures and targets
    - Monitor, using performance measures, how resilience strategies are performing so that the planners can report on the performance to influence decisions in the update cycle for the Long-Range Transportation Plan
    - Other (Please specify.)

10. What kinds of technical assistance does your municipality need to understand the hazards and vulnerabilities of the transportation system? (Check all that apply.)
    - Facilitate and promote the sharing of best practices for regional collaboration, cost sharing, and identification of gaps in vulnerability assessments
    - Convene regional discussions about climate change mitigation and adaptation goals
    - Provide technical assistance, tools, and resources on topics such as stormwater and land use planning for communities seeking to mitigate and adapt to climate change locally through their own facilities and resources
    - Offer guidance on updating design standards for projects (such as those addressing roads, bridges, and culverts) based on climate projections for Massachusetts
    - Other (Please specify.)

Appendix D

Candidate Corridors

Table 1
Candidate Locations for Incorporating Resiliency

ID	Corridor or Intersection	Town	Ownership	Reasons for Incorporating Resilience	Type of Flooding	Projects and Studies	Priority	Contact	MPO Resilience Survey Response
1	Alewife Brook Parkway including the intersection of Route2/Massachusetts Avenue/Route 16.	Arlington and Cambridge	MassDOT District 4 and DCR	Route 2 and Alewife Brook Parkway including Route 16 (between Massachusetts Avenue and Route 2) and the Exit Ramp to Alewife T station off Route 2 Eastbound, where significant flooding frequently impact travel during heavy precipitation. Roadway infrastructure is highly vulnerable to flooding and has low adaptive capacity. The area was mentioned in the MVP or HMP report for attention.	Inland flooding	No project or study planned for the intersection. Climate Change Vulnerability Assessments identified that the area's direct exposure to localized flooding makes the roads impassable or inaccessible and have cumulative and cascading impacts on multiple critical transportation assets including MBTA Station, bus routes, and access to Alewife Brook Parkway at Route 2 intersection.	**High**	Jennifer Raitt Andrew Reker	Yes
2	Columbus Avenue, Tremont Street, Morrissey Boulevard	Boston	MassDOT/ Boston	Transportation infrastructure will be impacted by frequent stormwater flooding at multiple scales ranging from sidewalks to local streets to major thoroughfares like highways including Columbus Avenue, Tremont Street, and Morrissey Boulevard. Many of the impacted transportation routes are also designated evacuation routes, which may become increasingly more flood prone to coastal storms with heavy rainfall.	Coastal flooding/ Inland flooding	Expand the use of green infrastructure and other natural systems to manage stormwater, mitigate heat, and provide additional benefits. Advancing bus priority infrastructure installation (25 miles of new lanes). Increase public transit commuter rates by a third by 2030- various methods planned. Improve and expand active transportation infrastructure in areas most in need (i.e. those with more children, high crash rates, near public spaces, etc.)	**High**	Zoe Davis	Yes
3	Union Street at Route 3 interchange and Ivory Street intersection	Braintree	MassDOT District 4 and Town	Union Street and Ivory Street intersection and the Union Street interchange with Route 3 are critical flooding areas during heavy rainstorms because centuries of land filling in the Monatiquot River floodplain. Union Street is a critical roadway for emergency evacuation and response, access to the MBTA Station and commercial areas along Ivory Street. The area was mentioned in the MVP or HMP report for attention.	Inland flooding	No project or study planned for the intersection or corridor. This critical intersection, provides access to the South Shore Plaza, the MBTA Braintree garage and station, and the Ivory Street business corridor. Two MAPC studies "Braintree Ivory Street Corridor: A Transit Oriented Development (TOD) Opportunity" and "Climate Vulnerability Assessment" identified the area as vulnerable to flooding and climate change impacts. Comprehensive flooding mitigations on Union Street from Ivory Street to Cleveland Avenue is critical because of evacuation routes and impact on development and area	**High**	Kelly Phelan	No
