Massachusetts Bay Transportation Authority: Climate Change Vulnerability Assessment for the Blue Line (Draft)

1. Introduction

Transportation systems are sensitive to short-term intense weather events, as well as to long-term incremental changes in climate (Rowan et al. 2013; FTA 2011). The climate-related stressors of concern for transportation planners include extreme heat events, heavy precipitation, storm surge, and sea-level rise. In order to ensure that transportation systems are resilient when exposed to such stressors, decision-makers from the local to Federal level are conducting vulnerability assessments to determine which transportation assets and services are the most susceptible to climate and weather stressors. Likewise, Massachusetts Bay Transportation Authority (MBTA) is concerned with identifying vulnerabilities within its system in order to minimize service disruptions, ensure reliable transportation to support the regional economy, and protect taxpayer investments.

By the end of this century, the Boston area will experience sea-level rise of three to seven feet (not including the impacts of storm surge events) and as many as 90 extreme heat (≥ 90°F) days each year (Climate Ready Boston 2016). Intense rain events are also trending upward. The anticipated 25-year, 48-hour storm as of the 2030s and the 2070s is 8.6 inches and 9.8 inches, respectively. This represents an increase of 22-40% over the baseline of seven inches. Similarly, the anticipated 100-year, 48-hour storm as of the 2030s and the 2070s is 10.2 inches and 11.7 inches, respectively. This represents an increase of 32-57% over the baseline of ten inches.

As a first step in identifying and preparing for future climate change, the MBTA has conducted a pilot climate change vulnerability assessment (CCVA) of its Blue Line rapid transit line (RTL), which runs from downtown Boston—through East Boston—to Revere. This RTL was chosen for the pilot assessment for several reasons:

(1) It has been previously identified by Massachusetts Department of Transportation (MassDOT) as being particularly exposed to potential storm surge in its Boston Harbor-Flood Risk Model (BH-FRM) (MassDOT 2015);

(2) The MBTA recognizes from the outset, conceptually, that the portal between the Maverick and Airport Stations—if inundated—could expose most of the subway system, even beyond the Blue Line, to the hazards associated with saltwater flooding; and

(3) East Boston's Neighborhood Organization for Affordable Housing (NOAH), funded by a Kresge Foundation grant, is pursuing an evaluation of East Boston's vulnerabilities to climate change and has requested the MBTA's support in evaluating the vulnerability of our transit services in the area.

The scope of this high level CCVA is to assess the exposure, sensitivities, and adaptive capacity of the Blue Line to sea-level rise, storm surge, precipitation, extreme high temperature events, wind, snow, and ice.

This report presents information on each major Blue Line asset, the vulnerabilities for each asset, and the MBTA's proposed next steps.

2. The Blue Line

The focus of this pilot CCVA, the MBTA's Blue Line, runs from downtown Boston at its southwest end to Revere at its northeast end. The following stations service the line:

<u>Boston</u>

- Bowdoin
- Government Center
- State
- Aquarium

<u>East Boston</u>

- Maverick
- Airport
- Wood Island
- Orient Heights
- Suffolk Downs

<u>Revere</u>

- Beachmont
- Revere Beach
- Wonderland

There are also non-passenger facilities on the line. At either end, there are storage yards (Bowdoin Yard and Wonderland Yard). Behind the Orient Heights Station, there is a maintenance and storage facility that provides routine scheduled maintenance, performs necessary repairs, and washes the cars.

The Blue Line is depicted in the map provided as Exhibit 1 on the next page.

2.1 Ridership and Demographics

According to a 2010 study of Blue Line ridership, conducted for the MBTA by the Boston Region Metropolitan Planning Organization's Central Transportation Planning Staff (CTPS), almost 90 percent of passenger trips on the line are taken to or from riders' homes. Of these, 72 percent of the trips are for the purpose of getting to or from work. A majority of riders reported utilizing no alternative means for making these trips on other days, indicating that the Blue Line is a critical transportation route for many passengers. The most common entry points for the Blue Line are the Wonderland (16 percent) and Maverick Stations (15 percent), and the most common exit point is State Station (20 percent). More than half of all passengers surveyed indicated their destination is downtown Boston, split nearly equally between the Financial/ Retail District and Government Center (CTPS 2010).

At the time of the CTPS survey, nearly 57 percent of riders on the Blue Line were women. The majority self-identified as being white (78 percent), with 7 percent identifying as African American and 5 percent as Asian. Separately, about 16 percent identified as Hispanic (encompassing both white and non-white populations). More than 60 percent of all riders indicated household income of less than $75,000 and 27 percent with income less than $40,000, in 2009 dollars (CTPS 2010) (inflated to $83,900 and in $44,750 in 2016, respectively (BLS 2017)).

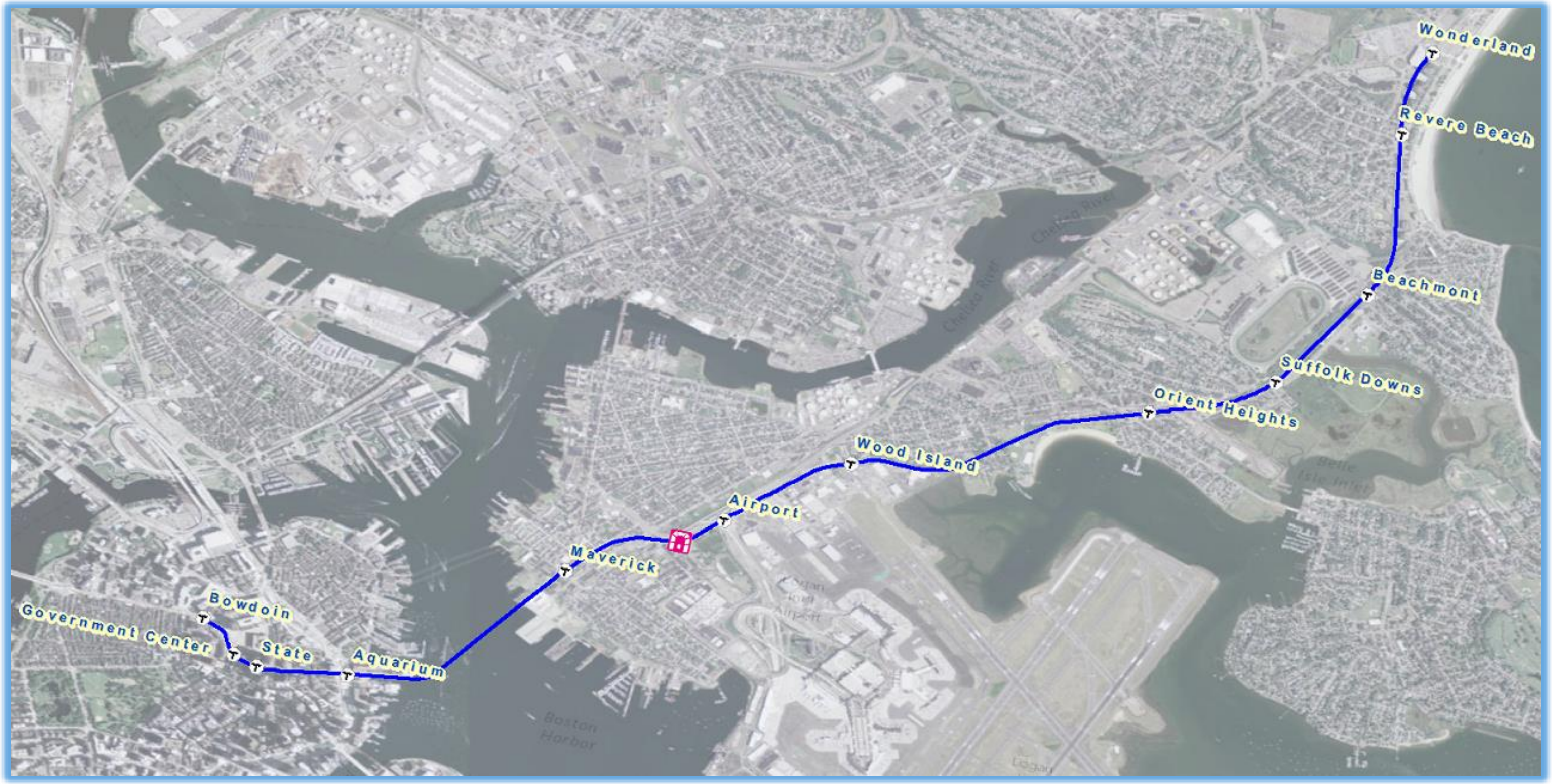


Exhibit 1. MBTA Blue Line

Although the MBTA has invested in modern cars (Siemens 700-series, purchased by the MBTA in 2007) and several renovated stations for the line, much of its infrastructure is aging and in use beyond its intended lifespan, consistent with the MBTA's other rapid transit lines (Red, Orange, and Green).

The Blue Line's major features are listed in Exhibit 1, ordered from the southwest end of the line (downtown Boston) to the northeast end of the line (Revere). The exhibit includes asset type, age, NAVD88 elevation at the asset's lowest point (often the track elevation), and latitudinal and longitudinal coordinates for each asset.

