



# Cape Cod Bridges Program

## Bourne, Massachusetts

### Appendix 4.21 Adaptation and Resiliency

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## Acronyms and Abbreviations

| Acronym/Abbreviation | Definition                                      |
|----------------------|-------------------------------------------------|
| F                    | Fahrenheit                                      |
| FEMA                 | Federal Emergency Management Agency             |
| FHWA                 | Federal Highway Administration                  |
| LSCSF                | Land Subject to Coastal Storm Flowage           |
| MassDOT              | Massachusetts Department of Transportation      |
| MHHW                 | Mean Higher High Water                          |
| NAVD88               | North American Vertical Datum of 1988           |
| NOAA                 | National Oceanic and Atmospheric Administration |
| Program              | Cape Cod Bridges Program                        |

# 1 Introduction

The Adaptation and Resiliency Appendix<sup>1</sup> assesses the potential extreme weather risks to the No Build Alternative and Build Alternative under various conditions related to:

- Sea levels and storm surge
- Extreme precipitation
- Extreme heat
- Winter weather
- Extreme wind

This section evaluates potential risks to the following affected environments referenced in other Final Environmental Impact Statement sections:

- Cape Cod Canal operations
- Bridge infrastructure
- Stormwater control measures
- Land cover
- Highway-traffic operations and safety
- Mobility and accessibility for all road users

## 1.1 Regulatory Context

This Adaptation and Resiliency Appendix was prepared using the following federal and Massachusetts regulatory directives and guidance:

- 23 Code of Federal Regulations (CFR) Section 515.7(c)(1) – Risk management plan for bridges on the National Highway System
- 33 CFR 207.2: Navigation Regulations, Cape Cod Canal, Massachusetts; Use, Administrative and Navigation
- 23 CFR Part 650(A): Location and Hydraulic Design of Encroachments on Flood Plains
- 23 USC 176: Promoting Resilient Operations for Transformative, Efficient, and Cost-Savings Transportation Program
- Federal Highway Administration (FHWA) Hydraulic Engineering Circular Number 25 (HEC-25) Highways in the Coastal Environment, Third Edition (2020)
- FHWA HEC-18 Evaluating Scour at Bridges, Fifth Edition (2012)

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<sup>1</sup> This appendix has been newly prepared for inclusion in the Final Environmental Impact Statement and was not part of the previously submitted Draft Environmental Impact Statement; therefore “New Text” formatting has not been applied.

## 1.2 Study Areas

For the purposes of assessing the impacts of extreme weather, the Study Areas consist of the refined construction Project Limits and a 500-foot buffer for Sagamore Bridge and Bourne Bridge (**Figure 1**).

## 2 Methodology

Past observations and/or modeled conditions were used in conjunction with the affected environment to inform the recommendations for data and methods to assess the impact on the No Build and Build Alternatives. The methodology consisted of reviewing published studies and environmental data, including:

- [Federal Emergency Management Agency \(FEMA\), Flood Insurance Study Number 25001CV000B, Effective July 7, 2021](#)<sup>2</sup>
- [FEMA Policy: Federal Flood Risk Management Standard, Effective September 9, 2024](#)<sup>3</sup>
- Dangendorf, S. (2024). [Kalman Smoother Sea Level Reconstruction \[Data set\]](#). Zenodo<sup>4</sup>
- National Oceanic and Atmospheric Administration (NOAA), [Precipitation-Frequency Atlas of the United States](#), Northeastern states - Atlas 14, Volume 10 (2018)<sup>5</sup>
- [NOAA Sea, Lake, and Overland Surges from Hurricanes \(SLOSH\) model \(Version 3 – June 2022\)](#)<sup>6</sup>

The following additional published studies and plans were reviewed to evaluate impacts on the affected environment:

- U.S. Army Corps of Engineers (USACE), [Massachusetts Hurricane Evacuation Study Technical Data Report, Chapter 2 Hazards Analyses \(2016\)](#)<sup>7</sup>
- USACE, [New England Hurricane Evacuation Study Technical Data Report](#) (June 2016)<sup>8</sup>
- Massachusetts Emergency Management Agency, [Cape Cod Emergency Traffic Plan](#) (2018)<sup>9</sup>

**Table 1** summarizes the affected environments within the refined Project Limits and Study areas and the primary risks assessed.

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<sup>2</sup> <https://map1.msc.fema.gov/data/25/S/PDF/25001CV000B.pdf?LOC=51a412c9cdcc22ab0113e2e0169d67bd>

<sup>3</sup> <https://www.federalregister.gov/documents/2024/07/11/2024-15170/fema-policy-federal-flood-risk-management-standard-ffrms>

<sup>4</sup> <https://doi.org/10.5281/zenodo.10621070>

<sup>5</sup> [https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14\\_Volume10.pdf](https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume10.pdf)

<sup>6</sup> <https://gis.data.mass.gov/maps/a9e9d37e363f434f84b28e791b23398b/about>

<sup>7</sup> [https://www.nae.usace.army.mil/Portals/74/docs/Topics/HurricaneStudies/2016%20State%20Updates/Massachusetts/MA\\_Ch%202\\_Hazards%20Analysis.pdf](https://www.nae.usace.army.mil/Portals/74/docs/Topics/HurricaneStudies/2016%20State%20Updates/Massachusetts/MA_Ch%202_Hazards%20Analysis.pdf)

<sup>8</sup> <https://www.nae.usace.army.mil/portals/74/docs/Topics/HurricaneStudies/2016%20State%20Updates/Massachusetts/New%20England%20Hurricane%20Evacuation%20Study.pdf>

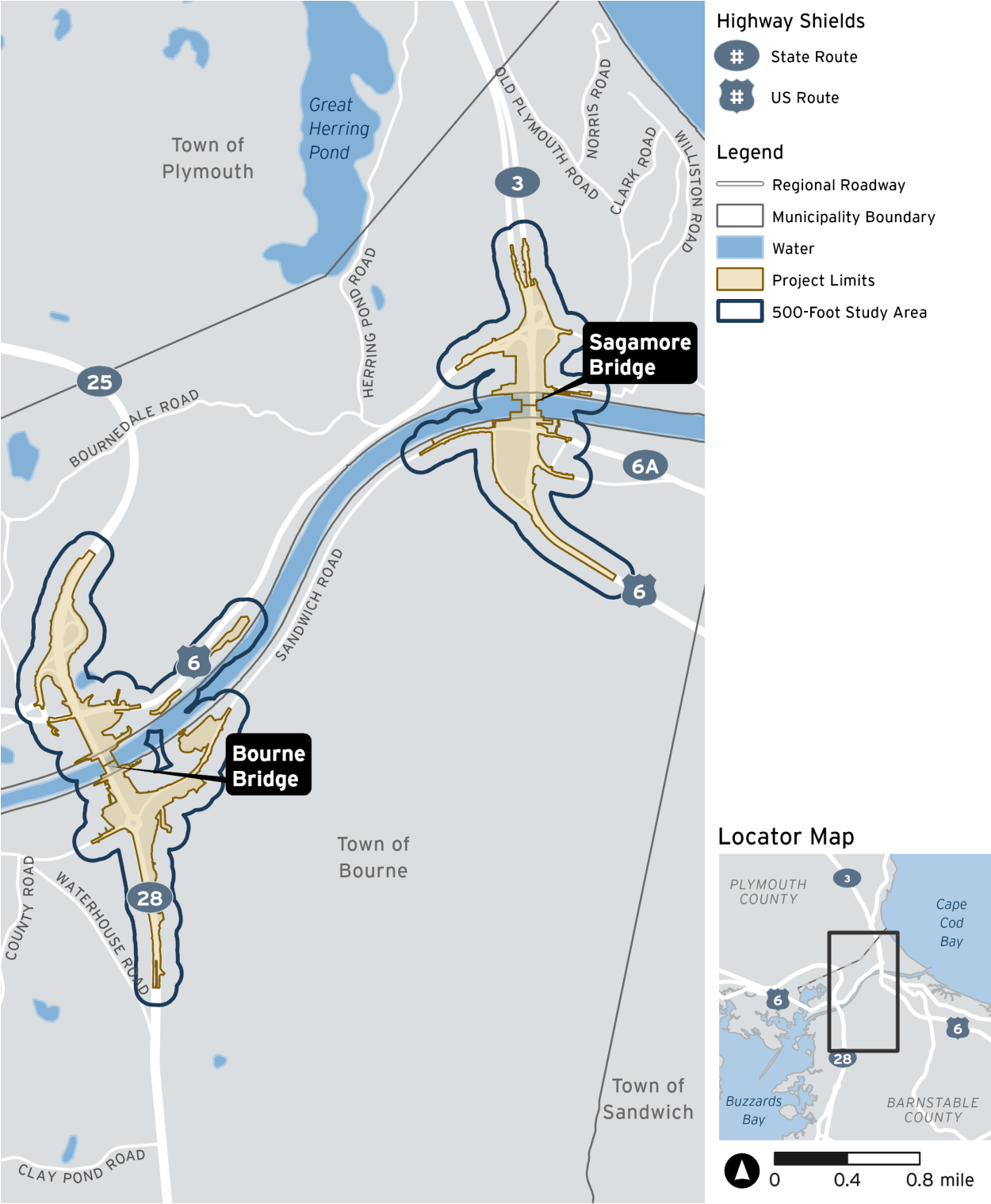
<sup>9</sup> <https://www.mass.gov/doc/cape-cod-emergency-traffic-plan/download>

**Table 1. Adaptation and Resiliency Affected Environment**

| Affected Environment        | Related Final Environmental Impact Statement Section                                                                                                              | Impacts Assessed                                   |                                |                           |                          |                                  |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------|--------------------------------|---------------------------|--------------------------|----------------------------------|
|                             |                                                                                                                                                                   | Sea Levels and Storm Surge                         | Extreme Precipitation          | Extreme Heat              | Winter Weather           | Extreme Wind                     |
| Canal                       | <b>Section 4.4, Maritime Transportation, Traffic, and Safety</b>                                                                                                  | Navigational Clearance                             | NA                             | NA                        | NA                       | NA                               |
| Bridge                      | <b>Chapter 3, Proposed Action and Alternatives</b>                                                                                                                | Pier Scour                                         | NA                             | Joint Expansion           | Icing on Cables          | Design and Aerodynamic Stability |
| Stormwater Control Measures | <b>Section 4.10, Water Quality and Stormwater</b>                                                                                                                 | Submerged Outfalls*<br>Infiltration Basin Flooding | Infiltration Basin Performance | NA                        | NA                       | NA                               |
| Land Cover                  | <b>Section 4.6, Land Use, Zoning, and Community Cohesion</b><br><b>Section 4.9, Wetlands and Floodplains</b><br><b>Section 4.10, Water Quality and Stormwater</b> | Floodplain Function                                | Localized Flooding             | Surface temperature       | NA                       | NA                               |
| Transportation              | <b>Section 4.2, Transportation, Traffic, and Safety</b>                                                                                                           | Roadways and Evacuation Route Flooding             | Localized Flooding             | Pavement Performance      | Snow and ice on roadways | Vehicle Rollover                 |
| Mobility                    | <b>Section 4.3, Pedestrian and Bicycle Facilities</b>                                                                                                             | Shared-use path Flooding                           | Localized Flooding             | Active Transportation Use | NA                       | NA                               |

Notes: NA = Not assessed for affected environment. \*Outfalls are within the Study Areas are shown in [Figure 1](#), but are not part of the Cape Cod Bridges Program; they were assessed due to their impact on stormwater systems (flooding and performance) within the Study Areas.

Figure 1. Study Areas for Adaptation and Resiliency Evaluation



Source:Massachusetts Department of Transportation, 2025

## 2.1 Sea Levels and Storm Surge Methodology

The methodology included reviewing published observed sea level data from the closest tide gauge (Woods Hole, MA - NOAA Station ID: 8447930), SLOSH models, and FEMA maps and studies. [Table 2](#) and [Table 3](#) include summaries of sea level and storm surge design criteria used to assess the affected environment, impacts assessed, and methodology.

**Table 2. Affected Environment and Impacts Assessed: Inundation, Sea Level, and Storm Surge**

| Design Criteria                    | Affected Environment        | Impact                                                                                                                                           | Inundation Scenario Assessed                                                                                                       |
|------------------------------------|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| Tidal Datums                       | Canal                       | Navigational clearance                                                                                                                           | Mean Higher High Water (MHHW)                                                                                                      |
|                                    | Stormwater Control Measures | <ul style="list-style-type: none"> <li>Submerged or partially submerged outfalls</li> <li>Infiltration Basin Flooding and Performance</li> </ul> | MHHW                                                                                                                               |
| Storm Surge and Coastal Inundation | Stormwater Control Measures | <ul style="list-style-type: none"> <li>Submerged or partially submerged outfalls</li> <li>Infiltration Basin Flooding</li> </ul>                 | <ul style="list-style-type: none"> <li>Federal Emergency Management Agency (FEMA) 100-year</li> <li>Category 2 + 3 feet</li> </ul> |
|                                    | Land Cover                  | Floodplain Function                                                                                                                              | <ul style="list-style-type: none"> <li>FEMA 100-year</li> <li>Category 2 + 3 feet</li> </ul>                                       |
|                                    | Transportation              | Roadways and Evacuation Route Flooding                                                                                                           | <ul style="list-style-type: none"> <li>FEMA 100-year</li> <li>Category 2 + 3 feet</li> </ul>                                       |
|                                    | Mobility                    | Shared-Use Path Flooding                                                                                                                         | <ul style="list-style-type: none"> <li>FEMA 100-year</li> <li>Category 2 + 3 feet</li> </ul>                                       |
| Wave Hazards                       | None <sup>[1]</sup>         | None                                                                                                                                             | None                                                                                                                               |
| Scour                              | Bridge                      | Pier Scour                                                                                                                                       | <ul style="list-style-type: none"> <li>200-year (Design Storm)</li> <li>500-year (Check Storm)</li> </ul>                          |

<sup>[1]</sup> Given the extent of the Study Areas, FEMA special flood hazard area designations, proposed replacement bridges' deck height and location of piers/abutments, land use and development between the shoreline and proposed land-based infrastructure (roadways, ramps, and stormwater control measures), and lack of structures proposed along the shoreline that could reflect waves, wave hazards were not formally assessed in this study due to the lack of an affected environment.