4	Jeffrey's Neck Road	Ipswich	Ipswich	The roadway is extremely susceptible to flooding from coastal storm surge events and white-out closures during blizzards. Flooding cuts off access to residents (isolates 1200 winter residents in about 600 homes) as well as emergency services. The roadway was mentioned in the MVP or HMP report for attention.	Coastal flooding	No project planned for the roadway. The Town of Ipswich is already addressing some of these concerns with FEMA funding to support the design phase of raising the portion of Jeffrey's Neck Road from Island Park to Eagle Hill. The DPW staff predicts this work will reduce road flooding to one or two times a year, such that during flood events the road would likely remain passable to emergency vehicles with higher clearance. The design is considering additional safety improvements, including guard rails or a roadside flood gauge and restoration of natural water movement under Jeffrey's Neck Road.	**Medium** Town has done considerable work on climate change impacts and resilience through partnerships.	Ethan Parsons	Yes
5	Route 1A, Lynnway.	Lynn	MassDOT District 4	Vulnerable to repeated flooding and possibly sea level rise. The Waterfront acts as a safety barrier for the coast to absorb some of the initial flood damage and reduce the risk to population's further inland. However, in an especially large storm surge the Lynnway would be largely under water and provide little intended protection. Those affected include the businesses along the Lynnway such as car dealerships, Wal-Mart, Dunkin Donuts, Garelick Farms milk factory and a few grocery stores. The corridor was mentioned in the MVP or HMP report for attention.	Coastal flooding	No project or study planned for the corridor. In addition, a CTPS Priority Corridor Study was conducted in 2015 for this corridor.	**High** Incorporate resilience into prevoius CTPS study "Route 1A Lynnway Corridor Study"	Aaron Clausen	Yes
6	Roadway assets near North River Canal, within the Lawrence Brook Watershed, in the downtown area, and along various brook channels.	Peabody	Peabody	Many areas of Peabody experience inland flooding caused by precipitation events. This issue is worsened by the high level of impervious cover in some areas of the City combined with undersized, old, damaged or clogged drainage infrastructure. One of the City's top priority is to assess alternatives for managing commonly flooded areas with public safety concerns located throughout the City. These areas were included in the MVP and HMP reports.	Inland flooding	The City had already engaged consultants to evaluate alternatives, including Low Impact Development (LID) and Green Infrastructure (GI) approaches, to mitigate flooding and improve stormwater quality. Through a MVP grant, City is exploring options for improving the flood resiliency of Peabody Square and to specifically target a stretch of the North River Canal that will improve flood resilience, address site contamination, and evaluate a park resource and Riverwalk that would enhance public access and vitality of the area.	**Medium** City has several projects ongoing.	Brendan Callahan	Yes
7	North Quincy Station and MBTA bus barn	Quincy	MBTA/Quincy	North Quincy Station is located on the banks of the Neponset River basin close to the coast. The station and access roads are vulnerable to rising tides and sea level rise especially during coastal storms and heavy precipitation. Included in the mitigation measures are tide gates and management plan at North Quincy station and restoration of saltwater marsh.	Inland flooding/ Coastal flooding	Quincy has received multiple grants for seawall improvements for Houghs Neck and Adams Shore, Broad Meadow Marsh Restoration, Furnace Brook Restoration, and Stormwater Pumping Station	**High** Coordinate with MBTA and Quincy to identify ongoing projects, capital improvement program, and Focus 2040	Robert Stevens	Yes
8	Route 1A, Mills Avenue, Rice Avenue, and Revere Beach Boulevard	Revere	MassDOT/ DCR/ Revere	These roadways are extremely susceptible to flooding from coastal storm surge events, sea level rise, and closures during blizzards. They have experienced localized flooding and drainage issues. Route 1A is a major artirial connecting many north shore communities to Boston and Logan Airport. Flooding causes major detours, impacting emergency services, and congested roadways.	Coastal flooding	No project planned for these roadways. The City is considering the following adaptation measures: reconstruct seawall and revetments, improve emergency access and reduce hazards to vehicles by changing one-way traffic patterns and encouraging use of public parking garages during high tide and storm events, and repurpose Route 1A oil tanks for stormwater storage. Additional action plans include repair, replace, and install flood gates as well as increasing public awareness about best mitigation plan to address flooding, erosion, and storm impacts.	**High** Coordinate with City, MassDOT or DCR	Frank Stringi	Yes