Exhibit 2. Major Blue Line Features

Asset Name	Asset Type	Construction/ Renovation Date	Elevation, Feet (NAVD88)	Coordinates (Decimal Degrees)
Bowdoin Yard	Storage Yard	-	10.1	42.361, -71.062
Bowdoin Station	Passenger Station	1968	9.0	42.361, -71.062
Government Center Station	Passenger Station	2016	-3.2	42.359, -71.059
State Station	Passenger Station	2011	-13.5	42.358, -71.057
Aquarium Station	Passenger Station	2004	-48.3	42.359, -71.051
Aquarium Substation	Electrical Substation	2000		42.359, -71.051
Tunnel under Boston Harbor	Tunnel	1904	-85.8	42.365, -71.044
Maverick Station	Passenger Station	2009	-19.0	42.369, -71.039
Maverick-Airport Portal	Portal	1904	-7.5	42.372, -71.032
Airport Substation	Electrical Substation	1980	8.9	42.374, -71.030
Airport Station	Passenger Station	2004	8.5	42.374, -71.030
Prescott Tube	Tunnel	-	-19.8	42.377, -71.026
Wood Island Station	Passenger Station	2008	5.17	42.379, -71.022
Byron Street Overhead Bridge	Bridge	-	11.8	42.381, -71.015
Trident Street Overhead Pedestrian Bridge	Bridge	-	11.0	42.385, -71.010
Saratoga Street Overhead Bridge	Bridge	-	9.3	42.386, -71.006
Orient Heights Substation	Electrical Substation	1980	4.9	42.387, -71.004
Orient Heights Station	Passenger Station	2013	4.9	42.374, -71.030
Orient Heights Facility	Maintenance and Storage Facility	2004	7.0	42.385, -70.997
Bennington Street Overhead Bridge		-		42.388, -70.999
Suffolk Downs Station	Passenger Station	1995	10.7	42.390, -70.997

Asset Name	Asset Type	Construction/ Renovation Date	Elevation, Feet (NAVD88)	Coordinates (Decimal Degrees)
Belle Isle Inlet Undergrade Bridge	Bridge	-	9.2	42.394, -70.995
Beachmont Station	Passenger Station	1995	9.0	42.397, -70.992
Winthrop Avenue Undergrade Bridge	Bridge	-	32.1	42.398, -70.992
Revere Beach Parkway Overhead Bridge	Bridge	-	9.0	42.399, -70.991
West Street Overhead Pedestrian Bridge	Bridge	-	6.8	42.404, -70.992
Shirley Avenue Overhead Bridge	Bridge	-	6.4	42.407, -70.992
Revere Beach Station	Passenger Station	1995	6.4	42.407, -70.992
Beach Street Overhead Bridge	Bridge	-	6.4	42.408, -70.992
Wonderland Station	Passenger Station	2008	7.4	42.414, -70.992
Wonderland Substation	Electrical Substation	1979	7.4	42.412, -70.993
Wonderland Yard	Storage Yard	1954	7.4	42.416, -70.990

3. Vulnerabilities

The vulnerability of a system, service, or asset to climate change is a function of exposure, sensitivity, and adaptive capacity (FHWA 2012). The conceptual model for determining vulnerability is illustrated in Exhibit 3.

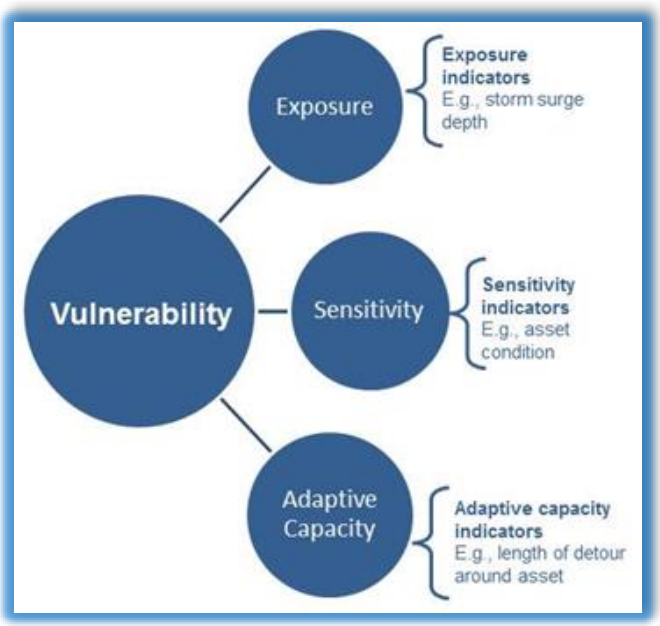


Exhibit 3. Indicators of Climate Change Vulnerability (FHWA 2014)

- ***Exposure*** is the degree to which a system, service, or asset is experiencing, or is projected to experience, weather and climate stressors, such as extreme temperatures, intense precipitation, sea-level rise, storm surge, wind, snow, and ice (*e.g., will a particular passenger station experience storm surge?*).
- ***Sensitivity*** refers to the impact on a system, service, or asset when exposed to weather and climate stressors (*e.g., if a passenger station is exposed to storm surge, how will its ability to function be affected?*).
- ***Adaptive Capacity*** is the ability of a system, service, or asset to adjust to impacts from weather and climate stressors (*e.g., how will a passenger station cope with a storm surge event?*).

3.1 Exposure and Sensitivity

The MBTA considered the following climate and weather stressors in this assessment:

- Heat
- Heavy precipitation and inland flooding
- Sea-level rise and storm surge
- Snow and ice
- Wind

3.1.1. Heat

The MBTA assumes that each above-ground Blue Line asset is uniformly exposed during a high heat event, although there is local variability due to the urban heat island effect (i.e., assets surrounded by dark and paved surfaces will be hotter than those that are adjacent to vegetated surfaces). Below-ground stations on the Blue Line are not likely to experience direct, damaging, exposure to high heat, though electrical brownouts could result in short-term service interruptions. As described in Exhibit 4, electrical substations are very sensitive to extreme heat events and, if exposed, their failures could be very disruptive to the entirety of the line. Similarly, extreme heat at the Orient Heights Maintenance Facility could result in damage or destruction of expensive equipment that is critical to vehicle maintenance and operations.

According to the Climate Ready Boston's Boston Research and Advisory Group (BRAG) Report, the Boston area has historically experienced an average 1.3 days of temperatures exceeding 95°F each year. Under the medium-high emissions future climate scenario (referred to as Representative Concentration Pathway (RCP) 6.0), conservatively representing our current observed emissions trajectory, this is projected to increase to as many as 3.9 days in the 2030s, 7.1 days in the 2050s, and 24.4 days by 2100 (BRAG 2016). Although any one year could be an anomaly, it is noted that in 2016 Boston experienced 6 days with temperatures at or above 95°F and 22 days at or above 90°F, well above the historical annual average number of days for each benchmark (NOAA 2017).

Sensitivities of assets and services to heat are provided in Exhibit 4, below.

Exhibit 4. Asset Sensitivities to Heat (Source: Climate Change Sensitivity Matrix (FHWA 2015), except where noted)

Asset	Sensitivities and Thresholds
Maintenance Facility and Storage Yard	Computer and electrical equipment may overheat if not adequately covered by HVAC systems. This includes wheel truing machinery and vehicle lifts. In cases of power loss due to heat, equipment offline temporarily but no long-term damage.
Track, third rail, and guard rails	Rails at or above their threshold temperature for buckling are more likely to buckle (either horizontally or vertically) or break under normal railroad travel and operations. 110°F is often a threshold for buckling (also known as heat kinks). Continuous welded rail (CWR) is particularly susceptible to temperature-related buckling. 22°C (72°F) is considered ideal temperature for stable tracks, although NDLR is often set to 95-110°F in the United States to accommodate heat events.
Tunnel	Buckled track requires replacement of the affected section of track.
Rail Ties, Ballast, Sub-Ballast	None directly, although buckles from heat "more often affect track with rock ballast than concrete slab track with a paved right-of-way, as the concrete slab provides stronger support. Other risk factors include weakened ballast or ties from poor maintenance, above-ground tracks exposed to direct sunlight, and curved areas of track" (FTA, 2011).
Electrical and Communications Equipment (including substations, signals, switches, switch heaters, and crossings)	Electrical equipment is susceptible to overheating and malfunction. Overheating may lead to melting of electronics or temporary shutdown in cases for which temperature thresholds result in an automatic shutdown. Possible malfunctions of track sensors and signal sensors are possible above threshold temperatures. Ambient temperature of 90°F is recognized as a threshold for worsening threats to electrical overheating. Damage from system overheating is more likely to occur when ambient temperatures reach this level.
Sump Pump, Drainage	Sump pump may be unavailable during a brownout unless backup power is available
HVAC/ Ventilation/ Tunnel Fans	During heat events, electric utility brownouts can affect tunnel lighting and cooling, which can render tunnels and stations temporarily unusable. These are indirect impacts of heat events.
Bridge (including Pedestrian Bridge) or Culvert; Surface Parking Lots	Increased wear and tear on paved surfaces, joints. Rutting and potholes more common on pavement that has softened from heat. Impacts mitigated with Ultra-high Performance Concrete (UHPC) or Shape Memory Alloys (SMAs), or even a hybrid composite (SMA Reinforced UHPC) (Ozbulut et al. 2016). Thresholds vary depending on pavement design. Pavement binder may exhibit sensitivity beginning at 108°F, particularly if combined with truck traffic.
Station (Building)	Greater cooling and ventilation needs accompany higher temperatures. Buildings with more glass than brick or masonry may lead to higher ambient indoor temperatures (greenhouse effect).
Catenary Lines and Poles	Sagging and snapping catenary lines (lines that provide electricity to trains) due to increased temperature are possible. Tension is maintained from 32°F to 120°F.
Trains	Risk of overheating

Asset	Sensitivities and Thresholds
Operations, Maintenance, and Safety	Buckled tracks remove rail lines from service, at least temporarily until sections are replaced. Buckled tracks cannot be traveled. The threat of heat damage to tracks and catenary lines reduces travel speed in many cases (depending on owner/ operator guidance), which reduces efficiency. The risk of heat exhaustion among workers increases at higher ambient temperatures and higher heat indices. High heat can affect passengers waiting in station shelters or in inadequately ventilated stations. Inadequate ventilation may also affect service buildings such as maintenance garages and rail yard buildings (including impacts to service personnel and to equipment). Health and safety risk, as well as possible engine/equipment heat stress begins at around 85°F, but the situation becomes more critical at 105-110°F. Restrictions limiting the number of hours that road crew maintenance can work begin at 85°F. At 110°F, operations are generally restricted.

