MTA Maryland

Maryland Department of Transportation

Office of Planning and Programming
June 2016

Climate Change Vulnerability Assessment

Transit agencies in cities around the world are increasingly responding to disruptions in service and damage to sensitive locations and assets associated with gradual changes in climate and extreme weather events. In the face of increased frequency and intensity of extreme weather events, several public transit and transportation agencies are taking initiative to adapt their systems to make them more resilient to changing climate conditions.

The Maryland Transit Administration (MTA) Climate Change Vulnerability Assessment has been developed in response to Maryland's Climate Action Plan (2008), produced by the Maryland Climate Change Commission, and to the Climate Change and Coast Smart Construction Executive Order (2012) as well as MTA's climate change policy (**Appendix G**). **The purpose of the study is to identify MTA sensitive locations and assets that are vulnerable to three expected results of global climate change:**

1. **Sea level rise**
2. **Increased hurricane storm surge; and**
3. **Flooding due to major rain events.**

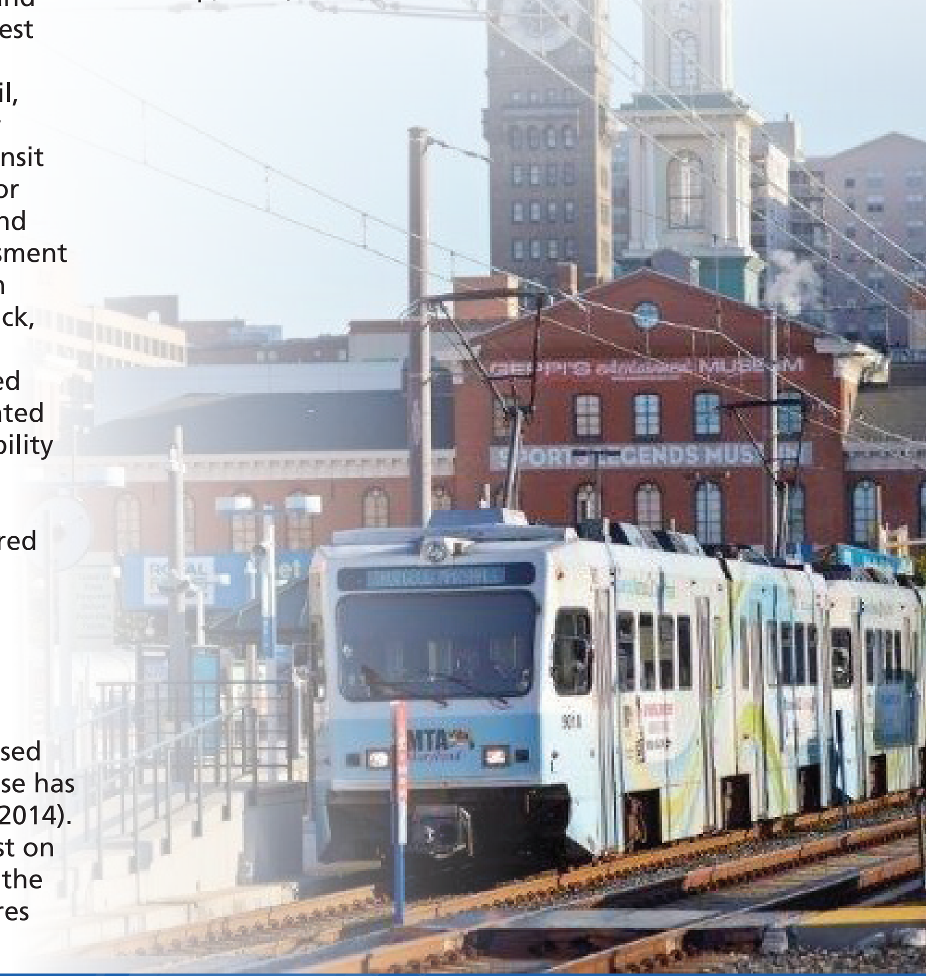
MTA is a transportation business unit of the Maryland Department of Transportation, and one of the largest multi-modal transit systems in the United States. MTA operates Local and Commuter Buses, Light Rail, Metro Subway, Maryland Area Regional Commuter (MARC) Train Service, and a comprehensive Paratransit (Mobility) system. In addition, MTA is responsible for the maintenance of freight rail lines in Maryland and Delaware. This Climate Change Vulnerability Assessment considers potential inundation of MTA assets which primarily include maintenance facilities, railway track, stations and parking lots. While bus maintenance facilities and fixed infrastructure have been included in this study Local and Express Bus routes are operated on roadways and highways which are the responsibility of the relevant County, State or Federal agency. Additionally, Bus stops are flexible and able to be altered if inundated and are therefore not considered within this assessment.

Climate Change and Transit

The average temperature across the U.S. has increased by 1.3°F to 1.9°F since 1895, and most of this increase has occurred since 1970 (National Climate Assessment, 2014). The most recent decade (2004-2014) was the hottest on record, and 2012 was the hottest year on record in the continental United States. Additionally, temperatures are projected to rise another 2°F to 4°F in most areas of the United States over the next few decades (National Climate Assessment, 2014).

Water expands as it warms, causing global sea levels to rise. Melting of land-based ice also raises sea level by adding water to the oceans. Sea level rise, combined with coastal storms, has increased the risk of erosion, storm surge damage and flooding for coastal communities (National Climate Assessment, 2014). Coastal infrastructure, including roads, rail lines and transit structures are increasingly at risk from sea level rise and damaging storm surges.

Maryland is vulnerable to sea level rise due to comprising more than 3,100 miles of tidal shoreline and low-lying topography. Historically, shorelines eroded and low-relief lands and islands were inundated largely due to subsidence, or the slow sinking of the land, since Earth's crust is still adjusting to the melting of large masses of ice following the last glacial period. Over the 20th century, however, the rate of rise of the average level of tidal waters has increased, at least partially as a result of global warming (Scientific and Technical Working Group, 2013).



Methodology

Incorporation of climate change impacts into transportation decisions is still a relatively new concept. As managers in various sectors grapple with information on climate change effects and how they may or may not impact their agency's mission(s), they are turning to existing tools and approaches for guidance. To date, three closely-related approaches are being used to help transportation managers consider and prepare for future climate impacts:

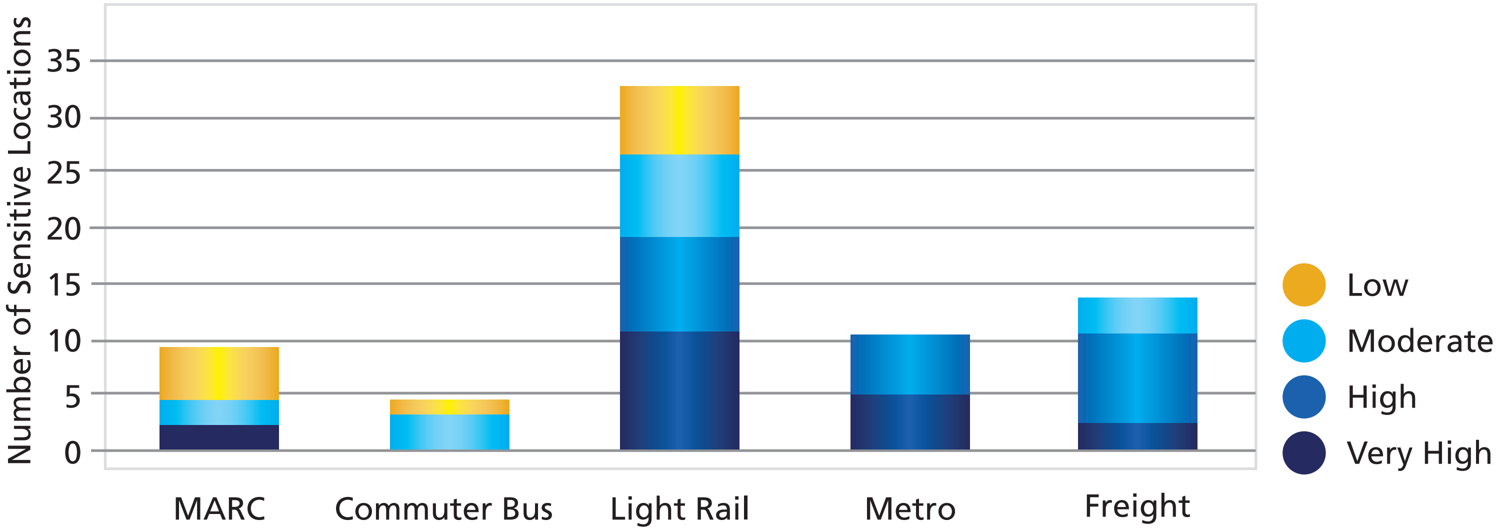
- **Site and stresser identification** begins with the identification of existing stressors facing transportation systems and projects how climate change will impact and/or introduce new stressors in the future. These stressors are then reviewed in relation to the overall transportation system to identify potentially effected sites and infrastructure.
- **Risk assessments** evaluate the likelihood and consequence of climate-related impacts on transportation. Many times this assessment will quantify the product of the probabilities of exposure, sensitivity and adaptive capacity. This assessment provides transportation policymakers with guidance based on quantitative analysis of the level of risk associated with changing climate conditions. Risk assessments are often conducted with the assistance of agency personnel most familiar with the vulnerable sites through workshops and consultation.
- **Adaptation development** identifies, plans, prioritizes, implements and measures transportation management options available for effectively adapting to climate change impacts. Adaptation development may include ways to reduce transportation vulnerability, increase resilience and/or highlight regions of retreat.

The MTA Vulnerability Assessment incorporates a risk assessment for each of the identified vulnerable sensitive locations and assets and determines which sites are high priorities and most at risk of being impacted due to sea level rise, storm surge or flooding events. A second phase of this project will identify and develop practicable adaptation measures.

Results

Seventy-five (75) sensitive locations and assets have been identified as being inundated under one or more of the three scenarios. Of these, twenty-five (25) are considered to pose a 'Very High' risk to MTA service and operations should they become inundated. Twenty-two (22) pose a 'High' risk, fifteen (15) pose a 'Moderate' risk and twelve (12) have a 'Low' risk of impacting MTA services and operations if inundated.

Figure 1. Sensitive Location and Asset Risk Ratings for each Mode



The Very High Risk Sites Include:

MARC Train and Commuter Bus	Light Rail	Metro	Freight
• Brunswick MARC Station and Maintenance Facility • Penn MARC Station • Points of Rock MARC Station	• Light Rail segment south of Timonium Business Park Station (0.12 miles) • Timonium Business Park Light Rail Station • Light Rail segment between Mount Washington and Cold Spring (1.8 miles) • Light Rail segment north of Westport Station (0.28-0.48 miles) • Nursery Road Light Rail Station • Mount Washington Light Rail Station • Track at Cold Spring Light Rail Station • Cold Spring Light Rail Station • Bridge near Nursery Road Light Rail Station • Light Rail segment between Linthicum and BWI Stations (0.13 miles) • Track at the Mount Washington Light Rail Station • Light Rail segment south of Cold Spring Station (0.4 miles) • Hamburg Light Rail Station • Control Instrument Housing at Hamburg Light Rail Station	• Substation at Owings Mills Metro Station • Aerial Structure at Owings Mills Metro Station • Substation at Shot Tower Market Place Metro Station • Shot Tower Market Place Metro Station • Gold Street Metro Pumping Station (Metro tunnel low point) • Pumps at Shot Tower Market Place Metro Station	• Edmonds Creek Bridge on the Massey/ Centreville Freight Line • Bridge over Marshyhope River on the Seaford/ Cambridge Freight Line No Bus or Mobility Maintenance Facilities have been identified as being at risk of inundation

Table of Contents

List of Tables

APPENDICES

List of Figures

1. Introduction

Transit agencies in cities around the world are increasingly responding to disruptions in service and damage to sensitive locations and assets associated with gradual changes in climate and extreme weather events. In the face of increased frequency and intensity of extreme weather events, several public transit and other transportation agencies are taking the initiative to adapt their systems to make them more resilient to changing climate conditions. A growing number of public transit agencies have identified their vulnerable sensitive locations and assets and are prioritizing improvements to develop a more robust and resilient system. As a result, they will be in a better position to withstand climate hazards while providing cost-effective service to their customers.

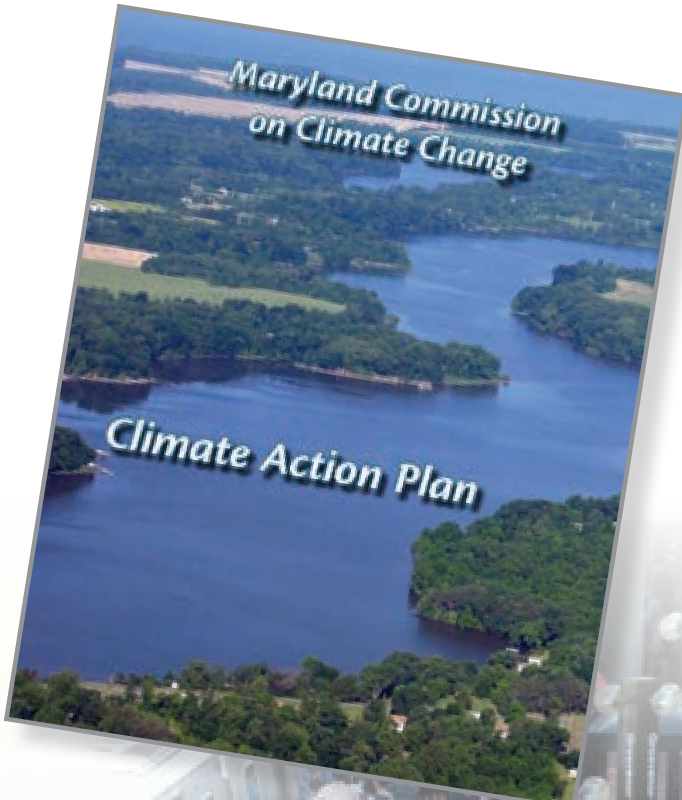
The Maryland Transit Administration (MTA) Climate Change Vulnerability Assessment has been developed in response to Maryland's Climate Action Plan (2008), produced by the Maryland Climate Change Commission, and to the Climate Change and Coast Smart Construction Executive Order (2012) as well as MTA's climate change policy (Appendix G). The purpose of the study is to identify MTA sensitive locations and assets that are vulnerable to three expected results of global climate change: sea level rise; increased hurricane storm surge; and flooding due to major rain events. The information contained in this report will be used to inform planning decisions when determining which sites and sensitive locations and assets require investment to reduce the likelihood or consequence of potential inundation and impair MTA from providing services.

1.1 Policy

In 2007, the Maryland Commission on Climate Change (MCCC) was launched, charting Maryland's course as a national leader on climate science, carbon mitigation and climate change adaptation. A key component of the State's Climate Action Plan is the Adaptation Strategy which details the actions necessary to protect Maryland's environmental heritage, public safety and future economic well-being from the impacts of climate change. This includes a recommendation for all Maryland state agencies affected by issues of climate change induced sea level rise to develop adaptation measures for implementation and monitoring.

In addition to planning for future impacts to MTA sensitive locations and assets, the Climate Change Vulnerability Assessment project will meet the requirements of MTA's Policy on Incorporating Climate Change and Sea Level Rise Information into the Maryland Transit Administration's (MTA) Capital Planning Process – 2010 (Appendix G). This policy states that MTA will:

- Address the siting and design of all capital planning and infrastructure projects in areas vulnerable to sea level rise or increased storm surge
- Evaluate existing MTA owned infrastructure on the vulnerability to sea level rise and storm inundation
- Develop adaptation measures to address infrastructure vulnerability



1.2 Climate Science

The average temperature across the U.S. has increased by 1.3°F to 1.9°F in total since 1895, and most of this increase has occurred since 1970 (National Climate Assessment, 2014). The most recent decade was the hottest on record, and 2012 was the hottest year on record in the continental United States. Additionally, temperatures are projected to rise another 2°F to 4°F in most areas of the United States over the next few decades (National Climate Assessment, 2014). Water expands as it warms, causing global sea levels to rise; melting of land-based ice also raises sea level by adding water to the oceans. Over the past century, global average sea level has risen by about 8 inches. Sea level rise, combined with coastal storms, has increased the risk of erosion, storm surge damage and flooding for coastal communities, especially along the Gulf Coast, the Atlantic seaboard and in Alaska (National Climate Assessment, 2014). Coastal infrastructure, including roads, rail lines and transit structures are increasingly at risk from sea level rise and damaging storm surges.

Maryland is particularly vulnerable to sea level rise due to more than 3,100 miles of tidal shoreline and low-lying topography. Historically, shorelines eroded and low-relief lands and islands were inundated largely due to subsidence, or the slow sinking of the land since Earth's crust is still adjusting to the melting of large masses of ice following the last glacial period. Over the 20th century, however, the rate of rise of the average level of tidal waters has increased, at least partially as a result of global warming (Scientific and Technical Working Group, 2013).

Figure 2 provides the Maryland Commission on Climate Change prediction of sea level rise for the State by 2050 and 2100 in comparison to the predicted global sea level rise.

Potential impacts will vary, but all regions and public transportation systems will be affected by climate change. The most disruptive near-term impact is likely to be intense, high velocity rainfall and storm surge that floods underground tunnels and low-lying facilities, bus lots and rights-of-way. Heat waves will stress materials, buckle rails, and jeopardize customer and worker safety and comfort. In the longer term, rising sea-levels, compounded by worsening storm surges, will threaten assets in many coastal areas.

The increased frequency of extreme events, including severe storms, will be more challenging to manage than gradual effects, such as a steady rise in average temperatures and sea levels.

Figure 2. Global and Maryland Sea Level Rise Predictions[1]

Global Mean Sea-level Rise (National Research Council 2012)	Thermal (m)	Glaciers (m)	Greenland (m)	Antarctica (m)	GMSL Rise	
					meters	feet
2050 best	**0.10**	**0.06**	**0.06**	**0.07**	**0.3**	**0.9**
2050 low	0.04	0.05	0.04	0.03	0.2	0.6
2050 high	0.19	0.07	0.10	0.13	0.5	1.6
2100 best	**0.24**	**0.14**	**0.20**	**0.24**	**0.8**	**2.7**
2100 low	0.10	0.13	0.15	0.08	0.5	1.7
2100 high	0.46	0.19	0.34	0.48	1.4	4.6

Maryland Relative Sea-level Rise	Thermal (m)	Glaciers (m)	Greenland (m)	Antarctica (m)	Dynamic (m)	VLM* (m)	Relative SLR	
							meters	feet
2050 best	**0.10**	**0.05**	**0.03**	**0.09**	**0.09**	**0.075**	**0.4**	**1.4**
2050 low	0.04	0.05	0.02	0.04	0.07	0.065	0.3	0.9
2050 high	0.19	0.06	0.05	0.16	0.10	0.085	0.7	2.1
2100 best	**0.24**	**0.13**	**0.10**	**0.30**	**0.17**	**0.15**	**1.1**	**3.7**
2100 low	0.10	0.12	0.08	0.10	0.13	0.13	0.7	2.1
2100 high	0.46	0.17	0.17	0.58	0.19	0.17	1.7	5.7
Land ice change fingerprint scale factors		0.9	0.5	1.25				

** Vertical Land Movement (VLM)*

[1] Scientific and Technical Working Group; Maryland Climate Change Commission (2013). Updating Maryland's Sea Level Rise Predictions, 2013.

1.3 Transportation Agencies and Vulnerability Assessments

The Federal Highway Administration (FHWA) published the Climate Change and Extreme Weather Vulnerability Assessment Framework in December 2012, which provides a guide for transportation agencies interested in assessing their vulnerability to climate change and extreme weather events. It gives an overview of key steps in conducting vulnerability assessments and uses in-practice examples to demonstrate a variety of ways to gather and process information. Similarly FTA's "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation" (2011) report provides a summary of key transit agency's assessments of potential climate change impacts and development of adaptation strategies.

In 2012, FTA awarded $1 million in research funding for seven transit agencies to conduct climate change adaptation assessments. The pilot projects were aimed at advancing the state of practice for adapting transit systems to the impacts of climate change. The effort is in keeping with broader long-term goals to address state-of-good repair needs and enhance transit safety. The selected projects assessed the vulnerability of transit agency sensitive locations and assets to climate change hazards such as heat waves and flooding. The purpose of the pilot projects was to synthesize data in FTA's "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation" (FTA 2011) and lessons learned from a series of Federal Highway Administration (FHWA) pilot projects focusing on climate adaptation for state and regional highway systems.

The seven transit agencies included:

1. **San Francisco Bay Area Rapid Transit (BART)** – Assessed inundation related to sea level rise and flooding
2. **Chicago Transit Authority (CTA)** – Assessed extreme heat events and flooding
3. **Gulf Coast (Houston Metro, Tampa Hart and Island Transit)** – Assessed impacts from increasing temperatures, sea level rise, hurricane activity and flooding events
4. **Los Angeles County Metropolitan Transportation Authority (LACMTA)** – Primarily considered extreme heat events and heavy rainfall events
5. **Metropolitan Atlanta Rapid Transportation Authority (MARTA)** – Used FTA's Asset Management Guide to apply transit asset management principles to climate change adaptation
6. **Southeastern Pennsylvania Transportation Authority (SEPTA)** – Conducted a vulnerability and risk assessment of extreme weather events on one transit line including extreme heat, heavy rain, snow and severe storms.
7. **Central Puget Sound Regional Transit Authority (Sound Transit)** – Identified potential climate change impacts including heavy rain events and increased mudslides. Developed methods to integrate resiliency into the Agency's planning and operations.

Figure 3. FTA's Seven Climate Change Vulnerability Assessment Pilot Projects

The Maryland State Highway Administration (SHA) undertook a Climate Change Adaptation Plan with Detailed Vulnerability Assessment in 2014. The assessment included:

- Assessing the vulnerability of SHA's transportation assets (bridges/small structures, roads and small culverts/drainage conveyances) to climate variables and stressors;
- Developing engineering approaches to address current and future climate induced risks; and
- Making recommendations for policy or process changes to improve the resiliency of Maryland's highway system.

In addition, the Transportation Research Board's Climate Change, Energy and Sustainability Impacts on the Transportation Infrastructure Subcommittee has undertaken a synthesis of existing climate change vulnerability and adaptation plans worldwide.

Review of the above information sources and projects, as well as consultation with SHA, assisted in the development of the methodology utilized for completion of MTA's Climate Change Vulnerability Assessment.

2. Maryland Transit Administration Background

The Maryland Transit Administration (MTA) is a transportation business unit of the Maryland Department of Transportation (MDOT), and one of the largest multi-modal transit systems in the United States. MTA operates Local and Commuter Buses, Light Rail, Metro Subway, Maryland Area Regional Commuter (MARC) Train Service, and a comprehensive Paratransit (Mobility) system. Additionally, MTA is responsible for the maintenance of freight rail lines in Maryland and Delaware.

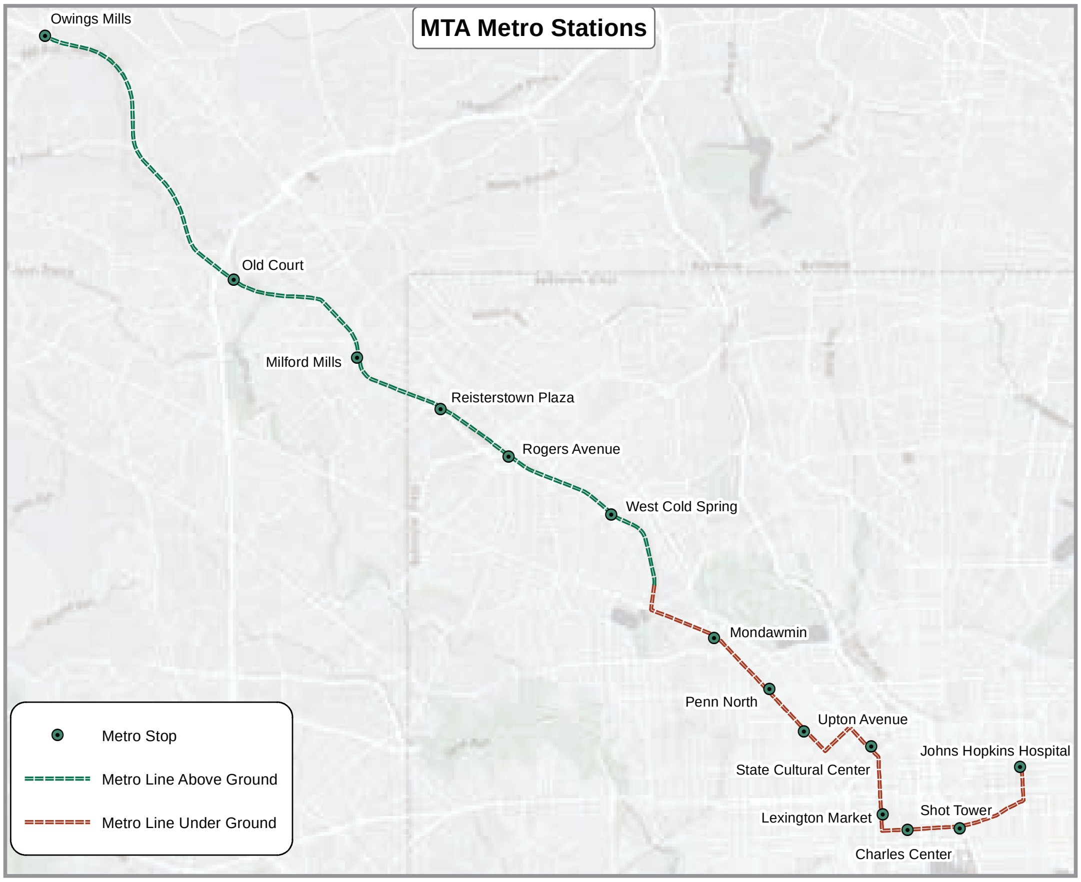
This Climate Change Vulnerability Assessment considers potential inundation of MTA assets which primarily include maintenance facilities, railway track, stations and parking lots. While bus maintenance facilities and fixed infrastructure have been included in this study Local and Express Bus routes are operated on roadways and highways which are the responsibility of the relevant County, State or Federal agency. Additionally, Bus stops are flexible and able to be altered if inundated and are therefore not considered within this assessment.

2.1 Metro

The Baltimore Metro subway system consists of 14 stations over 15.5 miles from Owings Mills through downtown Baltimore to Johns Hopkins Hospital. The system links suburban Baltimore County communities to large governmental and private employers, major sports complexes and universities.

Shot Tower Metro Station is located at the lowest elevation of the Metro system. The top-of-rail elevation is approximately 40 feet below sea level. In 2006, MTA completed a Flood Mitigation Assessment of Baltimore Metro System and found that the Shot Tower station is a critical point for flooding, due to tidal surge and heavy rainfall along the Metro system as the entrance is below the 100-year floodplain elevation.

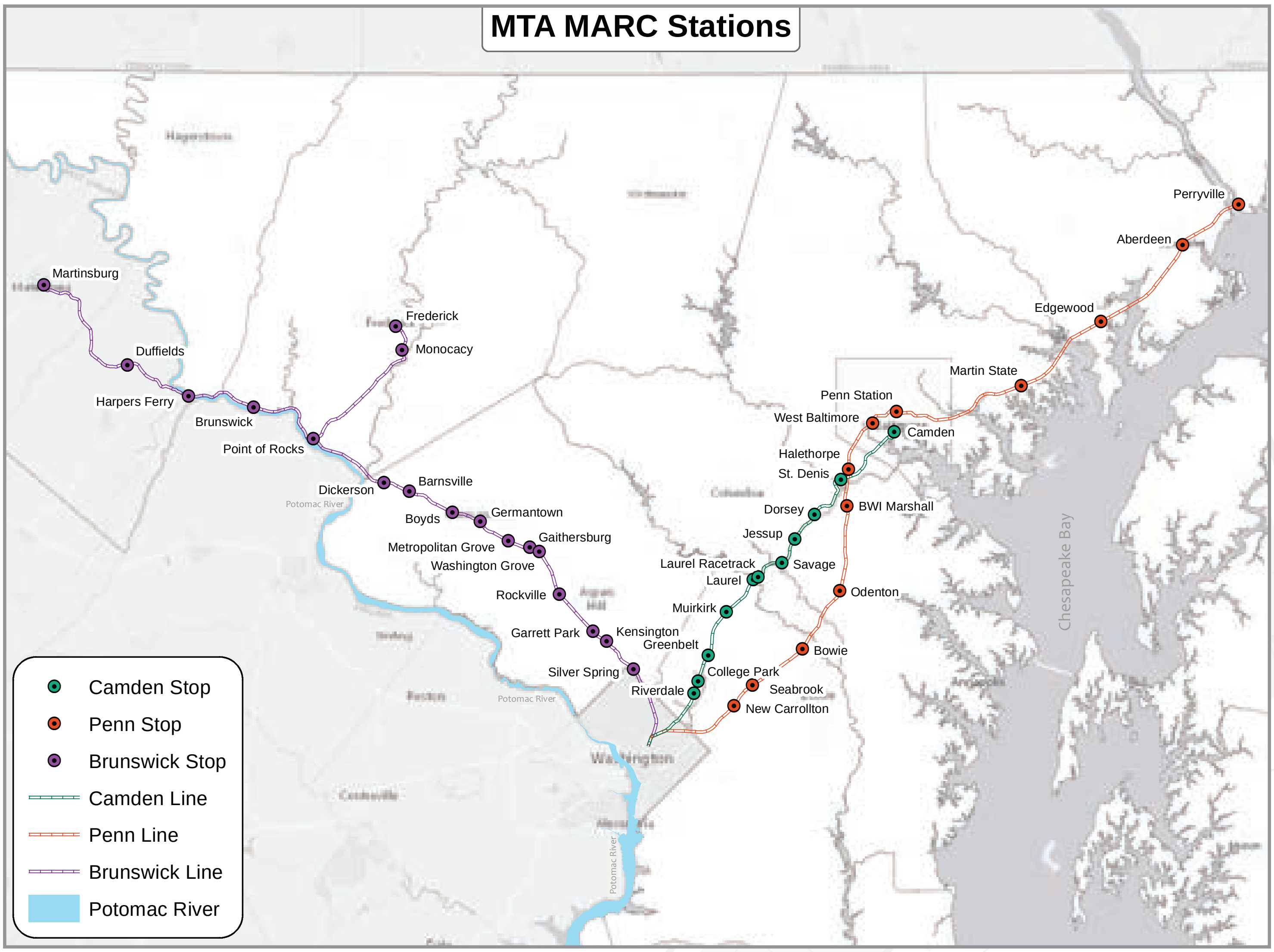
Figure 4. MTA Metro System



2.2 MARC

The Maryland Area Regional Commuter (MARC) is a commuter rail system comprising three lines in the Baltimore-Washington Metropolitan Area. The three MARC operating lines are the Brunswick Line, Camden Line and Penn Line. MARC is administered by the MTA and is operated under contract by Bombardier Transportation Services USA Corporation and Amtrak over tracks owned by CSX Transportation and Amtrak. The Penn and Camden MARC lines run adjacent to the Chesapeake Bay tidal region and cross waterways at many locations. A portion of the MARC Brunswick line crosses and runs adjacent to the Potomac River and also crosses many waterways. Many of the stations and facilities located adjacent to waterways are prone to inundation through flooding and hurricane storm surge.