**Table 3. Affected Environment and Methodology: Sea Levels and Storm Surge**

| <b>Design Criteria</b>             | <b>Affected Environment</b> | <b>Methodology</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|------------------------------------|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Tidal Datums                       | Canal                       | To evaluate the effect of tidal datums on navigational clearance, the required vertical clearance determined by the United States Coast Guard was subtracted from the bridges' low chord elevation. If the Mean Higher High Water (MHHW) elevation was greater than resulting elevation, it was assumed to be affected. If affected, additional tidal datums were assessed to estimate the percentage likelihood of being affected over a tide cycle.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|                                    | Stormwater Control Measures | To evaluate the effect of tidal datums on outfalls associated with the stormwater control measures, the Massachusetts Department of Transportation (MassDOT) compared tidal datums to outfall invert and crown elevations. If the tidal datum exceeded the outfall invert elevation, MassDOT assumed it to be partially submerged, with potential backflow through the system. If the tidal datum exceeded the outfall crown elevation, MassDOT assumed it to be fully submerged, with potential backflow through the system. MassDOT applied similar comparisons to the infiltration basins, with bottom of basin and top of basin elevations. <sup>[1]</sup> If the tidal datum exceeded the proposed basin bottom elevation, MassDOT assumed the basin to have reduced infiltration capacity due to groundwater rise. If the tidal datum exceeds the proposed overflow structure's outlet elevation, MassDOT assumed the basin to be partially filled to the elevation of the tide. If the tidal datum exceeded the proposed basin top elevation, MassDOT assumed that the tides overtopped the basin and resulted in localized flooding. |
| Storm Surge and Coastal Inundation | Stormwater Control Measures | To evaluate the effect of storm surge on the stormwater control measures, MassDOT compared storm surge elevations associated with the Federal Emergency Management Agency (FEMA) 100-year base flood elevation and a Category 2 Hurricane with 3-foot freeboard with the elevations of the outfalls and infiltration basins, in a similar fashion to the tidal datum methodology. In addition, the extent of storm surge inundation was overlaid with proposed basins to identify potential for overland flooding.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|                                    | Land Cover                  | To evaluate the impact on land subject to coastal storm flowage, MassDOT overlaid the extent of overland storm surge inundation with existing and proposed grades. Areas with lower elevation were assumed to be where coastal waters flooded first, which informed flood pathways. Grades that exceeded the storm surge elevation were assumed to not be flooded. MassDOT evaluated cross-sections for potential channelization of flow and increased velocities based on grading and land cover surface type.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|                                    | Transportation Mobility     | To evaluate the impact on roadways and active transportation, MassDOT overlaid the extent of overland storm surge inundation with roadways, sidewalks, and shared-use paths. If those routes were within the extent of inundation, MassDOT assumed them to be affected.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |

| Design Criteria | Affected Environment | Methodology                                                                                                                                                                                                                                |
|-----------------|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Scour           | Bridge               | To evaluate the effect on bridge pier scour, MassDOT analyzed a 2D Hydraulic Model for Sagamore and Bourne Bridges. The maximum scour depth generated was used to assess impact, design foundations, and design scour protection measures. |

<sup>[1]</sup> Overflow outlet structure elevations are to be determined and should be assessed once known in accordance with this methodology.

## 2.2 Extreme Precipitation

The methodology included the Massachusetts Department of Transportation (MassDOT) reviewing published NOAA rainfall precipitation frequency estimates, as well as past observations, for 24-hour rainfall depths for Massachusetts. **Table 4** summarizes the extreme precipitation design criteria used to assess affected environment and impacts. **Section 4.10, Water Quality and Stormwater**, discusses the methodology used to assess the No Build Alternative and Build Alternative impacts on the affected environment. **Table 3** provides the methodology for combined impacts with tidal datums.

**Table 4. Affected Environment and Impacts Assessed: Extreme Precipitation**

| Design Criteria                  | Affected Environment                 | Impact                                                                                    | Extreme Precipitation Scenario Assessed          |
|----------------------------------|--------------------------------------|-------------------------------------------------------------------------------------------|--------------------------------------------------|
| Rainfall Depths                  | Stormwater Control Measures          | Sizing of Infiltration Basins                                                             | 500-year, 24-hour event                          |
|                                  | Land Cover; Transportation, Mobility | Localized flooding from capacity of drainage infrastructure                               | 500-year, 24-hour event                          |
| Rainfall Depths and Tidal Datums | Stormwater Control Measures          | Performance of stormwater control measures with submerged or partially submerged outfalls | Varying tidal datums and 500-year, 24-hour event |

## 2.3 Extreme Heat

The methodology included reviewing land cover characteristics and observations of days over 90 degrees Fahrenheit (F). [Table 5](#) and [Table 6](#) summarize how extreme heat was used to assess the affected environment.

**Table 5. Affected Environment and Impacts Assessed: Extreme Heat**

| Design Criteria         | Affected Environment | Impact                    | Extreme Heat Scenario Assessed                                                                                                               |
|-------------------------|----------------------|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| Max Temperatures        | Bridge               | Bridge joint expansion    | Temperature exceeding 120 degrees Fahrenheit (F)                                                                                             |
| Days above 90 degrees F | Transportation       | Pavement performance      | Days above 90 degrees F                                                                                                                      |
|                         | Mobility             | Active transportation use | Days above 90 degrees F                                                                                                                      |
| Impervious surface area | Land cover           | Surface temperatures      | Percentage area <ul style="list-style-type: none"> <li>• Less than 10%</li> <li>• Between 10% and 50%</li> <li>• Greater than 50%</li> </ul> |

**Table 6. Affected Environment and Methodology: Extreme Heat**

| Design Criteria         | Affected Environment | Methodology                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------------------------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Max Temperatures        | Bridge               | To evaluate the effect on the bridge joint expansion, the Massachusetts Department of Transportation (MassDOT) assessed maximum temperatures greater than 120 degrees Fahrenheit (F). The design temperature of steel structures ranges from -30 to 120 degrees F. If the maximum temperature exceeded 120 degrees F, it was assumed to be affected because it is beyond the design range.                                                                             |
| Days Above 90 degrees F | Transportation       | To evaluate the effect on pavement performance, MassDOT assessed the number of days greater than 90 degrees F; days over 90 degrees F were assumed to affect pavement performance.                                                                                                                                                                                                                                                                                     |
|                         | Mobility             | To evaluate the effect on use of pedestrian and shared-use paths, MassDOT assessed the number of days greater than 90 degrees F; days over 90 degrees F were assumed to affect active transportation use.                                                                                                                                                                                                                                                              |
| Impervious surface area | Land cover           | To evaluate the effect on the land surface temperature, MassDOT assessed the percentage of impervious area within the Project Limits. If the percentage was less than 10%, it was assumed to reduce land surface temperature. If the percentage was between 10% to 50%, it was assumed to have a negligible effect on land surface temperatures. If the percentage was greater than 50%, it was assumed to affect land surface temperature and increase heat severity. |

## 2.4 Winter Weather

The methodology included reviewing results from an extreme value analysis to assess maximum thicknesses for combined snow and ice and observations of days below 32 degrees F. [Table 7](#) and [Table 8](#) summarize how MassDOT used winter weather to assess the affected environment.

**Table 7. Affected Environment and Impacts Assessed: Winter Weather**

| Design Criteria                     | Affected Environment | Impact                                 | Winter Weather Scenario Assessed   |
|-------------------------------------|----------------------|----------------------------------------|------------------------------------|
| Combined Ice and Wet Snow Thickness | Bridge               | Icing on cables and members            | 500-year (0.2%) thickness (inches) |
| Freezing temperatures               | Transportation       | Potential for snow and ice on roadways | Days below 32 degrees Fahrenheit   |

**Table 8. Affected Environment and Methodology: Winter Weather**

| Design Criteria                     | Affected Environment | Methodology                                                                                                                                                                                                                                                                                                                                                |
|-------------------------------------|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Combined Ice and Wet Snow Thickness | Bridge               | To evaluate the effect of icing on bridge members/cables, the Massachusetts Department of Transportation (MassDOT) assessed the maximum thickness of combined ice and wet snow using extreme value analysis and comparing with the values specified in American Society of Civil Engineers/Structural Engineering Institute 7-22 for the project location. |
| Freezing temperatures               | Transportation       | To evaluate the effect on highway transportation from snow and ice, MassDOT assessed the number of days below 32 degrees Fahrenheit (F); days below 32 degrees F were assumed to create conditions where snow and ice are possible.                                                                                                                        |

## 2.5 Extreme Wind

The methodology included reviewing wind climate analysis for the replacement bridges' design wind speeds and flutter verification, which included a Monte Carlo simulation of tropical cyclone and hurricane wind speeds. [Table 9](#) and [Table 10](#) summarize how extreme winds were used to assess the affected environment.

**Table 9. Affected Environment and Impacts Assessed: Extreme Winds**

| Design Criteria                               | Affected Environment | Impact                | Extreme Wind Scenario Assessed                                                                                   |
|-----------------------------------------------|----------------------|-----------------------|------------------------------------------------------------------------------------------------------------------|
| 1-hour Mean Wind Speed                        | Bridge               | Design                | <ul style="list-style-type: none"> <li>• 97-year (construction)</li> <li>• 1,400-year (completed)</li> </ul>     |
| 10-minute wind speeds/<br>3-second wind gusts | Bridge               | Aerodynamic Stability | <ul style="list-style-type: none"> <li>• 1,000-year (construction)</li> <li>• 10,000-year (completed)</li> </ul> |
| 3-second wind gusts                           | Transportation       | Vehicle Rollover      | Gusts greater than 50 miles per hour                                                                             |

**Table 10. Affected Environment and Methodology: Extreme Winds**

| Design Criteria                               | Affected Environment | Methodology <sup>[1]</sup>                                                                                                                                                                                                                                        |
|-----------------------------------------------|----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1-hr Mean Wind Speed                          | Bridge               | To evaluate wind loads for bridge design, the Massachusetts Department of Transportation (MassDOT) modeled the mean wind speed at deck level for 1 hour to produce the worst-case loading conditions.                                                             |
| 10-minute wind speeds/<br>3-second wind gusts | Bridge               | To evaluate aerodynamic stability, MassDOT analyzed extreme wind speeds associated with less-frequent return periods (10-minute mean wind speeds associated with a 1,000-year return period for construction and 10,000-year return period for completed bridge). |
| 3-second wind gusts                           | Transportation       | To evaluate potential vehicle rollover, MassDOT analyzed the likelihood of wind gust speeds greater than 50 miles per hour at deck level.                                                                                                                         |

<sup>[1]</sup> Methodology aligns with American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Design Factor Bridge Design Specifications (10th edition) and AASHTO Guide Specifications for Wind Loads on Bridges During Construction (GSWLB-1) return-period recommendations. A specialized wind subconsultant conducted wind tunnel testing of the replacement bridges and a buffeting analysis to determine the wind force effects on structures.

## 3 Affected Environment

### 3.1 Cape Cod Canal

**Section 4.4, Maritime Transportation, Traffic, and Safety**, identifies the affected environment for navigation.

#### 3.1.1 Sea Levels and Storm Surge

Cape Cod Canal is a navigational channel that requires a vertical clearance of 138.3 feet.<sup>10</sup> The existing and replacement bridges are and would be fixed structures, so fluctuations in sea level elevation and storm surge affect the ability to maintain the required vertical clearance.

### 3.2 Bridge

**Chapter 3, Proposed Action and Alternatives**, describes the existing and replacement bridges.

#### 3.2.1 Sea Levels and Storm Surge

The existing and replacement bridge piers are and would be along the Cape Cod Canal banks and subject to coastal processes, including inundation and scour. Fluctuations in sea level elevation and storm surge affect the coastal processes and may affect water levels by increasing velocities and flows, while also affecting attack angles related to flow directions that impact scour potential.

#### 3.2.2 Extreme Heat

The existing and replacement bridges' expansion joints are and would be thermally sensitive to extreme temperatures. Temperatures below or exceeding steel design threshold of -30 degrees F to +120 degrees F may affect the performance of the expansion joints.

#### 3.2.3 Winter Weather

Ice accretion affects static loads and wind drag, which may affect aerodynamic stability of the replacement bridges. Icing on bridge structures above the bridge deck (i.e., cables or overhead cross-members) poses a risk to safety, including traffic below, when the accumulated ice or snow sheds off the bridge members and falls down on the bridge deck.<sup>11</sup>

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<sup>10</sup> The First Coast Guard District issued a Preliminary Navigation Clearance Determination dated March 11, 2025, to MassDOT and the U.S. Army Corps of Engineers. The determination stated the replacement Sagamore and Bourne Bridges should provide at least 138.3 feet of vertical clearance and at least 500 feet of horizontal clearance to not unreasonably obstruct the free navigation of the waters over which the bridge is constructed.

<sup>11</sup> Lubomir, M. and C. T. Georgakis.2022. "[A review of ice and snow risk mitigation and control measures for bridge cables](https://doi.org/10.1016/j.coldregions.2021.103429)," Cold Regions Science and Technology, Volume 193, 103429, ISSN 0165-232X. January. <https://doi.org/10.1016/j.coldregions.2021.103429>

### 3.2.4 Extreme Wind

Wind causes static loads on a bridge and also results in a special dynamic behavior that affects aerodynamic stability.<sup>12</sup>

## 3.3 Stormwater Control Measures

**Section 4.10, Water Quality and Stormwater**, discusses stormwater control measures.

### 3.3.1 Sea Levels and Storm Surge

Stormwater is ultimately discharged into Cape Cod Canal through outfalls by gravity flow, and fluctuations in sea level elevation and storm surge affect the ability of the existing outfalls to discharge flow freely (without submerged or partially submerged conditions). **Table 11** summarizes the outfalls and associated elevations.

**Table 11. Existing Stormwater Outfalls that Discharge into Cape Cod Canal**

| Outfall Location<br>(quadrant) | Description                      | Invert Elevation<br>(feet-NAVD88) | Crown Elevation<br>(feet-NAVD88) |
|--------------------------------|----------------------------------|-----------------------------------|----------------------------------|
| Sagamore North                 | 24-inch reinforced concrete pipe | 5.15                              | 7.15                             |
| Sagamore South – West          | 36-inch cast iron                | 4.43                              | 7.43                             |
| Sagamore South – East          | 36-inch cast iron                | 7.50                              | 10.50                            |
| Bourne North*                  | 43-inch by 68-inch concrete      | 0.46                              | 4.04                             |
| Bourne North*                  | 43-inch by 68-inch concrete      | 0.36                              | 3.94                             |
| Bourne South                   | 24-inch reinforced concrete pipe | 4.67                              | 6.67                             |

NAVD88 = North American Vertical Datum of 1988

Note: \* Twin elliptical culverts

The existing outfalls do not have gates or backflow preventers and modifications to the outfall structures are not proposed as part of the Cape Cod Bridges Program (Program). If tides exceed the invert elevations, flow inundates the system and may prevent stormwater from discharging during rain events. This can cause flooding from either coastal or precipitation events. Coastal inundation also reduces the ability of the infiltration basins to manage stormwater generated by rainfall events.

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<sup>12</sup> Federal Highway Administration. 2011. “[Framework for Improving Resilience of Bridge Design](https://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf).” Publication No. FHWA-IF-11-016. January. Pg. 56. <https://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf>

### 3.3.2 Extreme Precipitation

Extreme precipitation combined with fluctuations in sea level elevations affects the performance of the overall system—from managing stormwater quality and quantity, to discharging into Cape Cod Canal. Extreme precipitation events also affect the size of the stormwater basin needed to manage rainfall quality and quantity.

## 3.4 Land Cover

Land cover is described in several sections, including **Section 4.9, Wetlands and Floodplains**, **Section 4.10, Water Quality and Stormwater**, and **Section 4.6, Land Use, Zoning, and Community Cohesion**, which address resource areas, impervious surfaces, and land clearing.