3.1.2. Heavy Precipitation and Inland Flooding

The MBTA's primary concern with heavy precipitation is the potential for associated inland flooding. Assets at low-lying elevations, particularly those that are lower than adjacent features, are more exposed to the effects of river and urban flooding.

As the stations and assets west of the Maverick-Airport Portal are all below-grade, the MBTA assumes that any grade-level urban flooding in this area (containing Bowdoin, Government Center, State, Aquarium, and Maverick Stations) may also expose stations and MBTA assets to flooding. East of the Maverick-Airport Portal, stations are at or above-grade level. However, as each station in this area is at or below the elevation of surrounding topographic features, the MBTA assumes all facilities in this area (Airport, Wood Island, Orient Heights (incl. Maintenance Facility), Suffolk Downs, Beachmont, Revere Beach, and Wonderland Stations) could be exposed to precipitation-driven inland flooding.

According to the BRAG Report, citing the Cambridge Climate Change Vulnerability Assessment (CCVA), the historical 25-year, 24-hour design storm (i.e., the heaviest 24-hour rainfall to occur every 25 years, on average) has been 6.2 inches. By the 2030s, this is projected to be about 7.3 inches and by the 2070s, about 8.2 inches (City of Cambridge 2015 as cited in BRAG 2016). These estimates represent increases of 18 and 32 percent over the historical baseline, respectively.

The MBTA has demonstrated sensitivity to inland flooding during previous events. The most notable and damaging flood event was a two-day rain event in October 1996, which resulted in the Muddy River flooding Kenmore Station on the Green Line, via the Fenway Portal on the "D" Branch of the line. This 7.5-inch storm was considered to be approximately a 25-year, 48-hour event storm (i.e., the heaviest 48-hour rainfall to occur every 25 years, on average). According to records, the historical 25-year, 48-hour event for Boston is exactly 7.0 inches. The CCVA estimates that the 25-year, 48-hour event will increase from 7.0 to 8.6 inches by the 2030s and to 9.8 inches by the 2070s (City of Cambridge 2015). These estimates represent increases of 23 and 40 percent over the historical baseline, respectively. Regarding an assessment of exposure, any stations that have historically experienced inland flooding are likely to experience it in the future, absent any interventions. Sensitivities of assets and services to heavy precipitation and inland flooding are provided in Exhibit 5, below.

Exhibit 5. Asset Sensitivities to Heavy Precipitation and Inland Flooding (Source: Climate Change Sensitivity Matrix (FHWA 2015), except where noted)

Asset	Sensitivities and Thresholds
Maintenance Facility and Storage Yard	Inundation, rendering facility inaccessible. Possibility of damage from debris.
Track, third rail, and guard rails	In electrified transit systems, there is the risk of flooding reaching the third rail if sump pumps and drainage systems are unable to keep up with the precipitation rate. This prevents the third rail from supplying electricity to trains, but will not necessarily cause permanent damage to rail unless shorting occurs.
Tunnel	Flooding may limit access. General guidance is that 2.5 inches of rain in a 24 hour period can result in overflow of sewers, which may flood subway stations and other infrastructure.
Rail Ties, Ballast, Sub-Ballast	Track stability may decrease if supporting earthen structures, ballast, and bridges are damaged from moving water.
Electrical and Communications Equipment (including substations, signals, switches, switch heaters, and crossings)	Temporary or permanent damage due to water exposure is possible. Extent of impact is dependent on the availability of replacement components and the time required to repair or replace components.
Sump Pump, Drainage	Sump pumps and drainage can become overwhelmed by heavy precipitation and unable to properly keep tunnels and the ROW clear of water.
HVAC/ Ventilation/ Tunnel Fans	Flooding or precipitation-related disruption of electrical supply may prevent proper functioning of tunnel ventilation systems.
Station (Building)	Inundation, rendering facility inaccessible. Possibility of damage from debris.
Catenary Lines and Poles	Flood and debris damage to poles is possible, resulting in temporary electricity disruption to lines.
Trains	Inundation of electrical components including engine can cause irreparable damage. Several inches of flooding can short out locomotive motors.
Operations, Maintenance, and Safety	Flooded tracks can interfere with operations due to impassability and can also interfere with operations by affecting the electrical systems on the tracks themselves (or signaling equipment, posing safety hazards). This may lead to temporary or long-term operational interruptions, dependent on extent of damage. Heavy precipitation conditions can result in train speed reductions. It is also possible that train conductors will miss signals because of limited visibility from rain. Employees may have difficulty getting to work in heavy precipitation conditions.

3.1.3. Sea-level Rise and Storm Surge

Unlike extreme heat events, the potential exposure of each Blue Line asset to sea-level rise and storm surge varies by location and by timeframe (current, 2030s, or 2070s). The MBTA has estimated exposure for each asset based on the Boston Harbor-Flood Risk Model (BH-FRM)

(MassDOT 2015). Per the guidance provided by the BH-FRM maps, the exposure potential for a 0.1 percent storm surge event (i.e., a storm like 2012's Superstorm Sandy at high tide) for the Maverick-Airport Portal, electrical substations, passenger stations, and the Orient Heights Maintenance & Storage Facility is presented in Exhibit 6 below. Maps displaying inundation probability and potential depth for 2030 and 2070 are provided in Appendix A.

Exhibit 6. Asset Exposure to 0.1% Storm (Red shading indicates current exposure; orange indicates exposure by the 2030s)

Asset	Exposure to 0.1% Storm
Bowdoin Station and Storage Yard	
Government Center Station	
State Station	
Aquarium Station and Electrical Substation	
Maverick Station	
Maverick-Airport Portal	
Airport Station and Electrical Substation	
Wood Island Station	
Orient Heights Station and Electrical Substation	
Orient Heights Maintenance & Storage Facility	
Suffolk Downs Station	
Beachmont Station	
Revere Beach Station	
Wonderland Station, Electrical Substation, and Storage Yard	

Exposure for below-ground passenger stations refers to the exposure at the Maverick-Airport Portal, through which water could travel to stations west of the portal, at the surface-level station entry, or the surface-level ventilation grates. Additionally, Aquarium Station is currently exposed to brackish or saline groundwater at the mezzanine and platform levels via ventilation louvres and cracks in tunnel superstructures. The water table at a nearby monitoring well (at India and Milk Streets) is only three to four feet below the ground in that area of Boston, so most of the station is below the water table (Boston Groundwater Trust 2016). As the station is consistently exposed to groundwater, the MBTA designed the station with a slurry wall and drainage trough system in place, shown in Exhibit 8. The trough runs between the station walls and the slurry wall and carries away a nearly-constant supply of water away from the station. For station assets behind the walls, exposure to saltwater appears to have led to corrosion. In Exhibit 7, evidence of such exposure is visible. The consequences and extent of the impacts are unknown.

Exhibit 7. Visible Evidence of Exposure to Saltwater at Aquarium Station.

The MBTA's Engineering and Maintenance (E&M) staff routinely work to limit water's entry into the station, but keeping it out completely has not yet been possible. For example, the E&M staff has designed a temporary system for diverting saltwater away from the third rail just inside the tunnel at Aquarium Station, as shown in Exhibit 9 (wood panels diverting the leak are circled). This type of solution addresses the problem successfully in the short-term, but will ultimately require a longer-term solution that incorporates increasing volumes of water due to rising sea-level. The amount of water increases with the height of the tide, as the groundwater is tidally-influenced.

Exhibit 8. Drainage Trough and Pump at Aquarium Station

For above-ground stations (those east of Maverick), exposure is determined by the station elevation and the height of critical components at each station. It is noted as an exception that the tracks and platform of Beachmont Station are elevated; the tracks are approximately 20 feet above grade (33 feet above sea-level), but many components critical to the functioning of the station (e.g., communications, electrical equipment) are only slightly above grade level. During a survey of station assets that could be exposed to coastal inundation, the MBTA noted at multiple stations that generators, battery packs, communications equipment, and other electronics are often kept at grade-level. Example images of observed assets are provided in Exhibit 10. Facility and station features that are likely to be exposed to coastal inundation from a 0.1% storm, based on their elevations and the projected flood depth at each location, are provided in Exhibit 11.