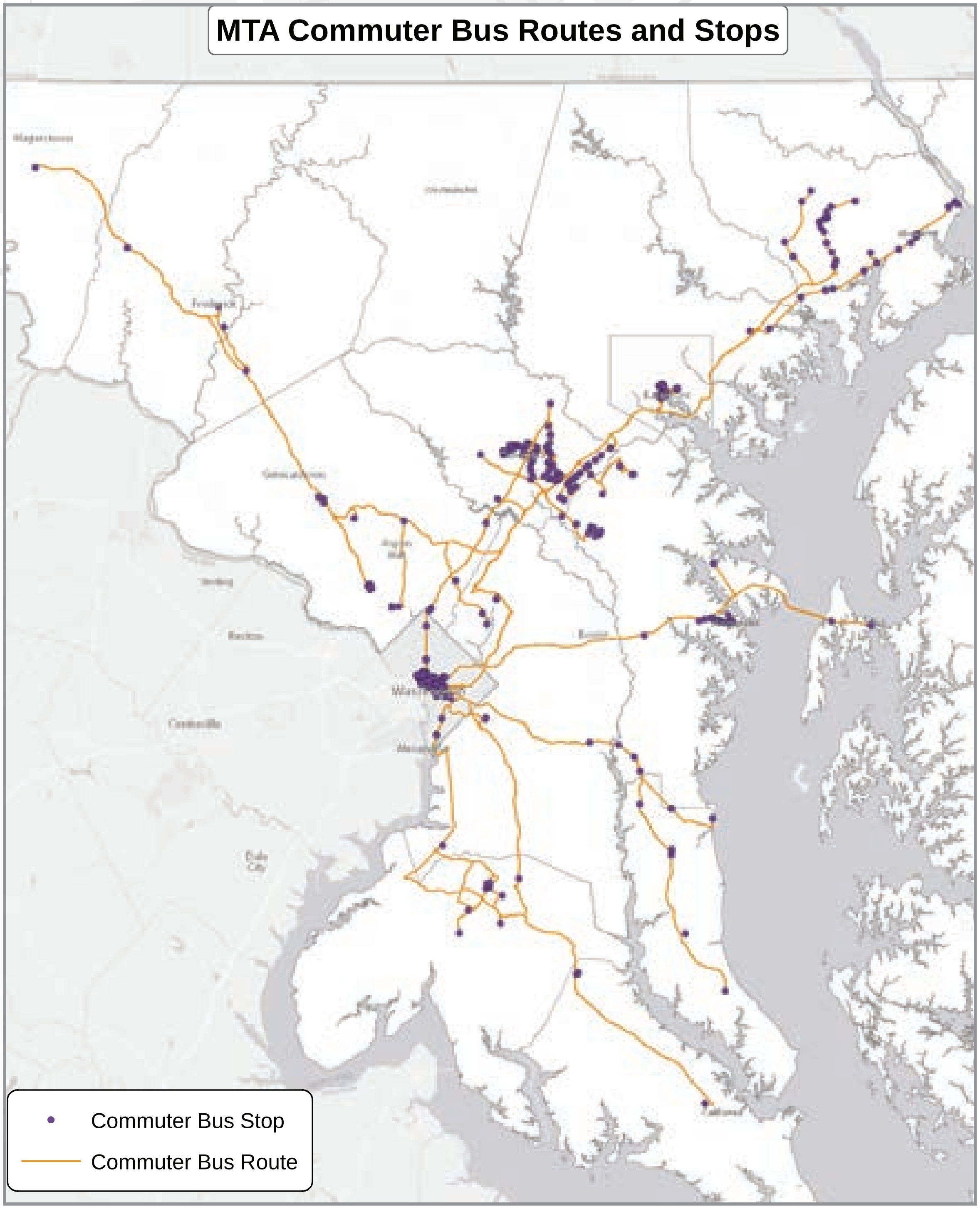
Figure 5. MTA MARC System



2.3 Commuter Bus

Commuter Bus operates weekdays during morning and evening rush hours. Currently, there are 25 routes with most operating Monday to Friday. Commuter Bus routes operate throughout much of the Baltimore and Washington metropolitan region. Patrons are able to leave their personal vehicles at park and ride lots owned and maintained by MTA and local governments. Some of these parking lots are susceptible to flooding from heavy rainfall events and are located within low-lying topography. Only MTA owned and maintained facilities are considered in this report.

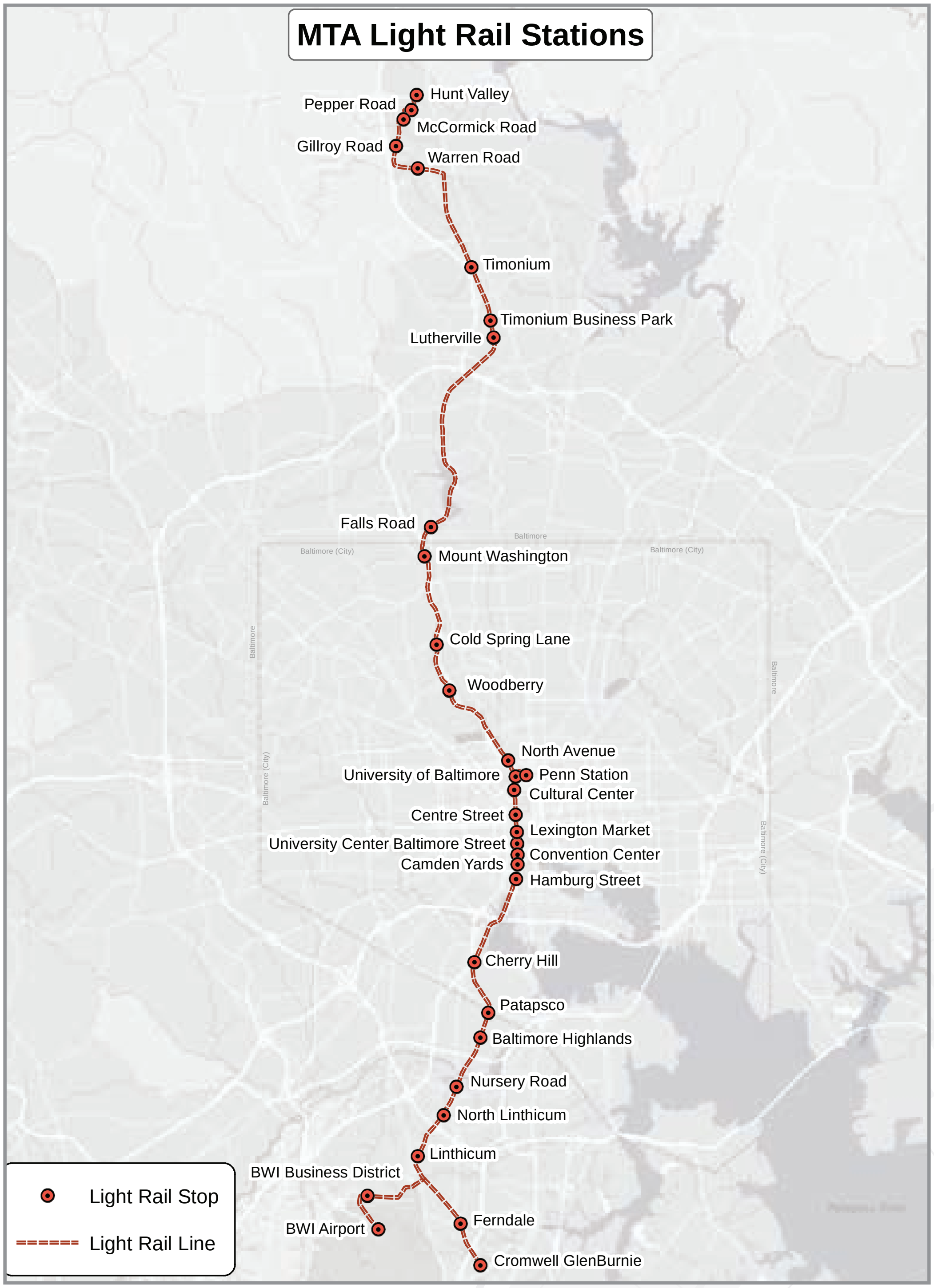
Figure 6. MTA Commuter Bus Routes and Stops



2.4 Light Rail

The Light Rail network consists of a 30 mile north-south railway line that includes a spur in Baltimore City connecting a single stop (Penn Station) to the main line and two branches at the south end of the line that serve two stops each. In downtown Baltimore, Light Rail right-of-way is located within city streets. Outside the central portions of the city, the line is built within and adjacent to streets. The Light Rail line is located adjacent to several waterways and flooding has occurred, particularly when culverts have been blocked or poorly maintained.

Figure 7. MTA Light Rail System



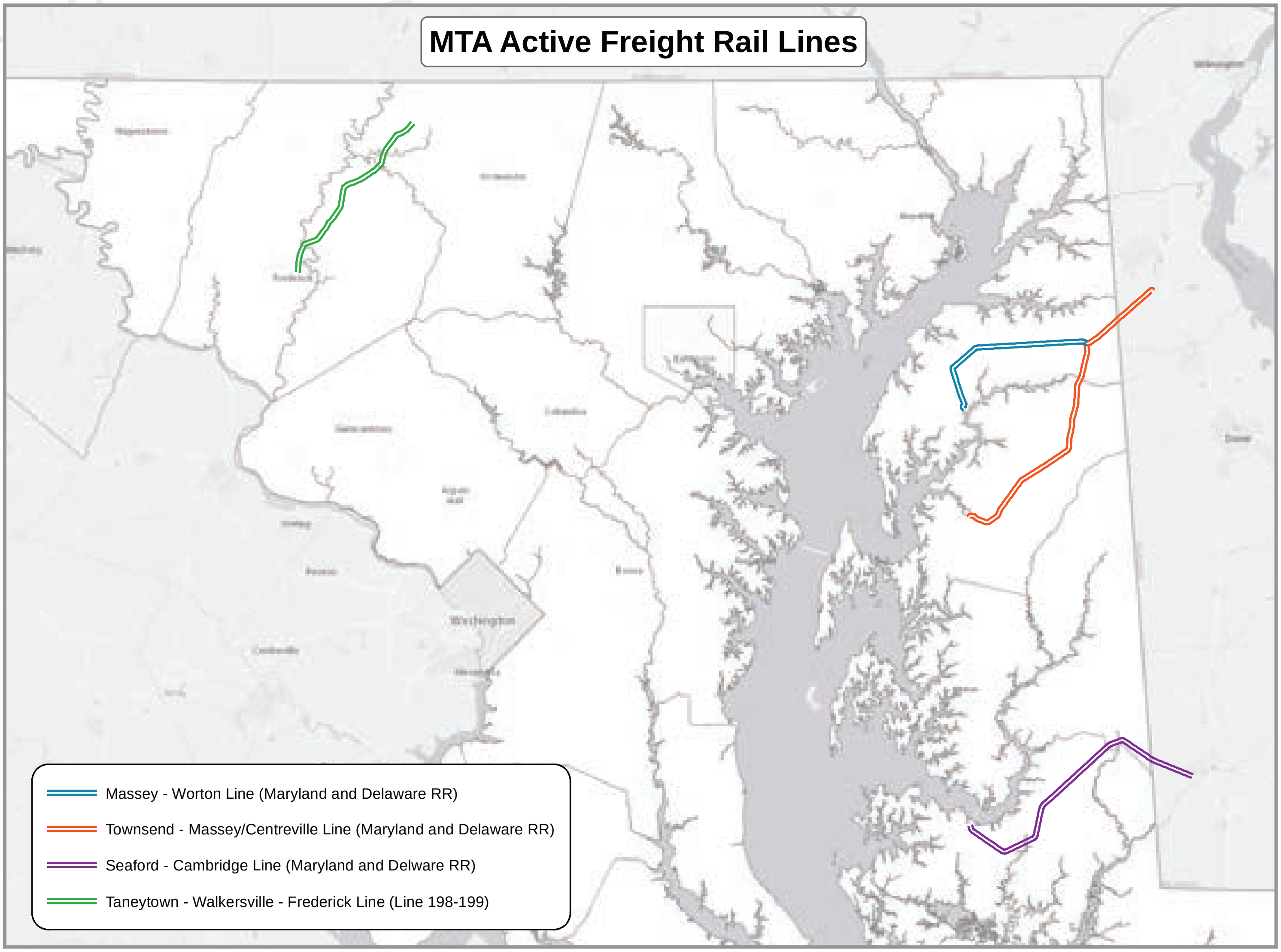
2.5 Freight

In addition to transit services, MTA also owns freight railways in rural parts of Maryland and Delaware. The MTA-owned rail ROW includes eight active and inactive segments on the Eastern Shore, totaling approximately 150 miles in total length, and one segment in Frederick County totaling approximately eight miles long. Active MTA-owned lines include:

1. Massey-Worton Line (Maryland and Delaware RR) – 29 miles
2. Townsend-Massey/Centreville Line (Maryland and Delaware RR) – 35 miles
3. Seaford-Cambridge Line (Maryland and Delaware RR) – 31.5 miles
4. The Taneytown-Walkersville (Frederick Line 198-199) – 8 miles

Sea level rise, hurricane storm surge and flooding have the potential to affect the freight lines along the Eastern Shore of Maryland due to the region's low-lying topography and location adjacent to the Chesapeake Bay and Atlantic Ocean. The freight line in Frederick Maryland, has the potential to be inundated during an extreme rainfall event but is not susceptible to sea level rise or hurricane storm surge.

Figure 8. MTA Active Freight Rail Lines

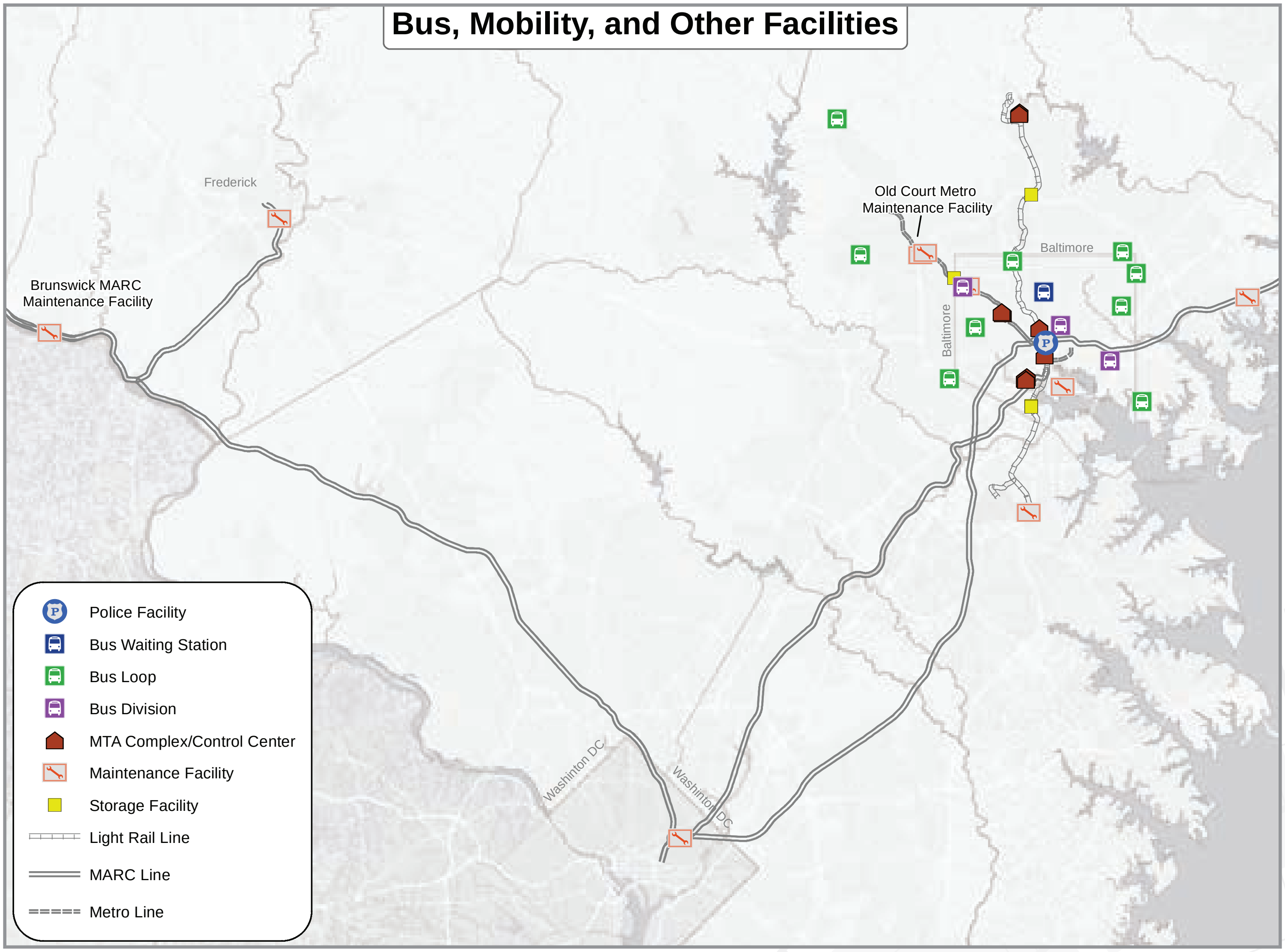


2.6 Bus, Mobility and Other Facilities

The MTA Climate Change Vulnerability Assessment focuses on potential impacts to MTA's services due to inundation of fixed assets contributing to the function of MTA's Metro, MARC, Commuter Bus, Light Rail and Freight services. This includes consideration of maintenance and administrative facilities which support these services as well as those of Bus and Mobility operations.

MTA's fixed facilities supporting its services are shown in the figure below. **Only the Brunswick MARC Maintenance Facility and Old Court Metro Maintenance Facility are located within areas likely to experience inundation.**

Figure 9. Bus, Mobility and Other Facilities



3. Methodology

In conducting a vulnerability assessment when planning for adaptation, it is important to recognize that there is no "one size fits all" approach. For given expectations about climate change, different adaptations are appropriate for different types of facilities and their different life spans or criticalities. Rail yards, for example, may need protection against rising sea levels and storm surges, whereas other facilities, such as open space and parking lots, can be allowed to flood temporarily at acceptable frequencies.

The MTA Climate Change Vulnerability Assessment involved the following:

1. Vulnerability mapping
2. Vulnerability risk assessment
3. Preliminary adaptation measures

Figure 10. Climate Change Vulnerability Assessment Methodology

	Activities	Outcome
Step 1	**Vulnerability Mapping** Reference Group Input Meeting	Vulnerability Maps GIS Layer Summary Report
Step 2	**Vulnerability Assessment** Adaptive Capacity and Sensitivity Assessment Consequence Assessment Reference Group Workshops	Risk Ratings
Step 3	**Preliminary Adaptation Measures**	Final Report

3.1 Step 1 - Vulnerability Mapping

The vulnerability mapping was completed between May 2014 and February 2016. The following sections below summarize the analysis undertaken.

Through preliminary research, numerous data sources were identified for inclusion in the assessment. These data sources included information on likely sea level rise, storm surge scenarios and flooding for the State of Maryland, Baltimore City, West Virginia and Delaware. Data sources considered for use by MTA included the following:

- Federal Emergency Management Agency (FEMA)–Effective Flood Plains
- National Oceanic and Atmospheric Administration (NOAA) – Sea Level Rise Dataset
- US Army Corps of Engineers – Hurricane Storm Surge http://www.stormsurge.noaa.gov/products_resources_prep.html
- State of MD GIS data http://imap.maryland.gov/Pages/default.aspx
- State of DE GIS data http://opendata.firstmap.delaware.gov/
- Publicly available GIS data from Maryland Counties-Hydrology, Cadastral Data etc.
- SHA Centerline Data & Vulnerability Analysis https://toolkit.climate.gov/taking-action/state-highway-administration-catalogs-vulnerabilities
- Baltimore City GIS data

3.1.1 Sea Level Rise Data Collection

Tide gauge measurements indicate that Maryland has experienced approximately one foot of sea level rise over the last century. The rate of sea level rise within Maryland waters is expected to more than double in the second half of this century, resulting in a 1.4 to 2.1 feet increase of relative sea level rise by 2050 and a 3.7 to 5.7 feet increase by 2100.[2]

Research to obtain sea level rise data for the predicted 1.4 to 2.1 feet by 2050 and 3.7 to 5.7 feet by 2100 identified a number of potential data sources. There were a number of attempts made to create a uniform sea level rise inundation dataset for the state of Maryland. The NOAA Sea Level Rise Dataset included contours for every foot of sea level rise for all Maryland Counties, including Baltimore City. two, four, and six foot inundation layers were extracted from this dataset for the assessment.

3.1.2 Hurricane Storm Surge Data Collection

Hurricane storm surge data was produced by the US Army Corps of Engineers (USACE) Baltimore District Planning Division. The GIS data received from the USACE contains flooding information from the Maryland Western Shore Hurricane Evacuation Study Storm Surge Map completed in 2006. The data shows areas of possible flooding during Category 1, 2, 3 and 4 hurricanes.

According to the USACE Baltimore District Planning Division, the map and associated data classifies potential tidal flooding from hurricanes. Potential flood areas are based on storm surge heights calculated by the National Weather Service's SLOSH (Sea, Lake and Overland Surge from Hurricanes) Model.

Hurricane categories 1 through 4 refer to the Saffir-Simpson scale of hurricane intensity. Storm surge elevations present 'worst case' combinations of direction, forward speed, landfall point and astronomical tides for each category. These surge elevations do not include wave heights that accompany storm surge.

The GIS data received from USACE contains separate polygon shape files for each of the four hurricane categories for each of the Maryland counties affected. The data represents the following storm surge heights:

- Category 1 – 6.7 Feet
- Category 2 – 10.0 Feet
- Category 3 – 13.8 Feet
- Category 4 – 17.4 Feet

In order to create a single statewide dataset that could be used to analyze MTA properties and transportation statewide, the USACE GIS data was first combined by hurricane category, then by county. The resulting dataset was symbolized by category for map production.

3.1.3 Flooding Data Collection

The 100-year and 500-year (1 percent and 0.2-1 percent chance of flooding annually) floodplain data was obtained from FEMA's National Flood Hazard Layers (NFHL). Effective NFHL were obtained for Maryland, Delaware, West Virginia, Virginia and the District of Columbia and used to establish MTA sensitive locations and assets as risk of inundation.

Sites that are located within the 100 year floodplain have a 1% chance of flooding to the mapped extent each and every year. Whereas sites that are located within the 500 year floodplain have a 0.2% chance of flooding to the mapped extent each and every year.

3.1.4 MTA Sensitive Location and Asset Data Collection

Existing MTA sensitive locations and assets were verified internally and brought into the map document. TThese included the Metro line and stations, Light Rail line and stations, Bus and Mobility facilities, maintenance facilities, MARC stations and the freight rail lines. The location of these sensitive locations and assets were overlaid with the sea level rise, hurricane storm surge and flooding layers to identify which sensitive locations and assets are vulnerable.

A GIS dataset was developed for MTA sensitive locations and assets potentially impacted by sea level rise at two, four and six feet, hurricane storm surge for categories 1-4 (approximately 6-17 feet inundation) and the 100 and 500 year flooding events. In addition to including MTA facilities and stops the layers outlined core transit routes and locations where these routes will be impacted by each of the scenarios.

3.1.5 Reference Group Meeting

A meeting with personnel from MARC/Commuter Bus, Light Rail, Metro, Freight, Operation Support, Safety, Engineering and Planning was held in July 2015. The results of the vulnerability mapping exercise and information regarding the study were outlined during the meeting and input on the results was encouraged. The goal of the meeting was to determine the legitimacy of the vulnerable sites and identify missing sites based on personnel field knowledge.

[2] *Boesch, D.F., L.P. Atkinson, W.C. Boicourt, J.D. Boon, D.R. Cahoon, R.A. Dalrymple, T. Ezer, B.P. Horton, Z.P. Johnson, R.E. Kopp, M. Li, R.H. Moss, A. Parris, C.K. Sommerfield. 2013. Updating Maryland's Sea Level Rise Projections. Special Report of the Scientific and Technical Working Group to the Maryland Climate Change Commission, 22 pp. University of Maryland Center for Environmental Sciences, Cambridge MD.*

3.2 Step 2 - Vulnerability Assessment

Incorporation of climate change impacts into transportation decisions is still a relatively new concept. As managers in various sectors grapple with information on climate change effects and how they may or may not impact their Agency's mission(s), they are turning to existing tools and approaches for guidance. To date, three closely-related approaches are being used to help transportation managers consider and prepare for future climate impacts:

- **Vulnerability assessments** begin with the identification of existing stressors facing transportation systems and projects how climate change will impact and/or introduce new stressors in the future. The findings of the assessment can then be ranked to assess, prioritize and address vulnerabilities.
- **Risk assessments** evaluate the likelihood and consequence of climate-related impacts on transportation. Many times this assessment will quantify the product of the probabilities of exposure, sensitivity and adaptive capacity. This assessment provides transportation policymakers with guidance based on quantitative analysis of the level of risk associated with changing climate conditions. Risk assessments are often conducted with the assistance of agency personnel most familiar with the vulnerable sites through workshops and consultation.
- **Adaptation development** identifies, plans, prioritizes, implements and measures transportation management options available for effectively adapting to climate change impacts. Adaptation development may include ways to reduce transportation vulnerability, increase resilience and/or highlight regions of retreat.

The MTA Climate Change Vulnerability Assessment incorporates a risk assessment of each of the identified vulnerable sensitive locations and assets and determines which sites are high priorities and most at risk of being impacted due to sea level rise, storm surge or flooding events and consequently impacting the continual provision of MTA's services. A second phase of this project will identify and develop practicable adaptation measures.

The following sections outline how the risk assessment was undertaken.

3.2.1 Risk Assessment

Adaptive Capacity and Sensitivity

Adaptive Capacity refers to the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. Sensitivity refers to how the asset or system fares when exposed to an impact.

In completing the risk based vulnerability assessment, the likelihood criteria were defined by determining a sensitive location or asset's adaptive capacity and sensitivity. It is assumed that the event (e.g. sea level rise, storm surge or flooding) will occur and the goal of the risk assessment is to determine the relative risk to MTA's services due to inundation of sensitive locations and assets from the event. Therefore, the likelihood criteria were not based on the likelihood of an event occurring, but rather the likelihood that a sensitive location or asset would be impacted from a climate change scenario. For this project, the likelihood criteria are a direct result of a sensitive location or asset's determined adaptive capacity and sensitivity.

Table 1 outlines the adaptive capacity and sensitivity criteria used to determine the likelihood.

Table 1. Adaptive Capacity and Sensitivity Criteria Descriptors and Values

Descriptors		
Criteria	Description	Value
Adaptive Capacity		
Alternative route available	No	2
	Yes	1
Duration of unavailability	> 1 week	2
	<1 week	1
Sensitivity		
Asset currently experiences flooding impacts	Yes	2
	No	1
Asset has been (or is scheduled to be) adapted to accommodate or prevent flooding	No	2
	Yes	1
Protection provided by natural barriers (e.g. wetlands)	No	2
	Yes	1

Each identified vulnerable asset or system was scored based on the criteria in **Table 1**. The average provides the final score which directly relates to the likelihood that the sensitive location or asset will be impacted by sea level rise, storm surge or flooding.

Table 2 outlines the likelihood descriptions for each corresponding likelihood score.

Table 2. Likelihood Scores

Likelihood Rating	Likelihood Score
Rare = Highly unlikely, but it may occur in exceptional circumstances. It could happen, but probably never will.	1.0-1.2
Unlikely = Not expected, but there's a slight possibility it may occur at some time.	1.3-1.4
Possible = The event might occur at some time as there is a history of some occurrence at similar MTA sensitive locations and assets.	1.5-1.6
Likely = There is a strong possibility the event will occur as there is a history of frequent occurrence at this or similar sensitive locations and assets.	1.7-1.8
Almost Certain = Very likely. The event is expected to occur in most circumstances as there is a history of regular occurrence at this asset.	1.9-2.0

Example: Brunswick Maintenance Facility

The Brunswick MARC Station and Maintenance Facility was assessed for its adaptive capacity and sensitivity to a 100 year flooding event.