### 3.4.1 Sea Levels and Storm Surge

**Section 4.9, Wetlands and Floodplains**, describes the floodplain within the Study Areas, which is considered a previously developed area within Minimal Wave Action Zone of Land Subject to Coastal Storm Flowage (LSCSF). LSCSF is presumed to be significant to storm damage prevention and flood control based on its following abilities:

- Dissipate wave energy and decrease the velocity of moving water.
- Receive coastal floodwaters that spread laterally and landward and infiltrate.
- Allow water to flow across the landform without redirecting or channeling the flow or increasing the velocity of flood waters.
- Slow moving water, thereby reducing erosion.
- Store floodwaters until they can return to the ocean or infiltrate into the ground.

Fluctuations in sea levels and storm surge may affect the horizontal and vertical extent of coastal inundation—even if it does not affect the LSCSF regulatory boundary.

#### Extreme Precipitation and Extreme Heat

Impervious surfaces exacerbate localized flooding caused by extreme precipitation and also increase surface temperatures. Vegetative cover improves infiltration and slows moving water.

## 3.5 Transportation

**Section 4.2, Transportation, Traffic, and Safety**, identifies the affected environment for transportation, traffic, and safety, including the Cape Cod Emergency Traffic Plan and Traffic Operations Annex, which identifies traffic control points along major routes to facilitate/expedite off-Cape traffic flow.<sup>13</sup>

### 3.5.1 Sea Levels and Storm Surge

Coastal inundation from storm surge may affect the likelihood of flooding on formal emergency evacuation routes and roadways. It is not safe to drive into flooded areas; 6 inches of water will reach the bottom of most passenger cars, which can cause loss of control and possible stalling, and cars can be swept away in only two feet of moving water.<sup>14</sup> During flood events, most casualties are caused by vehicles when drivers attempt to drive along flooded roads. Coastal flooding from storm surge events may result in damage to existing roadways, particularly in areas of channelized flow. Elevated sea levels increase the horizontal and vertical extent of the inundated area.

### 3.5.2 Extreme Precipitation

High intensity, short-duration events that exceed design criteria can overwhelm drainage infrastructure and result in localized flooding. The hazard of low-water depths is usually underestimated because it can be perceived as less threatening to drivers. These events can also reduce pavement strength and result in roadway washouts of varying magnitudes.

### 3.5.3 Extreme Heat

Warmer temperatures lead to higher asphalt-concrete pavement temperatures, which affect materials durability distress and fatigue cracking.<sup>15</sup> Extreme heat may reduce material stability, particularly pavement that softens and expands when exposed to extreme heat over long periods of time. This can cause buckling, rutting, and potholes. Combined with heavy precipitation events, this can lead to increased ponding on roadways and/or lead to failures that increase the frequency of repairs and replacements.

### 3.5.4 Winter Weather

Winter weather (including snow and ice) can cause slower speeds, reduce roadway capacity, increase travel-time delay, and increase crash risk as a result of reduced pavement friction, visibility, and vehicle maneuverability. Average arterial speeds decline by 30% to 40% on snowy or slushy pavement, and highway speeds are reduced by up to 13% in light snow and up to 40% in heavy snow. Winter weather

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<sup>13</sup> Commonwealth of Massachusetts. 2018. [Cape Cod Emergency Traffic Plan](https://www.mass.gov/doc/cape-cod-emergency-traffic-plan/download). July. <https://www.mass.gov/doc/cape-cod-emergency-traffic-plan/download>

<sup>14</sup> <https://www.mass.gov/info-details/flood-safety-tips>

<sup>15</sup> Federal Highway Administration. 2019. [FHWA-HRT-16-084: Impact of Environmental Factors on Pavement Performance in the Absence of Heavy Loads](https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/16084/16084.pdf). March. p. 222. <https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/16084/16084.pdf>

events also increase road maintenance costs, including salt management and costs to repair infrastructure damaged by snow and ice.<sup>16</sup>

### 3.5.5 Wind

Vehicles are more sensitive to wind while passing over long-span bridges compared to ground-level roads given the higher road elevations, exposure, and possible speed-up effects.<sup>17</sup>

## 3.6 Mobility

**Section 4.3, Pedestrian and Bicycle Facilities**, identifies the affected environment for pedestrian and bicycles facilities.

### 3.6.1 Sea Levels and Storm Surge

Coastal inundation from storm surge may affect the likelihood of flooding on shared-use paths and sidewalks. It is not safe for pedestrians or bicyclists to travel into flooded areas; 6 inches of fast-moving water can knock over an adult.<sup>18</sup> Coastal inundation can also reduce pavement strength and result in washouts of varying magnitudes. Elevated sea levels increase the horizontal and vertical extent of the inundated area.

### 3.6.2 Extreme Precipitation

High-intensity, short-duration events that exceed design criteria can overwhelm drainage infrastructure and result in localized flooding. It is not safe for pedestrians or bicyclists to travel into flooded areas; 6 inches of fast-moving water can knock over an adult.<sup>19</sup> These events can also reduce pavement strength and result in washouts of varying magnitudes.

### 3.6.3 Extreme Heat

People using alternative modes of transportation (such as bus, bicycle, and walk) are more vulnerable to extreme heat; under extreme heat, the use of shared-use paths and alternative modes of transportation is likely to be lower.<sup>20</sup> Extreme heat may reduce material stability, particularly pavement that softens and expands when exposed to extreme heat over long periods of time. This can cause buckling, rutting, and potholes that affect accessibility of active transportation networks and increase the frequency of maintenance.

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<sup>16</sup> Federal Highway Administration. 2024. n.d. [Snow and Ice](https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm). September. [https://ops.fhwa.dot.gov/weather/weather\\_events/snow\\_ice.htm](https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm)

<sup>17</sup> RWDI. n.d. "[Study of vehicle roll-over stability in strong winds](https://rwdi.com/en_ca/projects/vehicle-roll-over-stability-in-strong-winds-on-long-span-bridges/)," Long Span Bridges. [https://rwdi.com/en\\_ca/projects/vehicle-roll-over-stability-in-strong-winds-on-long-span-bridges/](https://rwdi.com/en_ca/projects/vehicle-roll-over-stability-in-strong-winds-on-long-span-bridges/)

<sup>18</sup> <https://www.mass.gov/info-details/flood-safety-tips>

<sup>19</sup> <https://www.mass.gov/info-details/flood-safety-tips>

<sup>20</sup> Batur, I., V.O. Alhassan, M.V. Chester, S.E. Polzin, C. Chen, C.R. Bhat, R.M. Pendyala. 2024. [Understanding how extreme heat impacts human activity-mobility and time use patterns](https://doi.org/10.1016/j.trd.2024.104431), Transportation Research Part D: Transport and Environment, Volume 136, 2024,104431, ISSN 1361-9209. November. <https://doi.org/10.1016/j.trd.2024.104431>

## 4 No Build Alternative

This section reflects No Build Alternative impacts with current and future conditions based on methodology and affected area described in previous sections. [Table 12](#) summarizes the No Build Alternative impacts on the affected environment.

Table 12. No Build Alternative Impacts

| Affected Environment        | Sea Levels and Storm Surge              | Extreme Precipitation                                          | Extreme Heat              | Winter Weather   | Extreme Wind          |
|-----------------------------|-----------------------------------------|----------------------------------------------------------------|---------------------------|------------------|-----------------------|
| Canal                       | Navigational clearance                  | NA                                                             | NA                        | NA               | NA                    |
| Bridge                      | NA                                      | NA                                                             | No Impact                 | Icing on Members | Aerodynamic Stability |
| Stormwater Control Measures | Submerged/partially submerged outfalls* | Refer to <b>Section 4.10, Water Quality and Stormwater</b>     | NA                        | NA               | NA                    |
| Land Cover                  | No impact to floodplain function        | NA. Refer to <b>Section 4.10, Water Quality and Stormwater</b> | No Impact                 | NA               | NA                    |
| Transportation              | Roadways and evacuation route flooding  | NA. Refer to <b>Section 4.10, Water Quality and Stormwater</b> | Pavement performance      | Snow and Ice     | Vehicle Rollover      |
| Mobility                    | Shared-use path flooding                | NA. Refer to <b>Section 4.10, Water Quality and Stormwater</b> | Active Transportation Use | NA               | NA                    |

NA = not assessed for affected environment.

\* Outfalls are within the Study Areas shown in [Figure 1](#), but are not part of the Program; they were assessed due to their impact on stormwater systems (flooding and performance) within the Study Areas.

## 4.1 Cape Cod Canal

Under the No Build Alternative, Cape Cod Canal and Sagamore Bridge and Bourne Bridge would remain as-is, but the navigational clearance would be affected.

### 4.1.1 Sea Levels and Navigational Clearance

Under the No Build Alternative, fluctuations in sea level elevation would affect the ability to meet the required 138.3-foot vertical navigational operational clearance through Cape Cod Canal.<sup>21</sup> The approximate low chord elevations would provide an approximate 137-foot clearance for both structures with existing Mean Higher High Water (MHHW).

## 4.2 Bridge

Under the No Build Alternative, the bridges' decks, superstructures, and substructures would remain as-is.

### 4.2.1 Sea Levels and Bridge Pier Scour

Since reuse of the existing structures is not proposed, a Build Alternative model to assess scour was developed for the replacement of Sagamore and Bourne Bridges.

### 4.2.2 Extreme Heat and Bridge Joint Expansion

The highest recorded temperature over the past 100 years at the East Wareham Weather Station was 100 degrees F (1948, 1949, 1975, and 2006). Design practices and standards for extreme heat have changed since construction of the existing structures, but the steel is likely to have the same sensitivity to heat. The No Build Alternative is unlikely to be affected by extreme heat.

### 4.2.3 Winter Weather and Icing

Design practices and standards for winter weather have changed since construction of the existing structures, including the link slabs and slab-over-backwall details to reduce risk of winter deicing treatment infiltrating into superstructure and substructure elements. Icing of the cross-members poses a risk to the existing structures as well. The No Build Alternative is likely to remain vulnerable to winter weather, including snow and ice.

### 4.2.4 Extreme Wind and Aerodynamic Stability

Design practices and standards for extreme wind have changed since construction of the existing structures. The bridges were designed in the 1930s and are composed of steel trusses forming continuous spans, with spans over Cape Cod Canal that are 616 feet long. Truss bridges tend to be

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<sup>21</sup> There is a third crossing over Cape Cod Canal, the Railroad Bridge, which is west of Bourne Bridge. The Railroad Bridge crossing has not been evaluated for its impacts to navigational clearance since it is outside the Study Areas and the scope for proposed improvements.

more vulnerable to progressive collapse due to lack of redundancy in design, and generally longer spans (i.e., greater than 300 feet) have issues related to deflections due to wind.<sup>22</sup> The No Build Alternative is vulnerable to extreme wind given the bridges' age and truss structure.

## 4.3 Stormwater Control Measures

Under the No Build Alternative, the stormwater control measures, including existing infiltration basins, piped infrastructure, and outfalls, would remain as-is.

### 4.3.1 Sea Levels and Submerged and Partially Submerged Outfalls

There are no tide gates or backflow preventers on the outfalls that discharge stormwater to Cape Cod Canal. The No Build Alternative would enable high tides and storm surges to back flow through the storm drain system, which may result in localized flooding from tides and/or the inability to convey stormwater runoff to the canal. The Bourne North quadrant outfall structure is very vulnerable to fluctuating sea level elevations. Current tidal datums restrict flow during high tide with the outfall approximately 50% submerged.

### 4.3.2 Stormwater Control Measure Performance and Extreme Precipitation

**Section 4.10, Water Quality and Stormwater**, discusses impacts to stormwater control measures from extreme precipitation under the No Build Alternative.

## 4.4 Land Cover

Under the No Build Alternative, the land cover, including impervious surfaces and land surface temperatures, would remain as-is.

### 4.4.1 Storm Surge and Land Subject to Coastal Storm Flowage Function

**Figure 2** and **Figure 3**, respectively, show the extent of overland coastal surge for the No Build Alternative for the Sagamore Bridge and Bourne Bridge Study Areas. **Figure 4** illustrates the existing flood pathways at the Bourne North quadrant near Belmont Circle. The vertical and horizontal extent of inundations changes slightly between the FEMA 100-year event and a Category 2 Hurricane with 3 feet freeboard. **Section 4.9, Wetlands and Floodplains**, discusses additional impacts to floodplains from the No Build Alternative.

### 4.4.2 Extreme Precipitation and Localized Stormwater Flooding

**Section 4.10, Water Quality and Stormwater**, discusses impacts to localized flooding from impervious surfaces and extreme precipitation under the No Build Alternative.

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<sup>22</sup> Federal Highway Administration. 2011. [Framework for Improving Resilience of Bridge Design](https://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf). Publication No. FHWA-IF-11-016. p. 25. January. <https://www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf>

### 4.4.3 Extreme Heat and Surface Temperatures

Under the No Build Alternative, the land cover (impervious surfaces) would remain as-is. [Figure 5](#) and [Figure 6](#) illustrate the existing impervious surfaces within the Study Areas based on the 2016 land cover dataset<sup>23</sup> hosted by the Massachusetts Office of Energy and Environmental Affairs. [Table 13](#) summarizes the impervious surface area with the Sagamore Bridge and Bourne Bridge Project Limits.