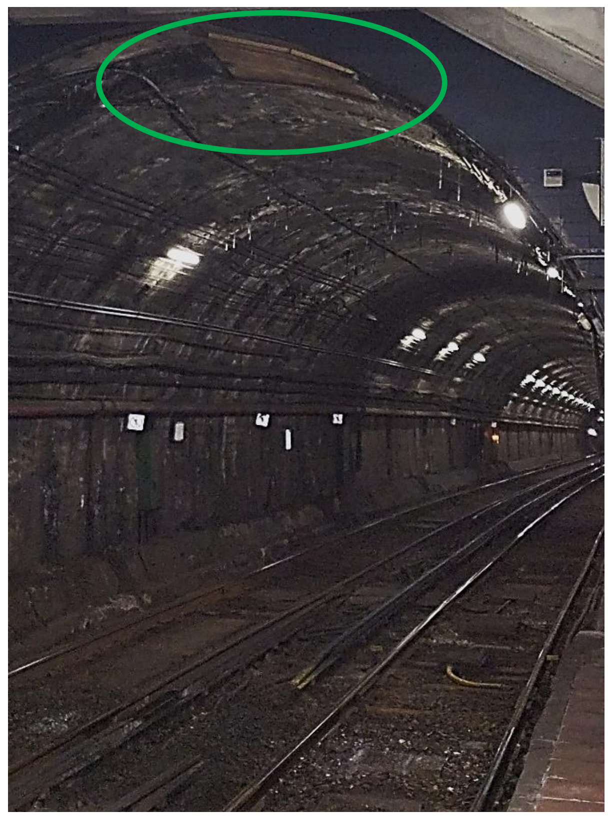
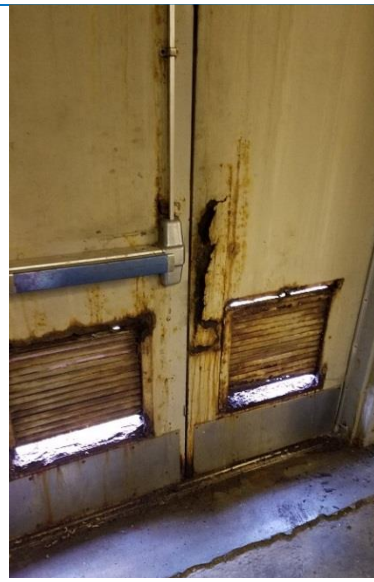


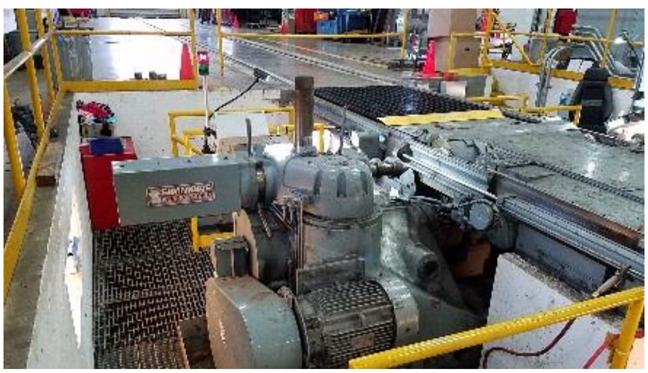
Exhibit 9. Temporary Diversion for Water Entering Tunnel at Aquarium Station.

Communications Room, Suffolk Downs Station



Generator Room Exterior Door, Suffolk Downs Station

Hydraulics Equipment, Orient Heights Maintenance and Storage Facility



Wheel Truing Machine (Below Grade), Orient Heights Maintenance and Storage Facility

Communications Cables, Airport Station

Emergency Battery System Packs, Wood Island Station

Exhibit 10. Example Images of Station Assets Potentially Exposed to Coastal Flooding

Exhibit 11. Exposure to Storm Surge, Sea-Level Rise, or Tide-Influenced Groundwater at Blue Line Facilities

Exposed Assets, by Facility		
Underground Stations		
Bowdoin Station and Storage Yard	Government Center Station	State Station
Track	Track	Track
Third Rail	Third Rail	Third Rail
Platform	Platform	Platform
Escalator Pit	Escalator Pit	Deep Sump Pit
Automated Fare Collection	Automated Fare Collection	Elevator Pit
Switch Room	Switch Room	Automated Fare Collection
Generator and Electric Room	Generator and Electric Room	Bathrooms
Vault Room	Bathrooms	Stair Landing
Bathrooms	Escalator	Elevator Machine Room
Escalator	Elevator	HVAC Systems
Elevator	Stair Landing	Pump Room
Stair Landing	Elevator Machine Room	Communications and Electrical Conduits
Elevator Machine Room	Glass Station Headhouse on City Plaza	Fan Room
Concrete Station Headhouse on Cambridge Street		Accessible Station Entrances at Old State House, 53 State Street, and 60 State Street

Aquarium Station and Electrical Substation	Maverick Station
Track	Track
Third Rail	Third Rail
Platform	Platform
Emergency Egress Door	Sewage Ejector
Louvres at Platform Level	Sewage Ejection Pit
Elevator Pits	Pipe Tunnel
Escalator Drains, Sump Pumps, and Oil/Water Separators	Signal Room
Generator and Electric Room	Automated Fare Collection
Fan Room	Bathrooms
Fire Pump Room	Escalator, Elevator, and Stair Landings
Steam Line/ Vault	Motor Control Room
Trench Drain	Emergency Electric
24" Drain Line	In-Station Electrical Substation Room
8" Sewer Line	Fire Department Panels and Police Call Box
Southwest Headhouse on State Street	Glass Station Headhouse
Station Entrances on State Street and Glass Station Headhouse at Long Wharf	

Exposed Assets, by Facility		
Above-ground Stations		
Airport Station and Electrical Substation (Max Inundation 10 feet)	Wood Island Station (Max Inundation 4.5 feet)	Orient Heights Station and Electrical Substation (Max Inundation 4.5 feet)
Gas Meter	4" Sanitary Sewer Line Invert	Elevator Pits
Elevator Pits	8" Rainwater Invert	Track
Track	4" Sanitary Sewer to Gasoline and Sand Traps	Escalator Pits
Beginning of Third Rail	Escalator and Elevator Pits	Platform
Escalator Pits	Track	4,500 Gallon Oil Tanks at Retired Transformers
Platform	Platform	Generator and Electric Room, Including Battery Packs just above Grade Level
Communications Rooms	Automated Fare Collection	Elevator Machine Room
Fire Alarm Control Panel and Fire Pump Room	Generator and Electric Room	Escalator, Elevator, and Stair Landings
Generator and Electric Room	Bathrooms	Train Operations Building, 1st Floor
Electrical Substation	Gas Meter	Passenger Emergency Call Box
Automatic Fare Collection	Escalator, Elevator, and Stair Landings	Gas Meter
Bathrooms	Ventilation Louvres	Bathrooms
Escalator, Elevator, and Stair Landings	Catenary System	Catenary System
Glass Walls, Mullions		
Split System Heat Pumps		
Catenary System		

Orient Heights Maintenance and Storage Facility (Max Inundation 4.5 feet)	Suffolk Downs Station (Max Inundation 4 feet)	Beachmont Station (Max Inundation 4.5 feet)
Train Wash Sewage Ejector Pit	Track	Elevator Pit
Sump Pump	Platform	Escalator Pit
Wheel Truing Machine	Generator and Electric Room, Including Battery Packs just above Grade Level	Signal Room
Oil Separator	Operations Call Center Phone	Generator and Electric Room
Water Line	Gas Blower	Escalator, Elevator, and Stair Landings
8" Sewer Line	Automated Fare Collection	Vendor Storage Room
Pit Floor	Emergency Call Box	Bathrooms
8" Gas Line	Bathrooms	Safe Room
Train Wash Drain Trench	Safe Room	Lamp Storage
Train Wash Water Recycling System	Catenary System	
Water Main Valve		
Fire Hydrant		
Oil Storage Tanks		
Sewer Pump Station, Paint Prep, Small Parts Storage, Electrical Closet, Extended Repair Shop, Oil Storage, Extended Car Wash, Bathrooms, Compressor Room		

Revere Beach Station (Max Inundation Unk., Assuming 4.5 feet)	Wonderland Station, Electrical Substation, and Storage Yard (Max Inundation Unk., Assuming 4.5 feet)
Track	Track
Platform	Elevator Pits
Elevator Pits	Platform
Elevator Machine Room	Elevator Machine Room
Elevator and Stair Landings	Elevator and Stair Landings
Generator and Electric Room, Including Battery Packs just above Grade Level	Generator and Electric Room, Including Battery Packs just above Grade Level
Switchgear Rooms	Operations Call Center Phone
Communications Room	Emergency Call Box
Sand Storage	Circuit Box
Offices, including Electronics	Junction Box
Porter Room	Bathrooms
Automated Fare Collection	Office, including Electronics
	Communications Room
	Signal Room
	Fire Panel
	Automated Fare Collection

Of the climate stressors analyzed in this vulnerability assessment, the sensitivities of transportation assets to sea-level rise and storm surge would likely be the most consequential for the MBTA. Exposure to salt water can have lasting impacts beyond the inundation event itself due to the long-term "latent" damage to metal infrastructure (e.g., tracks or third rail) and electrical systems from corrosive seawater. Any metals exposed to salt water are at risk of corrosion, even if the actual inundation is a short-lived event. To illustrate, inundation of New York's subways tunnels with salt water as a result of 2012's Superstorm Sandy led to extensive corrosive damage. The Canarsie Tunnel, shown in Exhibit 12, must be entirely reconstructed as a result of the damage left behind by the millions of gallons of salt water that entered the tunnel. Both tubes in the tunnel will be closed for 18 months, starting in 2019 (MTA 2016).

Exhibit 12. Corrosion in New York's Canarsie Tunnel after Flooding from Superstorm Sandy (Source: MTA 2016)

Sensitivities of assets and services to heavy precipitation and inland flooding are provided in Exhibit 13, below.