Table 3. Likelihood Scoring for the Brunswick Maintenance Facility and MARC Station

Descriptor	Description	Value	Reasoning
Alternative Route Available	Yes	2	MARC trains are unable to provide service to the station if inundated. The railway track and station platform are fixed assets and unable to be mobilized in the way a bus stop would be.
Duration of unavailability	>1 week	2	Inundation of the facility/station would potentially cause damage requiring significant rehabilitation and facility/ station closure for an extended period of time.
Asset currently experiences flooding impacts	Yes	2	The maintenance facility and MARC station are located within the 100 year floodplain and adjacent to the Potomac River indicating that flooding at this location is likely to occur during severe rain events. Additionally, personnel experienced with operations at the station and maintenance facility have experienced localized flooding.
Asset has been (or is scheduled to be) adapted to accommodate or prevent flooding	Yes	1	Some work has been undertaken to accommodate inundation.
Protection provided by natural barriers (e.g. wetlands)	Yes	1	Forested land associated with the C&O Canal National Park is located immediately adjacent to the Potomac River and can provide some barrier to rising river levels.
Final Score (average)	**1.6 - Likelihood Rating = Possible**		

Consequence

In a standard risk assessment the consequence to MTA's services, due to a sensitive location or asset being inundated, is determined through assessing the impact to each vulnerable site against a set of potential consequences. **Table 4** outlines the consequence descriptors, criteria and corresponding ratings.

Table 4. Consequence Descriptors and Ratings

Consequence Rating and Descriptors			
Rating	Financial*	Service Interruption	Reputation and Image
Insignificant	Minimal financial loss; <0.1% of service operating budget ($233,000 for rail and $343,140 for bus)	No interruption to service or interruptions lasting less than 1 hour.	No effect to MTA's reputation or image.
Minor	Financial cost to rehabilitate/replace between 0.2-0.5% of service operating budget ($466,201 - $1,164,503 for rail and $686,280 - $1,715,700 for bus)	Service interruption of less than 24 hours.	Adverse local media coverage only
Moderate	Financial cost to rehabilitate/ replace between 0.6-5% ($1,398,604 - $11,655,036 for rail and $2,058,840 - $17,157,006 for bus)	Service interruption less than 1 week	Adverse Baltimore and/or State media coverage
Major	Financial cost to rehabilitate/replace between 6-10% ($13,986,044 - $23,310,073 for rail and $20,588,408 - $34,314,013 for bus)	Service interruption less than 1 month.	Adverse and extended national media coverage
Catastrophic	Huge financial losses involving many people and/or corporations and/or local government (>$23,310,073 for rail and >$34,314,013 for bus)	Severe service interruption lasting several months or more.	Demand for government inquiry

* *Operating budget information was obtained from the Report on the Fiscal 2016 State Operating Budget (HB 70) and the State Capital Budget (HB 71) and Related Recommendations*

Example: Brunswick Maintenance Facility

Inundation of the Brunswick Maintenance Facility and MARC Station was assessed against the consequence descriptors outlined in **Table 4** and it was determined that a 100 year flooding event would cause severe service interruption to the MARC Brunswick Line due to the Brunswick Maintenance Facility and MARC Station both being unavailable while undergoing rehabilitation for flooding. This service interruption would likely last several months, thus this sensitive location and asset was attributed a consequence rating of **Catastrophic**.

Risk Rating

The likelihood and consequence are combined to determine MTA's overall risk in the event the sensitive location or asset were inundated under one or more of the three climate change scenarios. **Table 5** provides an illustration of the risk matrix used to identify each sensitive location and asset's risk rating.

Table 5. Risk Matrix

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Rare	Low	Low	Moderate	Moderate	High
Unlikely	Low	Low	Moderate	High	High
Possible	Low	Moderate	High	High	Very High
Likely	Moderate	Moderate	High	Very High	Very High
Almost Certain	Moderate	High	Very High	Very High	Very High

Example: Brunswick Maintenance Facility

In combining a likelihood rating of **Possible** with a consequence rating of **Catastrophic** the Brunswick MARC Station and Maintenance Facility asset has a risk rating of **Very High** should the site be inundated by a 100 year flooding event. This means that the impact to MTA's MARC service on the Brunswick Line would be **Very High** and adaptation measures to reduce either the likelihood of inundation or the consequence of inundation should be developed and implemented to reduce the overall risk to MTA's service to the greatest extent practicable.

Risk Assessment Workshops

Workshops were with the same MTA representatives whom provided input during the Reference Group meeting.

Four workshops were held in October 2015.

- October 9, 2015 – MARC and Commuter Bus
- October 16, 2015 – Light Rail
- October 23, 2015 – Metro
- October 26, 2015 – Freight

The workshops consisted of members from MARC/Commuter Bus, Light Rail, Metro, Freight, the Office of Engineering and Construction and the Office of Planning and Programming. They focused on the risk assessment, by mode, for each relevant sensitive site and asset identified as vulnerable.

Given that none of the Bus or Mobility maintenance facilities were identified as vulnerable through the inundation mapping or the reference group consultation, workshops were not held with representatives from these modes.

At the workshop, participants contributed to a round table discussion of each sensitive location and asset under threat of inundation from one or more of the three climate change scenarios and assisted in identifying the likelihood of being impacted, the consequence of each specific impact and the overall risk rating. In addition participants were also asked to identify conceptual adaptation measures which could be implemented to reduce the risk of MTA's services.

Additional meetings with individuals from the Office of Engineering and Construction were held after completion of the workshops to seek site specific information from experienced personnel.

Upon completion of the risk assessment workshops the results were amalgamated to provide a comprehensive determination of MTA sensitive locations and assets which would cause the greatest impact to MTA's services should they be inundated by one or more of the three climate change scenarios.

4. Results

This section outlines the results of the vulnerability mapping, vulnerability risk assessment, adaptation development and final analysis.

4.1 Vulnerability Mapping

Preliminary results of the mapping identified numerous locations along transit routes and around MTA owned and leased facilities which would potentially be inundated under the three climate change scenarios. These were further refined by conducting a detailed review of all MTA owned and leased property within the vicinity of the three climate change scenarios. This resulted in the identification of 75 sensitive locations and assets vulnerable to at least one of the three scenarios.

The final outcomes of the mapping exercise include stationary maps **Appendices A** through **E** as well as GIS datasets which will remain 'live' and be regularly updated. The GIS datasets prepared include:

- Layers which depict sea level rise, storm surge and flooding within all regions of Maryland, West Virginia and Delaware that incorporate MTA sensitive locations and assets.
- One layer which includes all MTA sensitive locations and assets identified as potentially being inundated and which were assessed in the risk assessment. Information in this layer includes the risk assessment results.

The GIS data is available on MTA's shared drive and can be accessed by all personnel with ArcMap software. It will be useful when planning projects on existing sites susceptible to inundation and new sites which may be within a region likely to flood.

Sixty-four (64) culverts along the Light Rail and Metro systems were identified as being within the 100 and/or 500 year floodplain. These were not assessed in the vulnerability assessment due to variability in function of these culverts. Culverts are designed to allow water to pass underneath the MTA asset (e.g. light rail track). This is intended to prevent flood water from over topping the asset and potential structural damage. MTA's culverts are regularly inspected and maintained. A more detailed study would be required to determine which, if any, of the 64 culverts overtop.

4.2 Vulnerability Risk Assessment

The likelihood and consequence to each of the 75 sensitive locations and assets were assessed during the workshops to determine the risk rating for each.

Assumptions made during the workshops include:

- Assume the worst case scenario occurs to each of the sensitive locations and assets being assessed.
- Consider aspects of each location which are inundated separately in order to account for varying likelihood ratings or consequences for each. For example, inundation of Light Rail station platforms may have a lower consequence to MTA's services when compared to inundation of Light Rail track at the same station.
- Impacts at railroad grade crossings (where MTA owns the track including Light Rail, Metro and Freight) are more severe than at other locations.

Each sensitive location and asset was reviewed and assessed during the risk assessment workshops and a total of 75 were identified as having a low, moderate, high or very high risk of affecting MTA services under the three scenarios.

More Light Rail sensitive locations and assets will be impacted than those of the other modes. **Table 6** provides a summary of the impacts per mode.

Table 6. Risk Summary by Mode

Risk Rating	Mode					
	Light Rail	Freight	Metro	MARC	Commuter Bus	Total
Very High	14	2	6	3	0	**25**
High	7	10	6	0	0	**23**
Moderate	7	3	0	2	3	**15**
Low	6	0	0	5	1	**12**
Total	**34**	**15**	**12**	**10**	**4**	**75**

Figures F1-F3 in Appendix F, display the locations of MTA's facilities and assets inundated under each of the climate change scenarios.

The majority of sites potentially inundated by the 100 and 500 year flood are located adjacent to waterways and within the floodplain. These include sensitive locations and assets located on the Eastern Shore, the Baltimore-Washington Metropolitan region as well as in Western Maryland. The majority of sensitive locations and assets inundated due to hurricane storm surge are located along the Chesapeake Bay and tidal riverine systems. The majority of sensitive locations and assets inundated due to sea level rise are located along the Chesapeake Bay and tidal riverine systems.

The final risk ratings for each of the 75 sensitive locations and assets are provided in **Tables 7** through **10**. The first column of these tables provides reference to the corresponding map included in **Appendices A** through **E**.

Table 7. MTA Sensitive Locations and Assets with a Very High Risk Rating

^Map #	Asset	*Mode	+Scenario	Inundation Scenario								
				Flooding (yr)		Sea Level Rise (feet)			Hurricane Storm Surge (category)			
				100	500	2	4	6	1	2	3	4
B1, B2	Brunswick MARC Station and Maintenance Facility	MARC	FL	x								
B6, B7	Penn MARC Station	MARC	FL	x								
B1, B2	Points of Rock MARC Station	MARC	FL	x								
C1, C3	Rail segment south of Timonium Business Park Station near mile post N1 – 545 (0.12 miles)	LR	FL	x	x							
C1, C6	Mount Washington Station	LR	FL	x								
C1, C5	Track at Mount Washington Station	LR	FL	x								
C1, C5	Rail segment between Mount Washington and Cold Spring (1.8 miles)	LR	FL	x								
C1, C5	Cold Spring Station	LR	FL	x								
C1, C5/C6	Rail segment south of Cold Spring (0.4 miles)	LR	FL	x								
C1, C3	Timonium Business Park	LR	FL	x	x							
C1, C3	Rail segment at Timonium Business Park (0.08 miles)	LR	FL	x	x							
C1, C9, C10, C12	Hamburg Station	LR	FL, HSS	x	x					x	x	x
C1, C9, C10, C12	Hamburg Control Instrument Housing (CIH) 42-S	LR	FL, HSS	x	x					x	x	x
C1, C9, C11	Rail segment north of Westport Station (0.28-0.48 miles)	LR	FL, HSS	x					x	x	x	x
C1, C9, C13	Nursery Road Bridge	LR	FL, HSS, SLR	x	x	x	x	x	x	x	x	x
C1, C9, C13	Nursery Road Station	LR	FL, HSS, SLR	x	x	x	x	x	x	x	x	x
C1, C8	Rail segment between Linthicum and BWI 19.35 - BW (0.13 miles)	LR	FL	x	x							
D1, D2	Substation at Owings Mills	Metro	FL	x	x							
D1, D2	Aerial structure at Owings Mills	Metro	FL	x	x							
D1, D4, D5	Shot Tower Market Place Station	Metro	FL, HSS	x	x					x	x	x
D1, D4, D5	Pumps at Shot Tower	Metro	FL	x	x					x	x	x
D1, D4, D5	Substation at Shot Tower	Metro	FL	x	x					x	x	x
D3	Gold Street Pumping Station	Metro	FL	x	x					x	x	x
E1, E4	Bridge on Massey/Centreville (Edmonds Creek Bridge – Kent)	Freight	FL, HSS, SLR	x		x	x	x	x	x	x	x
E2, E9	Bridge over Marshyhope River Seaford/Cambridge	Freight	FL, HSS, SLR	x		x	x	x	x	x	x	x

**LR = Light Rail, CB = Commuter Bus, ^ Reference maps provided in the appendices, + FL = Flooding, SLR = Sea Level Rise, HSS = Hurricane Storm Surge*

Table 8. MTA Sensitive Locations and Assets with a High Risk Rating

^Map #	Asset	*Mode	+Scenario	Inundation Scenario								
				Flooding (yr)		Sea Level Rise (feet)			Hurricane Storm Surge (category)			
				100	500	2	4	6	1	2	3	4
C1, C2	Warren Road Station and Rail segment north 798 – N	LR	FL	x								
C1,C2	Rail segment south of Warren Road Station 767 – N (0.06 miles)	LR	FL	x								
C1, C4	Rail segment at Control Instrument Housing (CIH) Beltway 535-N (0.27 miles)	LR	FL		x							
C1, C4	Roland Run Bridge	LR	FL		x							
C1,C3	Rail segment at Control Instrument Housing (CIH) Timonium 658-N (0.05 miles)	LR	FL	x	x							
C1, C3	Timonium Station	LR	FL	x	x							
C1, C9, C12, C13	Nursery Road Rail Segment	LR	FL, HSS, SLR	x	x	x	x	x	x	x	x	x
D1, D2	Rail segment south of Owings Mills Station (0.01 miles)	Metro	FL	x	x							
D1, D2	Rail segment north of Old Court Metro Station (0.14 miles)	Metro	FL	x	x							
D1, D2	Old Court Station	Metro	FL	x	x							
D1, D2	Old Court Maintenance Facility	Metro	FL		x							
D1, D2	Interlocking at Old Court	Metro	FL	x	x							
D1, D2	Rail segment south of Old Court Metro Station (0.1 miles)	Metro	FL	x	x							
E1, E5	Rail segment on Massey/Centreville (south of Mile Post 13 – Kent)	Freight	FL	x								
E1, E5	Rail segment Massey/Centreville (west of Mile Post 5 - DE) (0.03 miles)	Freight	FL	x	x							
E1, E5	Rail segment Seaford/Cambridge west of 4 Mile Post (in DE) (0.15 miles)	Freight	FL	x	x							
E10	Rail segment Seaford/Cambridge at Skinners Run Bridge (0.04 miles)	Freight	HSS	x	x							x
E2	Rail segment Seaford/Cambridge at Guard Road Crossing (0.32 miles)	Freight	FL	x	x							
E9	Bridge Seaford/Cambridge timber bridge over Transquaking River	Freight	HSS									x
E8	Bridge Seaford/Cambridge Steel beam bridge over Transquaking River	Freight	FL, HSS, SLR	x				x	x	x	x	x
E10	Rail segment Seaford/Cambridge Bucktown Road Grade Crossing (0.94 miles)	Freight	HSS									x
E3, E6	Rail segment and Bridge Frederick Line over Big Pipe Creek (0.09 miles)	Freight	FL	x								
E3, E6	Rail segment and Bridge Frederick Line over Little Pipe Creek (0.11 miles)	Freight	FL	x								
E3, E7	Rail segment and Bridge Frederick Line west of Cash Smith Road and Woodsboro Pike (0.07 miles)	Freight	FL	x								

**LR = Light Rail, CB = Commuter Bus, ^ Reference maps provided in the appendices, + FL = Flooding, SLR = Sea Level Rise, HSS = Hurricane Storm Surge*

Table 9. MTA Sensitive Locations and Assets with a Moderate Risk Rating

^Map #	Asset	*Mode	+Scenario	Inundation Scenario								
				Flooding (yr)		Sea Level Rise (feet)			Hurricane Storm Surge (category)			
				100	500	2	4	6	1	2	3	4
A1, A2, A3, A4	North Beach Park and Ride	CB	SLR, HSS				x	x	x	x	x	x
A1, A2, A3, A5	Kent Narrows Park and Ride	CB	FL, SLR, HSS	x	x		x	x	x	x	x	x
A1, A2, A7	Juniata Park and Ride	CB	FL, HSS	x								x
B1, B2	Duffields MARC Station	MARC	FL	x								
B6, B7	Penn MARC Station	MARC	FL	x								
C1, C2	Rail segment south of McCormick Road Station (852 – N) (0.01 miles)	LR	FL	x								
C1, C4	Rail segment near Culvert 430-N (0.075 miles)	LR	FL	x								
C1, C7	Rail segment south of Woodberry Station (0.32 miles)	LR	FL	x								
C1, C7	Rail at Penn Station	LR	FL	x								
C1, C7	Control Instrument Housing (CIH) Penn Station 70-N	LR	FL	x								
C1, C9, C12, C13	Nursery Road Control Instrument Housing (CIH)	LR	FL, SLR, HSS	x	x	x	x	x	x	x	x	x
C1, C6	Control Instrument Housing (CIH) Falls Road 342 – N	LR	FL	x	x							
E1, E5	Rail segment on Massey/Centreville (south of Mile Post 12 – Kent) (0.09 miles)	Freight	FL	x	x							
E1, E5	Rail segment Massey/Centreville (west of Mile Post 5 - DE) (0.2-0.46 miles)	Freight	FL		x							
E3, E6	Rail segment and bridge Frederick Line south of Allendale Lane (0.14 miles)	Freight	FL	x	x							

**LR = Light Rail, CB = Commuter Bus, ^ Reference maps provided in the appendices, + FL = Flooding, SLR = Sea Level Rise, HSS = Hurricane Storm Surge*

Table 10. MTA Sensitive Locations and Assets with a Low Risk Rating

^Map #	Asset	*Mode	+Scenario	Inundation Scenario								
				Flooding (yr)		Sea Level Rise (feet)			Hurricane Storm Surge (category)			
				100	500	2	4	6	1	2	3	4
A2, A6	Essex Park and Ride	CB	HSS									x
B3, B4	Dorsey MARC Station	MARC	FL	x	x							
B1, B2	Frederick MARC Station	MARC	FL		x							
B6	Halethorpe MARC Station	MARC	FL	x	x							
B3, B5	Laurel Racetrack MARC Station	MARC	FL	x	x							
B3, B5	Laurel MARC Station	MARC	FL	x								
C1, C3	Rail segment north of Timonium Station Traction Power Sub Station (TPSS) Texas 1 (0.13 miles)	LR	FL	x								
C1, C4	Control Instrument Housing (CIH) Beltway 535-N	LR	FL		x							
C1, C3	Control Instrument Housing (CIH) Timonium 658-N	LR	FL	x	x							
C9, C11	Middle Branch Sub-Station	LR	HSS									x
C1, C5	Traction Power Sub Station (TPSS) TPSS 315 -N	LR	FL		x							
C1, C5	Control Instrument Housing (CIH) Newbury 315 - N	LR	FL		x							

**LR = Light Rail, CB = Commuter Bus, ^ Reference maps provided in the appendices, + FL = Flooding, SLR = Sea Level Rise, HSS = Hurricane Storm Surge*

The severity of impact and final risk rating for each sensitive location and asset within a mode was developed independent of the other modes. The risk assessment does not provide a comparison between modes. Comparisons should only be made for sensitive locations and assets within a mode and not between modes.

Figures 11 to **14** provide examples of potential inundation at four of the High Risk sensitive locations. Through the Climate Change Vulnerability Assessment it was determined that should these locations be inundated the impact to MTA's services would be significant thus elevating the risk rating to High Risk. Maps depicting inundation of all sensitive locations and assets assessed in this study are included in **Appendices A** through **E**.

Figure 11. Brunswick MARC Station and Maintenance Facility – Floodplain Vulnerability

Figure 12. Nursery Road and Nursery Bridge Light Rail – Hurricane Storm Surge Vulnerability

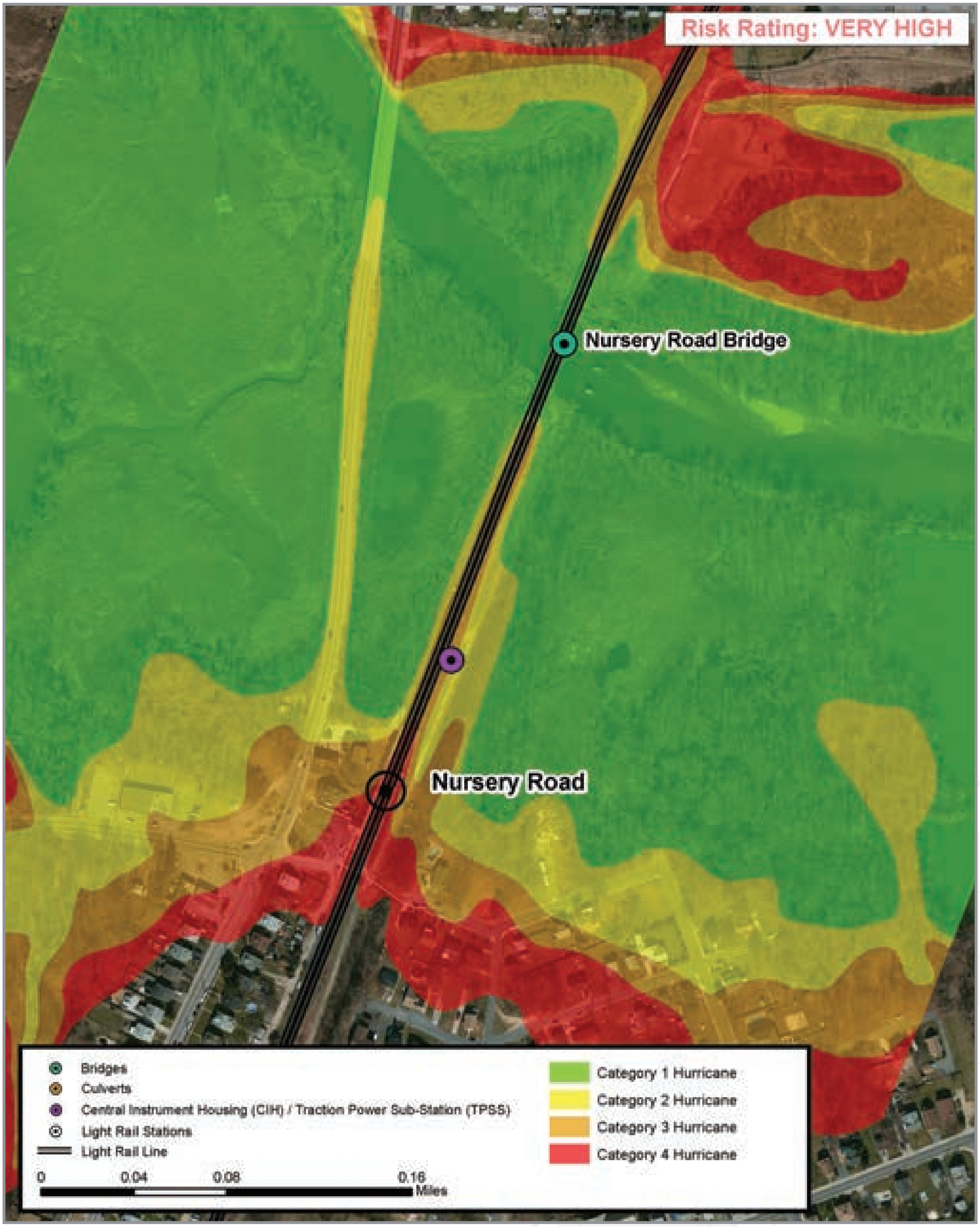


Figure 13. Shot Tower and Market Place Metro Station – Hurricane Storm Surge Vulnerability

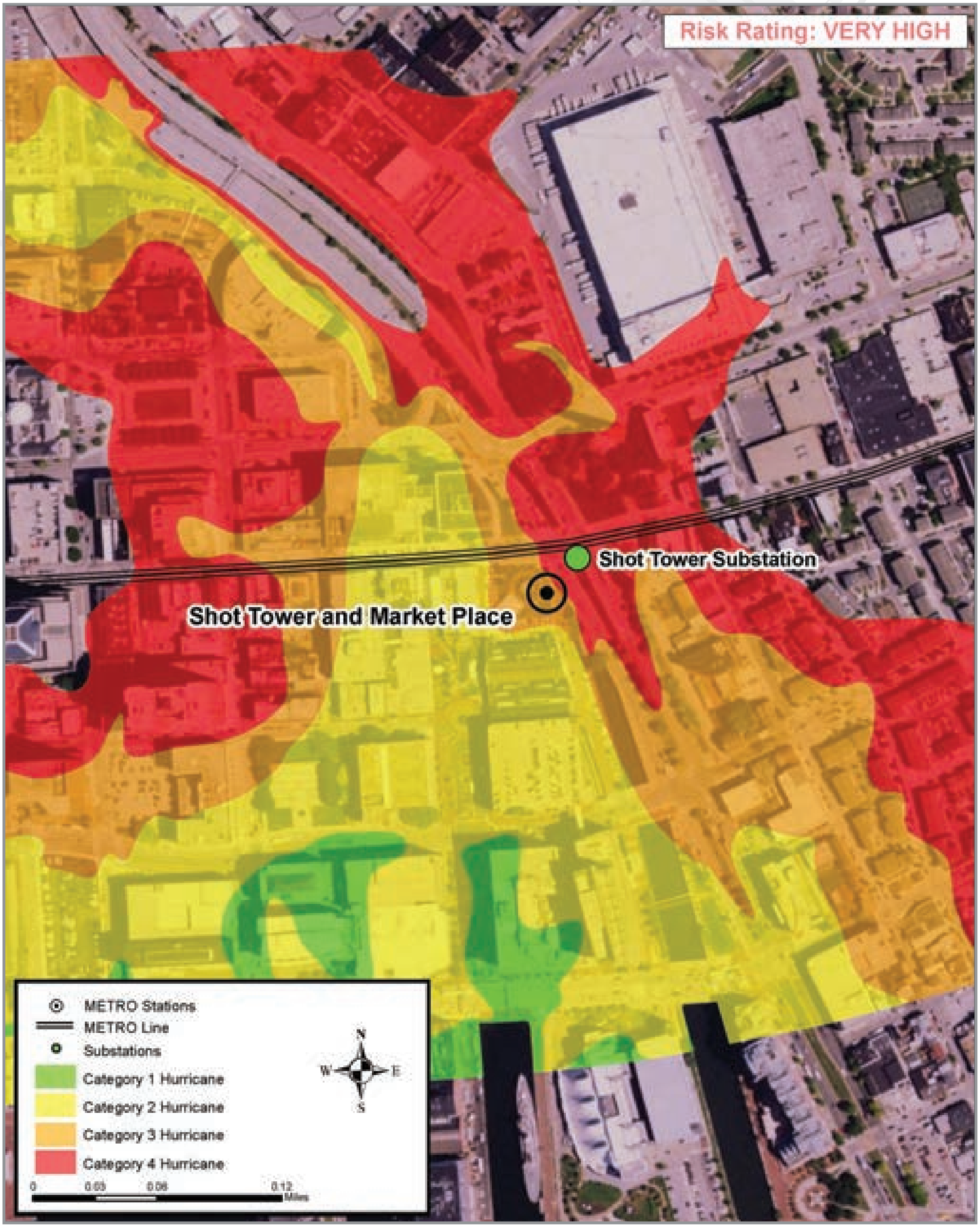


Figure 14. North Beach Commuter Bus Park and Ride – Sea Level Rise Vulnerability

4.3 Step 3 - Adaptation Measures

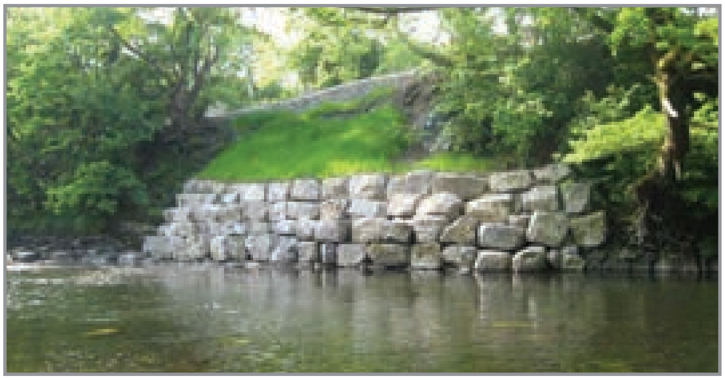
During the workshops, participants were asked what adaptation measures could be implemented to reduce the likelihood or consequence of flooding for the **Very High** and **High** risk sites. Suggestions included the following:

Metro

- Raise vents and street entrances. This was proposed by engineering previously at a cost of approximately $25 million for the Shot Tower Marketplace Metro Station.
- Provide generators to add electrical redundancy. These would need to be located above street level to avoid inundation.
- Install storm doors on entrances.
- Install self-closing vents.
- Modify vents to be above the flood level.
- Move equipment to avoid flooding.
- Provide a mobile power unit to ensure pumps don't lose power.
- Relocate vents off of the street.

Figure 15. Sandbags being Used at Shot Tower Metro Station During Category 2 Hurricane Isabel in 2003

Figure 16. Example of Embankment Aromouring (photo: Kaymac Marine)



MARC and Commuter Bus

- Elevate tanks and air compressors. This is already being done at some locations.
- Run trains to another maintenance yard to avoid inundated track.
- Use permeable pavement in parking lots.
- Elevate platforms and critical infrastructure.
- Allow for a section of the parking lot to flood and raise one third of the parking lot to allow continued use of the site when flooded, while minimizing cost to reconstruct. This could be applied to most MARC and Commuter Bus parking lots.
- Provide water proof covers and sealing doors over maintenance pits.
- Include a treatment facility in the maintenance pit to pump water.
- Increase stormwater management retention at the sites.
- Raise fuel tanks to above flood level.
- Use flood resistant materials and breakaway materials to increase infrastructure resiliency during inundation.
- Allow flow through under structures in the design.
- Anchor temporary structures.
- Provide a silt trap around a whole site to reduce damage due to sedimentation.