**Table 13. No Build Alternative: Impervious Area within Sagamore Bridge and Bourne Bridge Project Limits**

| Project Limits  | Project Limits Area (acres) | Roadway Surface Area (acres) <sup>[1]</sup> | Total Impervious Surface (acres) <sup>[2]</sup> | No Build Alternative Percentage Impervious |
|-----------------|-----------------------------|---------------------------------------------|-------------------------------------------------|--------------------------------------------|
| Sagamore Bridge | 197.6                       | 45.1                                        | 65.3                                            | 33.0%                                      |
| Bourne Bridge   | 249.9                       | 45.6                                        | 70.1                                            | 28.1%                                      |

Notes:

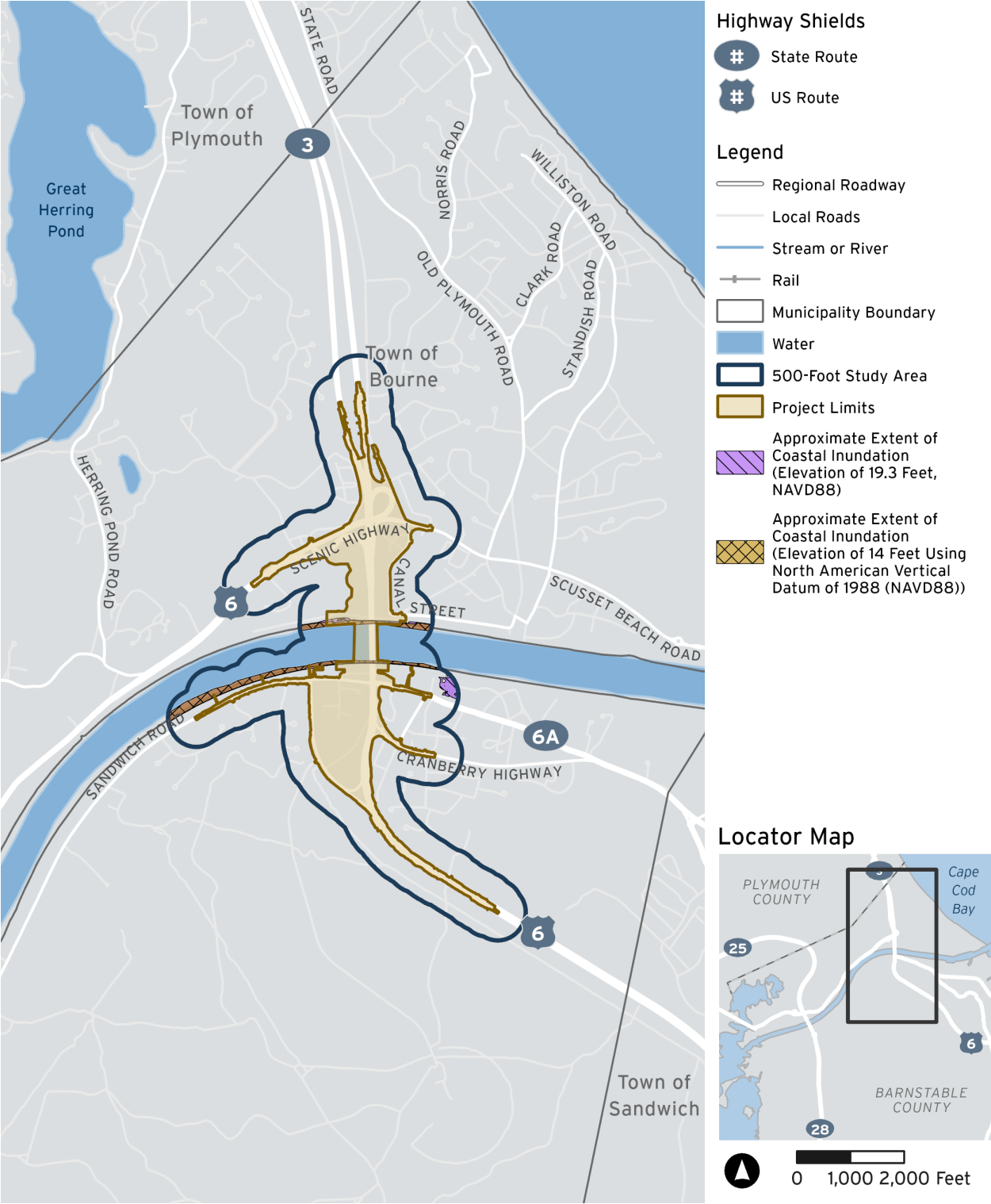
<sup>[1]</sup> The existing roadway surface area is based on survey measurements for north and south quadrants of each Project Limits as presented in [Section 4.10, Water Quality and Stormwater](#).

<sup>[2]</sup> Impervious surface areas are based off Massachusetts Department of Transportation (MassDOT) Land Cover Land Use Data, filtered to right-of-way and other impervious and encompasses more than roadway surfaces.

Surface temperature is a function of impervious surfaces, so the No Build Alternative is not assumed to be affected.

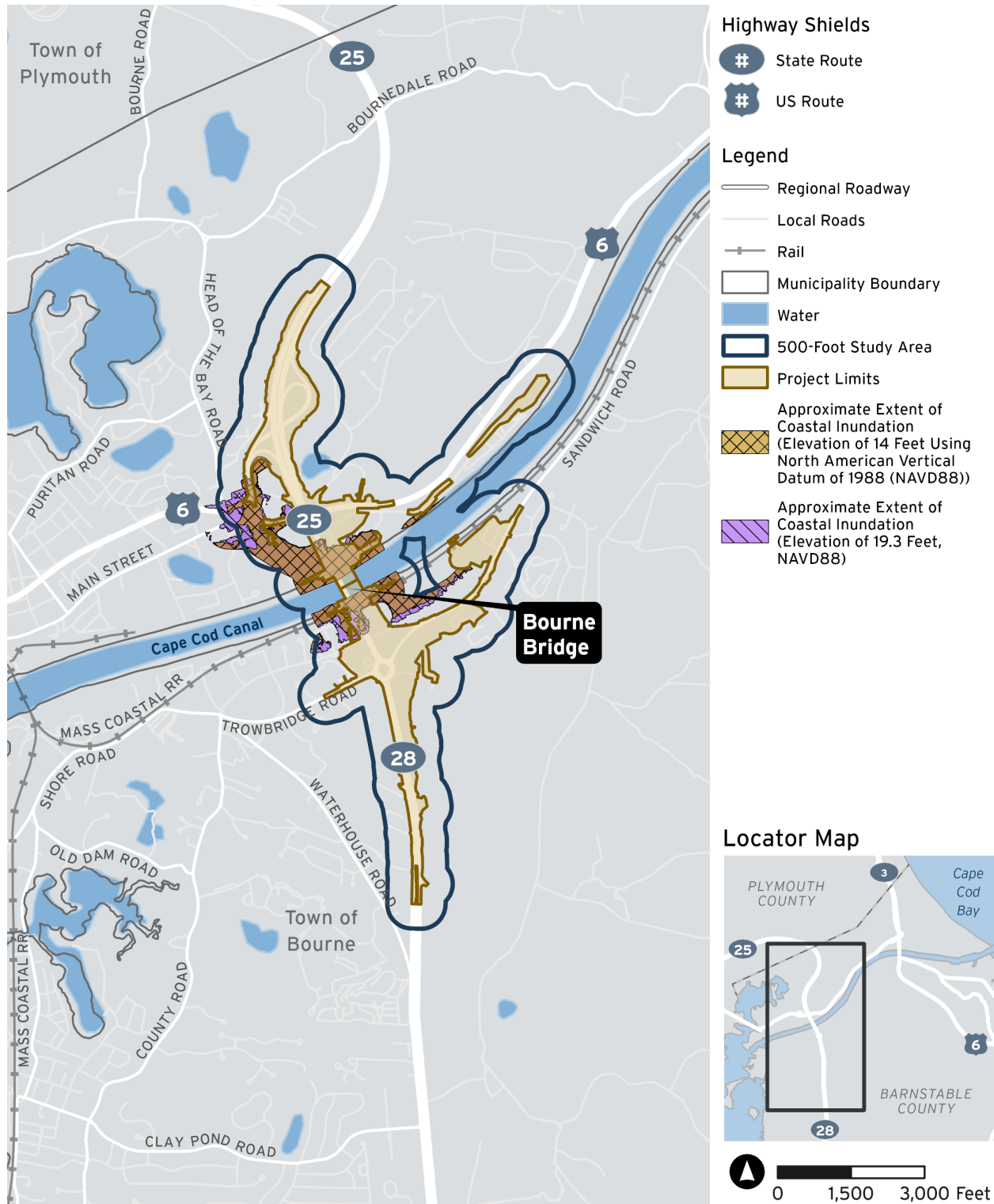
<sup>23</sup> The Commonwealth of Massachusetts, Executive Office of Technology Services and Security. [MassGIS Data: 2016 Land Cover/Land Use](#). May 2019. Accessed December 30, 2025. <https://www.mass.gov/info-details/massgis-data-2016-land-coverland-use>

Figure 2. No Build Alternative: Coastal Surge Flood Extents (Sagamore Bridge Study Area)



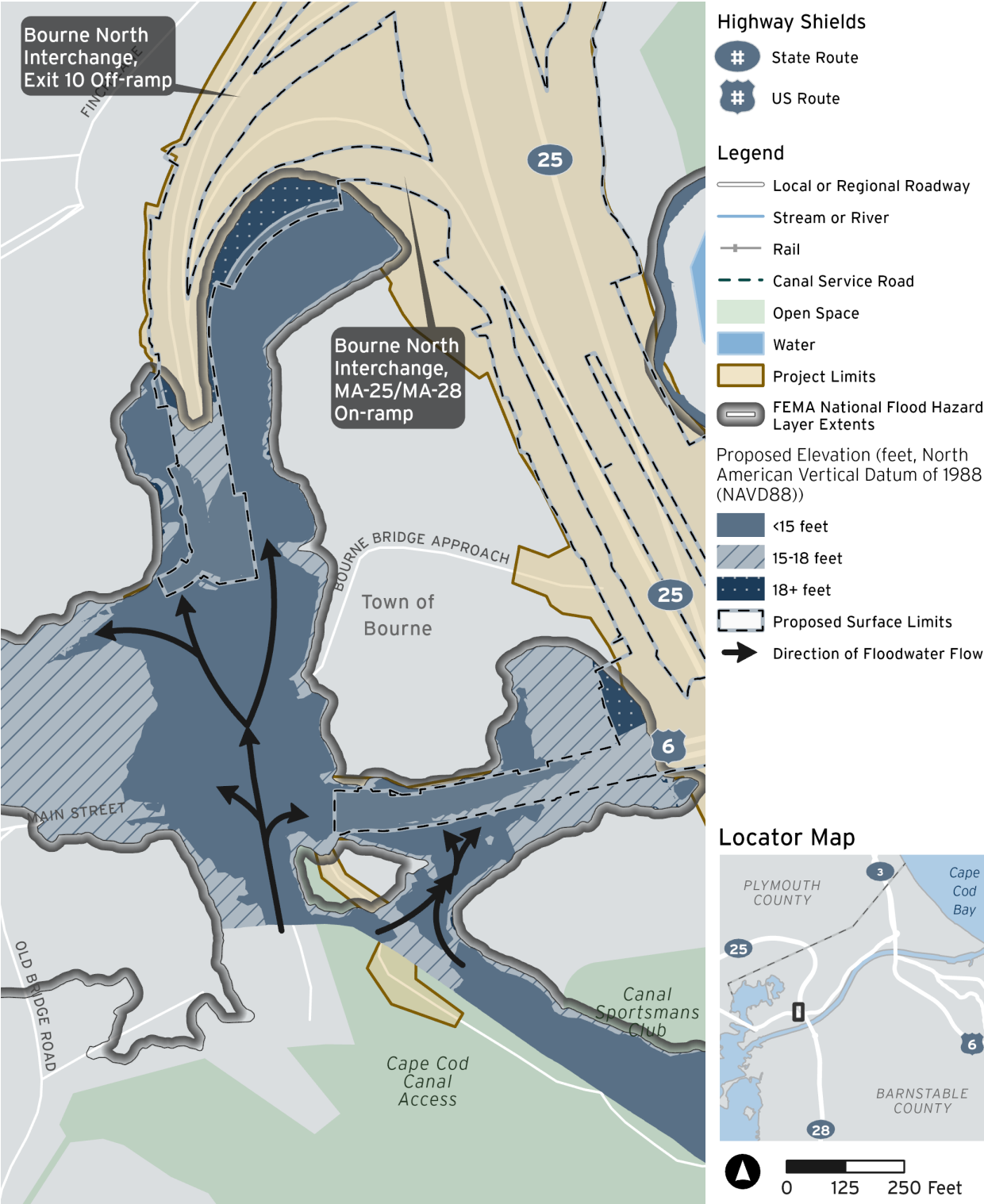
Source:Massachusetts Department of Transportation, 2025

Figure 3. No Build Alternative: Coastal Surge Flood Extents (Bourne Bridge Study Area)



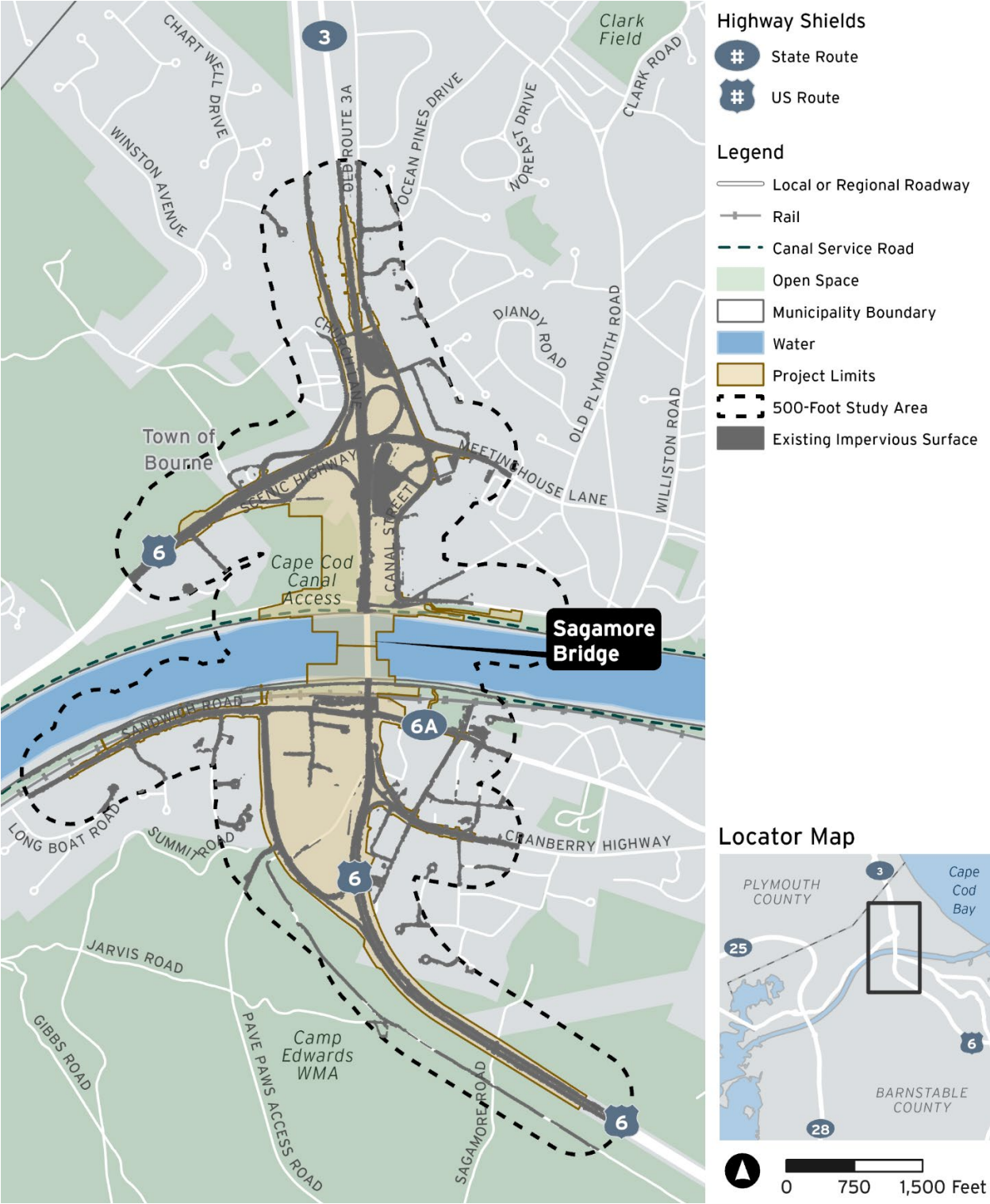
Source:Massachusetts Department of Transportation, 2025