Exhibit 13. Asset Sensitivities to Sea-level Rise and Storm Surge (Source: Climate Change Sensitivity Matrix (FHWA 2015), except where noted)

Asset	Sensitivities and Thresholds
Maintenance Facility and Storage Yard	Inundation of facility, damaging or destroying contents (records, electrical). Exposure to saltwater would destroy sophisticated electronic equipment, such as wheel truing machines.
Track, third rail, and guard rails	Track stability may decrease if supporting earthen structures, ballast, and bridges are damaged from moving water. Exposure to salt water may corrode track (FHWA 2014). Rail base corrosion can occur when water becomes trapped between the flange base and tie plate–the rate of corrosion may be accelerated if electrical current moves through the track into the underlying ground. Similarly, normal fatigue loads that generate cracks in track provide space for water intrusion in flooding, or even precipitation, events. Corrosion that occurs in such cracks significantly reduces track strength (FRA 2014).
Tunnel	Flooding will render tunnels unusable.

Asset	Sensitivities and Thresholds
Rail Ties, Ballast, Sub-Ballast	Ballast and sub-ballast destruction due to storm surge and wave action is possible. The amount of destruction is dependent on ballast material and severity of surge. Wave action can strip the rail, ties, and ballast off of railroad bridges and off coastal area rail lines if they are exposed.
Electrical and Communications Equipment (including substations, signals, switches, switch heaters, and crossings)	Inundation can cause rail sensor failure, as well as other electrical failures (switches, gates, signals). There are also potential corrosive damages from salt. For example, metal and electrical components exposed to salt water from Hurricane Sandy are experiencing accelerated corrosion. MTA has seen long term deterioration of small gauge electrical connections (MTA, 2017).
Sump Pump, Drainage	May be overwhelmed by amount of inundation. Clogging with debris is possible.
HVAC/ Ventilation/ Tunnel Fans	Subsurface ventilation systems could be inundated in flooding event. Possibility of corrosion if exposed to salt water.
Bridge (including Pedestrian Bridge) or Culvert; Surface Parking Lots	Waves stress both the superstructure and the substructure of bridges, particularly when wave crests directly hit the bridge superstructure. Storm surge can wash large pieces of debris, such as cars, into bridges, damaging bridge components such as the girders, piers, bent caps, and bridge parapets. In addition, storm surge can erode the bridge piers over time, as waves hit the pier and then are channeled down to the pier's base. Flooded surface parking lots and garages are inaccessible. After a flood event, they may be covered with debris. Long-term damage is possible if large, heavy debris compromise critical structural components.
Station (Building)	Earthen support for station structures may erode, reducing the foundation's stability. In cases for which water enters buildings, the structural integrity may remain but flooding can require temporary closures due to clean-up and interior rebuilding.
Catenary Lines and Poles	In flooding events, catenary poles may be damaged by debris carried in the water. Additionally, moving water may damage earthen supports for poles. If any catenary lines are exposed to saltwater, they may experience corrosion.
Trains	Exposure to wave action can topple or derail vehicles. Inundation of electrical components including engine can cause irreparable damage.
Operations, Maintenance, and Safety	Inaccessibility of stations, maintenance facilities, and tunnels due to flooding can shut down operations and maintenance activities.

3.1.4. Snow and Ice

Although access to all stations could be affected during snow and ice events, the primary exposure occurs at above-ground stations (Maverick to Wonderland). As experienced during prior heavy winter events, such as during the winter of 2015, snow may limit station and track access, while ice can affect catenary lines anywhere they are exposed outside of station cover. More broadly, the MBTA can be indirectly exposed to the impacts of snow and ice by regional impacts to the electrical grid, such as ice damage to power lines. Although the Boston region is projected to experience increasingly-warmer winters, as temperatures hover more closely to the freezing line, it's possible that damaging ice events may become more frequent than the historical average. Additionally, according to the BRAG report (2016), though the overall annual snowfall amount is project to decrease, individual snow events will continue and could be more intense than the historical average/ than large snow events.

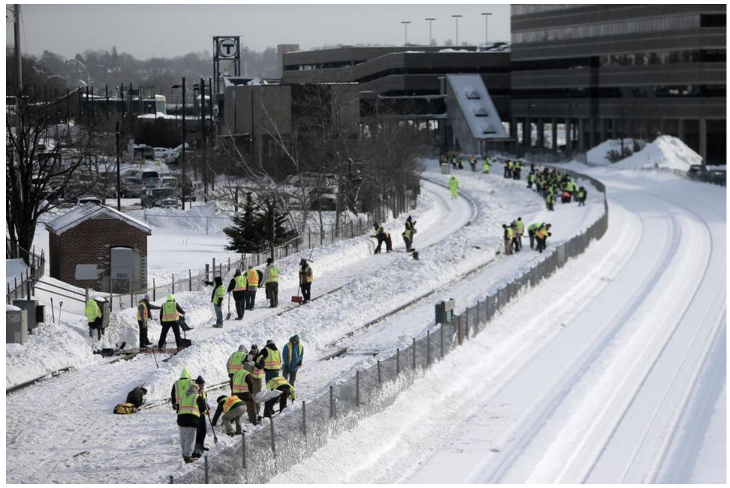


Exhibit 14. Track Snow Removal, Winter 2015 (Source: Boston Globe 2015)

Sensitivities of assets and services to snow and ice are provided in Exhibit 15.

Exhibit 15. Asset Sensitivities to Snow and Ice (Source: Climate Change Sensitivity Matrix (FHWA 2015), except where noted)

Asset	Sensitivities and Thresholds
Maintenance Facility and Storage Yard	Snow and ice can limit access to facility via roads and tracks.
Track, third rail, and guard rails	Cold temperatures lead to track that is more brittle, increasing risk of breakage and separation. Additionally, the expansion of ice in between track sections may cause separation. The accumulation of snow on track is not a significant direct physical stressor, but it may disrupt normal service. Increased icing can reduced traction on rails, interfering with the ability to both operate at higher speeds and to also brake as expected. Rail seat deterioration (RSD) is linked in part to freeze-thaw cycling, due to the expansion of freezing water, as well as the flow of water during freezing.
Tunnel	None.
Rail Ties, Ballast, Sub-Ballast	Frost heaves possible from water within a gravel ballast freezing and expanding. Similarly, concrete ballast, may destabilize if ice enters cracks and expands. Additionally, if snow and ice accumulate on top of the ballast, the underpressure of the passing train may pick up the compacted snow, ice, and gravel (sail-effect), destabilizing the track bed and potentially causing damage to trains (Transrail, 2006).

Asset	Sensitivities and Thresholds
Electrical and Communications Equipment (including substations, signals, switches, switch heaters, and crossings)	Increased icing can damage any exposed equipment. Switches can malfunction or fail when covered by snow and ice. Switch heaters limit this sensitivity.
Sump Pump, Drainage	Drainage systems may become clogged with ice and snow, leading to localized flooding.
HVAC/ Ventilation/ Tunnel Fans	None.
Bridge (including Pedestrian Bridge) or Culvert; Surface Parking Lots	Snow and ice conditions can render bridges and parking lots inaccessible. Bridges freeze earlier than the ground and are likelier to be ice and snow covered than other areas.
Station (Building)	Snow and ice may limit station access.
Catenary Lines and Poles	Icing may limit transmission of electricity from catenary lines to traction systems. Catenary lines may also break due to ice loading.
Trains	In cold conditions with dry, light snow, fine particles of snow that are kicked up during passage of a train can accumulate in air intakes, bogies, and disc brakes. In conditions of melting and re-freezing, bogies can become clogged with ice and dense snow (Transrail 2006).
Operations, Maintenance, and Safety	Increased icing can interfere with ability of trains to travel at higher speeds and also to brake as expected. Heavy snows can limit normal operations and maintenance activities.

3.1.5. Wind

There are no reliable projections of storm intensity and frequency in the future. However, the MBTA currently experiences occasional wind damage to assets due to heavy storms and understands that damaging winds can occur during spring or summer straight-line wind events, small tornadoes, nor'easters, or tropical storms. Direct, wind-related, damages can occur to any exposed asset. Indirectly, impacts could be experienced due to power interruptions that affect both above- and below-ground stations and facilities. On the Blue Line, the primary exposure occurs at above-ground stations (Airport to Wonderland).

Sensitivities of assets and services to wind are provided in Exhibit 16, below.

Exhibit 16. Asset Sensitivities to Wind (Source: Climate Change Sensitivity Matrix (FHWA 2015), except where noted)

Asset	Sensitivities and Thresholds
Maintenance Facility and Storage Yard	Facility roof could be weakened if wind exceeds thresholds. Building could be damaged by flying debris.
Track, third rail, and guard rails	Fallen trees or other debris may block access or damage track.
Tunnel	None.
Rail Ties, Ballast, Sub-Ballast	Fallen trees or other debris may block access or damage track bed.