Light Rail

- Raise the track, however this would greatly impact service during construction.
- Construct retaining walls in locations along waterways.
- Implement stream aversion and embankment armouring.
- Increase pervious area to reduce flooding but this requires additional right of way.
- Maintain vegetated slopes to ensure maximum water flow retention.

Freight

- Raise the impacted bridges above expected flood levels.
- Include new, larger culverts to alleviate flood water.
- Maintain existing culverts with regular inspections and cleaning.

In addition to the measures listed above, all maintenance activities undertaken at sites identified as inundated, under one or more of the climate change scenarios, should be documented. This will assist in identifying infrastructure that undergoes regular maintenance due to inundation (e.g. culverts), and in determining the most effective and site specific, adaptation measures to implement.

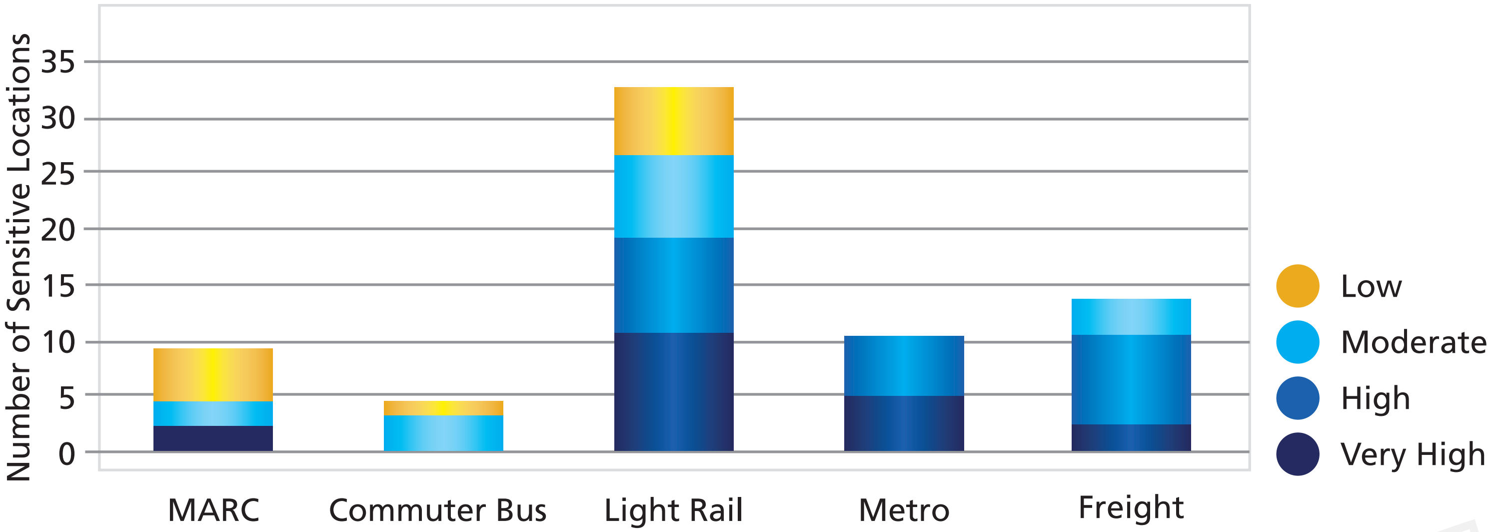
Once designed and implemented, adaptation measures identified as a result of the study would provide security and resilience for MTA sensitive locations and assets susceptible to sea level rise, flooding events and storm surge impacts.

5. Conclusion and Next Steps

This Climate Change Vulnerability Assessment identifies MTA sensitive locations and assets at risk of being inundated by sea level rise, hurricane storm surge and significant rain events. Seventy-five (75) sensitive locations and assets have been identified as being inundated under one or more of the three scenarios. Of these twenty-five (25) are considered to pose a **Very High** risk to MTA service and operations should they become inundated. Twenty-two (22) pose a **High** risk, fifteen (15) pose a **Moderate** risk and twelve (12) have a **Low** risk of impacting MTA services and operations if inundated.

The information contained in this report will be used to inform planning decisions when determining which sites and sensitive locations and assets require investment to reduce the likelihood or consequence of potential inundation and impair MTA from providing services. The mapping tool will assist in site selection of future planning projects by identifying if a proposed site is located within an area likely to be inundated under one of the three scenarios. Additionally, the results of this study are to be used when conducting design reviews of projects as they develop.

Figure 17. Sensitive Location and Asset Risk Ratings for each Mode



5.1 Next Steps

The information obtained from this Climate Change Vulnerability Assessment should be used to develop and implement mitigation or adaptation measures at the sites identified as **Very High** and **High** risk. The adaptation and mitigation measures should reduce the likelihood and/or consequences of inundation to MTA services and operations. The adaptation measures identified by workshop attendees provide an example of measures which can be employed to protect MTA's vulnerable sensitive locations and assets and could form the basis for design at existing and new sites.

In addition cost estimates associated with climate change related disruption should be developed. FEMA's HAZUS (Hazards U.S.) assessment approach has been modified in support of risk assessments to support economic loss assessments. The adapted HAZUS model could be utilized to identify the economic effects to MTA and the State of Maryland due to the three climate change scenarios. Additional information required to conduct an economic analysis include:

- Reimbursement information submitted to FEMA or FTA to cover costs associated with weather disasters.
- Weekly labor costs that correspond to the same dates as major weather events attributable to hurricane storm surge, flooding or sea level rise.

These cost estimates can be used to develop a cost-benefit analysis when determining which sites identified as having a **Very High** or **High** risk rating should be prioritized for adaptation funding.

5.1.1 Additional Studies

Using FEMA floodplain depth grids conduct additional detailed analysis of each sensitive location and asset identified as having a **Very High** or **High** risk. Additional analysis will improve understanding of impact to each of the sensitive locations and assets based on the level of inundation at each location.

MTA's vulnerability to climate events extends beyond inundation and includes variables such as heat (i.e. rail buckling) as well as snow and ice (i.e. downed catenary). In order to fully describe and prioritize improvements to MTAs sensitive locations and assets, the consideration of additional climate related impacts to MTA sensitive locations and assets, and the associated service disruption, should be considered, assessed and funding prioritized.

5.1.2 Incorporation into Current Plans

MTA's Asset Management Plan is currently under development and once complete will enable MTA to continually improve the reliability of the transit system and the Administration's overall efficiency. MTA's maintenance and capital programs will be assessed to minimize downtime, reduce risk, reduce state of good repair backlog and improve system performance agency-wide.

The Transit Asset Management Plan includes seven vision elements:

- **Safety** – provide a safe and secure environment for the entire MTA community.
- **Accountability** – meet the new legal and regulatory requirements under MAP-21.
- **Environmental sustainability** – reduce the impact of our activities on the environment.
- **Fiscal responsibility** – prioritize funding needs and make more informed capital investment decisions.
- **Operational performance** – minimize downtime, reduce risk and improve system performance.
- **Resiliency** – develop ways to make our transit system more resilient.
- **Customer service** – improve internal/external communications, convenience and accessibility.

The results of the Climate Change Vulnerability Assessment will inform the resiliency and environmental sustainability measures of MTA's Asset Management Plan.

References

Federal Highway Administration (2014). Highways in the Coastal Environment; Assessing Extreme Events. Hydraulic Engineering Circular No. 25, Volume 2. Washington D.C. 2014.

Federal Highway Administration (2012). Climate Change and Extreme Weather Vulnerability Assessment Framework. Washington D.C., 2012.

Federal Transit Administration (2014). Transit and Climate Change Adaptation; synthesis of FTA-Funded Pilot Projects. Washington D.C. 2014.

Federal Transit Administration (2013a). A Vulnerability and Risk Assessment of SEPTA's Regional Rail; A Transit Climate Change Adaptation Assessment Pilot. New Jersey, 2013.

Federal Transit Administration (2013b). Gulf Coast Climate Change Adaptation Pilot Study. Galveston Texas, 2013.

Federal Transit Administration (2013c). Los Angeles County Metropolitan Transportation Authority Climate Change Adaptation Pilot Project Report. Los Angeles California, 2013.

Federal Transit Administration (2013d). San Francisco Bay Area Rapid Transit District (BART) Climate Change Adaptation Assessment Pilot. San Francisco California, 2013.

Federal Transit Administration (2013e). Sound Transit Climate Risk Reduction Project. Seattle Washington, 2013.

Federal Transit Administration (2013f). Transit Climate Change Adaptation/Asset Management Pilot for the Metropolitan Atlanta Rapid Transit Authority. Atlanta Georgia, 2013.

Federal Transit Administration (2011). Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation, Washington D.C., 2011.

Los Angeles County (2012). Metropolitan Transportation Authority Climate Action and Adaptation Plan. Los Angeles California, 2012.

Maryland Commission on Climate Change Scientific and Technical Working Group (2013). Updating Maryland's Sea-level Rise Projections. Maryland, 2013.

Maryland Commission on Climate Change Adaptation and Response Working Group (2008a). Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change. Maryland, 2008.

Maryland Commission on Climate Change Adaptation and Response Working Group (2008b). Comprehensive Assessment of Climate Change Impacts in Maryland, 2008.

Maryland State Highway Administration (2014). Climate Change Adaptation Plan with Detailed Vulnerability Assessment. Baltimore Maryland, 2014.

Maryland Transit Administration (2015). Analysis of the FY 2016 Maryland Executive Budget, Annapolis Maryland, 2015.

Maryland Transit Administration (2010). Incorporating Climate Change and Sea Level Rise Information into the Maryland Transit Administration's (MTA) Capital Planning Process. Baltimore Maryland, 2010.

Maryland Transit Administration (2006). Flooding Mitigation Study of the Baltimore Metro System. Prepared by Jacobs Civil, Baltimore Maryland, 2006.

Transportation Research Board (2013). Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector; A Synthesis of Practice. Washington D.C. 2013.

United States Department of Transportation (2014). Climate Adaptation Plan; Ensuring Transportation Infrastructure and System Resilience. Washington D.C., 2014.

Appendix A
Commuter Bus Vulnerability Maps

Figure A-1 Park and Ride Floodplain Vulnerability

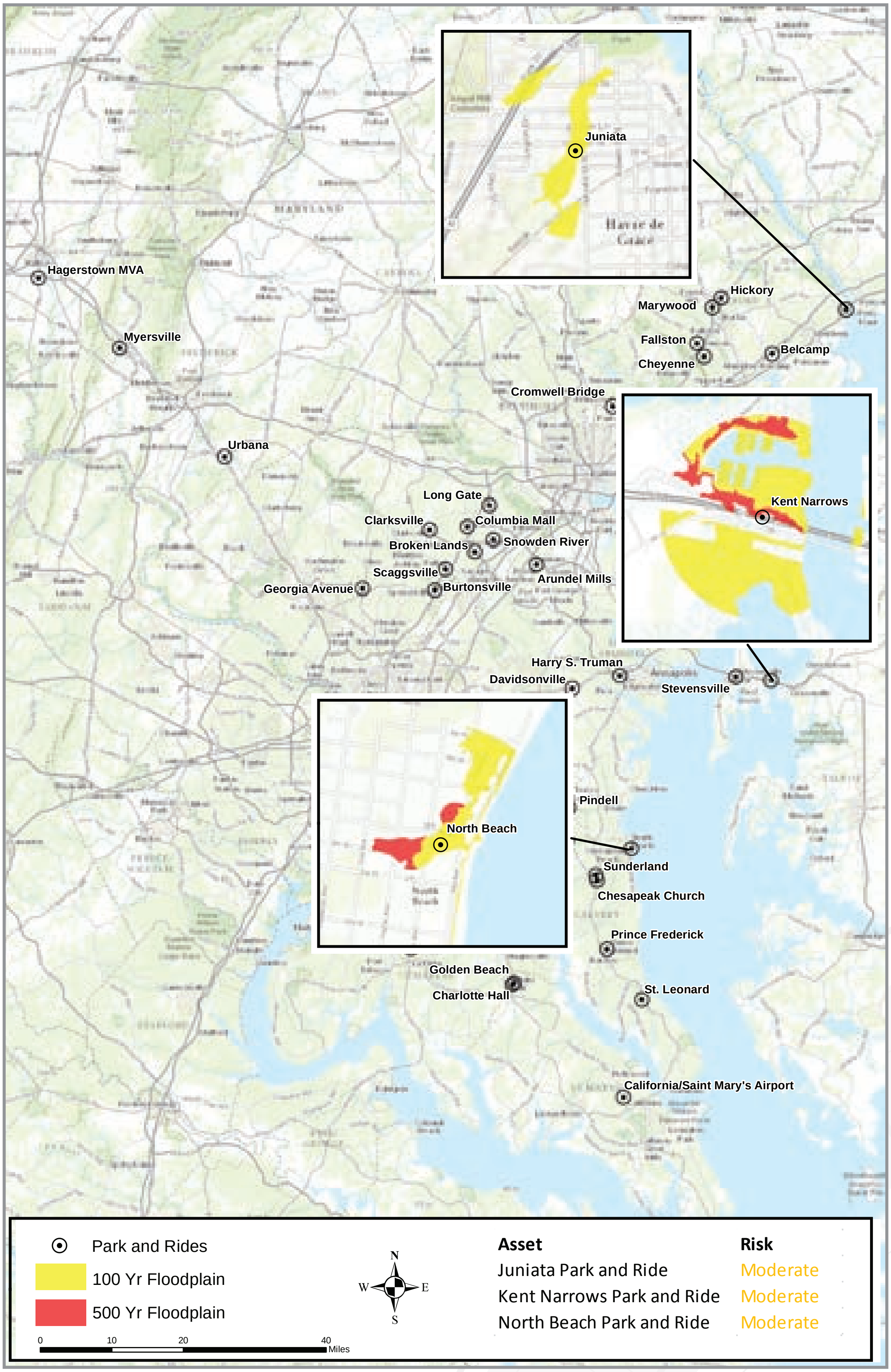
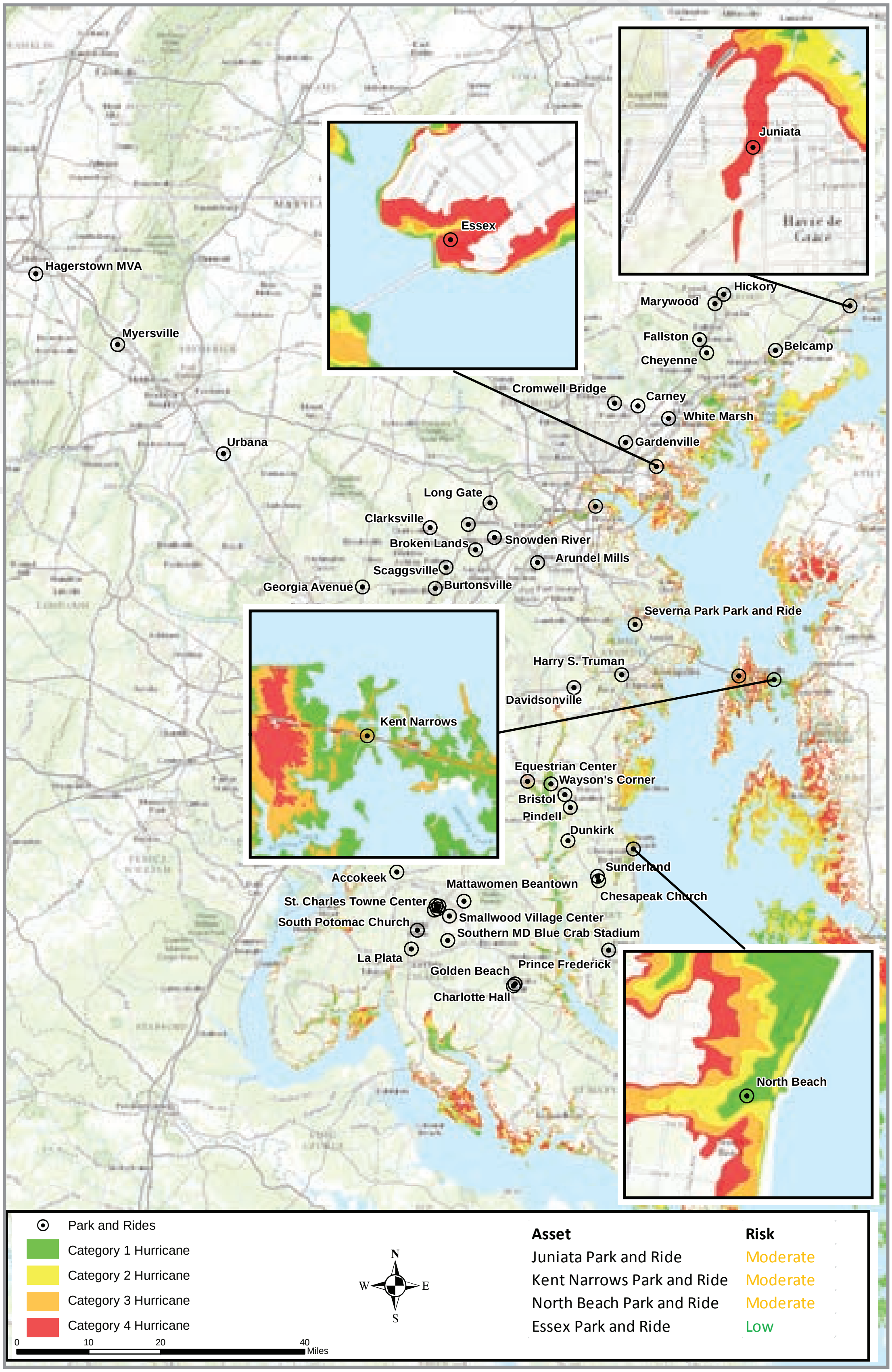
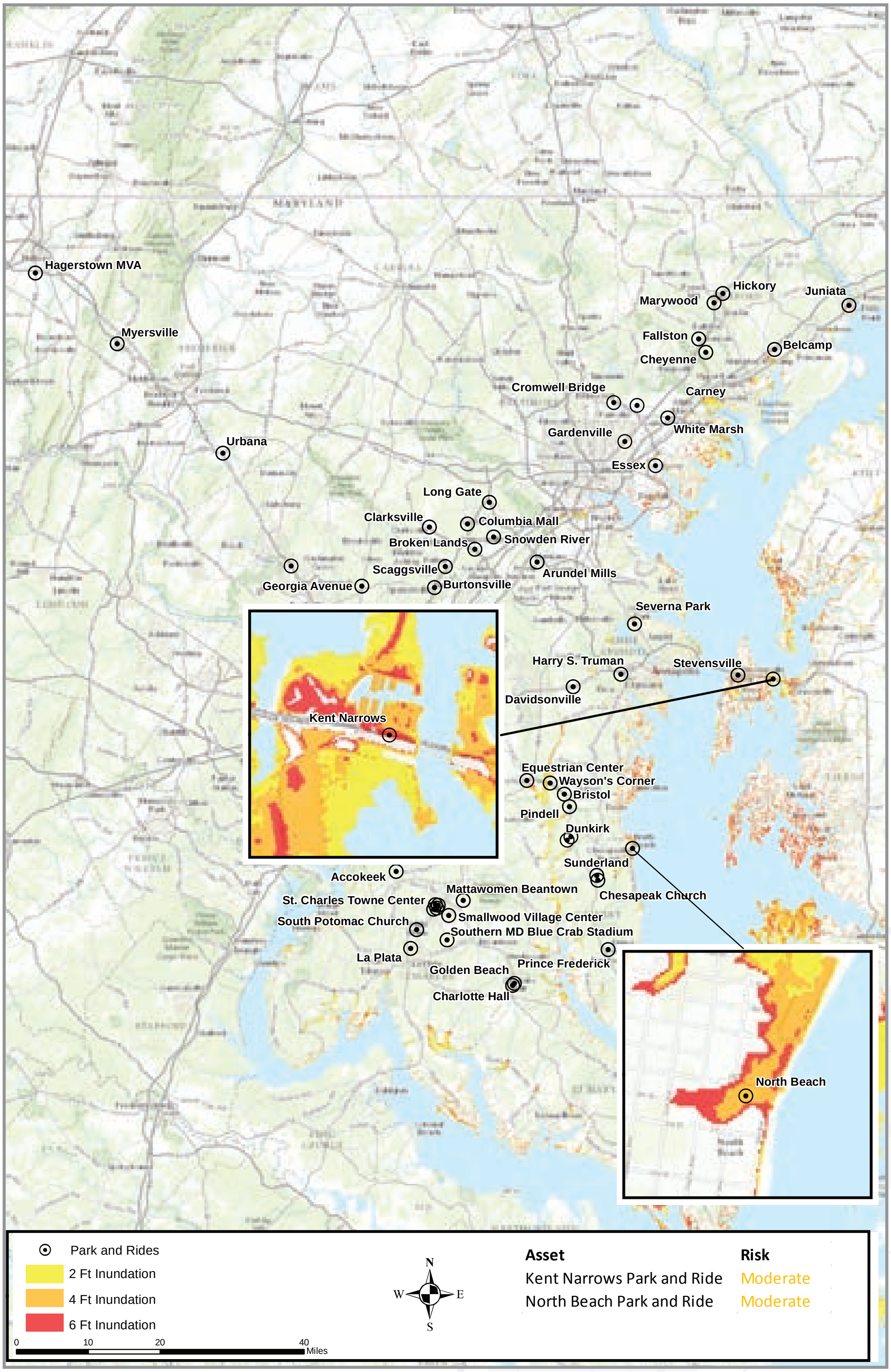


Figure A-2 Park and Ride Hurricane Storm Surge Vulnerability



Asset	Risk
Juniata Park and Ride	Moderate
Kent Narrows Park and Ride	Moderate
North Beach Park and Ride	Moderate
Essex Park and Ride	Low

Figure A-3 Park and Ride Sea Level Rise Vulnerability



Asset	Risk
Kent Narrows Park and Ride	Moderate
North Beach Park and Ride	Moderate

Figure A-4 Park and Ride Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability

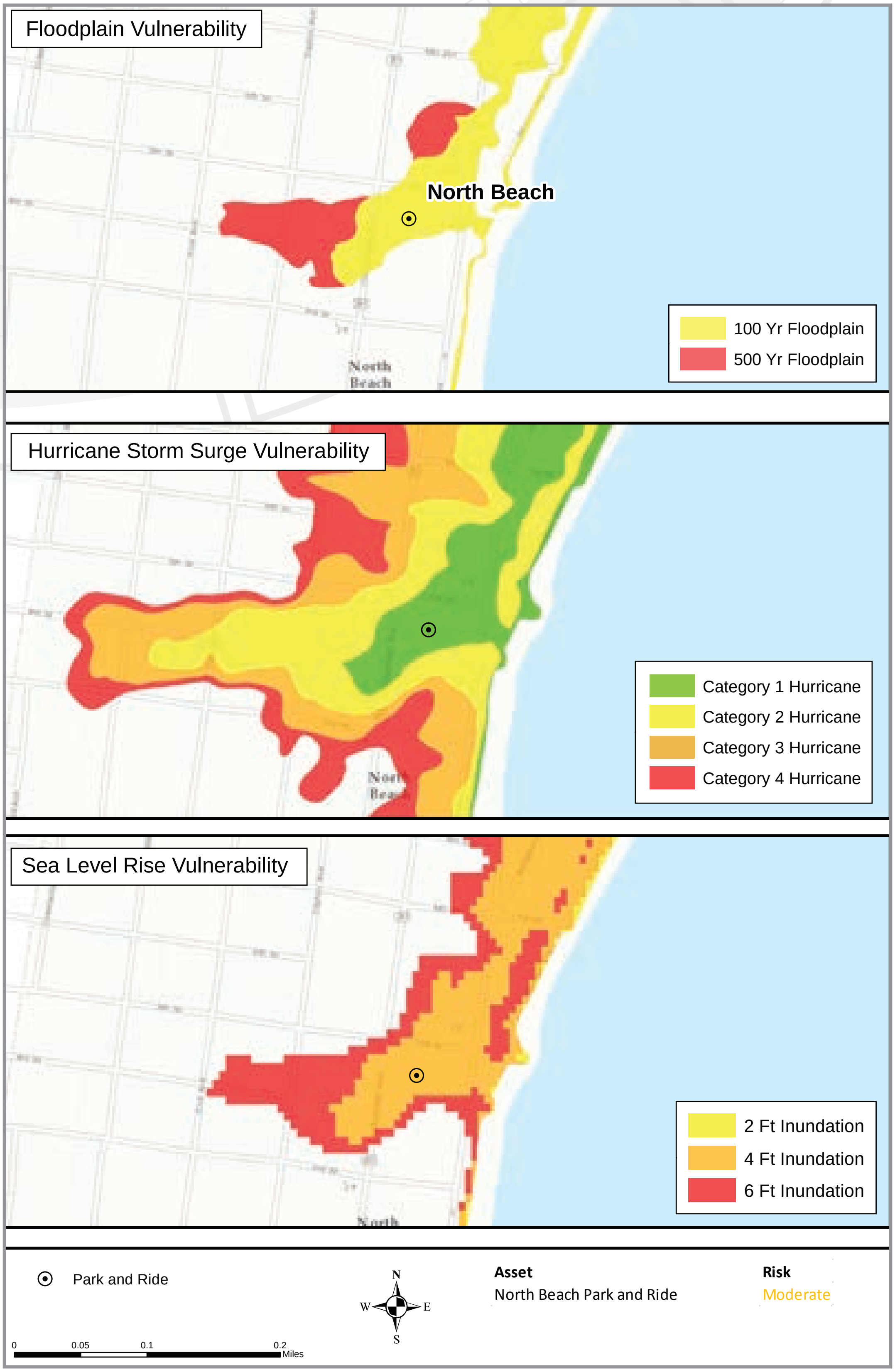


Figure A-5 Park and Ride Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability

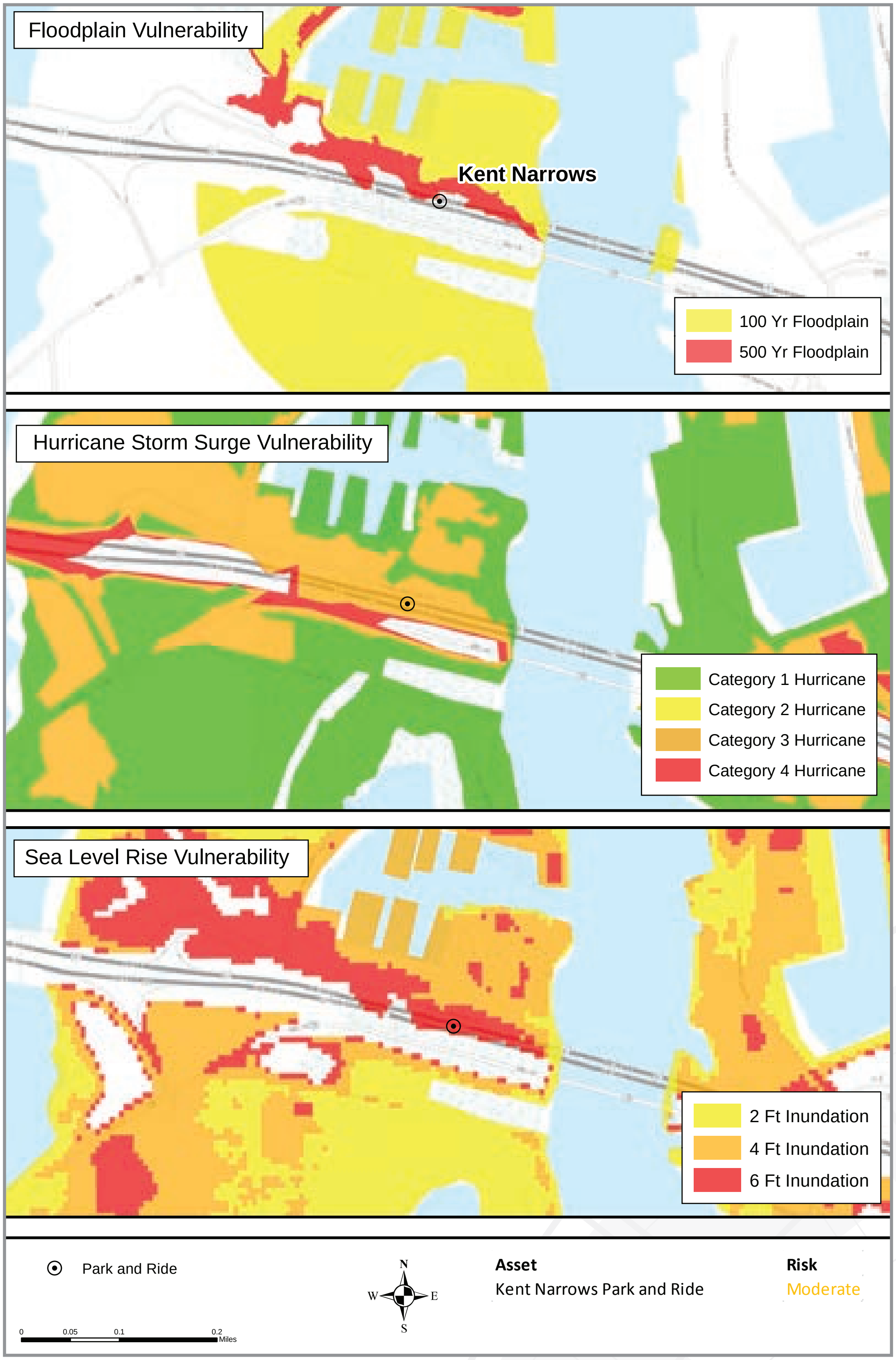


Figure A-6 Park and Ride Hurricane Storm Surge Vulnerability

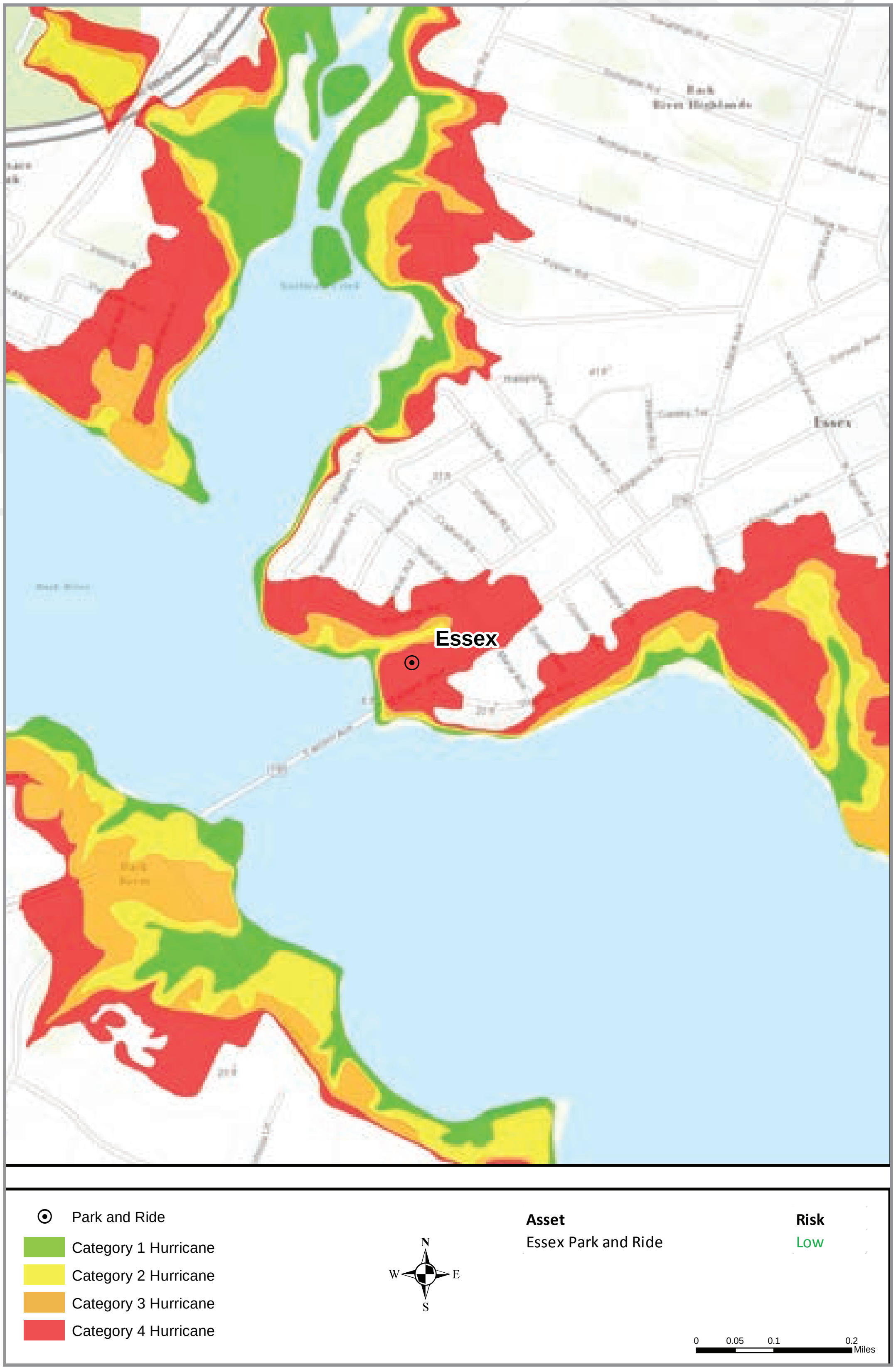
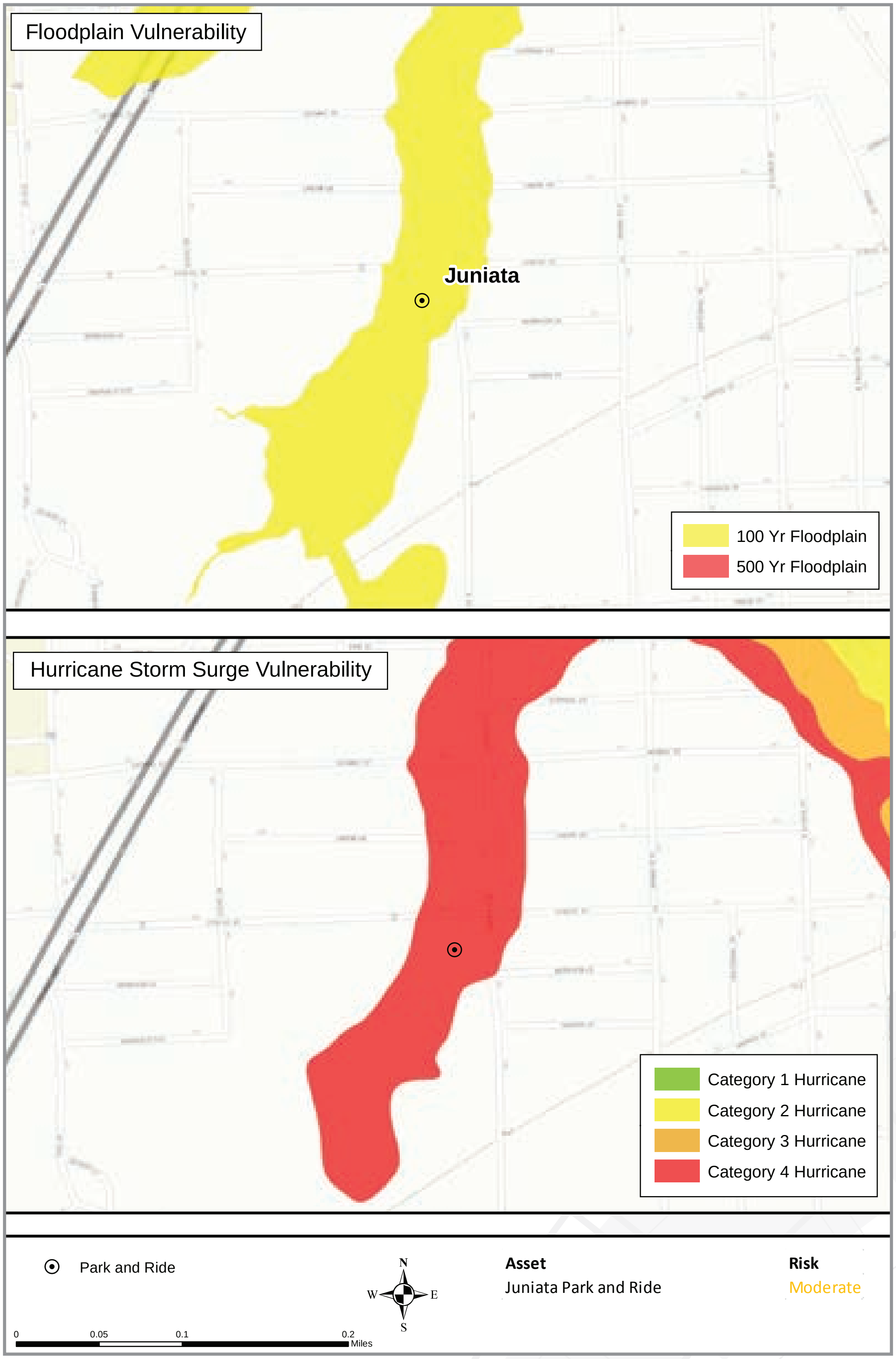