Figure 4. No Build Alternative: Existing Grading and Flood Pathways (Bourne North Quadrant)



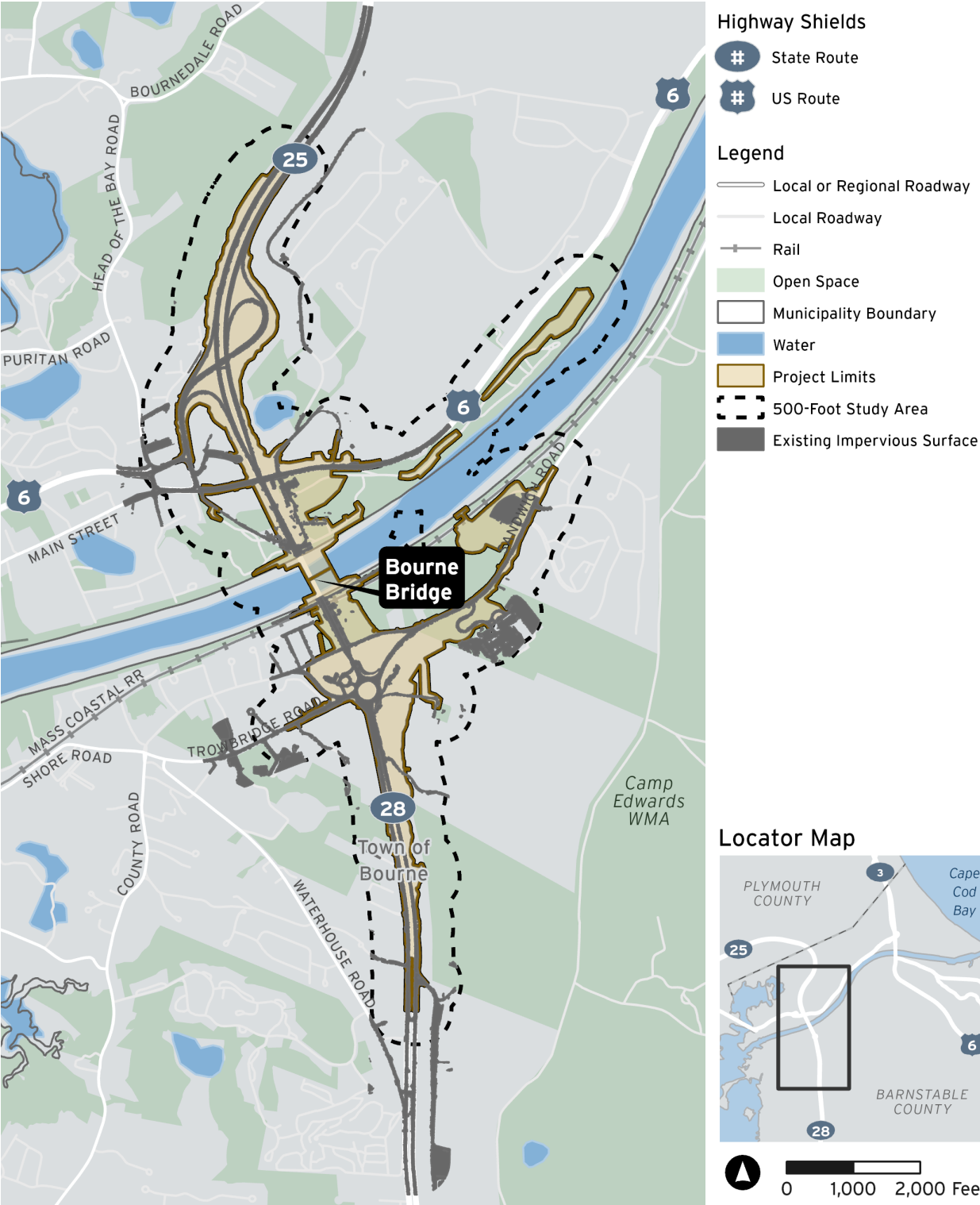
Source:Massachusetts Department of Transportation, 2025

Figure 5. No Build Alternative: Land Cover – Impervious Surfaces (Sagamore Bridge Study Area)



Source:Massachusetts Department of Transportation, 2025

Figure 6. No Build Alternative: Land Cover – Impervious Surfaces (Bourne Bridge Study Area)



Source:Massachusetts Department of Transportation, 2025

## 4.5 Transportation

Under the No Build Alternative, the highway transportation routes would remain as-is.

### 4.5.1 Storm Surge and Flooded Roadways and Evacuation Routes

The roadways within the Bourne North quadrant, in particular, those that travel through Belmont Circle, are vulnerable to coastal inundation; there is at least a 1% annual likelihood (or 1-in-4 chance over the next 30 years) for a coastal flood event. For the No Build Alternative, the likelihood of flooding and existing conditions would remain the same, with heavy traffic volumes exiting to Belmont Circle and merging from the entrance ramp from Belmont Circle. Flooding may cause roadway closures, increase traffic delays, and affect emergency services.

The Cape Cod Emergency Traffic Plan, which facilitates the egress of a high volume of traffic from Cape Cod in the event of a hurricane or other potential or actual hazard, particularly during peak tourist season, includes traffic operations that reduce traffic flow to Belmont Circle, including restricting access to State Routes 28/25 via Scenic Highway and closing Exit 10 (formerly Exit 3) that leads to U.S. Route 6 from State Route 25W.<sup>24</sup> Even with this plan, flooding of Belmont Circle would likely affect traffic plans and operations in emergency recovery and for events that do not trigger plan implementation.

### 4.5.2 Extreme Precipitation and Localized Stormwater Flooding

**Section 4.10, Water Quality and Stormwater**, discusses impacts to localized flooding from extreme precipitation for the No Build Alternative.

### 4.5.3 Extreme Heat and Pavement Performance

For the No Build Alternative, it is likely that the performance of the existing pavement would be affected by extreme heat, such as increased prevalence of buckling, rutting, and /or potholes.

### 4.5.4 Winter Weather and Snow and Ice on Roadways

Winter weather conditions that generate snow and ice on roadways are likely to affect the No Build Alternative traffic and safety conditions.

### 4.5.5 Extreme Wind and Vehicle Rollover Potential

Based on wind climate analysis results, 3-second wind gust speeds that can increase the likelihood of vehicle rollover occur 0.2% of the time (or an average of roughly 20 hours per year) at Sagamore Bridge, and 0.55% of the time (or an average of roughly 50 hours per year) at Bourne Bridge.

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<sup>24</sup> Commonwealth of Massachusetts. 2018. [Cape Cod Emergency Traffic Plan](https://www.mass.gov/doc/cape-cod-emergency-traffic-plan/download). July. <https://www.mass.gov/doc/cape-cod-emergency-traffic-plan/download>

## 4.6 Mobility

For the No Build Alternative, the alternative modes of transportation, such as bus, bicycle, and walk, would remain as-is.

### 4.6.1 Storm Surge and Flooded Shared-Use Paths

Alternative modes of transportation within the Bourne North quadrant, in particular, travel through Belmont Circle, are vulnerable to coastal inundation. In the No Build Alternative, existing conditions and likelihood of flooding would remain the same—at least a 1% annual likelihood (or 1-in-4 chance over the next 30 years).

### 4.6.2 Extreme Precipitation and Localized Stormwater Flooding

**Section 4.10, Water Quality and Stormwater**, discusses impacts to localized flooding from extreme precipitation for the No Build Alternative.

### 4.6.3 Extreme Heat and Active Transportation Use

In addition to affected pavement performance, it is likely that extreme heat events will affect people who use alternative modes of travel in the No Build Alternative.

## 5 Build Alternative

This section reflects Build Alternative impacts with current and future conditions based on the methodology and the affected area described in previous sections. **Table 14** summarizes the Build Alternative impacts on the affected environment.

Table 14. Build Alternative Impacts

| Affected Environment        | Sea Levels and Storm Surge                                              | Extreme Precipitation                                                   | Extreme Heat | Winter Weather | Extreme Wind |
|-----------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------|----------------|--------------|
| Canal                       | No impact                                                               | NA                                                                      | NA           | NA             | NA           |
| Bridge                      | No impact                                                               | NA                                                                      | No impact    | Reduced Impact | No impact    |
| Stormwater Control Measures | Submerged/partially submerged outfalls**<br>Infiltration basin flooding | No impact. Refer to <b>Section 4.10, Water Quality and Stormwater</b> . | NA           | NA             | NA           |

| Affected Environment | Sea Levels and Storm Surge | Extreme Precipitation                                                  | Extreme Heat              | Winter Weather | Extreme Wind     |
|----------------------|----------------------------|------------------------------------------------------------------------|---------------------------|----------------|------------------|
| Land Cover           | No impact                  | No impact. Refer to <b>Section 4.10, Water Quality and Stormwater.</b> | Surface temperature       | NA             | NA               |
| Transportation       | Reduced impact – flooding  | No impact. Refer to <b>Section 4.10, Water Quality and Stormwater.</b> | Reduced impact            | Reduced impact | Vehicle Rollover |
| Mobility             | Reduced impact - Flooding  | No impact. Refer to <b>Section 4.10, Water Quality and Stormwater.</b> | Active Transportation Use | NA             | NA               |

Notes:

NA = not assessed for affected environment. Reduced impact is in comparison to the No Build Alternative.

\*\* Outfalls are within the Study Areas shown in [Figure 1](#), but are not part of the Program; they were assessed due to their impact on stormwater systems (flooding and performance) within the Study Area.

## 5.1 Cape Cod Canal

Under the Build Alternative, Cape Cod Canal would remain as-is, but the Sagamore Bridge and Bourne Bridge low chord would be elevated to reduce the impact on navigational clearance.

### 5.1.1 Sea Levels and Navigational Clearance

The Build Alternative would raise the elevation of the replacement bridges to establish a vertical clearance of 138.3 feet under existing MHHW; therefore, the Build Alternative would be unlikely to affect navigational clearance.

## 5.2 Bridge

For the Build Alternative, the Sagamore Bridge and Bourne Bridge would be replaced with network tied-arch structures with piers along riprap armored banks. A network tied-arch structure is highly redundant in that it can lose any two cables without compromising stability.

### 5.2.1 Sea Levels and Bridge Pier Scour

MassDOT calculated maximum scour depths for design and check events (200-year and 500-year, respectively, in accordance with FHWA HEC-18). The foundations of the Build Alternative are designed to remain stable during the maximum scour design and check events, and the current design includes pier protection in the form of riprap along the northern and southern canal banks at both bridges. Therefore, the Build Alternative for Sagamore and Bourne Bridges is unlikely to be affected by scour.

### 5.2.2 Extreme Heat and Bridge Joint Expansion

Design practices and standards for new bridges include limiting the number of bridge expansion joints. Extreme heat is unlikely to affect the bridge joints in the Build Alternative.

### 5.2.3 Winter Weather and Icing

The Build Alternative would be designed for a 1-inch combined ice and wet snow thickness, which corresponds with a 500-year event, using mitigation measures as described in [Section 6](#).

Design practices and standards for new bridges include limiting the number of bridge expansion joints to reduce the risk of winter deicing treatment infiltrating superstructure and substructure elements. Because of this, the replacement bridges would unlikely be affected by snow and ice events with days below 32 degrees F.

### 5.2.4 Extreme Wind and Aerodynamic Stability

Network tied-arch bridges have better resistance against wind-induced vibrations and deformation. The Build Alternative would be designed to remain stable during the extreme wind conditions identified in the wind climate analysis; as such, extreme wind events would unlikely affect the replacement bridges.

## 5.3 Stormwater Control Measures

Under the Build Alternative, new infiltrations basins are proposed, including piped infrastructure to connect to the existing stormwater system. Existing piped infrastructure and outfalls would remain as-is.

### 5.3.1 Sea Levels and Submerged and Partially Submerged Outfalls

Because there are no tide gates or backflow preventers on the outfalls that discharge stormwater to the canal, the impacts of the Build Alternative would be the same as the No Build Alternative. Refer to [Section 4.3](#).

### 5.3.2 Storm Surge and Infiltration Basins

The Build Alternative would include 27 new stormwater control measure infiltration basins to manage stormwater quality and volumes; seven were identified as potentially vulnerable to storm surge. [Table 15](#) summarizes the Build Alternative infiltration basins where the basin elevations would be exceeded by storm events. Refer to [Section 4.10, Water Quality and Stormwater \(Figures 4-10.9 through 4-10.12\)](#), for locations of the infiltration basins.

Without mechanisms to prevent backflow into infiltration basins, coastal inundation may affect the basins when floodwater elevations exceed the overflow structure's outlet elevation, causing the structure to surcharge. Those events would affect the infiltration basins within the extent of coastal inundation with an overflow structure outlet elevation lower than the elevation of the storm surge.

**Table 15. Build Alternative: Potentially Affected Infiltration Basins**

| <b>Infiltration Basin ID</b> | <b>Overflow Outlet (feet-NAVD88)</b> | <b>Basin Top (feet-NAVD88)</b> | <b>Potential Inundation Impact</b>                                                                                                                             |
|------------------------------|--------------------------------------|--------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| SCM-SS01                     | 17.0                                 | 22.0                           | <ul style="list-style-type: none"> <li>• CAT 2 + 3 feet (El. 19.3): Exceeds overflow outlet</li> <li>• Top of basin not exceeded</li> </ul>                    |
| SCM-BN05                     | 11.5                                 | 24.0                           | <ul style="list-style-type: none"> <li>• FEMA 100-year (El. 16) Exceeds overflow outlet</li> <li>• Top of basin not exceeded</li> </ul>                        |
| SCM-BN07                     | 15.3                                 | 20.0                           | <ul style="list-style-type: none"> <li>• FEMA 100-year (El. 16): Exceeds overflow outlet</li> <li>• Top of basin not exceeded</li> </ul>                       |
| SCM-BN08                     | 18.0                                 | 21.0                           | <ul style="list-style-type: none"> <li>• CAT 2 + 3 feet (El. 19.3): Exceeds overflow outlet</li> <li>• Top of basin not exceeded</li> </ul>                    |
| SCM-BN10                     | 8.8                                  | 11.0                           | <ul style="list-style-type: none"> <li>• FEMA 100-year (El. 16): Exceeds top of basin</li> <li>• CAT 2 + 3 feet (El. 19.3): Exceeds top of basin</li> </ul>    |
| SCM-BN11.2                   | 18.5                                 | 20.0                           | <ul style="list-style-type: none"> <li>• CAT 2 + 3 feet (El. 19.3): Exceeds overflow outlet</li> <li>• Top of basin not exceeded</li> </ul>                    |
| SCM-BS1A                     | 15.8                                 | 18.5                           | <ul style="list-style-type: none"> <li>• FEMA 100-year (El. 16): Exceeds overflow outlet</li> <li>• CAT 2 + 3 feet (El. 19.3): Exceeds top of basin</li> </ul> |

FEMA = Federal Emergency Management Agency, NAVD88 = North American Vertical Datum of 1988; SCM = stormwater control measures, CAT = Hurricane Category

Note: The elevations of the proposed overflow outlets are to be determined at this time. They are between the bottom and top of the basins.