Asset	Sensitivities and Thresholds
Electrical and Communications Equipment (including substations, signals, switches, switch heaters, and crossings)	Intense crosswinds in some areas from microbursts or squall lines cut the electricity needed for gates/flashers and signal bungalow operation. Signals can also be knocked over.
Sump Pump, Drainage	None.
HVAC/ Ventilation/ Tunnel Fans	None.
Bridge (including Pedestrian Bridge) or Culvert; Surface Parking Lots	Winds stress bridges with additional horizontal loading; however, bridges are designed with a wind loading factor.
Station (Building)	High wind velocities can directly damage platforms, stations and other structures. Infrastructure in wooded areas may be also be indirectly affected by falling trees and other wind-related debris (NJTC, 2012).
Catenary Lines and Poles	Trees or other debris may fall across catenary lines, disrupting services and potentially causing significant damage if poles are affected
Trains	Crosswinds can destabilize or knock over cars
Operations, Maintenance, and Safety	Intense crosswinds in some areas from microbursts or squall lines can disrupt or halt service. Winds (head, cross, or tail) ≥ 50 mph can disrupt service due to slowed travel or obstructions affecting rail lines. High wind is one of the leading causing of rail collision; during late afternoon and evening hours, high wind is the leading cause of rail accidents. There are potential safety risks to railroad personnel (such as from rail car blow over and hazardous spills), as well, which may disrupt operations. Electrical outages due to wind can slow or completely disrupt service, especially for regional light rail that may rely on catenary lines.

4. Adaptive Capacity

To assess the adaptive capacity of the Blue Line's most sensitive, the MBTA referred to FHWA's guidance on key considerations for transportation assets:

- Is the system already able to accommodate changes in climate?
- Are there barriers to a system's ability to accommodate changes in climate?
- Is the system already stressed in ways that will limit the ability to accommodate changes in climate?
- Is the rate of projected climate change likely to be faster than the adaptability of the system?
- Are there efforts already underway to address impacts of climate change related to the system?

The MBTA did not conduct a detailed technical analysis of the adaptive capacity of each asset due to data limitations. However, utilizing the FHWA's guiding questions, the T was able to qualitatively assess adaptive capacity of the Blue Line's assets by considering information specific to our institution:

- The complexity of bringing a particular asset back "on-line";
- The MBTA's Fiscal Year (FY) 2016 capital investment plan (CIP);
- Institutional understanding of the data, fiscal, and political barriers to accommodate changes in climate;
- Existing non-climate stressors, such as the State of Good Repair (SGR) backlog (depicting asset ages and intended lifetimes) and competing demands for management attention and funding; and
- A new focus at the MBTA on climate resiliency

The relative adaptive capacities of the Blue Line's assets are provided in Exhibit 17. Adaptive capacities are categorized as *Low* (Red), *Medium* (Yellow), and *High* (Green). Low adaptive capacity indicates that an asset would be harder to restore to normal service; similarly, high adaptive capacity indicates that an asset would be easier to restore to normal service.

Exhibit 17. Adaptive Capacities of Blue Line Assets

Asset	Adaptive Capacity
Bowdoin Yard	
Bowdoin Station	
Government Center Station	
State Station	
Aquarium Station	
Aquarium Substation	
Tunnel under Boston Harbor	
Maverick Station	
Maverick-Airport Portal	
Airport Substation	
Airport Station	
Prescott Tube	
Wood Island Station	
Byron Street Overhead Bridge	
Trident Street Overhead Pedestrian Bridge	
Saratoga Street Overhead Bridge	
Orient Heights Substation	
Orient Heights Station	
Orient Heights Facility	
Bennington Street Overhead Bridge	
Suffolk Downs Station	
Belle Isle Inlet Undergrade Bridge	
Beachmont Station	
Winthrop Avenue Undergrade Bridge	
Revere Beach Parkway Overhead Bridge	
West Street Overhead Pedestrian Bridge	
Shirley Avenue Overhead Bridge	
Revere Beach Station	

Beach Street Overhead Bridge	Green
Wonderland Station	Red
Wonderland Substation	Red
Wonderland Yard	Yellow

5. Summary of Vulnerabilities

The MBTA reviewed the current and projected exposure, sensitivity, and adaptive capacity of Blue Line assets to heat; heavy precipitation and inland flooding; sea-level rise and storm surge; snow and ice; and wind in Sections 3 and 4. To summarize those detailed analyses, Exhibit 18, provides a qualitative overview of the relative "level of concern" for exposure and sensitivity of each of the MBTA's major Blue Line assets, categorized as *Low* (Green), *Medium* (Yellow), and *High* (Red).

Exhibit 18. Vulnerabilities of Blue Line Assets to Weather and Climate Stressors

Asset	Climate/ Weather Stressor				
	Heat	Heavy Precipitation and Inland Flooding	Sea-Level Rise and Storm Surge	Snow and Ice	Wind
Bowdoin Yard	Green	Green	Yellow	Green	Green
Bowdoin Station	Green	Green	Red	Green	Green
Government Center Station	Green	Green	Red	Green	Green
State Station	Green	Green	Red	Green	Green
Aquarium Station	Green	Yellow	Red	Green	Green
Aquarium Substation	Green	Yellow	Red	Green	Green
Tunnel under Boston Harbor	Green	Green	Red	Green	Green
Maverick Station	Green	Green	Red	Green	Green
Maverick-Airport Portal	Green	Yellow	Red	Green	Green
Airport Substation	Red	Yellow	Red	Green	Green
Airport Station	Yellow	Yellow	Red	Yellow	Yellow
Prescott Tube	Green	Green	Yellow	Green	Green
Wood Island Station	Yellow	Yellow	Red	Yellow	Yellow
Byron Street Overhead Bridge	Green	Green	Yellow	Green	Green
Trident Street Overhead Pedestrian Bridge	Green	Green	Yellow	Green	Green
Saratoga Street Overhead Bridge	Green	Green	Yellow	Green	Green
Orient Heights Substation	Red	Yellow	Red	Green	Green
Orient Heights Station	Yellow	Yellow	Red	Yellow	Yellow
Orient Heights Facility	Red	Red	Red	Green	Yellow

Asset	Climate/ Weather Stressor				
	Heat	Heavy Precipitation and Inland Flooding	Sea-Level Rise and Storm Surge	Snow and Ice	Wind
Bennington Street Overhead Bridge	Green	Green	Yellow	Green	Green
Suffolk Downs Station	Yellow	Yellow	Red	Yellow	Yellow
Belle Isle Inlet Undergrade Bridge	Green	Green	Yellow	Green	Green
Beachmont Station	Yellow	Yellow	Red	Yellow	Yellow
Winthrop Avenue Undergrade Bridge	Green	Green	Yellow	Green	Green
Revere Beach Parkway Overhead Bridge	Green	Green	Yellow	Green	Green
West Street Overhead Pedestrian Bridge	Green	Green	Yellow	Green	Green
Shirley Avenue Overhead Bridge	Green	Green	Yellow	Green	Green
Revere Beach Station	Yellow	Yellow	Red	Yellow	Yellow
Beach Street Overhead Bridge	Green	Green	Yellow	Green	Green
Wonderland Station	Yellow	Yellow	Red	Yellow	Yellow
Wonderland Substation	Red	Yellow	Red	Green	Green
Wonderland Yard	Green	Yellow	Red	Yellow	Green

6. Conclusions and Next Steps

This pilot vulnerability assessment has identified critical assets and services on the Blue Line that are vulnerable to weather- and climate-related stressors. Although most assets on the line will be vulnerable by mid-century, several assets are potentially critically-vulnerable now and would benefit from additional protections over the next 1-5 years:

- Aquarium Station,
- Maverick-Airport portal, and
- Orient Heights Maintenance and Storage Facility

If these assets were exposed to coastal flooding from a Superstorm Sandy-like storm, the consequences could be the inability of the Blue Line to function, requiring a large, medium-long term mobilization of alternative transit options in order to ensure that tens of thousands of East Boston and Revere residents are able to reach medical facilities, schools, and places of employment. The MBTA will prioritize developing plans to protect these assets during Fiscal Year (FY) 2018.

More broadly-speaking, the T conducted this pilot assessment of the Blue Line as a first step toward a comprehensive, system-wide vulnerability assessment, the completion of which will allow the T to work toward a system-wide climate change resiliency plan. The MBTA regards climate change resiliency as a living process, the approach and goals for which will be iteratively updated as new information is available. The system-wide vulnerability assessment and first resiliency plan will be developed during FY 2018.

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Appendix A. Storm Surge and Sea-Level Rise Exposure on the Blue Line

Note: The 2015 BH-FRM maps cover spatial areas on the Blue Line between the Bowdoin and Beachmont Stations, so the primary Blue Line inundation maps only include those stations. Woods Hole Group provided MBTA with separate inundation probability images for the spatial area that includes the Revere Beach and Wonderland Stations, which are provided adjacent to the primary inundation probability maps for 2030 and 2070. Revere Beach Station is not labeled, but is included in the 100 percent annual inundation probability area by 2030. Potential flood depths are not yet available for Wonderland Station.