Figure A-7 Park and Ride Floodplain and Hurricane Storm Surge Vulnerability



Appendix B
MARC Vulnerability Maps

Figure B-1 Brunswick MARC Floodplain Vulnerability

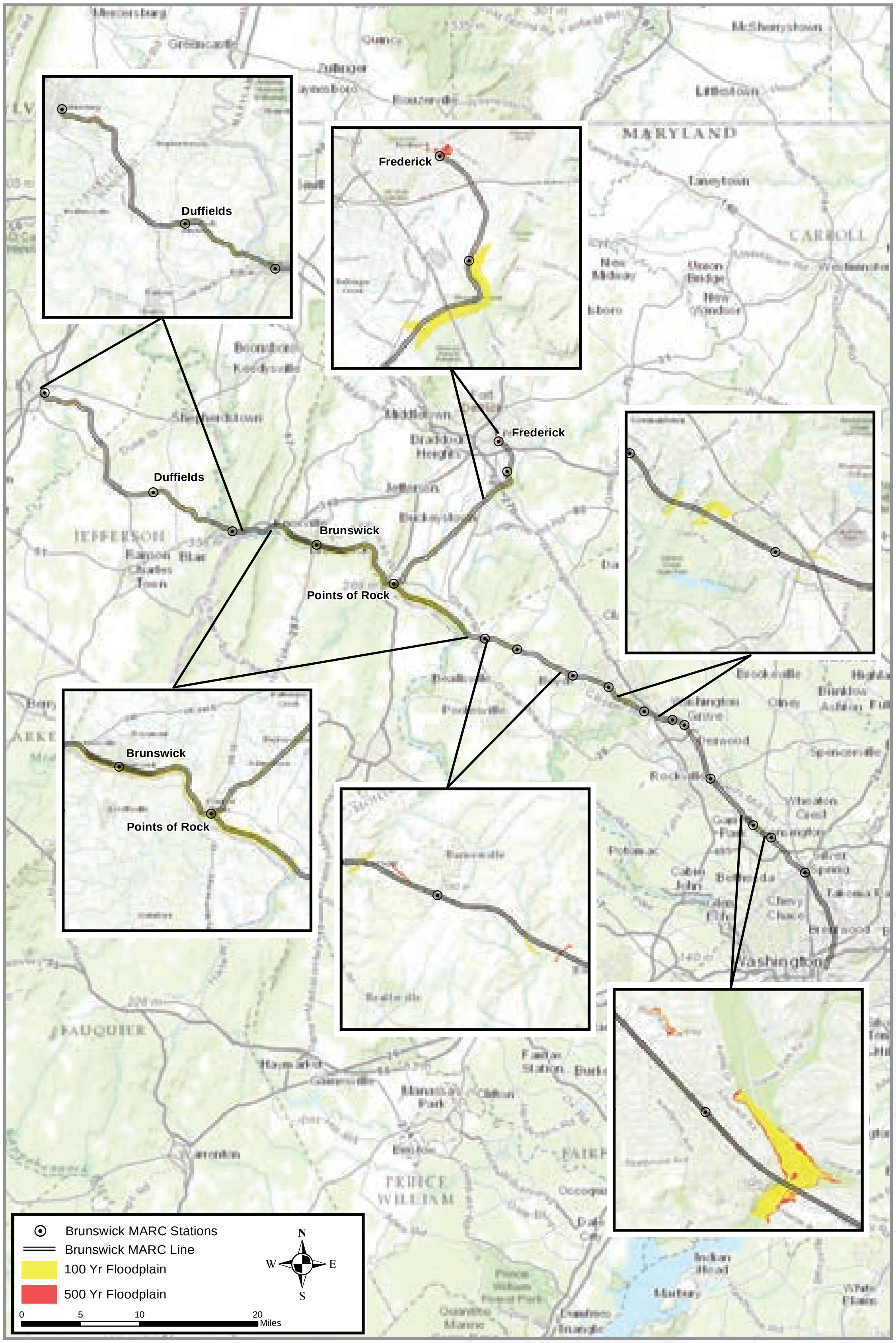


Figure B-2 MARC Stations Floodplain Vulnerability

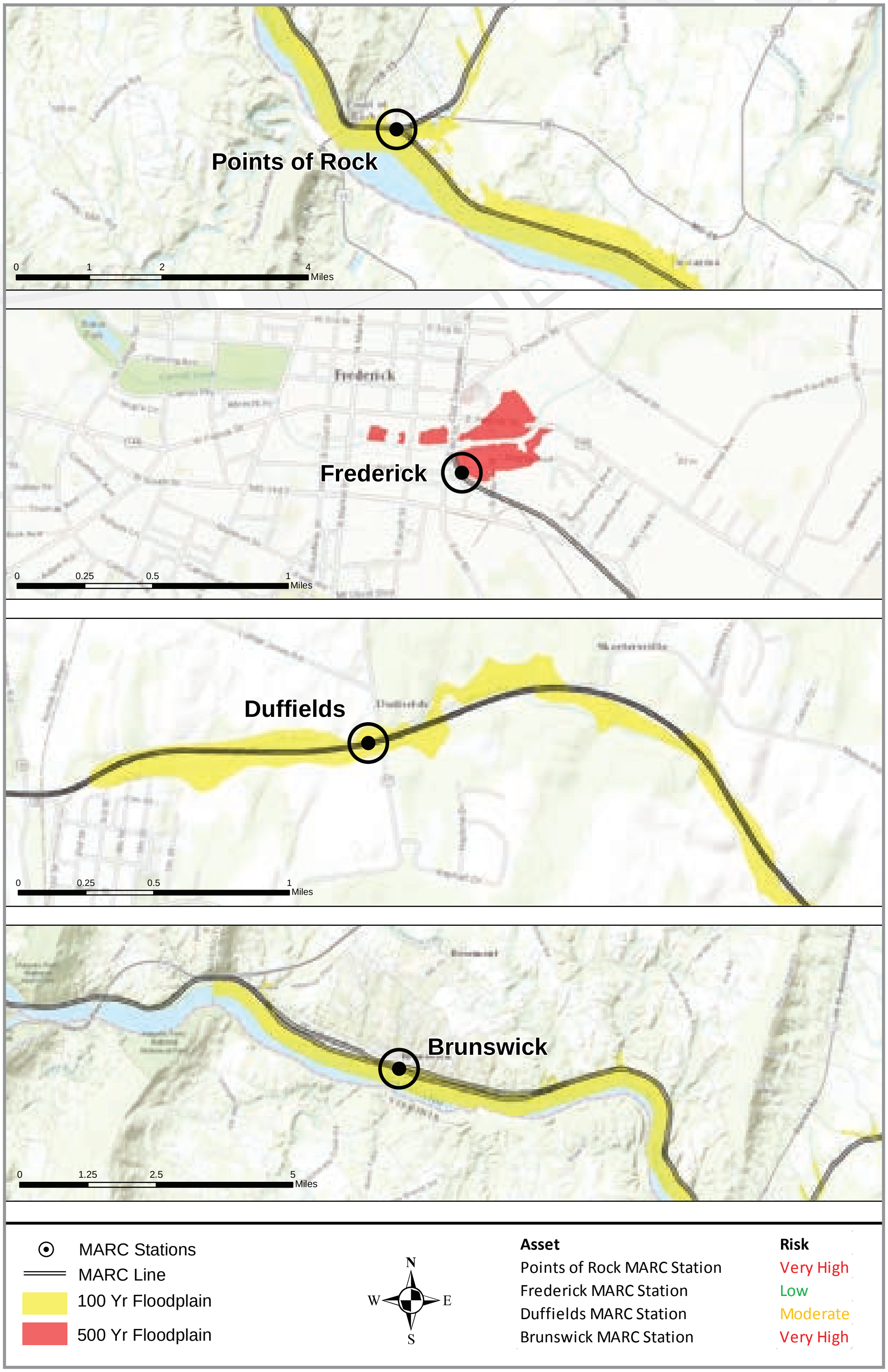


Figure B-3 Camden MARC Floodplain Vulnerability

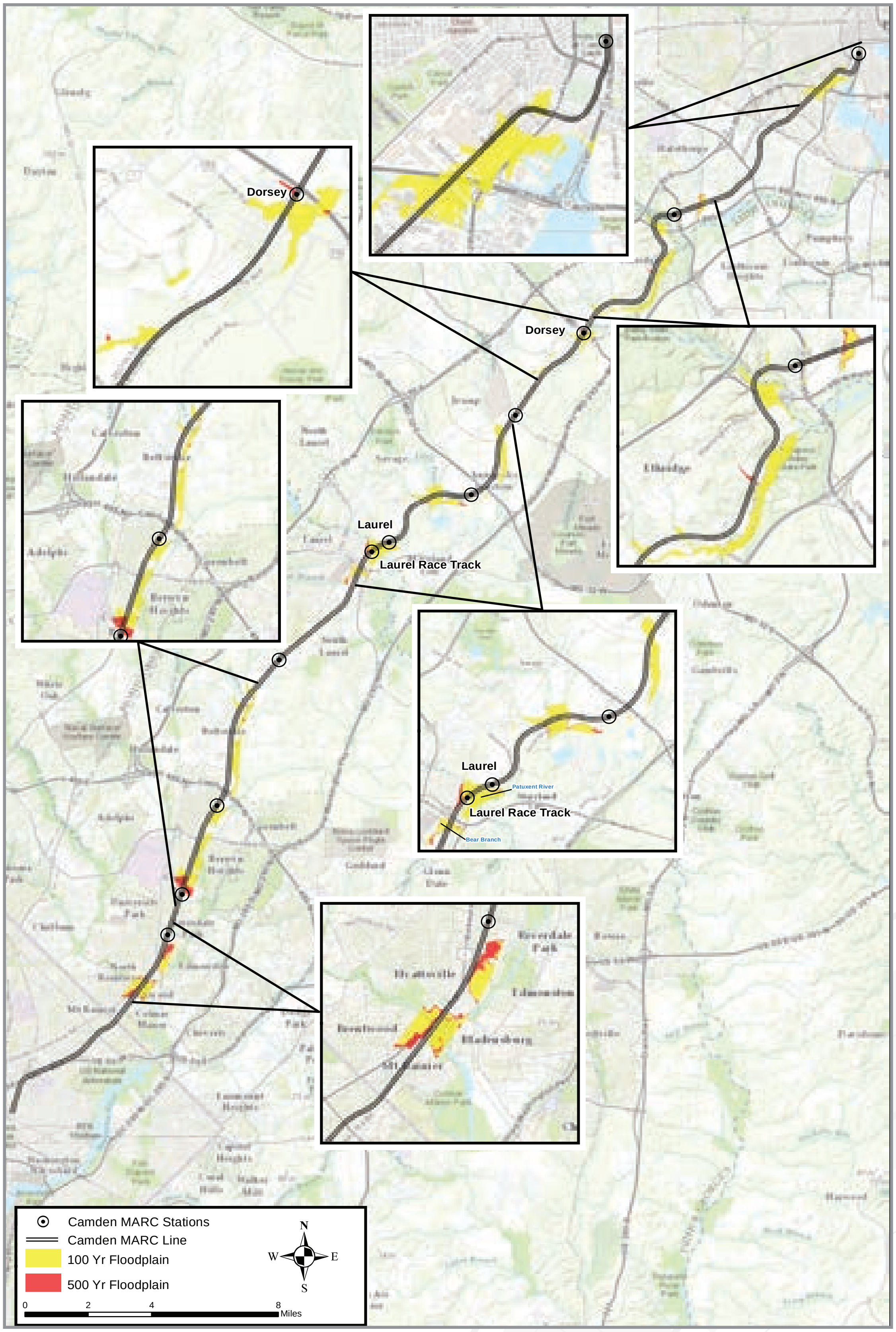


Figure B-4 MARC Station Floodplain Vulnerability

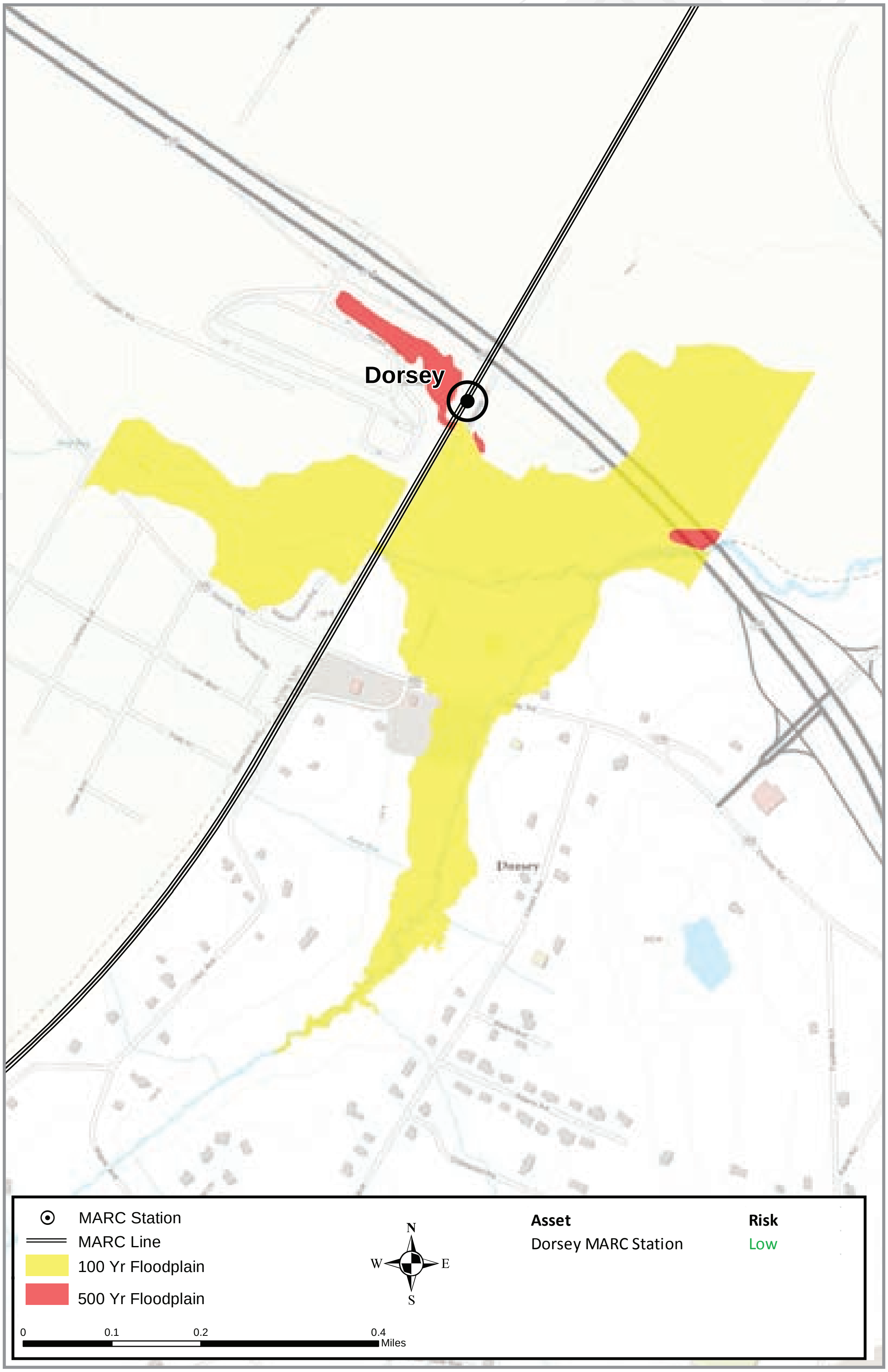


Figure B-5 MARC Station Floodplain Vulnerability

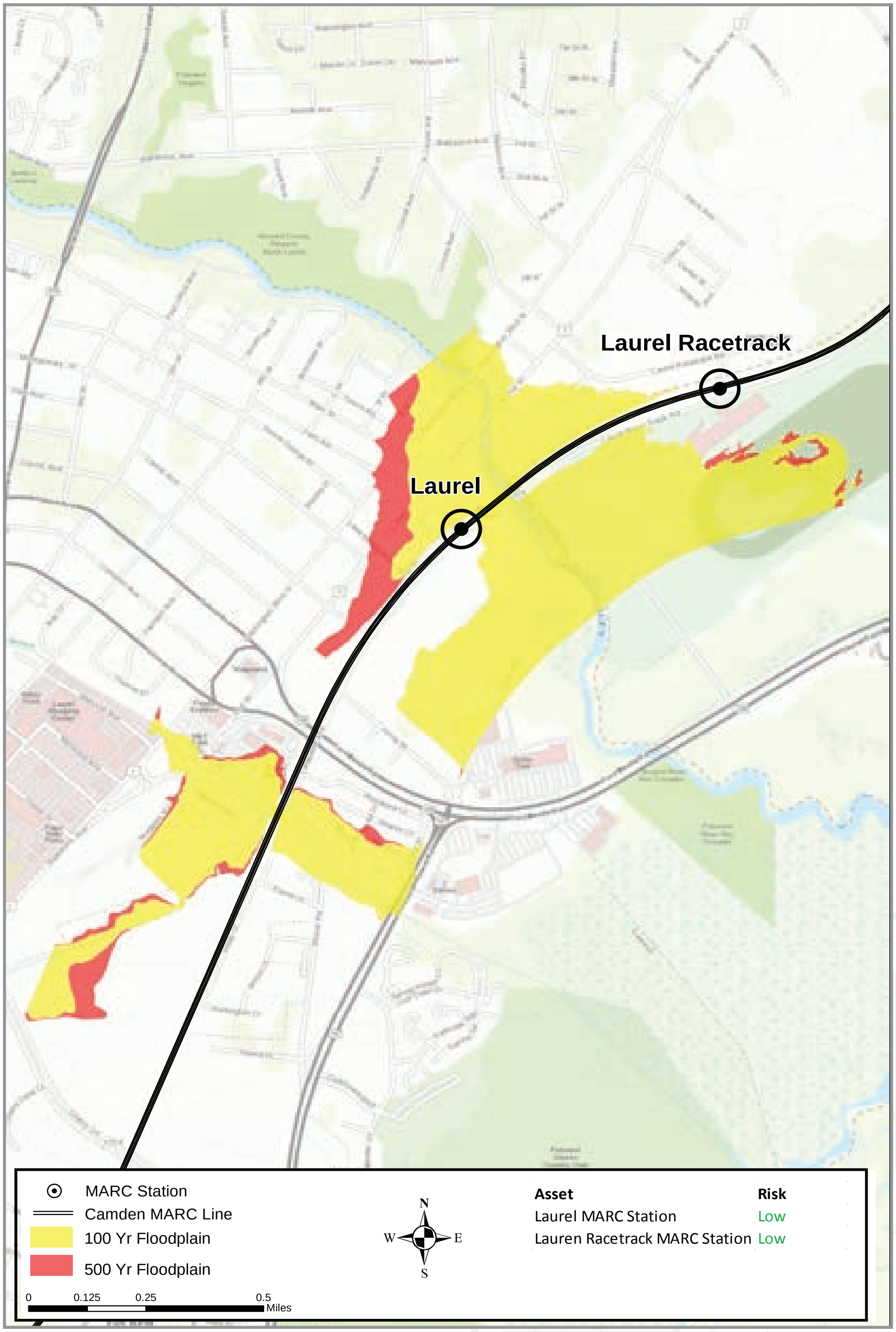


Figure B-6 Penn MARC Floodplain Vulnerability

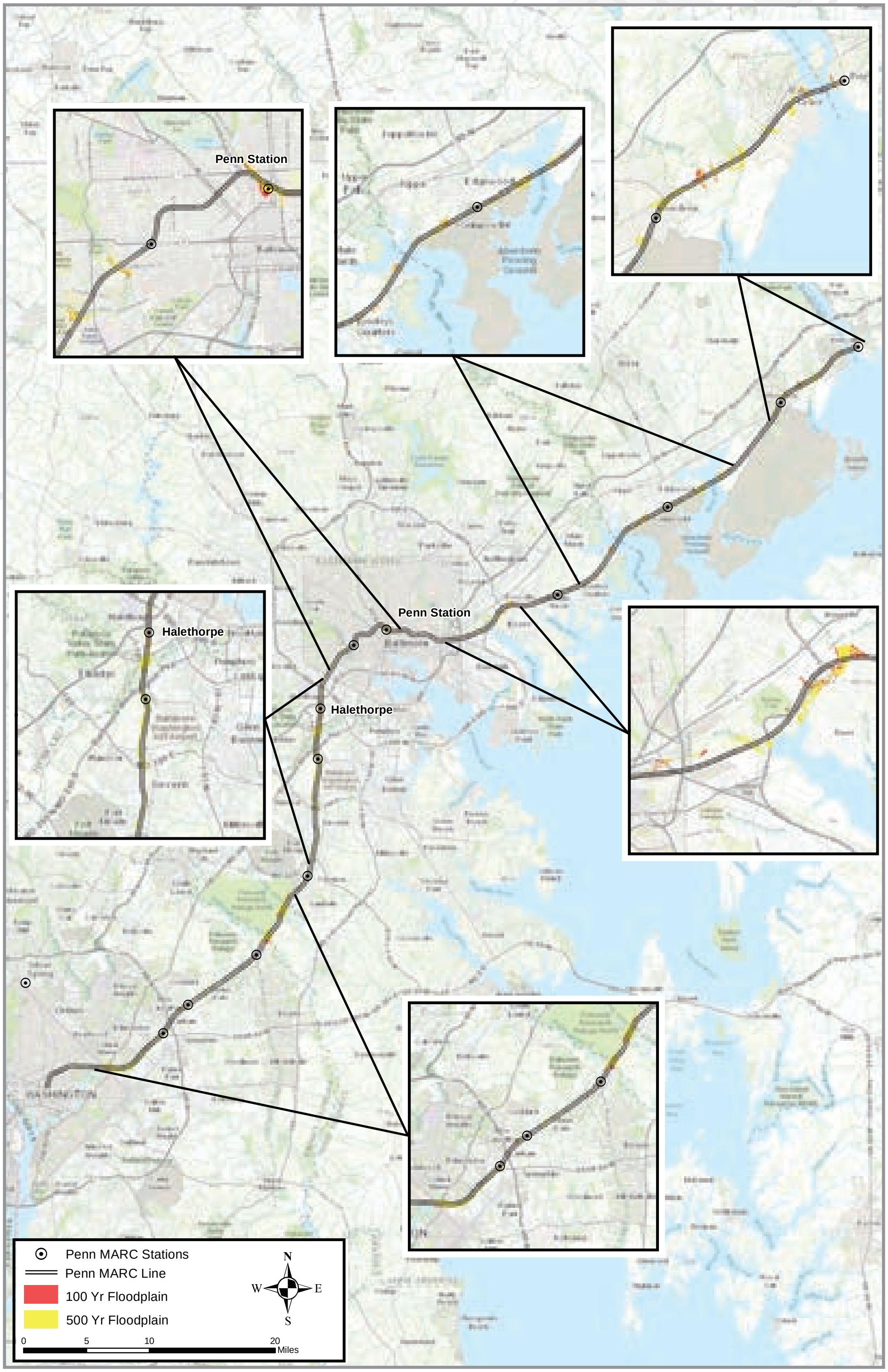
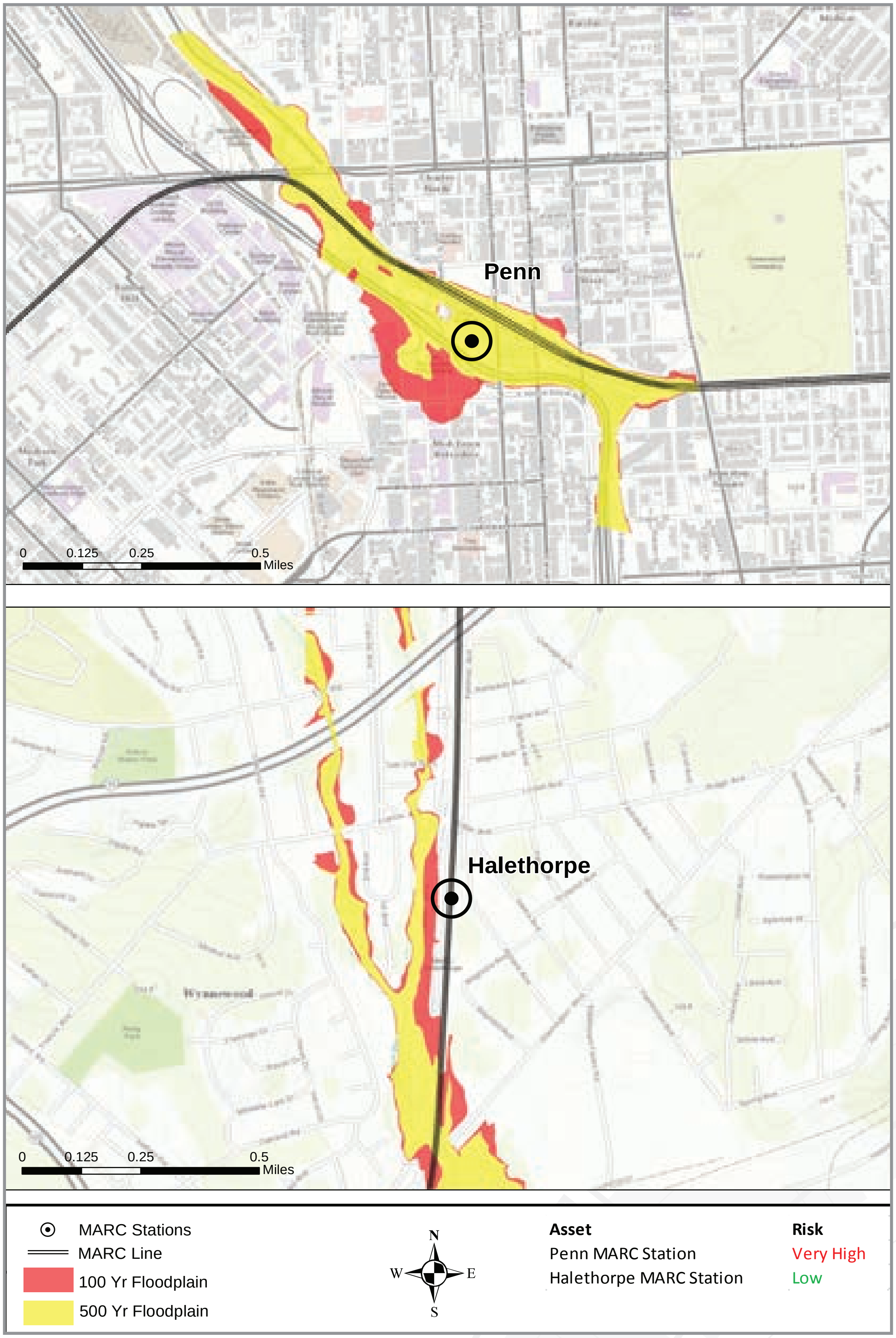


Figure B-7 MARC Stations Floodplain Vulnerability



Appendix C
Light Rail Vulnerability Maps

Figure C-1 Light Rail Floodplain Vulnerability

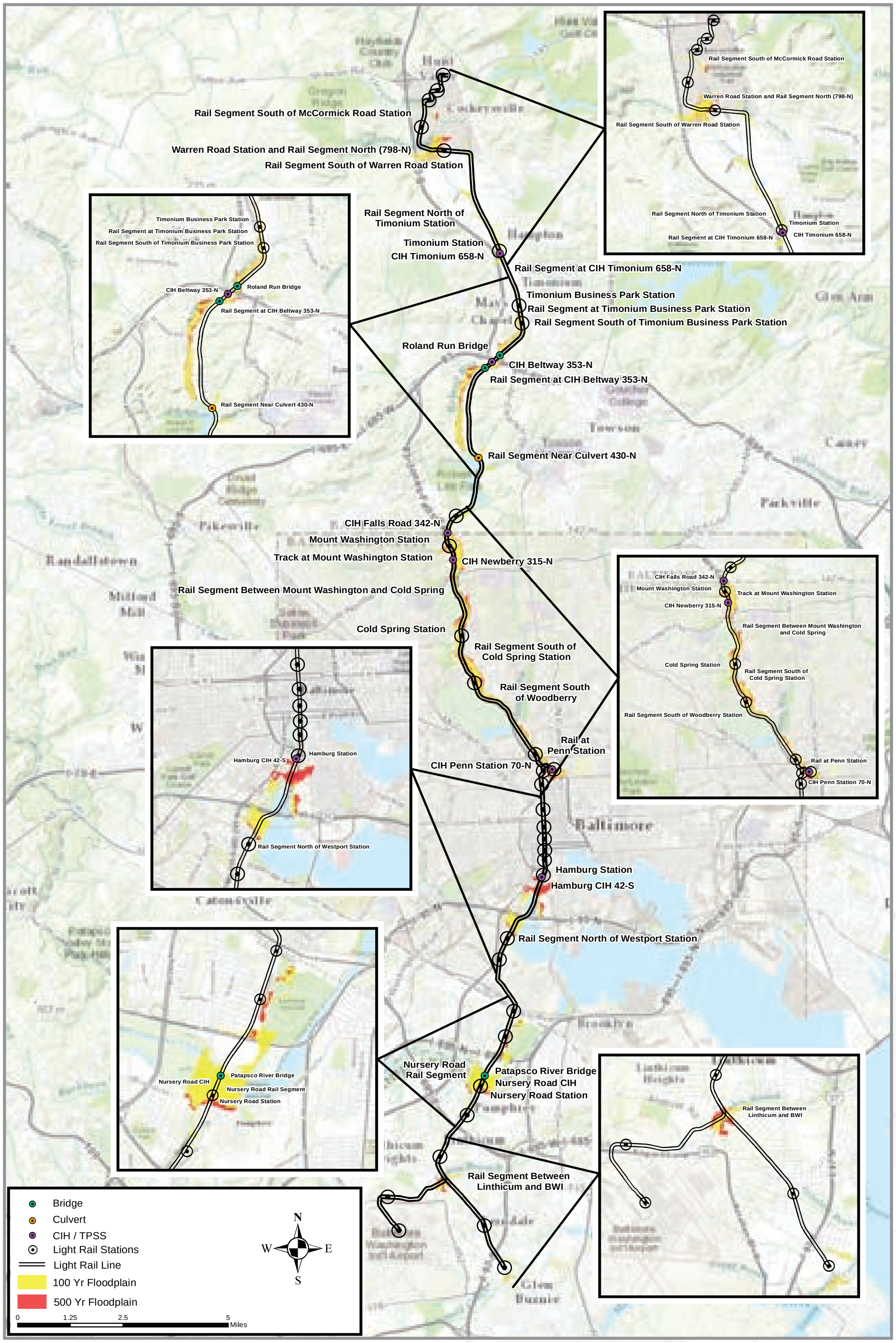


Figure C-2 Light Rail Segments

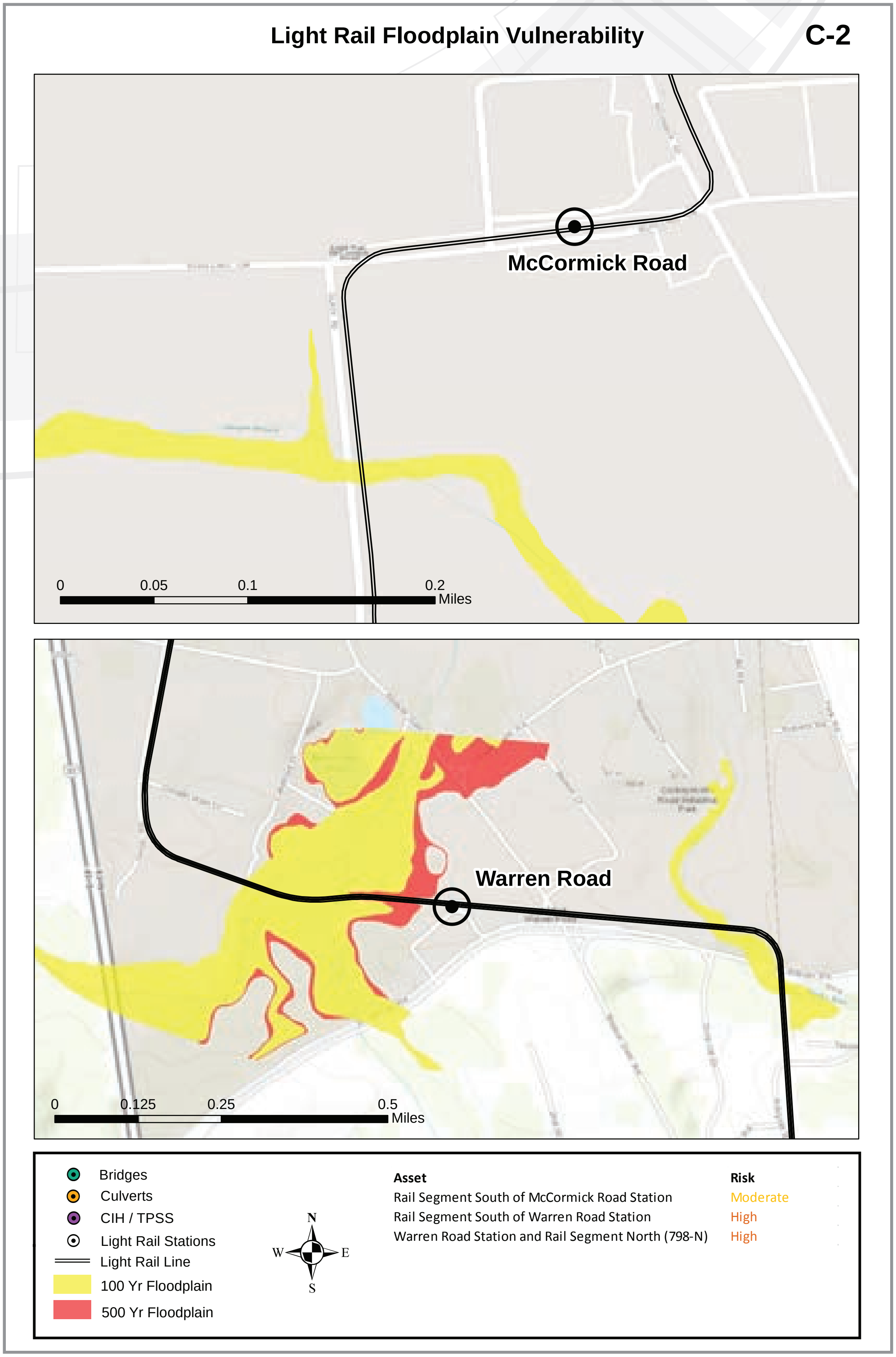
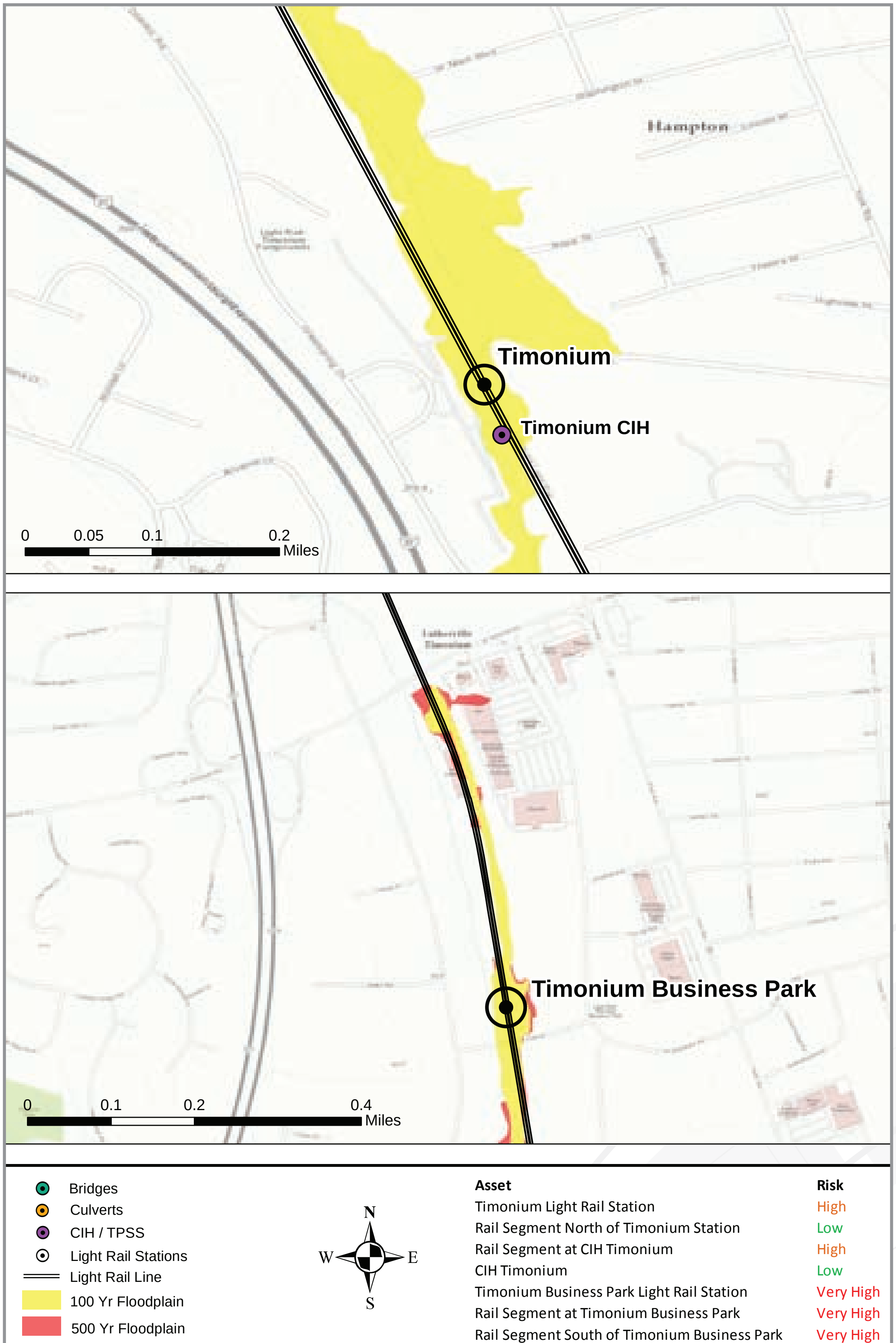
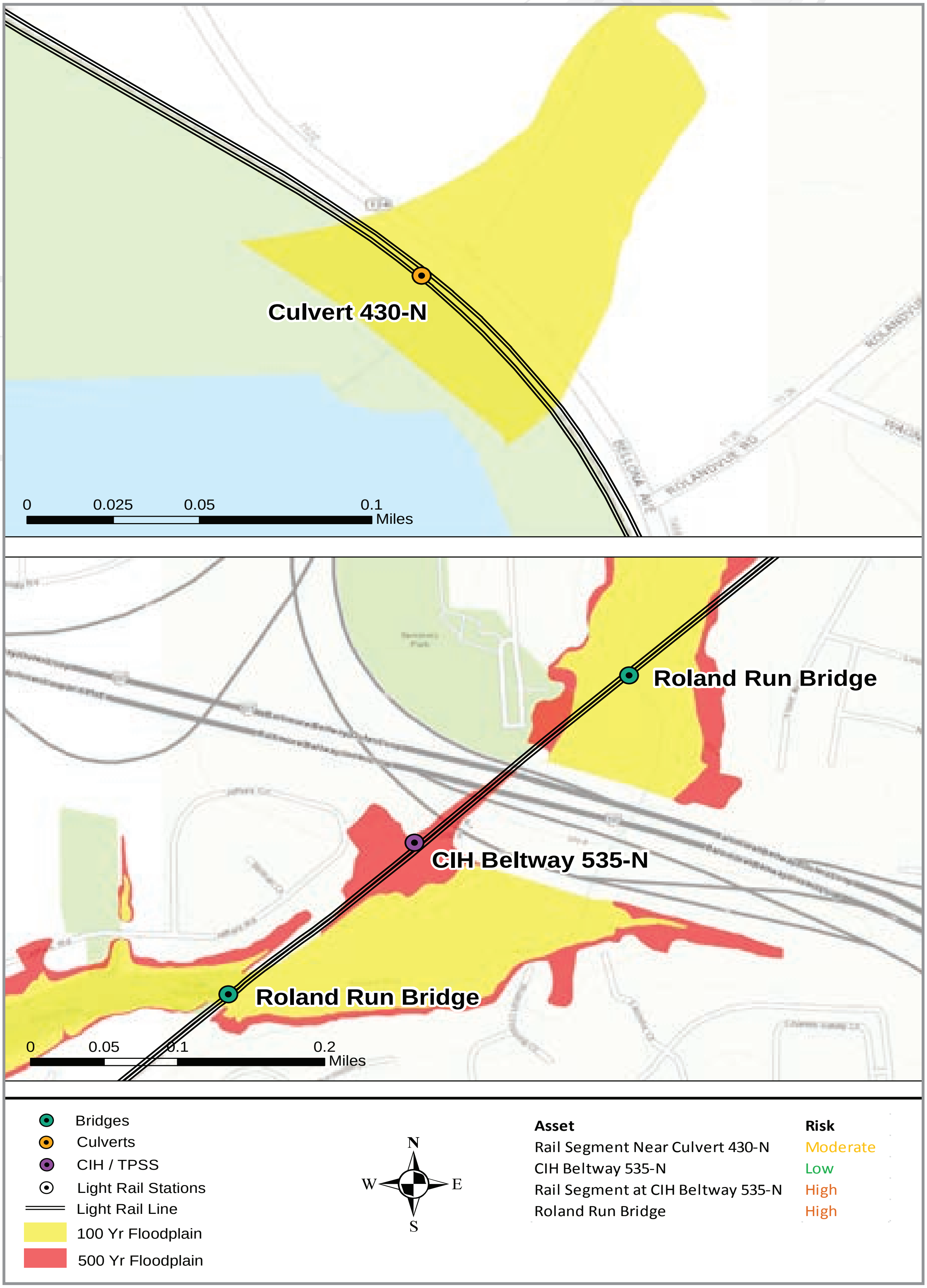


Figure C-3 Light Rail Floodplain Vulnerability



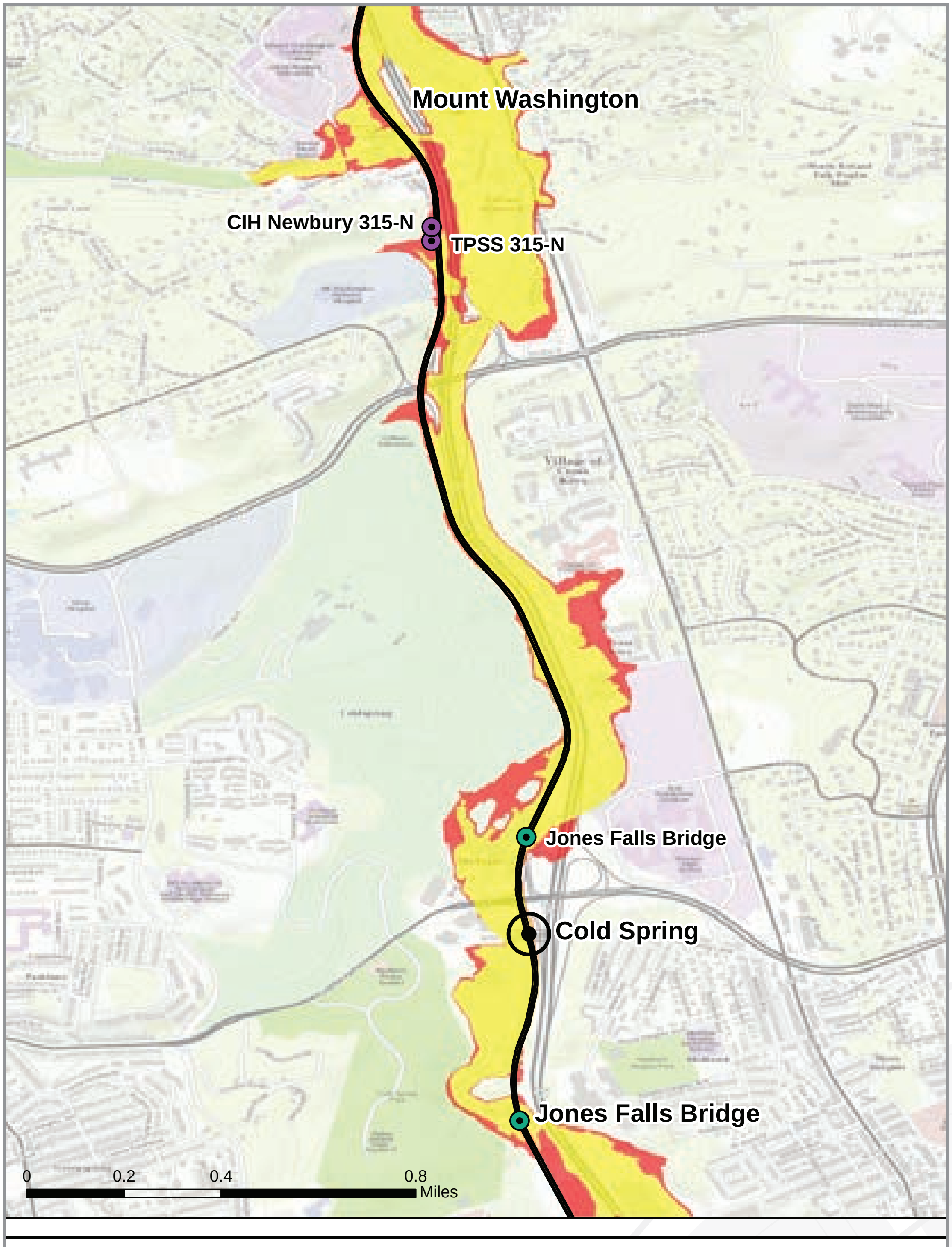
Asset	Risk
Timonium Light Rail Station	High
Rail Segment North of Timonium Station	Low
Rail Segment at CIH Timonium	High
CIH Timonium	Low
Timonium Business Park Light Rail Station	Very High
Rail Segment at Timonium Business Park	Very High
Rail Segment South of Timonium Business Park	Very High

Figure C-4 Light Rail Floodplain Vulnerability



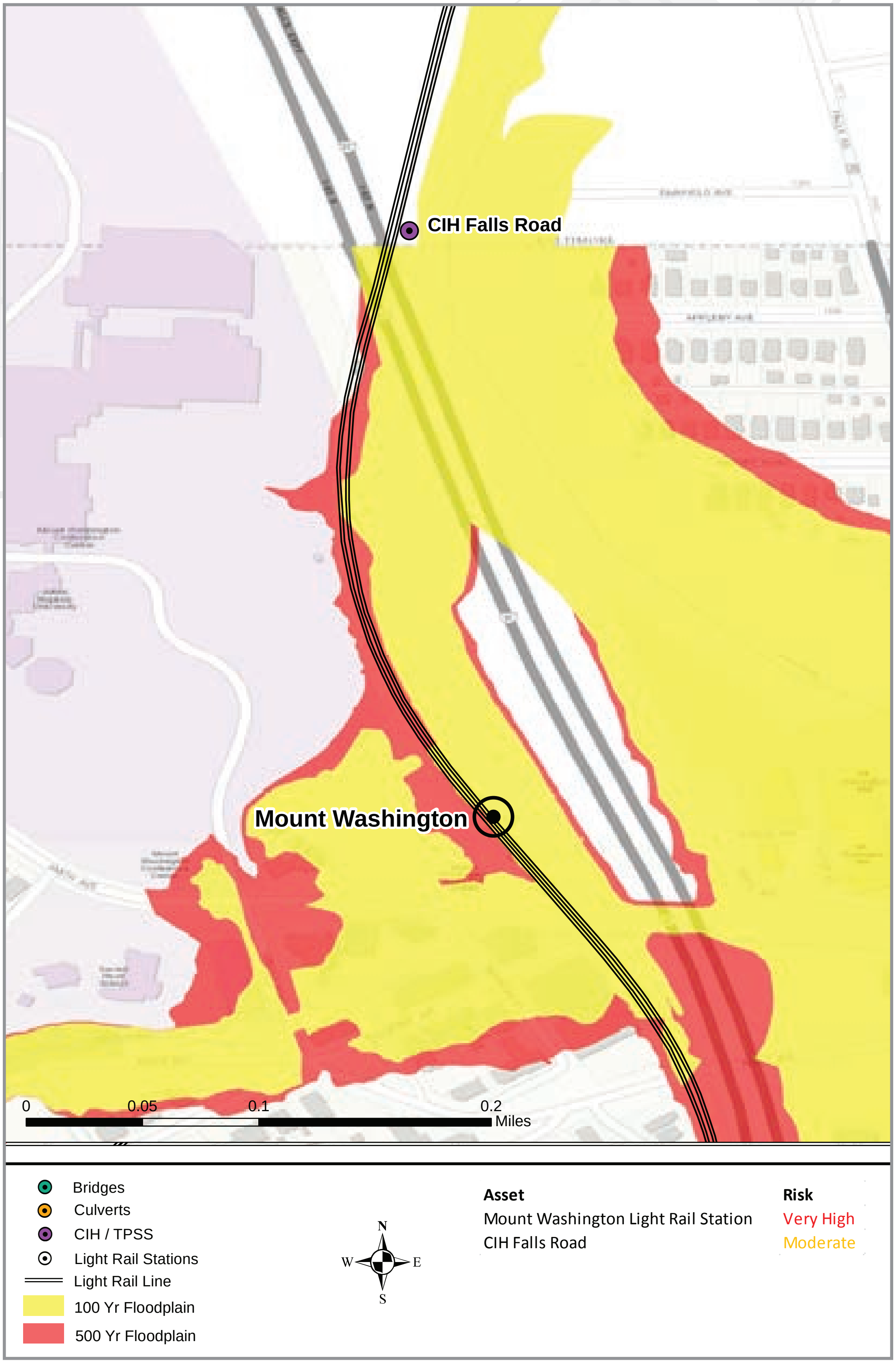
Asset	Risk
Rail Segment Near Culvert 430-N	Moderate
CIH Beltway 535-N	Low
Rail Segment at CIH Beltway 535-N	High
Roland Run Bridge	High