### 5.3.3 Extreme Precipitation and Stormwater Control Measure Performance

Stormwater control measures would function as intended with 500-year, 24-hour rainfall event under the Build Alternative as described in **Section 4.10, Water Quality and Stormwater**. The infiltration basins' performance may be altered under scenarios where tidal datums would exceed the outfall invert elevation (refer to [Table 15](#)). In these scenarios, a basin's ability to discharge would be reduced, which may result in the infiltration basin temporarily acting as a retention basin. The basins would provide peak flow attenuation and storage until the stormwater captured in the basins is able to infiltrate or discharge through the outfall. As such, extreme rainfall events with temporarily submerged outfalls would unlikely affect the proposed stormwater control measures.

## 5.4 Land Cover

Under the Build Alternative, the land cover, resource areas, and land use would change as described in **Section 4.9, Wetlands and Floodplains**, and **Section 4.6, Land Use, Zoning, and Community Cohesion**.

### 5.4.1 Storm Surge and Land Subject to Coastal Storm Flowage Function

**Figure 7** and **Figure 8** show the extent of overland coastal surge for the Build Alternative. These figures also identify areas where changes to site grading and topography are proposed below the associated storm surge elevations. The extent of overland coastal surge for the Build Alternative for Sagamore Bridge would be the same as the No Build Alternative (**Figure 2**) because there would be no proposed changes to grading within the flood extents. The extent of overland coastal surge for Bourne Bridge for the Build Alternative (**Figure 7** and **Figure 8**) would be the same as the No Build Alternative (**Figure 3**), with the exception of the Bourne North quadrant, where the proposed grade changes near Belmont Circle would accommodate the higher bridge deck elevation spanning the Cape Cod Canal to maintain navigational clearance and connect to existing grades. **Figure 9** shows the proposed grade changes and corresponding flood pathways in the Bourne North quadrant. These grade changes would slightly reduce the extent of coastal inundation at the edge of the floodplain but would not affect the flood pathways compared to the No Build Alternative (**Figure 4**).

MassDOT took five cross-sections where grade changes are proposed on the ramps and along U.S. Route 6 (**Figure 10**) to assess potential impacts to flow velocities. **Figure 11 through Figure 15** show the cross-sections, which depict the following:

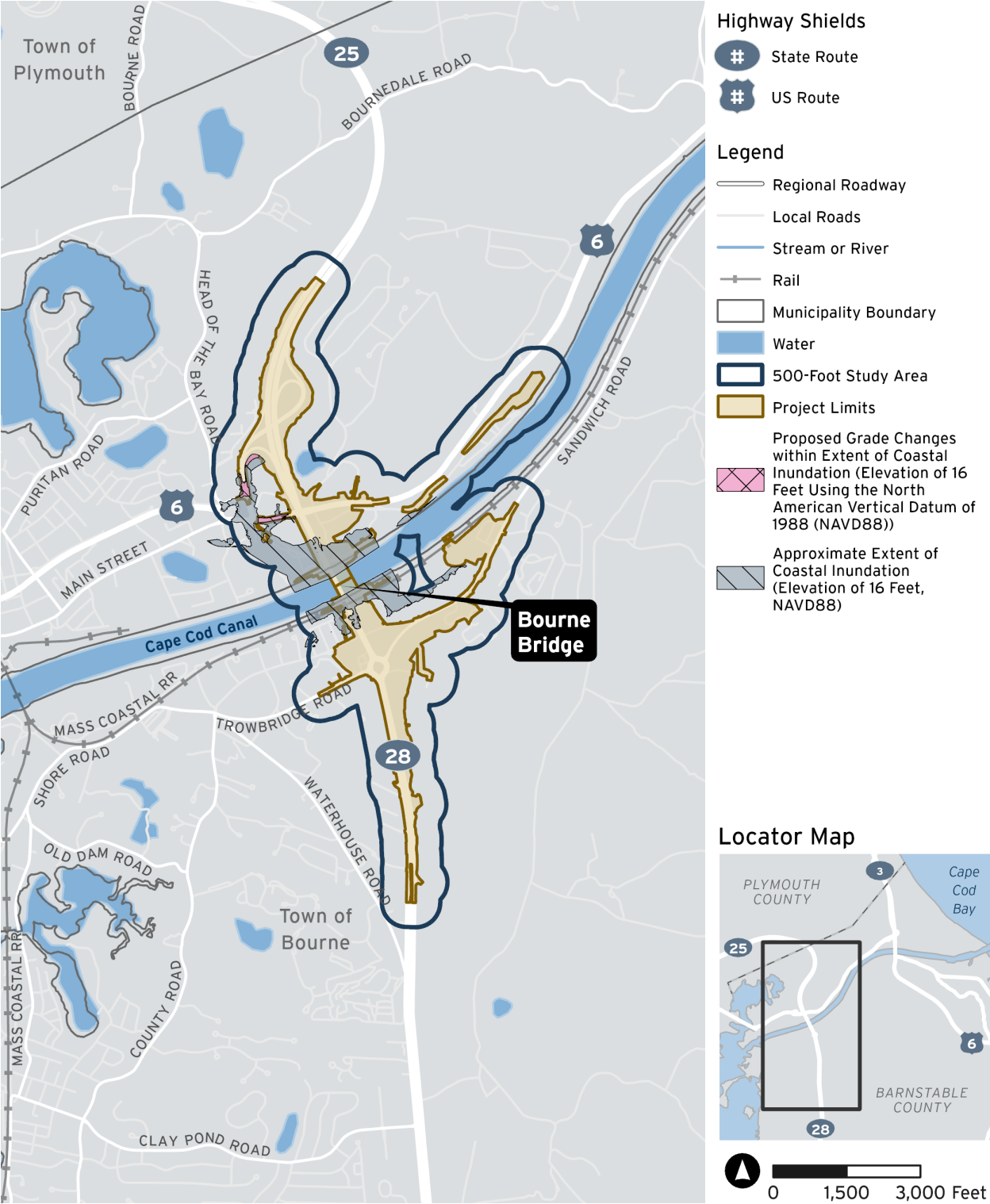
- Existing grade (Dashed Lines - No Build Alternative) and proposed topography (Solid Lines - Build Alternative)
- Proposed roadway surfaces, including shared-use paths and shoulders (SHLD)
- Existing edge of pavement (EOP), right-of-way, and driveways (DWY) to adjacent parcels
- Coastal surge flood elevations (El. 16 (FEMA 100-year) and El. 19.3 (Category 2 hurricane + 3-foot freeboard))

The cross-sections on U.S. Route 6 at 701+50 (**Figure 11**) and 704+50 (**Figure 12**) are subject to perpendicular and parallel flood pathways; when subject to perpendicular flows, the water travels right to left. The cross-sections on the westbound ramps at 102+50 (**Figure 13**) and 104+00 (**Figure 14**) are subject to parallel flood pathways, and the cross-section on the eastbound ramp at 405+00 (**Figure 15**) is subject to perpendicular flows where the water travels right to left.

These cross-sections illustrate that the Build Alternative for U.S. Route 6, including changes to landcover and grading, would not likely create channelized flow conditions within the extent of mapped inundation. The proposed changes to the westbound ramps for the Build Alternative would include the installation of retaining walls to increase grades, while reducing the impact on nearby wetlands. These cross-sections would be at the edge of the floodplain and would receive flow from pathways that would have already crossed developed areas with existing impervious surfaces and vertical impediments, such as curbs and structures. The areas farther inland from these cross-sections

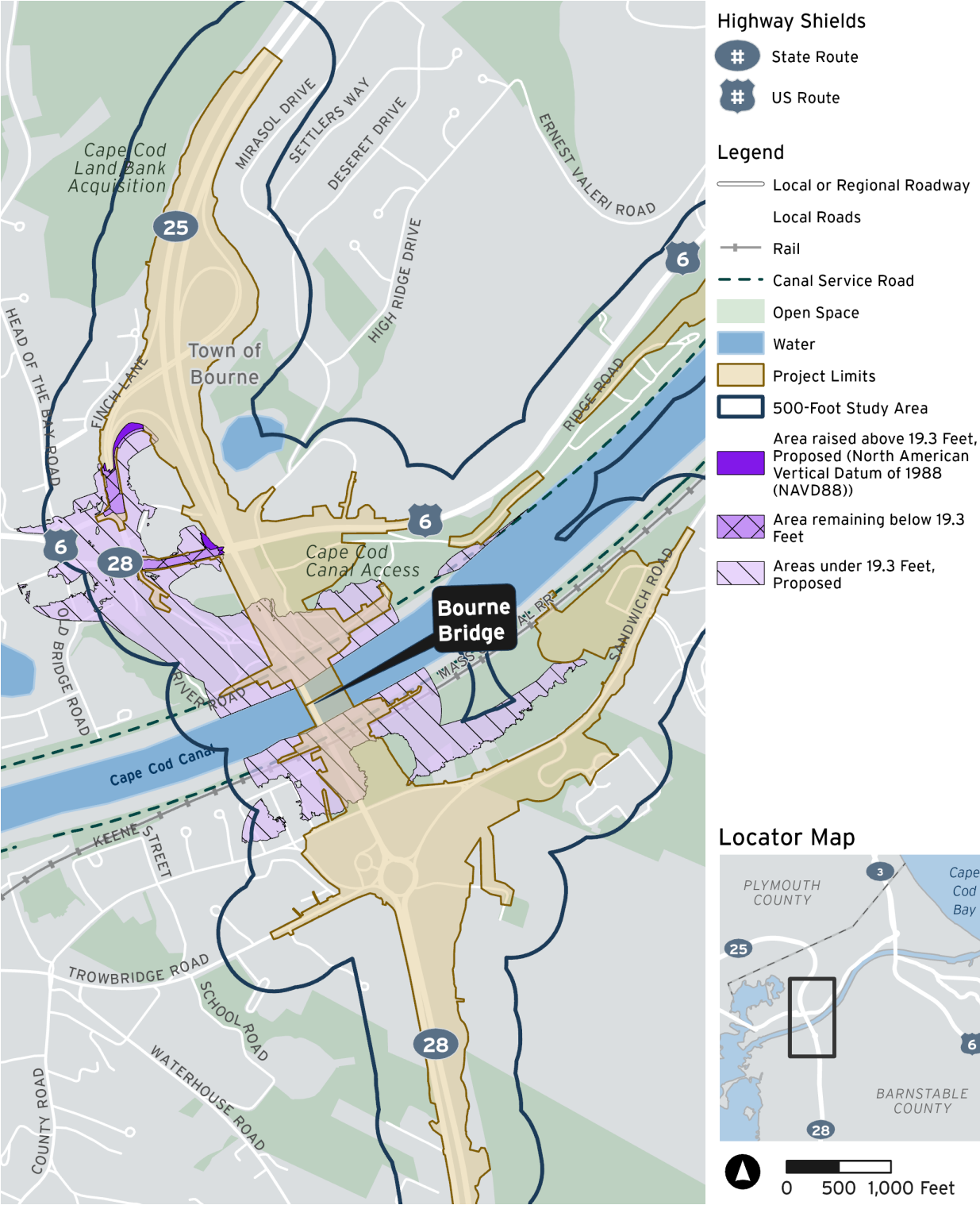
are low lying wetlands; therefore, the changes to land cover from the westbound ramps are not anticipated to have an impact on the land subject to coastal floodplain functions. The proposed changes to the eastbound ramps for the Build Alternative would include creating an embankment (2H:1V) to raise grades up to 28 feet at the edge of the floodplain, and would receive flow from pathways that would have already crossed developed areas and the existing wetland; therefore, the changes to land cover from the eastbound ramp are not anticipated to have an impact on the LSCSF functions.

**Figure 7. Build Alternative: Coastal Surge Flood Extents – Existing 100-year Floodplain (Bourne Bridge Study Area)**



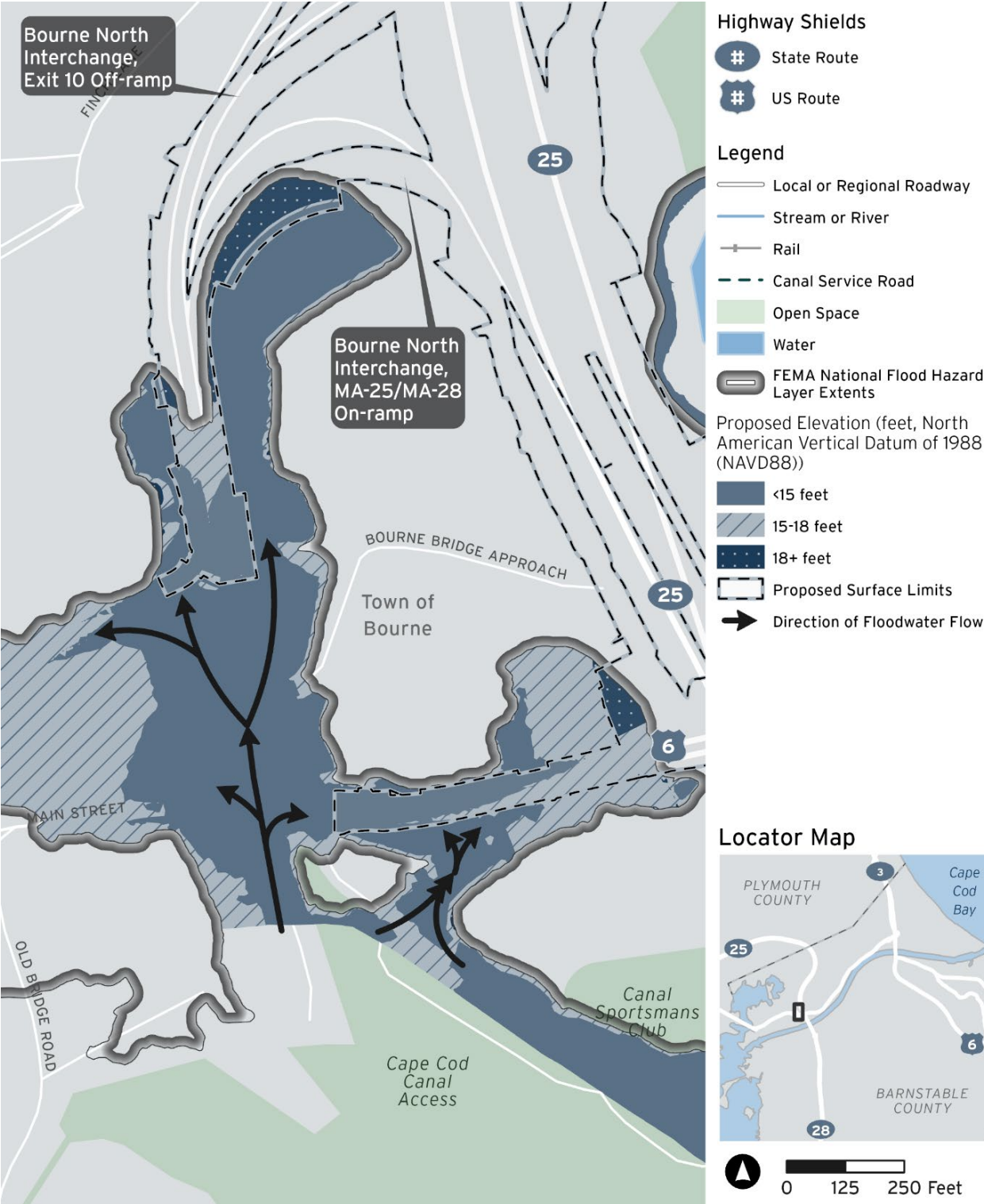
Source: Massachusetts Department of Transportation, 2025