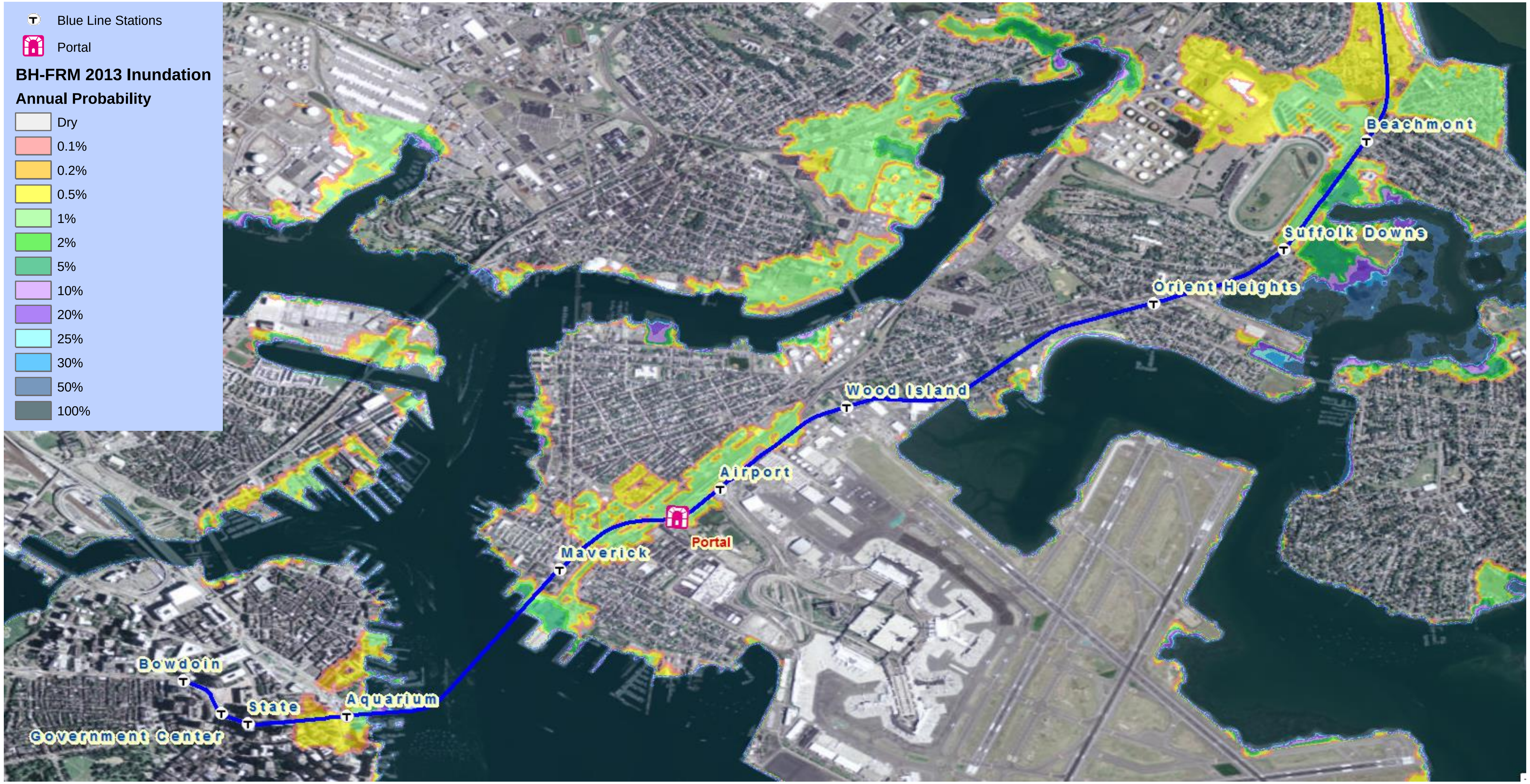

Exhibit A- 1. Current Annual Probability of Inundation (Bowdoin to Beachmont)

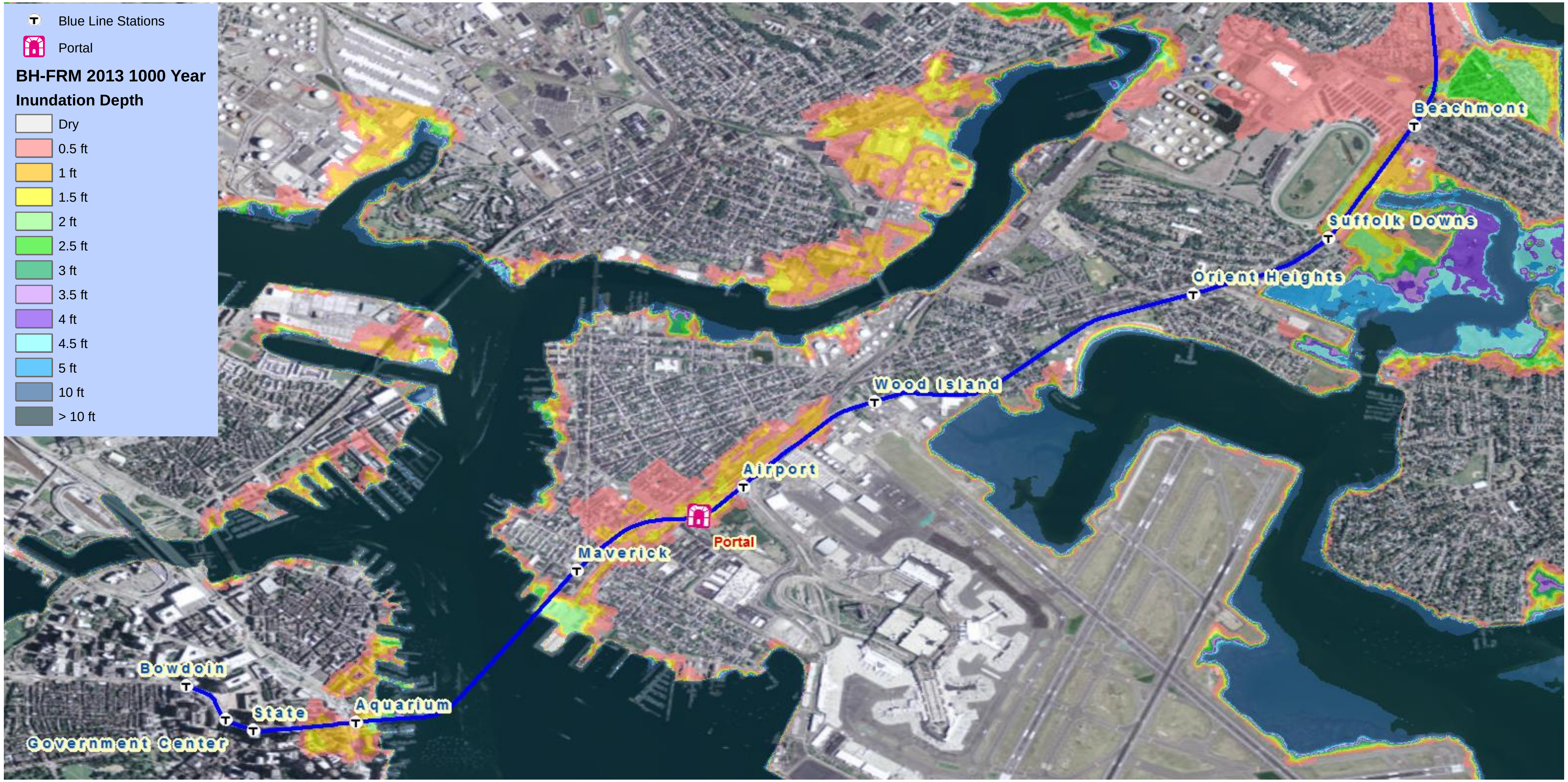

Exhibit A- 2. Current Potential Flood Depth from a 0.1% Storm (Bowdoin to Beachmont)