Figure C-5 Light Rail Floodplain Vulnerability



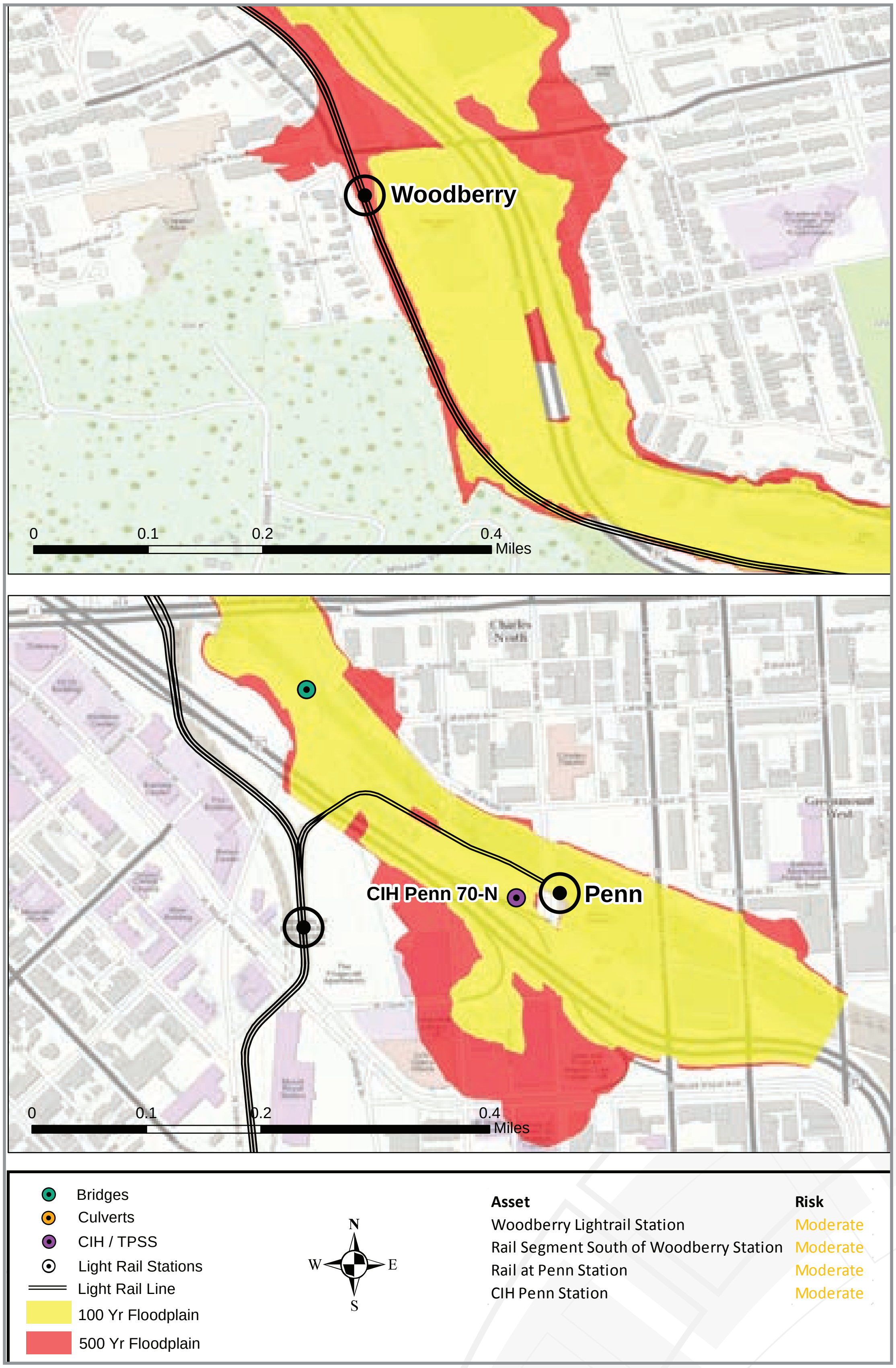
Asset	Risk
Mount Washington Light Rail Station	Very High
Cold Spring Light Rail Station	Very High
Track at Mount Washington Station	Very High
Rail Segment Between Mount Washington and Cold Spring	Very High
Rail Segment South of Cold Spring	Very High
TPSS 315-N	Low
CIH Newbury 315-N	Low

Figure C-6 Light Rail Floodplain Vulnerability



Asset	Risk
Mount Washington Light Rail Station	Very High
CIH Falls Road	Moderate

Figure C-7 Light Rail Floodplain Vulnerability



Asset	Risk
Woodberry Lightrail Station	Moderate
Rail Segment South of Woodberry Station	Moderate
Rail at Penn Station	Moderate
CIH Penn Station	Moderate

Figure C-8 Light Rail Floodplain Vulnerability

Figure C-9 Light Rail Hurricane Storm Surge Vulnerability

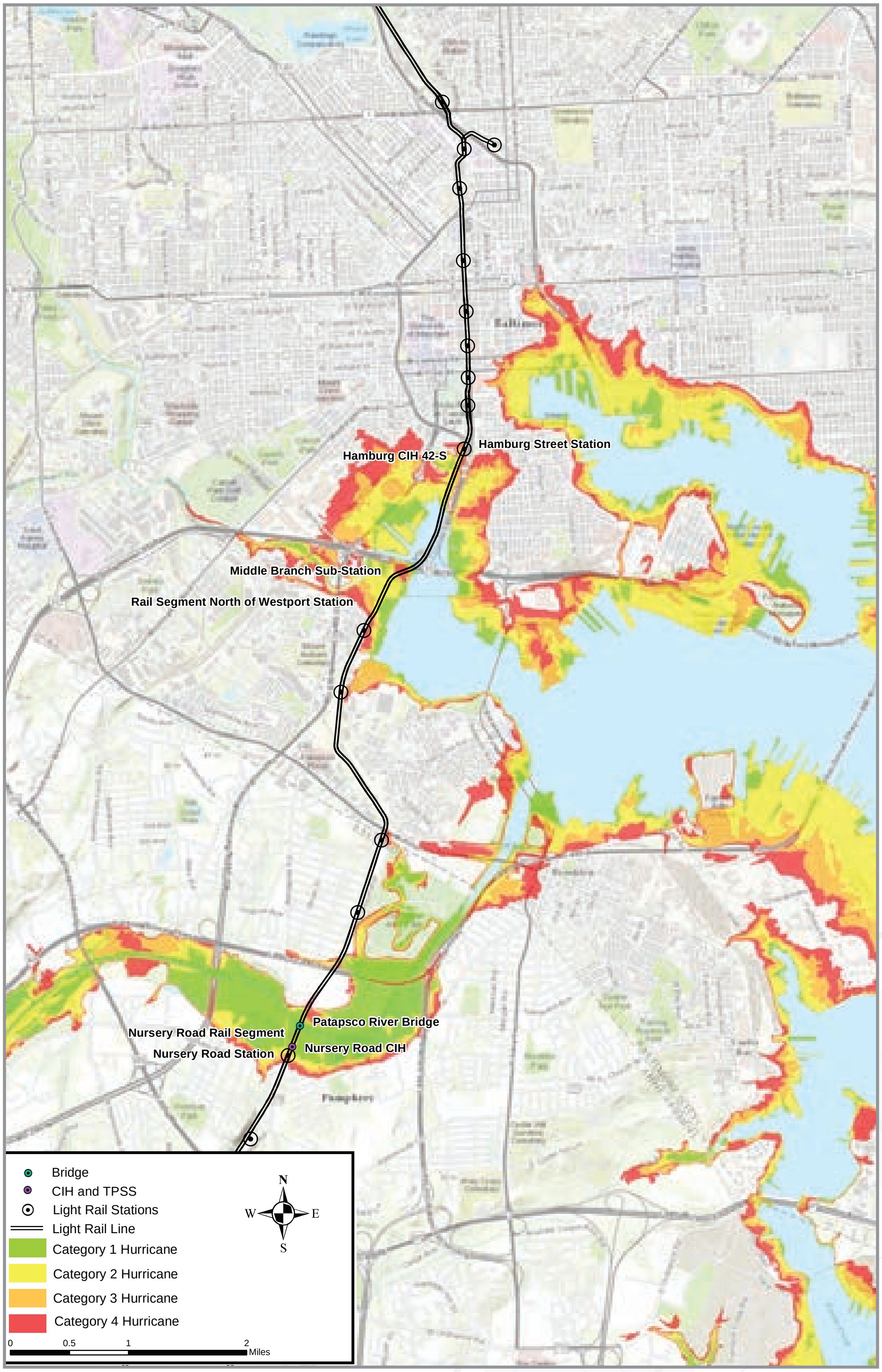


Figure C-10 Light Rail Floodplain and Hurricane Storm Surge Vulnerability

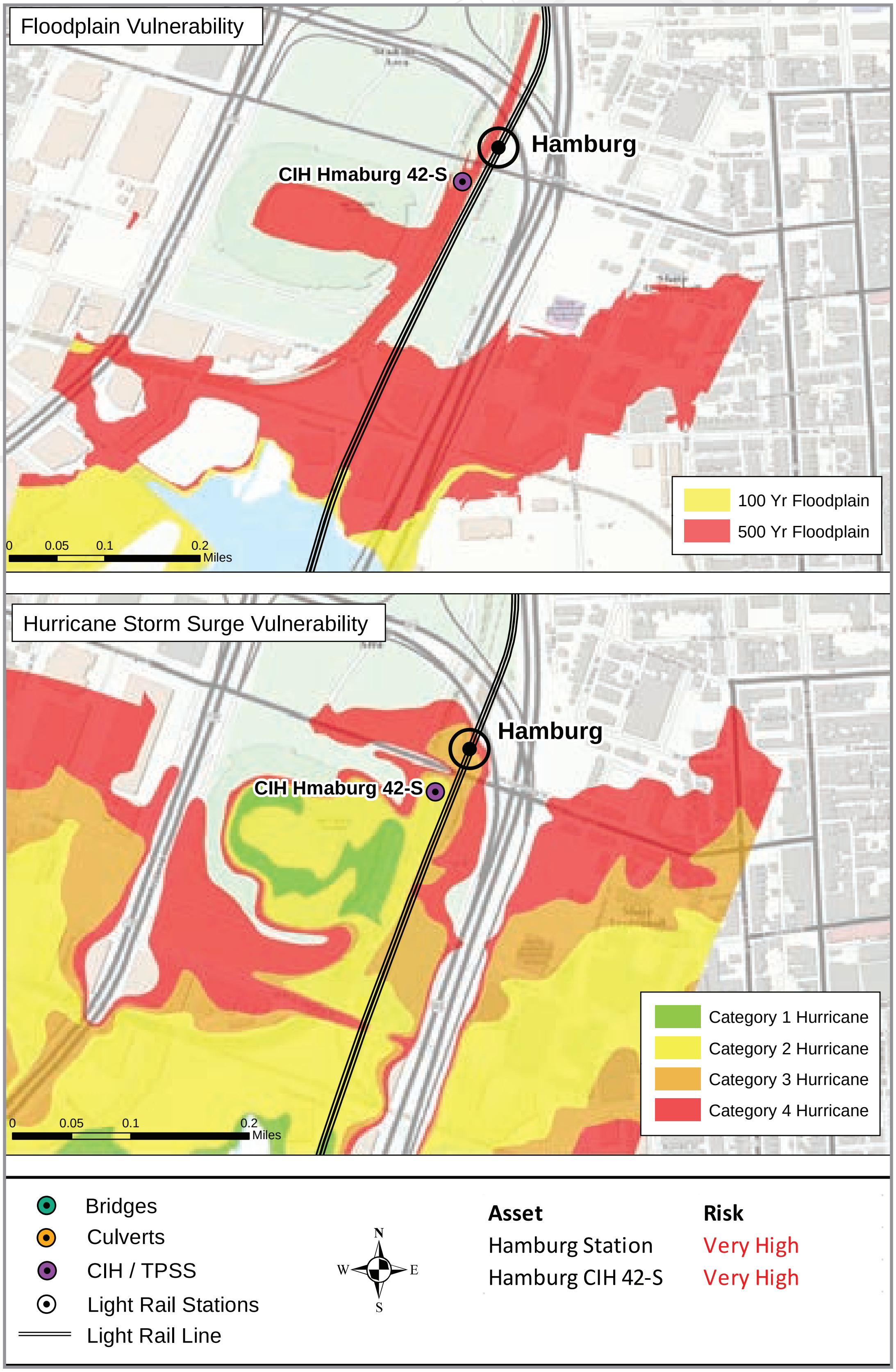


Figure C-11 Light Rail Floodplain and Hurricane Storm Surge Vulnerability

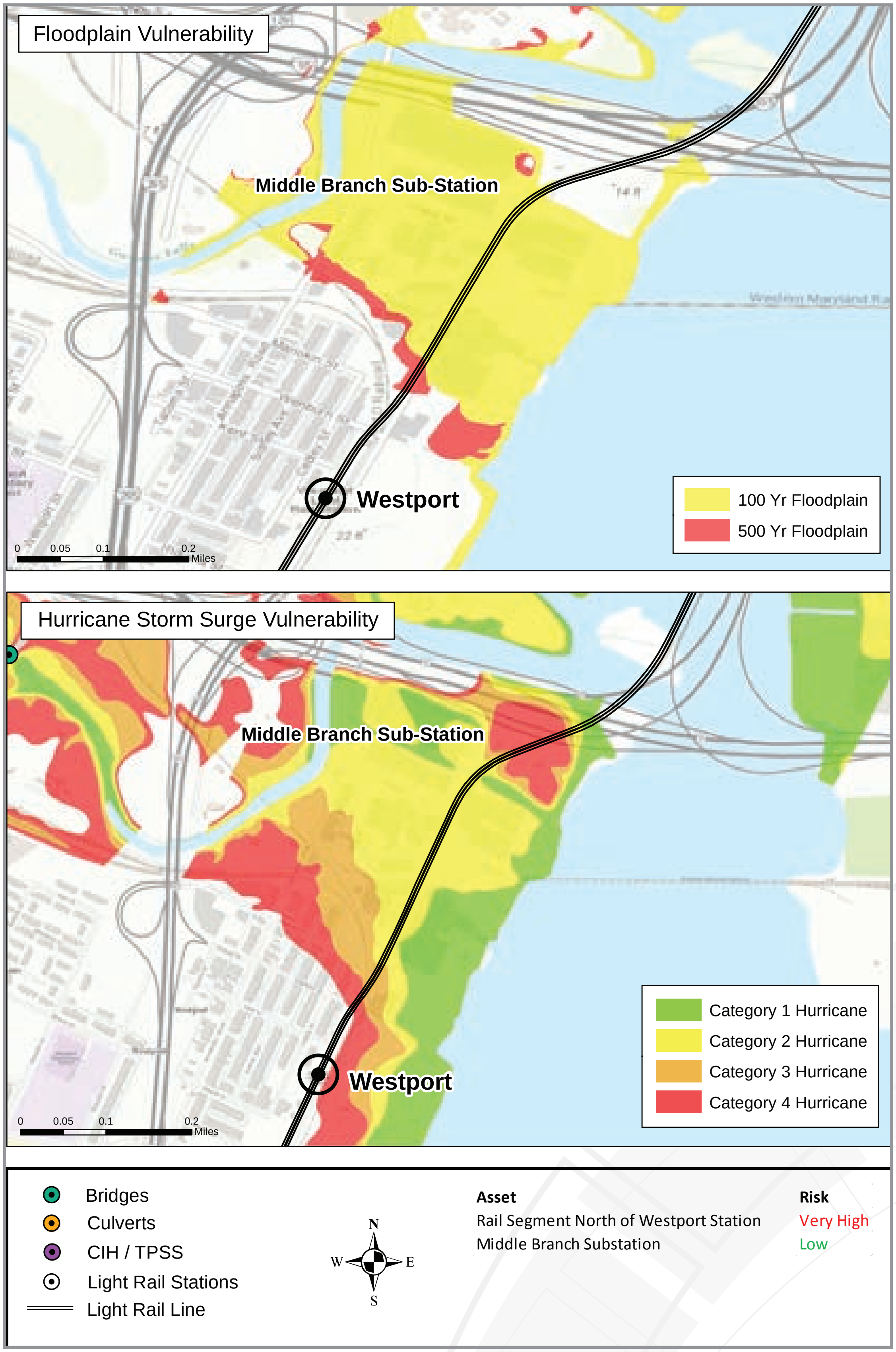
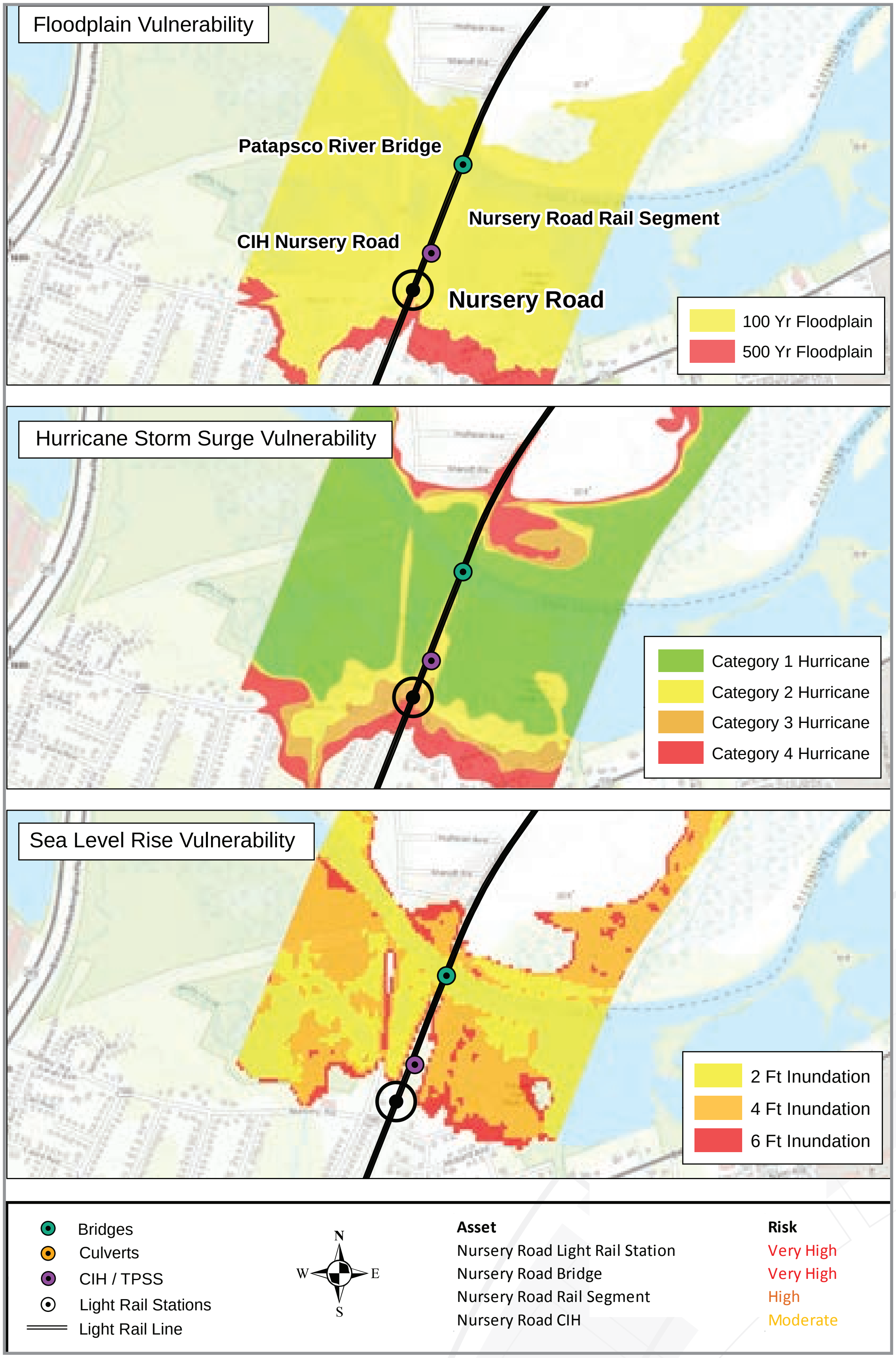


Figure C-12 Light Rail Sea Level Rise Vulnerability

Figure C-13 Light Rail Floodplain and Hurricane Storm Surge Vulnerability



Appendix D
Metro Vulnerability Maps

Figure D-1 METRO Floodplain Vulnerability

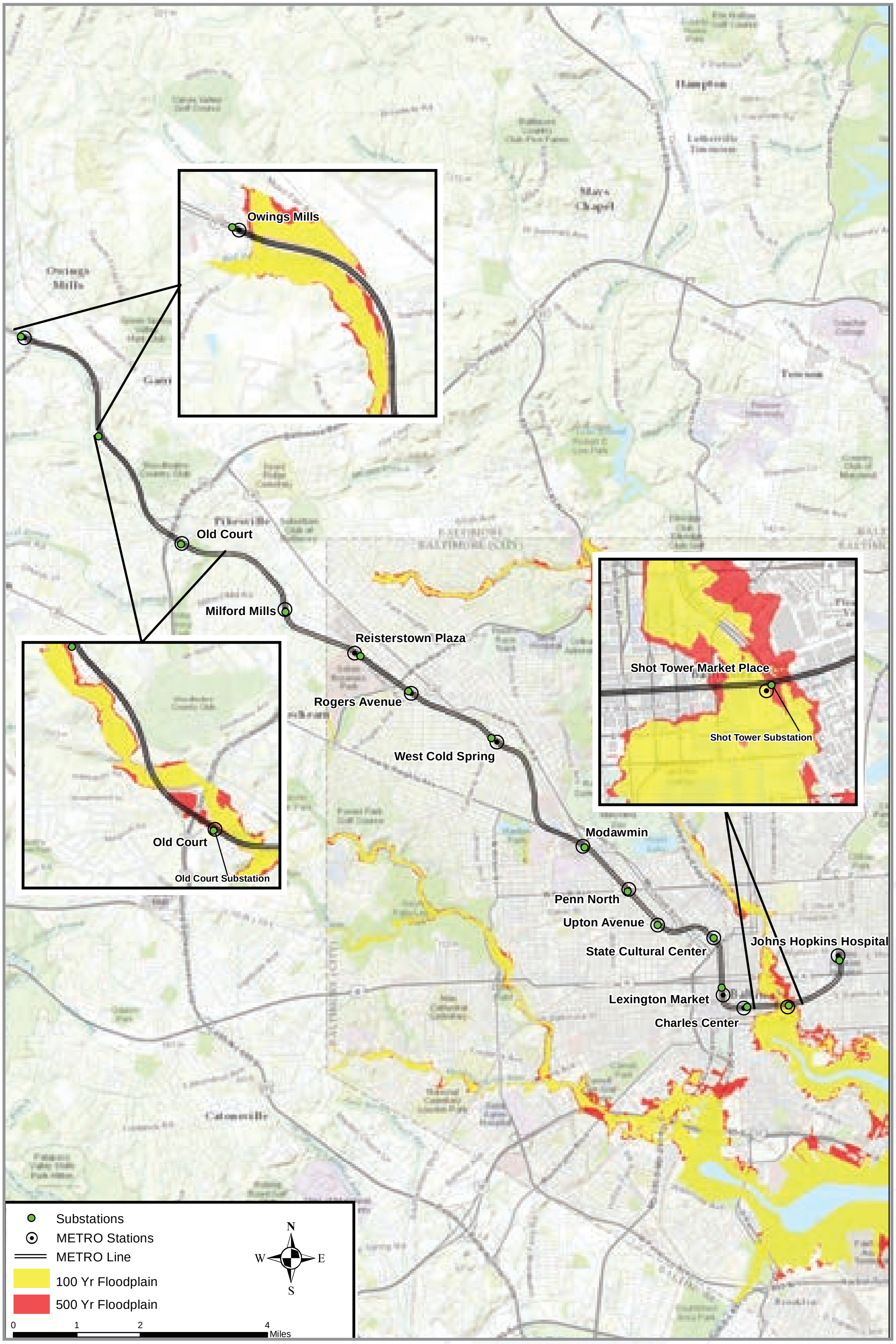
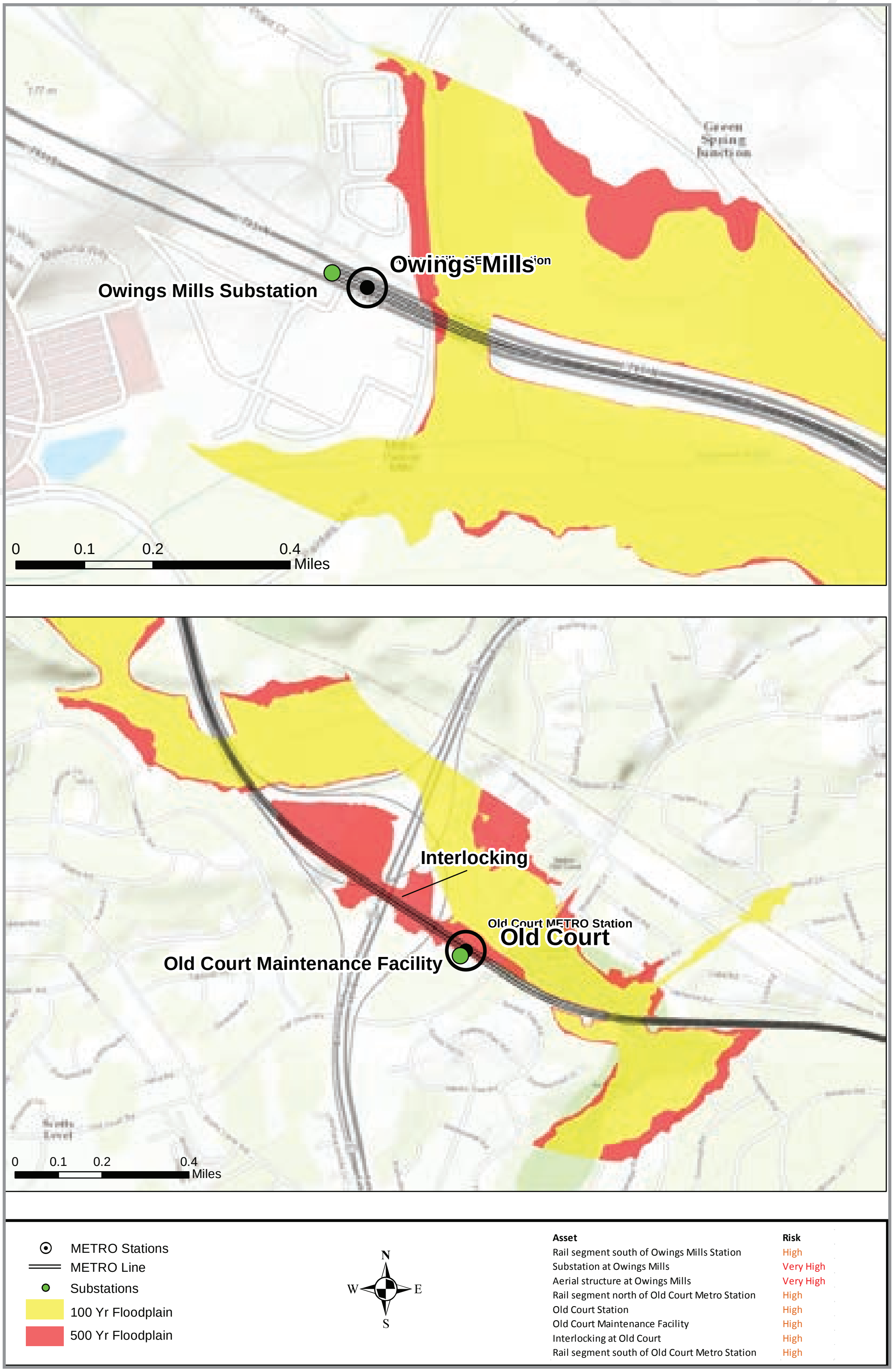
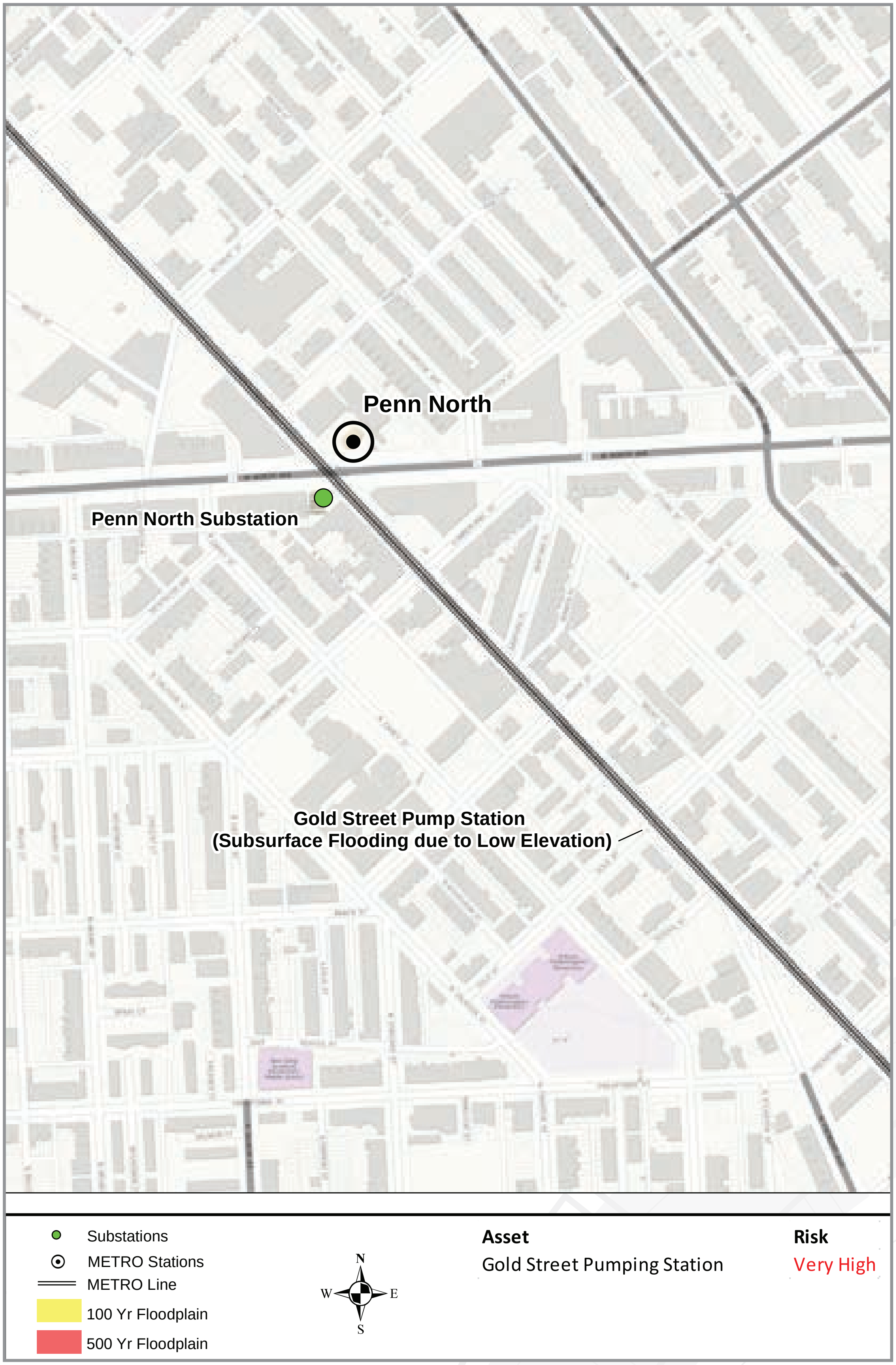