Table 1
Candidate Locations for Incorporating Resiliency

9	Loring Avenue, Route 1A, and Lafayette Street	Salem	MassDOT District 4	Sections the roadway closer to Salem coast experience flooding due to coastal storms and heavy precipitation as well as from storm drain overflow and overwhelmed seawalls. Route 1A is an evacuation route and a major arterial for north shore communities. It is expected that the roadway may experience more frequent flooding due to climate change as well as increased congestion, causing evacuation delays. The area was mentioned in the MVP or HMP report for attention.	Coastal flooding	No project or study planned for the corridor. A CTPS Priority Corridor Study and a Road Safety Audit had been conducted in the corridor.	**High**	David Knowlton	Yes
10	Mystic Avenue (Route 38) Somerville Community Path between Lowell Street and Davis Square	Somerville	MassDOT District 4 and Somerville	Several sections of the roadway are subjected to frequent flooding during heavy precipitation and coastal storm surges. Low point along Mystic Avenue roadway near Route 28 where flooding has occurred during large rain events. The community path experience flooding at several sections, particularly at the low points along the Somerville Community Path where there is limited drainage and ponding has been known to occur. Both locations were mentioned in the MVP or HMP report for attention.	Inland flooding	No project or study planned for the corridor. Another environmental concern facing Mystic Avenue in the long term is sea level rise. The Amelia Earhart Dam at the mouth of the Mystic River currently prevents the river from flooding, but that could change as early as 2040 when the water could rise above the height of the dam, according to Hunt.	**High**	Oliver Sellers-Garcia	Yes
11	Flooding impacts roadways including Routes 20 and 27 and Pelham Island Road.	Wayland	MassDOT District 3	Roadway frequently floods from heavy precipitation because of low roadway profile, poor stormwater drainage, and inadequate stormwater basins/retention. Several closures of the intersection had occurred because of flooding of the Sudbury River. Routes 20 and 27 are major principal arterials and flooding causes major detours, impact businesses and access to residential neighborhoods. The intersection was mentioned in the MVP or HMP report for attention.	Inland flooding	No project or study planned for the intersection. In 2007, signal and intersection improvements included widening and reconstruction, traffic signalization, drainage improvements, sidewalks, curbing, pavement markings, signing and landscape improvements.	**High**	Neil McPherson	No
12	Four Corners (at intersection of Cambridge Street, Russell Street, and Lexington Street).	Woburn	MassDOT District 4 and Woburn	The areas that flood most frequently were cited as a concern is the Four Corners area, which is often flooded during rain events. Flooding at Four Corners effects the road, parking lots, as well as adjacent businesses, cutting off direct access between the police and fire departments, and the west edge of the City. Intense precipitation, low-lying area, and poor drainage are some of the causes. The corridor was mentioned in the MVP or HMP report for attention.	Inland flooding	No project or study planned for the area. Woburn's action plan include increasing storage, drainage upgrades, drainage improvements, raising roads and adding green infrastructure in areas that flood regularly. The 24-hour, 100-year rain event increased from 6.5 inches to 8.4 inches. Four Corners culvert improvements, wetlands improvement, and stormwater BMPs.	**High**	John Corey	Yes