Exhibit A- 3. 2030 Annual Probability of Inundation

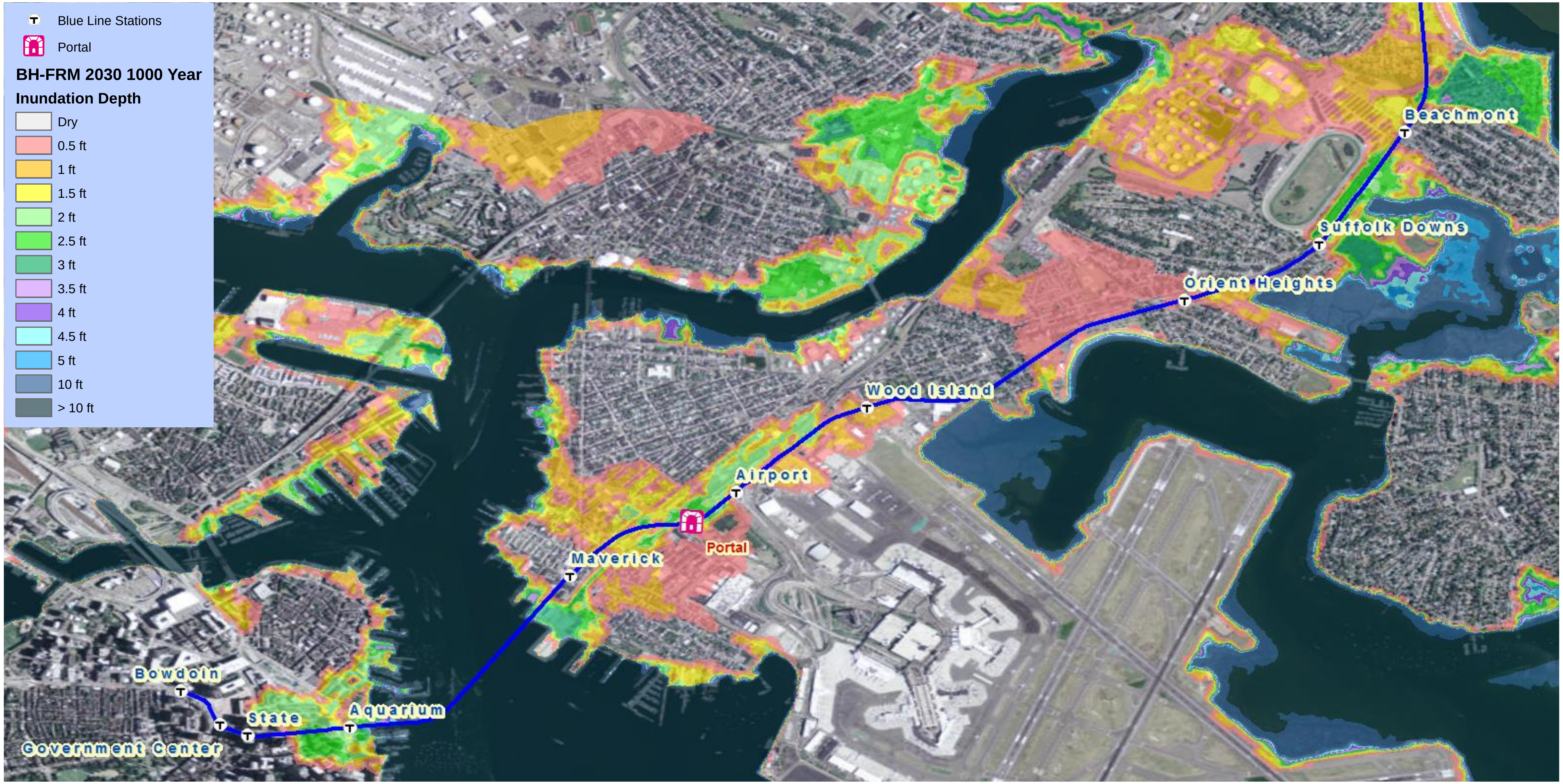

Exhibit A- 4. 2030 Potential Flood Depth from a 0.1% Storm (Bowdoin to Beachmont)

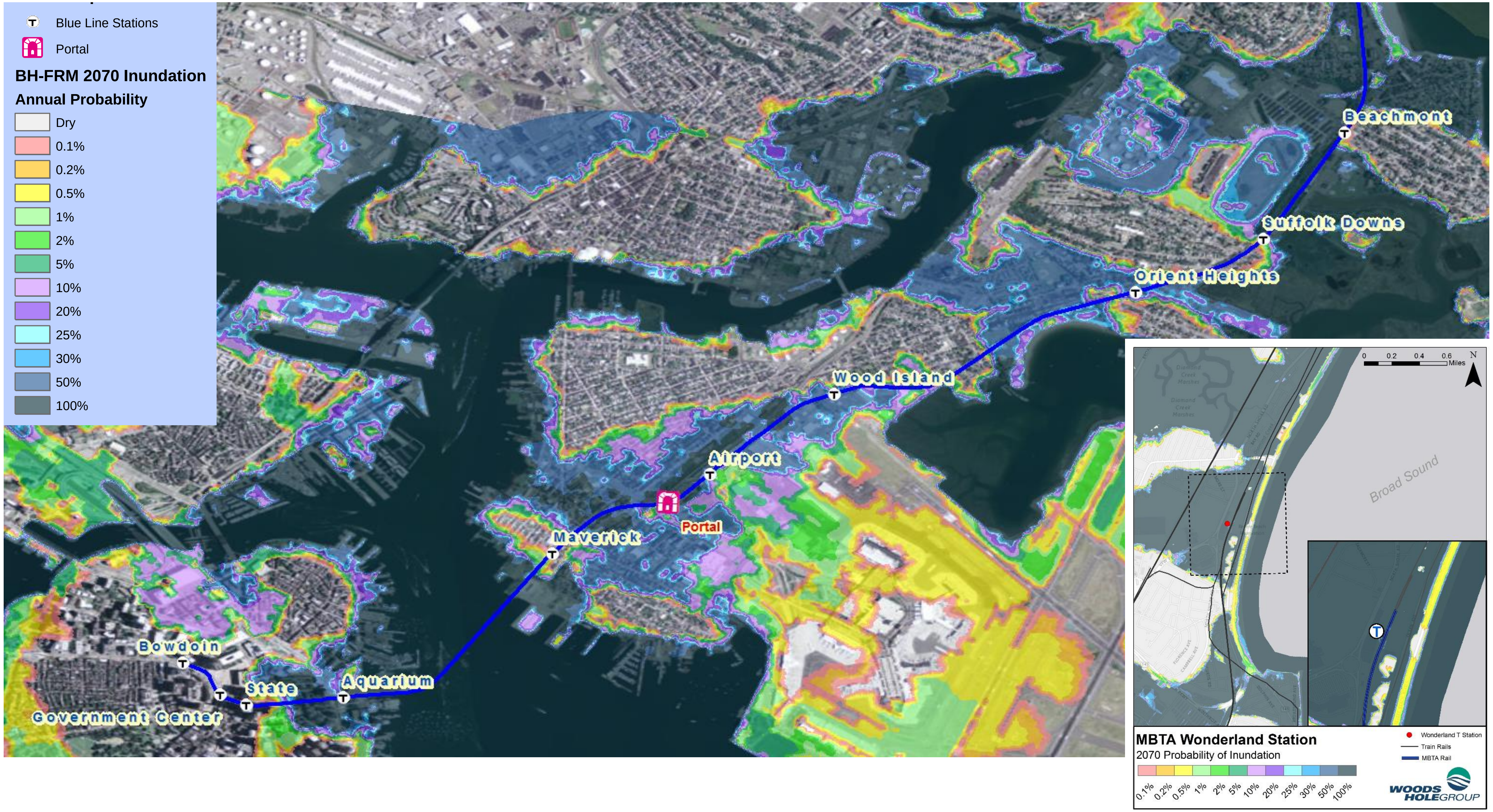

Exhibit A- 5. 2070 Annual Probability of Coastal Flooding

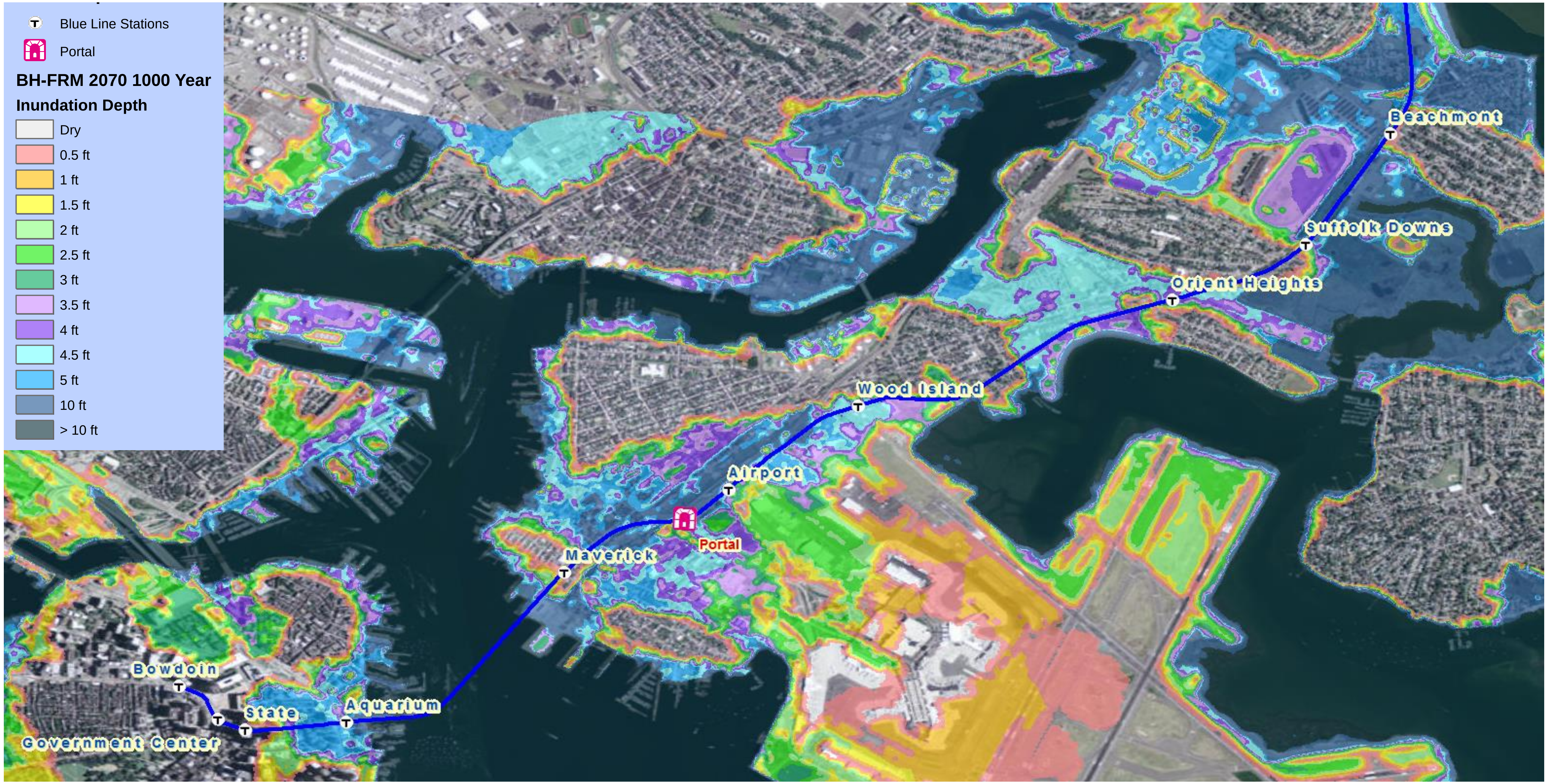

Exhibit A- 6. 2070 Potential Flood Depth from a 0.1% Storm (Bowdoin to Beachmont