**Figure 8. Build Alternative: Coastal Surge Flood Extents – Category 2 Hurricane + 3 feet Freeboard (Bourne Bridge Study Area)**



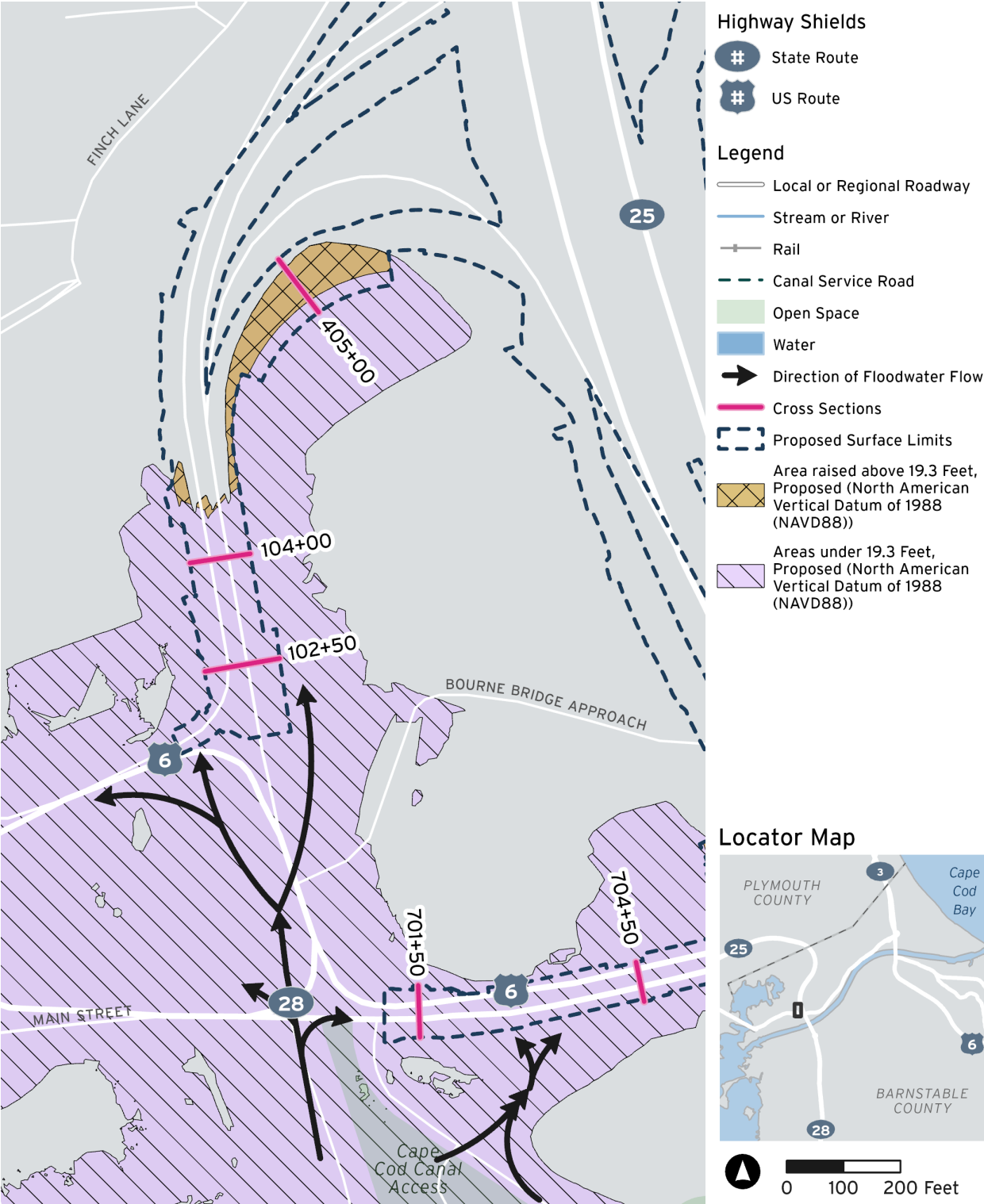
Source: Massachusetts Department of Transportation, 2025

Figure 9. Build Alternative: Proposed Grading and Flood Pathways (Bourne North Quadrant)



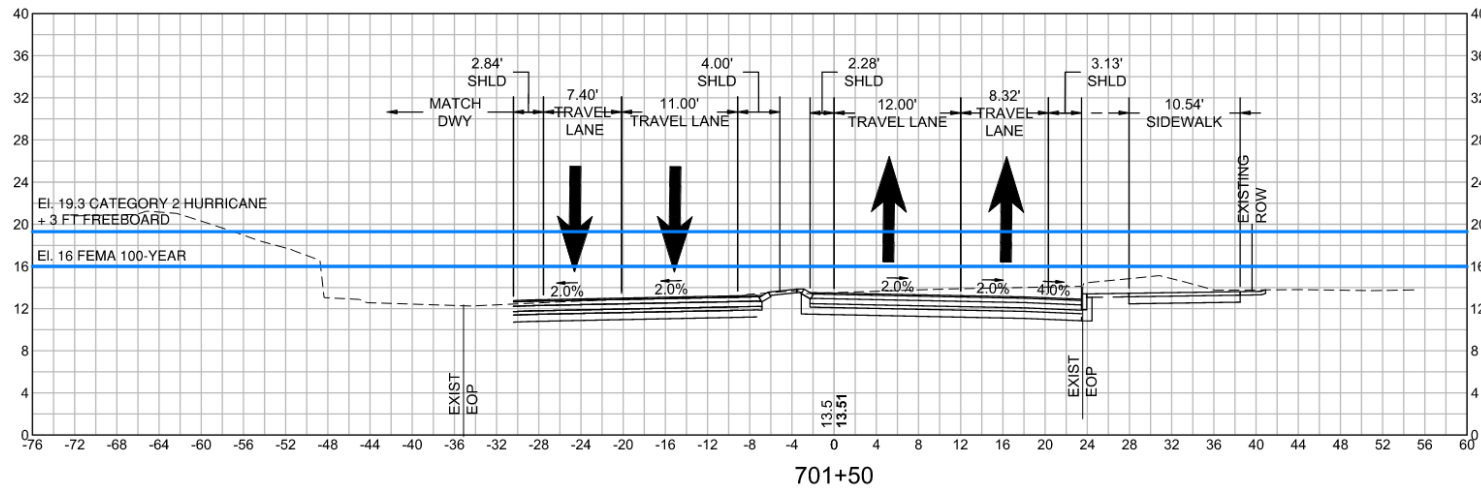
Source: Massachusetts Department of Transportation, 2025

Figure 10. Build Alternative: Cross-Section Reference for Bourne North Quadrant Grading Plan



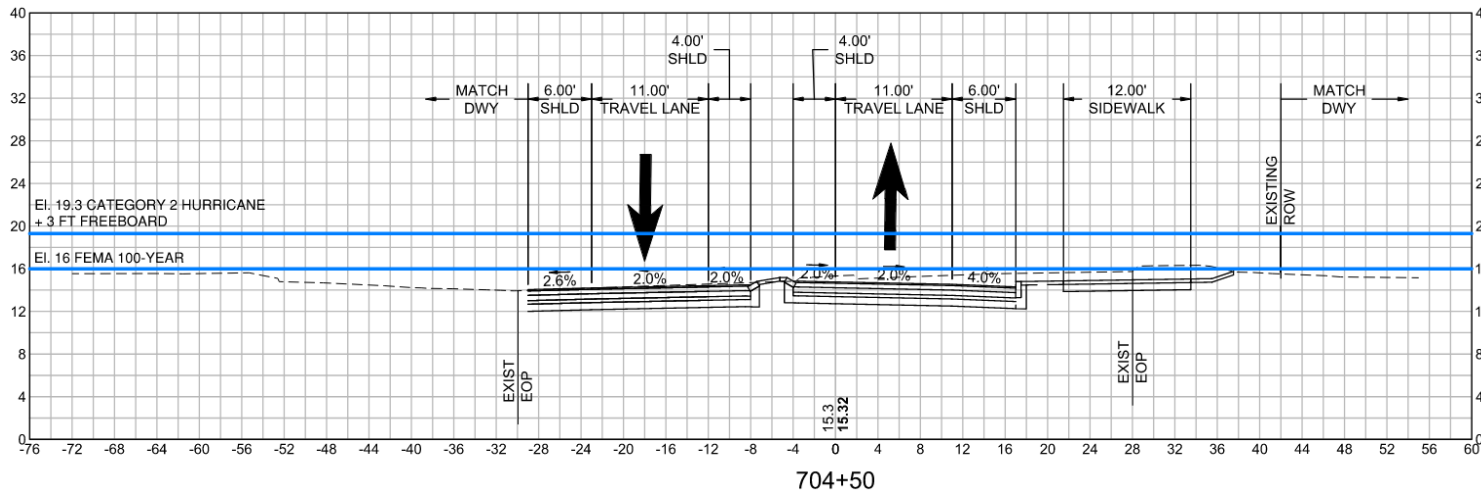
Source: Massachusetts Department of Transportation, 2025

**Figure 11. Build Alternative: Cross-Section U.S. Route 6: 701+50, Proposed Grading, Impervious Surfaces, and Coastal Surge Flood Extents (Bourne North Quadrant)**



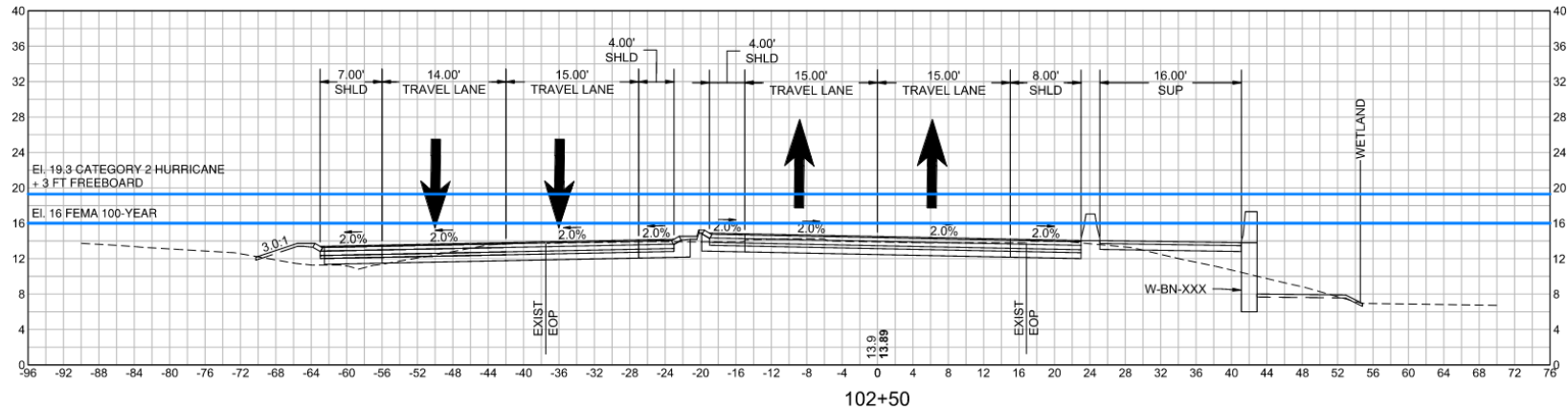
Source: Massachusetts Department of Transportation, 2024

**Figure 12. Build Alternative: Cross-Section U.S. Route 6: 704+50, Proposed Grading, Impervious Surfaces, and Coastal Surge Flood Extents (Bourne North Quadrant)**



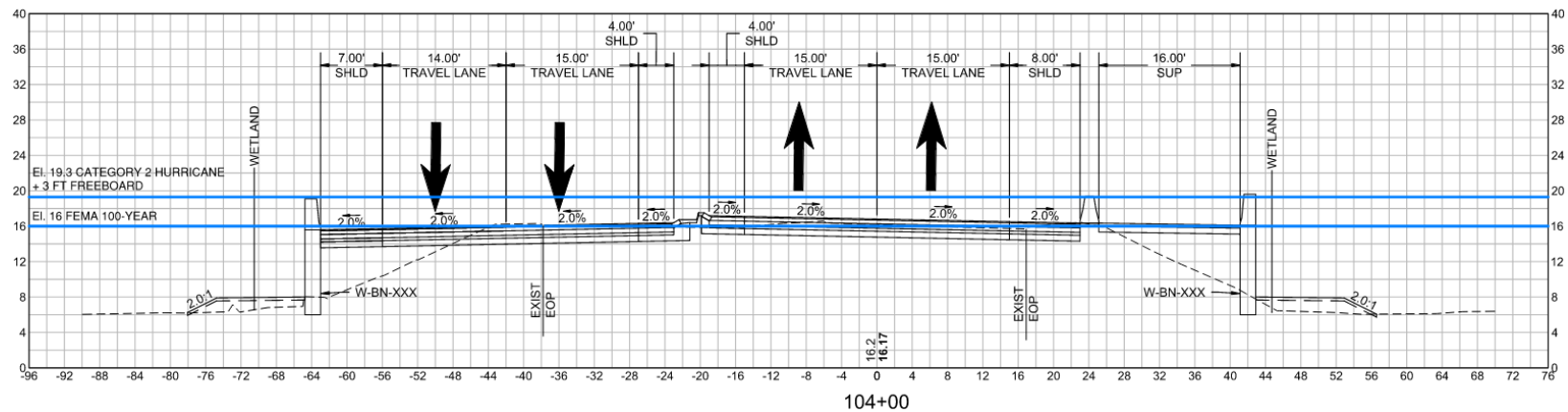
Source: Massachusetts Department of Transportation, 2024

**Figure 13. Build Alternative: Cross-Section Westbound On- and Off-Ramps: 102+50, Proposed Grading, Impervious Surfaces, and Coastal Surge Flood Extents (Bourne North Quadrant)**