Appendix E

Preliminary Exposure and Criticality Ratings

Table 2.17. Exposure Rating Scoring Derived from Project Inputs for the Tool

Climate Parameter	GIS Dataset (if applicable)	Question/Filter	Response/Score	Total Score (Calculated)	Exposure Rating (Calculated)
Sea Level Rise/Storm Surge	MC-FRM (Filter: tidal benchmarks shapefile, probability maps, planning horizon)	Is any part of the project located within the tidal benchmarks within the asset's useful life?	Yes = 3; No = 0	Total score determined by summing the values of all responses.	Not Exposed (Total Score 0); Low Exposure (1); Moderate Exposure (2); High Exposure (≥3)
		Is any part of the project in the 1% annual coastal flood exceedance probability (ACFEP) within the asset's useful life?	Yes = 2; No = 0		
	N/A - user question	Does the project site have a history of coastal flooding ?	Yes = 2; No = 0		
	MC-FRM (Filter: probability maps, planning horizon)	Is any part of the project within the 0.1% annual coastal flood exceedance probability (ACFEP) within the asset's useful life?	Yes = 1; No = 0		
Extreme Precipitation *Urban Flooding*	N/A - user question	Does the project site have a history of flooding during extreme precipitation events?	Yes = 2; No = 0	Total score determined by summing the values of all responses.	Low Exposure (0 - 1); Moderate Exposure (2); High Exposure (≥3)
	N/A - user question	Does the project result in a net increase in impervious area of the site?	Yes = 1; No = 0		
	Days >2 inches rainfall (Filter: RCP 8.5, Basin Scale, Planning Horizon)	How many days per year increase with rainfall greater than 2 inches within the asset's useful life?	< 0.2 days = 0; 0.2 to 0.5 days = 1; 0.5 days = 2		
Extreme Precipitation *Riverine Flooding*	FEMA flood zones	Is any part of the project within the current 1% annual chance (100-year) FEMA floodplain?	Yes = 2; No = 0	Total score determined by summing the values of all responses.	Not Exposed (Total Score 0); Low Exposure (1); Moderate Exposure (2); High Exposure (≥3)
	N/A - user question	Does the project site have a history of riverine flooding ?	Yes = 2; No = 0		
	FEMA flood zones	Is any part of the project within 500 ft. of an existing water body or the current 0.2% annual chance (500-year) FEMA floodplain?	Yes = 1; No = 0		
Extreme Heat	Days over 90 degrees (Filter: RCP 8.5, Basin Scale, Planning Horizon)	How many days increase in days over 90 degrees Fahrenheit are there within the asset's useful life?	< 10 days = 1; 10 to 30 days = 2; 30+ days = 3	Total score determined by summing the values of all responses.	Low Exposure (1); Moderate Exposure (2); High Exposure (≥3)
	GIS Map	Is any part of the project within 100 ft. of an existing water body?	Yes = 0; No = 1		
	N/A - user question	Does the project result in a net increase in impervious area of the site?	Yes = 1; No = 0		

DRAFT CRITICALITY WORKSHEET FOR INFRASTRUCTURE - INTRODUCTION

The primary goal of this worksheet is to illustrate the questions needed to evaluate criticality of Commonwealth-owned infrastructure for the application of Climate Resilience Design Standards. Separate criticality worksheets are provided for each asset category: Buildings, Infrastructure, and Natural Resources. The separate worksheets recognize that:
• the criticality of one asset category should not be compared to the criticality of another asset category
• the questions and answers should respond to the specific needs of that asset category

The intent of Criticality in the Climate Resilience Design Standards is not to rank one project versus another, rather to inform return periods/ confidence intervals, which tiered methodology to apply to determine design criteria values, and the Climate Risk Screening output.

Criticality is defined as a function of scope, time, and severity for building and infrastructure assets. Scope is defined as the geographic area and population that would be affected by the loss or inoperability of that asset; time is the length of time an asset can be inoperable without consequences; and severity are the consequences that are associated from the loss or inoperability of an asset – such as public health and safety impacts, economic impacts, environmental impacts, and cascading impacts.

SCOPE	TIME	SEVERITY
• The geographic area and population that would be affected by the loss or inoperability of an asset.	• The length of time an asset can be inoperable without consequences.	• The consequences associated from the loss and/or inoperability of an asset.

Criticality Scoring - Internal Metric Only (NOT SHOWN TO USERS)

The scores are determined through a series of questions related to scope, time, and severity with pre-populated responses. Weighting as described below are based on feedback from stakeholders during working groups held in February 2020.

Scope Score is the average score of the scope questions for population and geography affected. The scope score is doubled if the infrastructure is located in an environmental justice community and/or provides some services to vulnerable populations, AND/OR if the infrastructure serves or is proposed to function as flood protection.

Time Score is based on the length of time the building can be inoperable without consequences as described in the severity section.

Severity Score is based on eight (8) consequences that are assigned weights based on relative impact for infrastructure. Weights are indicated in parentheses in the questions for internal review purposes and will be removed in final tool. The most severe impacts are given the highest weights (3), and lowest impacts are given no weight (1). The composite severity score is a function based on the average of the weighted criteria as follows:
Composite Severity = $[3 \times \Sigma TOP+2 \times \Sigma MID+1 \times \Sigma LOW]/8$
The weighting is assigned to the consequences as follows:.
TOP: Public health and safety and Interdependency
MID: Economic, Environmental (Hazardous materials and Ecological), and Evacuation route (if asset type is Transportation)
LOW: Govermental and Psychological

Final Criticality Score
Composite criticality =AVERAGE [Scope,Time,Composite Severity]
The final score is the normalized value of the Composite Criticality score. The value is normalized on a scale of 10 (low) to 100 (high) due to inherent criticality of all sites.

An asset with final value above 70 is considered High Criticality and value below 40 is considered Low Criticality. Assets with values in between are considered as Medium Criticality. Criticality results are shown for internal review purposes to illustrate the relationships between answers and output. In the web-based tool, users will answer criticality questions and not receive a criticality score.

DRAFT CRITICALITY WORKSHEET FOR INFRASTRUCTURE - SCORING

Questions	Answer Choices	Assigned Scores	Weights	Selected Scores	Lowest Score	Highest Score
1. Identify the geographic area affected	Impacts limited to location of infrastructure only	1	None	1	1	4
	Impacts would be limited to local area and/or municipality	2		2		
	Impacts would be regional (more than one municipality and/or surrounding region)	3		3		
	State-wide or greater	4		4		
2. Identify the population affected	Less than 5,000 people	1	None	1	1	4
	Less than 10,000 people	2		2		
	Less than 100,000 people	3		3		
	Greater than 100,000 people	4		4		
3. Identify the enhanced impact on vulnerable populations (please refer to the SHMCAP for definition of vulnerable populations: elderly, medical needs, disabled, children, etc.)	The infrastructure does not provide services to vulnerable populations	1	None	1	1	2
	The infrastructure is located in an environmental justice community, and/or provides some services to vulnerable populations (services are not available elsewhere to same population)	2		2		
4. Does the infrastructure serve or is it proposed to function as flood protection?	No	1	None	1	1	2
	Yes	2		2		
5. Identify the length of time the infrastructure can be inoperable without consequences as described in the severity section	More than a week after event	1	None	1	1	4
	One to two days after event	2		2		
	Immediately after event	3		3		
	During natural hazard event	4		4		
6. Public health and safety impacts (3)	Loss of infrastructure may result in minor injuries	1	3	3	3	12
	Loss of infrastructure may result in severe injuries, chronic illnesses	2		6		
	Loss of infrastructure may result in severe injuries, possible loss of life	3		9		
	Loss of life expected as a result of loss of infrastructure	4		12		
7. Interdependency impacts (3)	Loss of infrastructure may have a minor impact on other facilities, assets, and/or infrastructure	1	3	3	3	12
	Loss of infrastructure may have a moderate impact on other facilities, assets, and/or infrastructure	2		6		
	Loss of infrastructure may have a significant impact on other facilities, assets, and/or infrastructure	3		9		
	Loss of infrastructure will likely have a debilitating impact on other facilities, assets, and/or infrastructure	4		12		

Questions	Answer Choices	Assigned Scores	Weights	Selected Scores	Lowest Score	Highest Score
8. Economic impacts (direct replacement and/or repair cost only) (2)	<$100,000	1	2	2	2	8
	<$1,000,000	2		4		
	<$10,000,00	3		6		
	>$10,000,000	4		8		
9. Environmental impacts – Haz. Mat (2)	No spills and/or releases of hazardous materials are expected	1	2	2	2	8
	Spills and/or releases of hazardous materials are expected with relatively easy cleanup	2		4		
	Spills and/or releases of hazardous materials are expected with moderately difficult cleanup	3		6		
	Spills and/or releases of hazardous materials are expected with difficult remediation	4		8		
10. Environmental impacts – Ecological (2)	No impact on surrounding natural resources	1	2	2	2	8
	Impact on natural resources can be mitigated naturally	2		4		
	Impact on natural resources will require remediation/rehabilitation	3		6		
	Impact on natural resources is irreversible/natural resource lost	4		8		
11. Transportation Only: Evacuation route impacts (2)	Infrastructure is not an evacuation route	1	2	2	2	8
	Infrastructure is part of an evacuation route	4		8		
12. Governmental impacts (1)	Loss of infrastructure may minimally reduce the ability to maintain state agency services to Commonwealth	1	1	1	1	4
	Loss of infrastructure may moderately reduce the ability to maintain state agency services to Commonwealth	2		2		
	Loss of infrastructure will significantly reduce the ability to maintain state agency services to Commonwealth	3		3		
	State agency will no longer able to maintain services to Commonwealth	4		4		
13. Psychological impacts (public morale) (1)	Reduced morale and public support	1	1	1	1	4
	Demonstrations, protests, and/or lobbying	2		2		
	Loss of confidence in State Agency	3		3		
	Loss of confidence in Commonwealth	4		4		