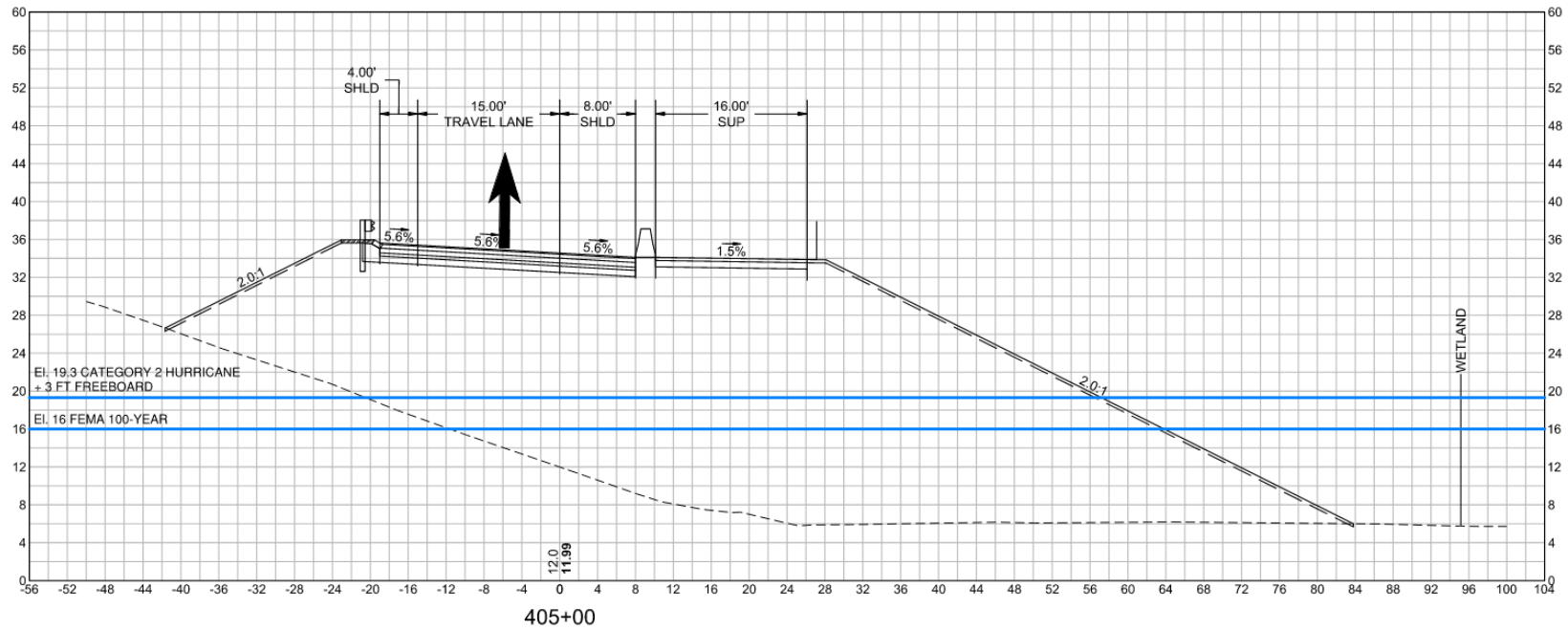
Source: Massachusetts Department of Transportation, 2024

**Figure 14. Build Alternative: Cross-Section Westbound On- and Off-Ramps: 104+00, Proposed Grading, Impervious Surfaces, and Coastal Surge Flood Extents (Bourne North Quadrant)**



Source: Massachusetts Department of Transportation, 2024

**Figure 15. Build Alternative: Cross-Section Eastbound On-Ramp: 405+00, Proposed Grading, Impervious Surfaces, and Coastal Surge Flood Extents (Bourne North Quadrant)**



Source: Massachusetts Department of Transportation, 2024

## 5.4.2 Extreme Precipitation and Localized Stormwater Flooding

Stormwater control measures function as intended for the Build Alternative; as such, localized flooding as a result of impervious surfaces and extreme precipitation will be mitigated through the proposed stormwater control measures presented in **Section 4.10, Water Quality and Stormwater**.

## 5.4.3 Extreme Heat and Surface Temperatures

The Build Alternative would result in a total estimated increase in impervious area across the Project Limits of 52.3 acres (**Table 16**). However, the final impervious area percentages would still be less than 50% for the Build Alternative. As described in **Section 6**, MassDOT developed landscaping plans that will mitigate the extreme heat and surface temperature impacts associated with tree clearing and increases in impervious surfaces. Refer to the landscaping plan in **Attachment 5 of Appendix 3.2, Construction Approach Technical Report** for additional details.

Table 16. Build Alternative: Impervious Surface Area within Project Limits

| Project Limit   | Impervious Surface Area Increase (acres) <sup>[1]</sup> | Percentage Impervious <sup>[2]</sup> |
|-----------------|---------------------------------------------------------|--------------------------------------|
| Sagamore Bridge | +23.9                                                   | 45.1%                                |
| Bourne Bridge   | +28.4                                                   | 39.4%                                |

<sup>[1]</sup> Increase in impervious surface area based on analysis in **Section 4.10, Water Quality and Stormwater**.

<sup>[2]</sup> Increase in Project Limits Percent Impervious from No Build Alternative of 33.0% (Sagamore Bridge) and 28.1% (Bourne Bridge)

## 5.5 Transportation

As described in **Section 4.2, Transportation, Traffic, and Safety**, the Build Alternative would change the highway transportation routes and traffic.

### 5.5.1 Storm Surge and Flooded Roadways and Evacuation Routes

In the Build Alternative, the combination of new direct connection ramps between State Route 25 and U.S. Route 6 (Scenic Highway) in the Bourne North quadrant would allow vehicles to bypass Belmont Circle and reduce travel in the existing floodplain and mapped areas of coastal inundation.<sup>25</sup> The Build Alternative would facilitate emergency egress of high traffic volumes from Cape Cod in the event of a hurricane or other potential hazards by replacing Bourne Rotary with a grade-separated diamond interchange and constructing a new flyover ramp connection from Scenic Highway to State Route 25 westbound. Construction of two separate deck structures for the replacement bridges for the Build Alternative would provide additional service redundancy in case of an emergency evacuation or a

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<sup>25</sup> Regionally these changes would result in a reduction of 1.7% in vehicle-miles traveled and 8% in vehicle-hours traveled from the No Build Alternative to Build Alternative.

compromising event that would affect a single bridge structure. Cross-canal pedestrian and bicycle lanes would also improve hurricane evacuation ability for all road users.

While flooding of Belmont Circle has at least a 1% annual likelihood of flooding (or a 1-in-4 chance of flooding over 30 years), the Build Alternative would increase the adaptive capacity of the network to reduce vulnerability to coastal inundation. Changes to traffic patterns associated with the Build Alternative should be updated for construction phases and completion of the Program within the Cape Cod Emergency Traffic Plan.

### 5.5.2 Extreme Precipitation and Localized Stormwater Flooding

Stormwater control measures would function as intended for the Build Alternative; as such, localized flooding as a result of impervious surfaces and extreme precipitation will be mitigated through the proposed stormwater control measures presented in **Section 4.10, Water Quality and Stormwater**.

### 5.5.3 Extreme Heat and Pavement Performance

MassDOT's Transportation Asset Management Plan includes best practices that have been incorporated into MassDOT standards to increase the resilience of Highway Division assets, including modifying pavement mixtures to provide additional stability in high temperatures and incorporating balanced mixture design methods to reduce mixture cracking and moisture damage. It is likely that extreme heat events under the Build Alternative would still affect the performance of the pavement, but to a lesser degree than the No Build Alternative.

### 5.5.4 Winter Weather and Snow and Ice on Roadways

The Build Alternative would be designed to meet existing performance standards, which would account for winter weather operational needs, such as plowing and road treatments. Winter weather conditions that generate snow and ice on roadways would still likely affect the Build Alternative traffic and safety conditions, but to a lesser degree than the No Build Alternative.

### 5.5.5 Extreme Wind and Vehicle Rollover Potential

For the Build Alternative, the impact from extreme wind and vehicle rollover potential would be the same as the No Build Alternative.

## 5.6 Mobility

Under the Build Alternative, the alternative modes of transportation, such as bus, bicycle, and walk, would change as described in **Section 4.3, Pedestrian and Bicycle Facilities**.

### 5.6.1 Storm Surge and Flooded Shared-Use Paths

Alternative modes of transportation within the Bourne North quadrant, in particular, those within Belmont Circle, are vulnerable to coastal inundation with a likelihood of flooding of at least a 1% annual likelihood (or 1-in-4 chance over the next 30 years). The Build Alternative would improve mobility within this area but would also significantly improve mobility outside of this area. Cross-canal

pedestrian and bicycle lanes proposed in the Build Alternative would improve hurricane evacuation ability for all road users and would reduce travel within the extent of inundation.

### 5.6.2 Extreme Precipitation and Localized Stormwater Flooding

Stormwater control measures would function as intended for the Build Alternative; as such, localized flooding as a result of impervious surfaces and extreme precipitation will be mitigated through the proposed stormwater control measures presented in **Section 4.10, Water Quality and Stormwater**.

### 5.6.3 Extreme Heat and Active Transportation Use

While a significant portion of the proposed active transportation use corridors and shared-use paths run adjacent to proposed tree clearing and impervious surface areas, under the Build Alternative the landscaping plan would mitigate the potential intensification of extreme heat impacts within the Sagamore and Bourne Bridge Study Areas through intentional revegetation. The landscaping and vegetation plan includes targeted tree plantings along the active transportation use corridors and shared-use paths to mitigate short-term extreme heat impacts, such as lack of shade, which may occur after tree clearing while smaller vegetation becomes established. Refer to the landscaping plan in **Attachment 5 of Appendix 3.2, Construction Approach Technical Report**, for additional details.

## 6 Mitigation

This section discusses proposed measures beyond standard design best practices to mitigate Build Alternative impacts on affected environments.

### 6.1 Cape Cod Canal

#### 6.1.1 Sea Levels and Navigational Clearance

No mitigation will be required.

### 6.2 Bridge

#### 6.2.1 Sea Levels and Bridge Pier Scour

Pier protection will be provided in the form of riprap along the northern and southern canal banks for Sagamore and Bourne Bridges. Given the assessed performance of this pier protection, no additional scour mitigation is required.

#### 6.2.2 Extreme Heat and Bridge Joint Expansion

No mitigation will be required.

### 6.2.3 Winter Weather and Icing

Deicing measures for bridge cables include a variety of passive mitigation measures, such as modifying the cable surface to reduce size and mass of shed ice fragments or laying heating cables or exchange pipes inside the bridge deck. MassDOT will detail these measures as designs advance, where appropriate, in accordance with best practices.

### 6.2.4 Extreme Wind and Aerodynamic Stability

No mitigation will be required.

## 6.3 Stormwater Control Measures

**Section 4.10, Water Quality and Stormwater**, describes the stormwater mitigation measures.

### 6.3.1 Sea Levels and Submerged and Partially Submerged Outfalls

Improvements to the existing outfalls are not part of the Build Alternative. Backflow preventers at the outfalls were considered, but they are not required for the drainage system and associated stormwater control measures to function as designed during regular tidal conditions with elevated sea levels under the Build Alternative.

### 6.3.2 Storm Surge and Infiltration Basins

The siting and elevations (bottom, overflow, and top) of stormwater infiltration basins proposed for water quality and stormwater mitigation in **Section 4.10, Water Quality and Stormwater**, will seek to reduce risk of inundation through piped infrastructure and from coastal overland flows. Backflow preventers at the stormwater control measure infiltration basins were considered and are recommended for the drainage system and associated stormwater control measures to function as designed during coastal storm surge events under the Build Alternative. To reduce the risk of backflow into basins during coastal storm surge events, backflow preventers will be included at the seven stormwater control measure infiltration basins listed in **Table 15** where a surge event of +19.3 feet North American Vertical Datum of 1988 (Category 2 Hurricane peak surge elevation +3 feet) would exceed the lowest basin outlet elevation. The proposed design for the outlet control structure at these seven basins includes an in-line check valve in the outlet pipe at the outlet control structure to prevent backflow.

### 6.3.3 Extreme Precipitation and Stormwater Control Measure Performance

No mitigation will be required beyond what is proposed in **Section 4.10, Water Quality and Stormwater**.

## 6.4 Land Cover

**Section 4.9, Wetlands and Floodplains**, and **Section 4.6, Land Use, Zoning, and Community Cohesion**, describe the land cover mitigation measures.

### 6.4.1 Storm Surge and Land Subject to Coastal Storm Flowage Function

No mitigation will be required because the Build Alternative would not increase the velocity of moving water, redirect, or channelize flow, but would allow water to spread laterally and landward.

Compensatory storage for floodplain volume lost will not be needed because the floodplain is LSCSF. **Section 4.10.7, Water Quality and Stormwater**, and **Section 4.9, Wetlands and Floodplains**, describe strategies that will mitigate the effects of impervious surface on infiltration.

### 6.4.2 Extreme Precipitation and Localized Stormwater Flooding

No mitigation will be required.

### 6.4.3 Extreme Heat and Surface Temperatures

Under the Build Alternative, the landscaping and vegetation plan would mitigate the potential intensification of existing extreme heat impacts within the Sagamore and Bourne Bridge Study Areas, thus no additional mitigation measures will be required.

## 6.5 Transportation

**Section 4.2, Transportation, Traffic, and Safety**, describes the highway transportation, traffic, and safety mitigation measures.

### 6.5.1 Storm Surge and Flooded Roadways and Evacuation Routes

While the Build Alternative would reduce the impact of flooded roadways and evacuation routes, the new traffic patterns should be reviewed and the Cape Cod Emergency Traffic Plan updated as necessary to reflect construction and proposed configurations and flows, as well as remaining flood risk at Belmont Circle. This may include signage and public notices when storms are forecast, as appropriate.

### 6.5.2 Extreme Precipitation and Localized Stormwater Flooding

No mitigation will be required.

### 6.5.3 Extreme Heat and Pavement Performance

MassDOT considered mitigation measures—such as modifying pavement mixtures to provide additional stability in high temperatures and incorporated balanced mixture design methods to reduce mixture cracking and moisture damage. No mitigation measures are recommended at this time.

#### 6.5.4 Winter Weather and Snow and Ice on Roadways

MassDOT considered mitigation measures—such as updated snow and salt management plans for the Program. No additional mitigation measures are recommended at this time.

#### 6.5.5 Extreme Wind and Vehicle Rollover Potential

Given that rollover potential remains unchanged compared to the existing condition, no mitigation to reduce the likelihood of vehicle rollover is required.

### 6.6 Mobility

**Section 4.3, Pedestrian and Bicycle Facilities**, describes the mitigation measures for pedestrian and bicycle facilities.

#### 6.6.1 Storm Surge and Flooded Shared-Use Paths

While the Build Alternative would reduce the impact of flooded shared-use paths and sidewalks, MassDOT will communicate the remaining flood risk in the Bourne North quadrant at Belmont Circle to the public. This may include National Weather Service safety signage, such as “Turn around, Don’t drown,” and public notices when storms are forecast, as appropriate.

#### 6.6.2 Extreme Precipitation and Localized Stormwater Flooding

No mitigation will be required.

#### 6.6.3 Extreme Heat and Active Transportation Use

No mitigation will be required. Under the Build Alternative, the landscaping and vegetation plan would mitigate the potential intensification of existing extreme heat impacts within the Sagamore and Bourne Bridge Study Areas, thus no additional mitigation measures are required.