Figure D-2 METRO Floodplain Vulnerability



Asset	Risk
Rail segment south of Owings Mills Station	High
Substation at Owings Mills	Very High
Aerial structure at Owings Mills	Very High
Rail segment north of Old Court Metro Station	High
Old Court Station	High
Old Court Maintenance Facility	High
Interlocking at Old Court	High
Rail segment south of Old Court Metro Station	High

Figure D-3 METRO Floodplain Vulnerability



Asset	Risk
Gold Street Pumping Station	Very High

Figure D-4 METRO Hurricane Storm Surge Vulnerability

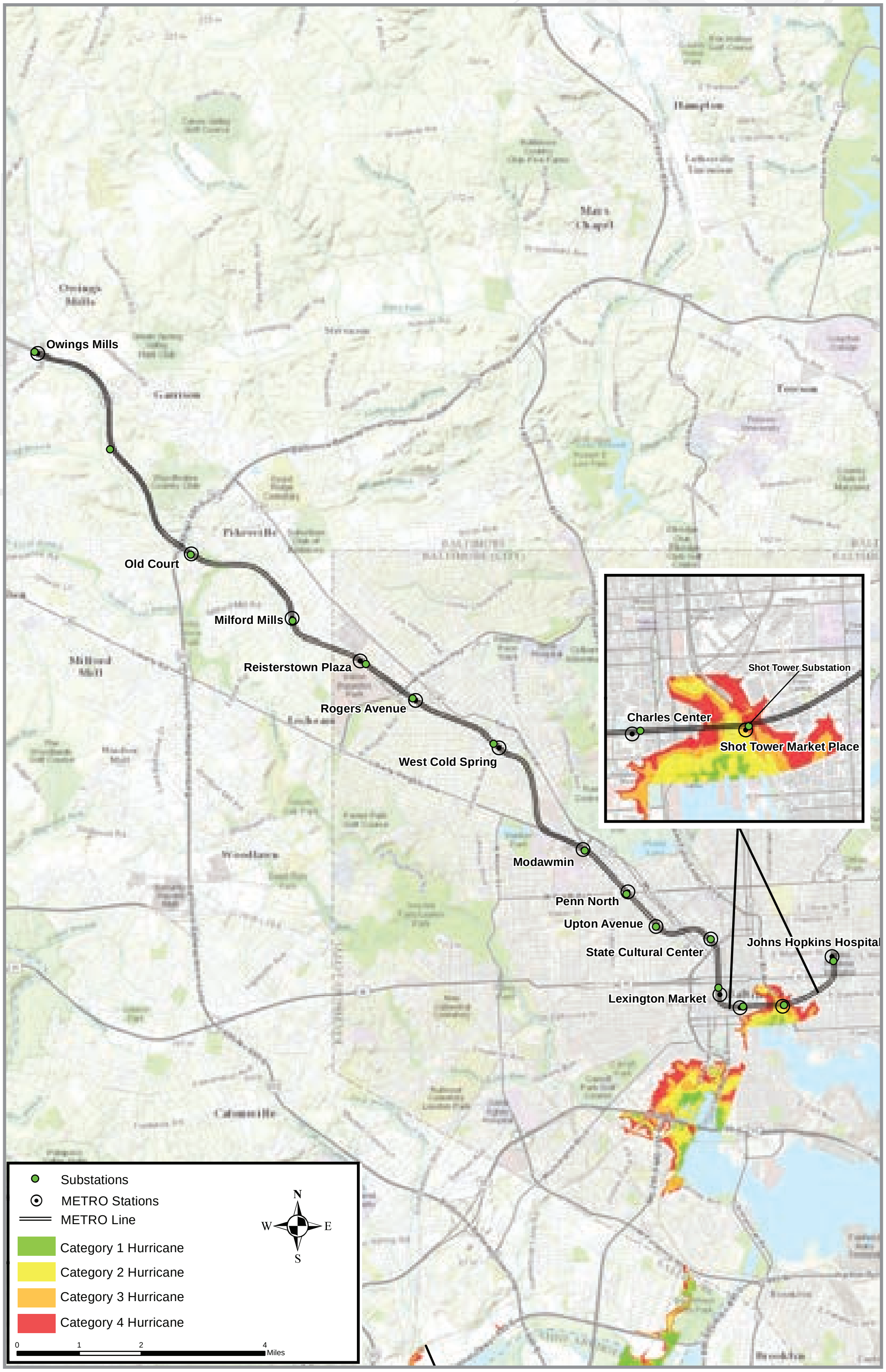
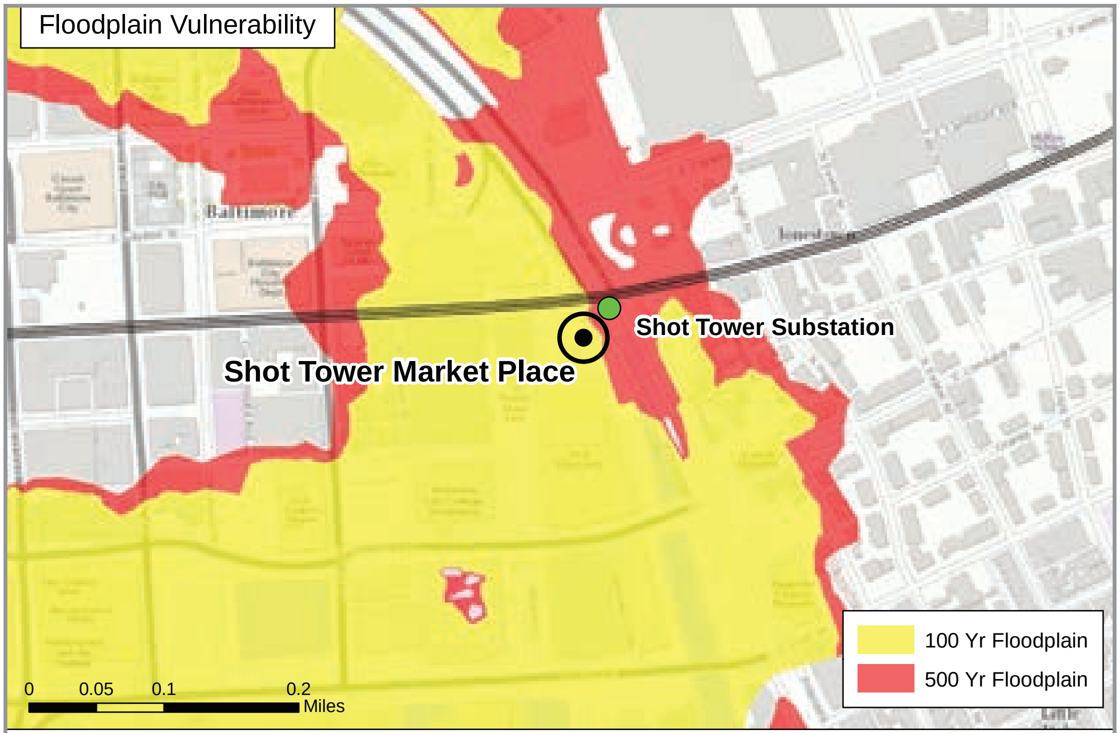
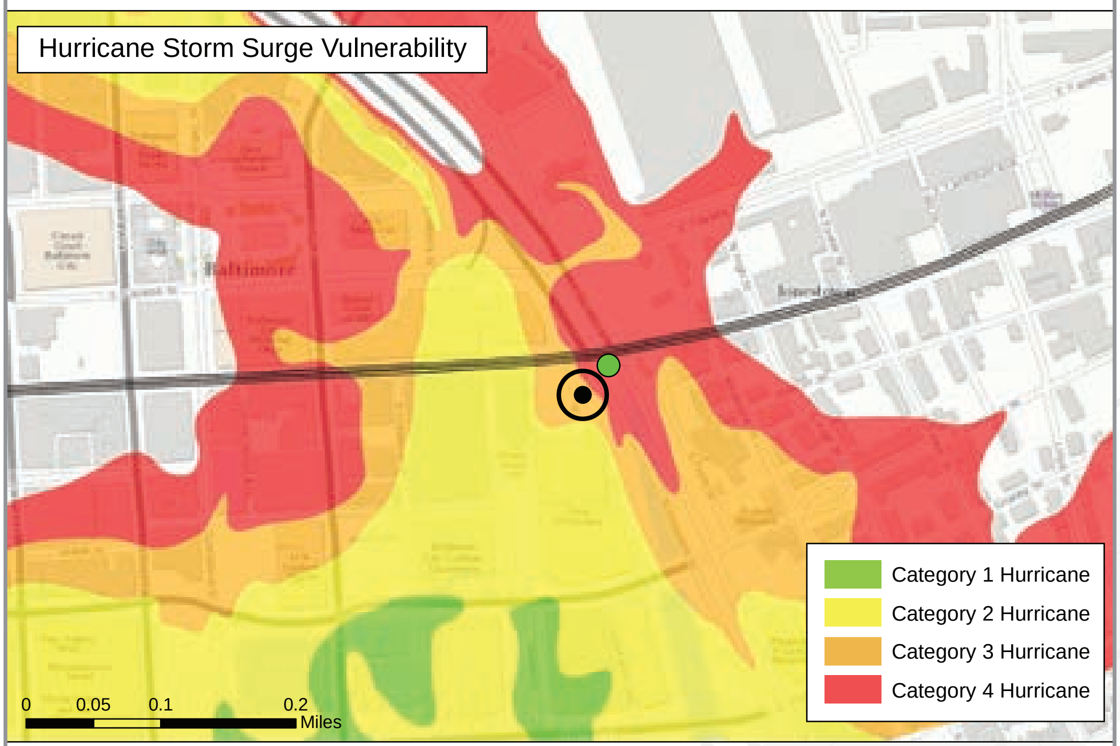


Figure D-5 METRO Floodplain Vulnerability





Substations
METRO Stations
METRO Line
100 Yr Floodplain
500 Yr Floodplain

Asset	Risk
Shot Tower Market Place Station	Very High
Pumps at Shot Tower	Very High
Substation at Shot Tower	Very High

Appendix E
Freight Vulnerability Maps

Figure E-1 Freight Rail Floodplain Vulnerability (North)

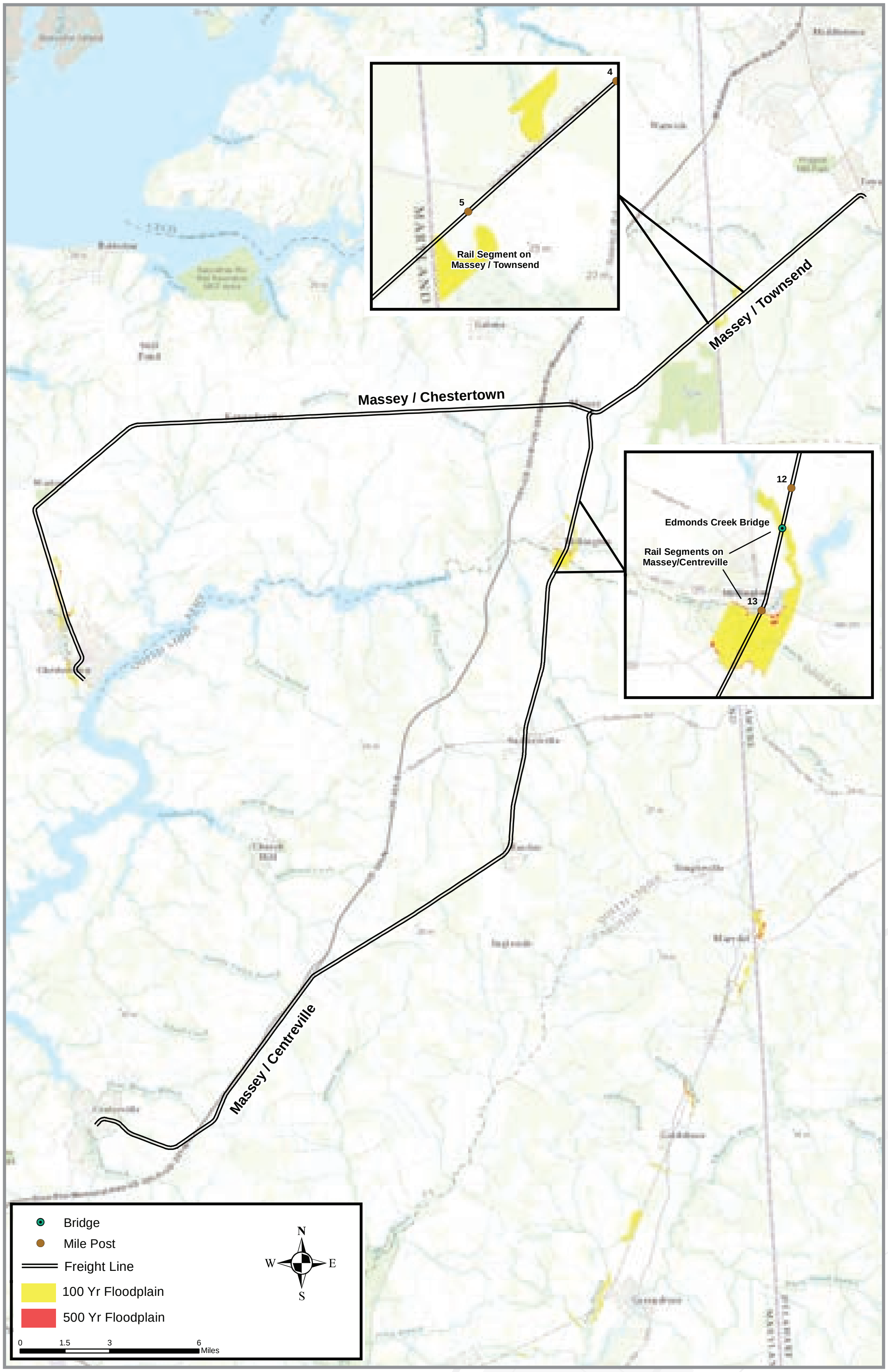


Figure E-2 Freight Rail Floodplain Vulnerability (South)

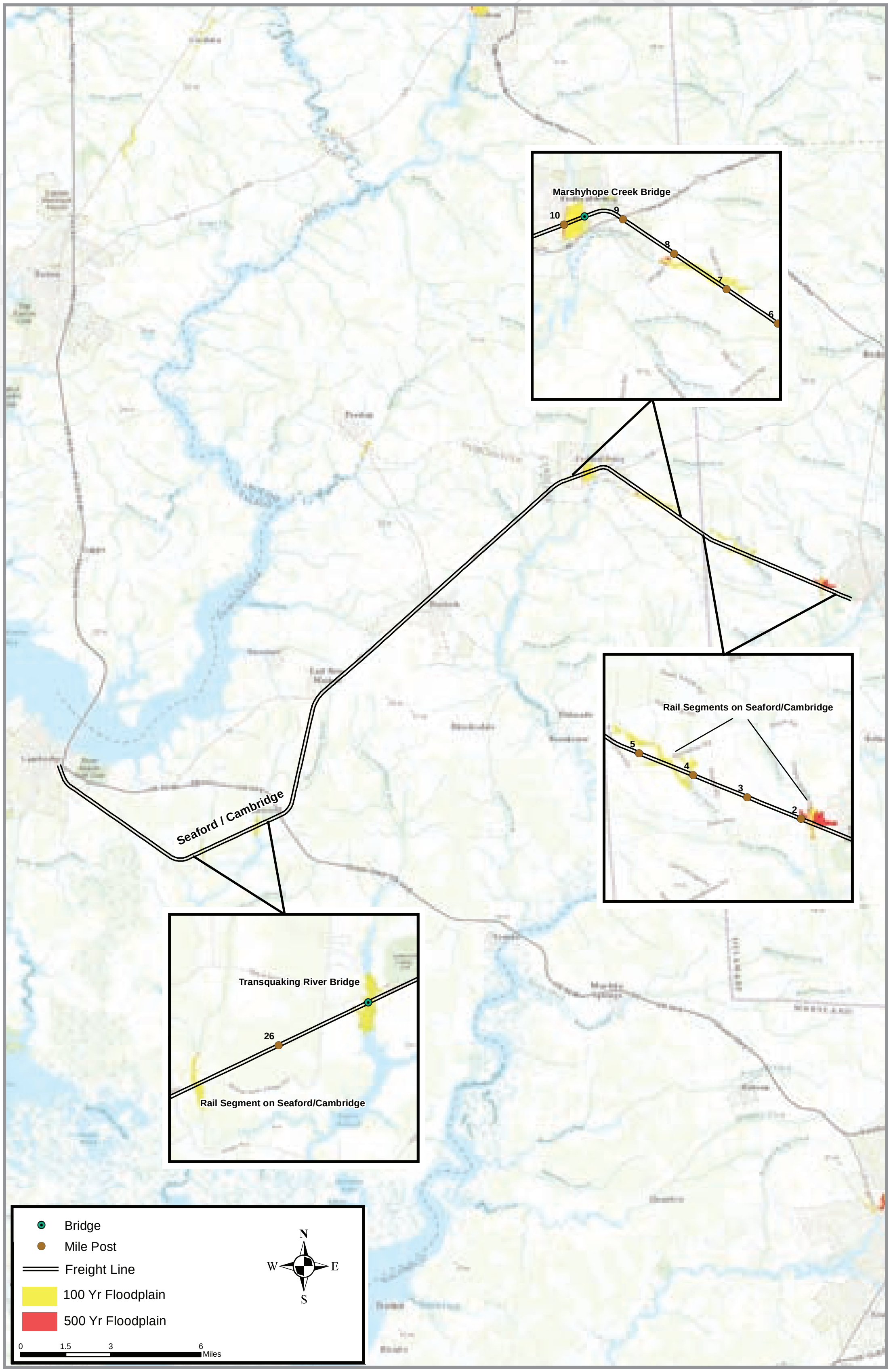


Figure E-3 Freight Rail Floodplain Vulnerability (West)

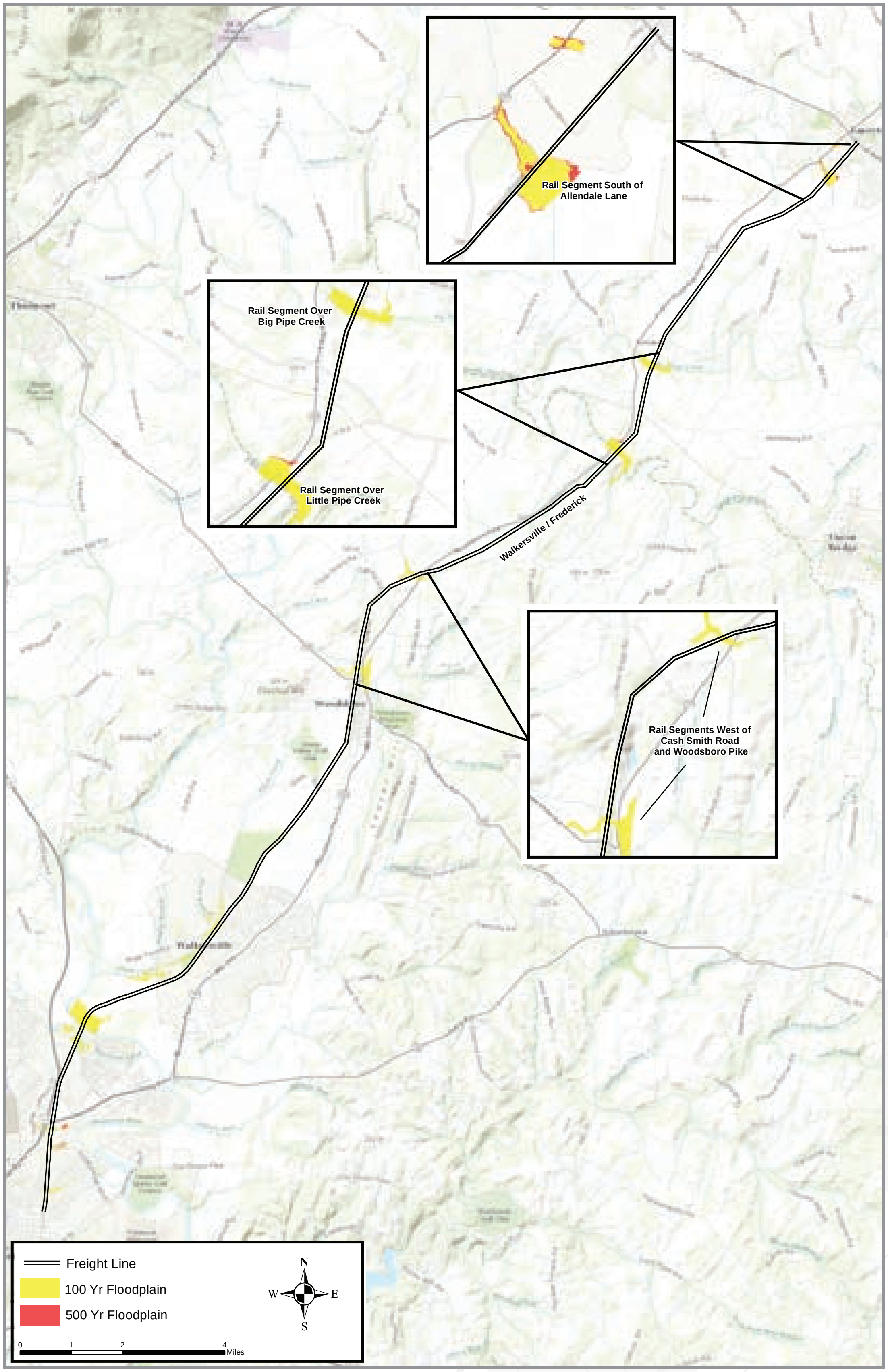
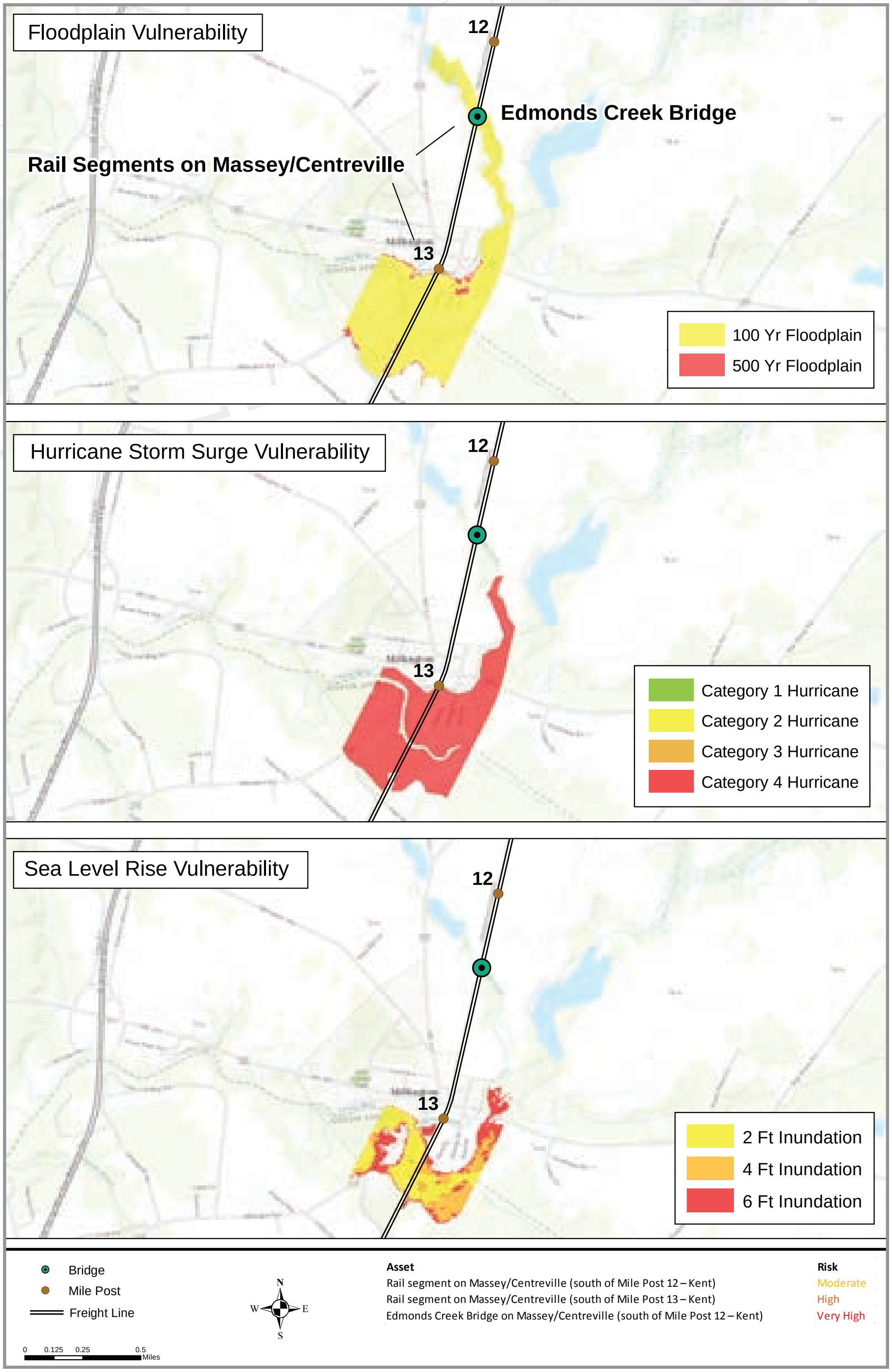


Figure E-4 Freight Rail Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability



Asset	Risk
Rail segment on Massey/Centreville (south of Mile Post 12 – Kent)	Moderate
Rail segment on Massey/Centreville (south of Mile Post 13 – Kent)	High
Edmonds Creek Bridge on Massey/Centreville (south of Mile Post 12 – Kent)	Very High

Figure E-5 Freight Rail Floodplain Vulnerability (DE)

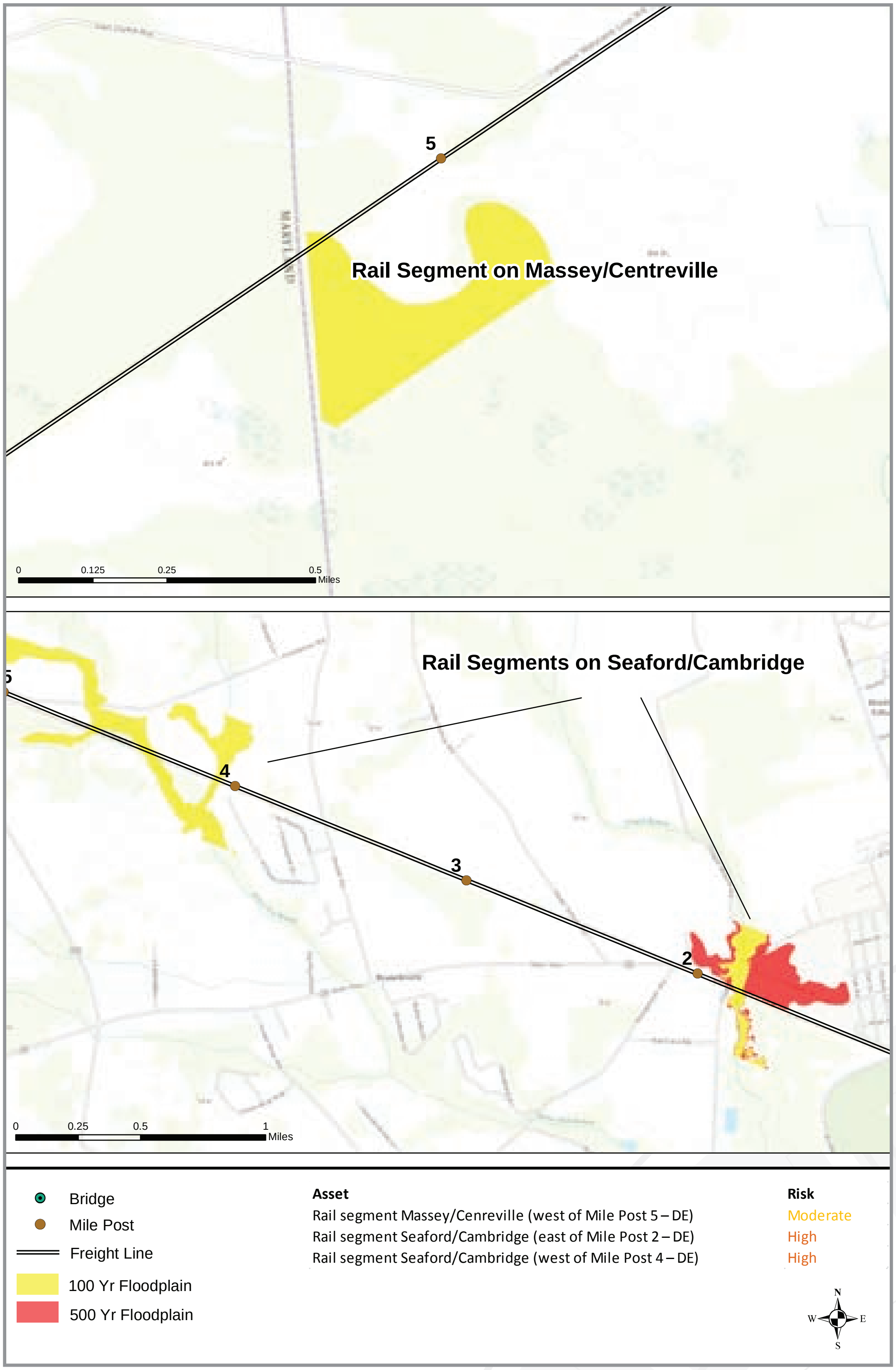


Figure E-6 Freight Rail Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability

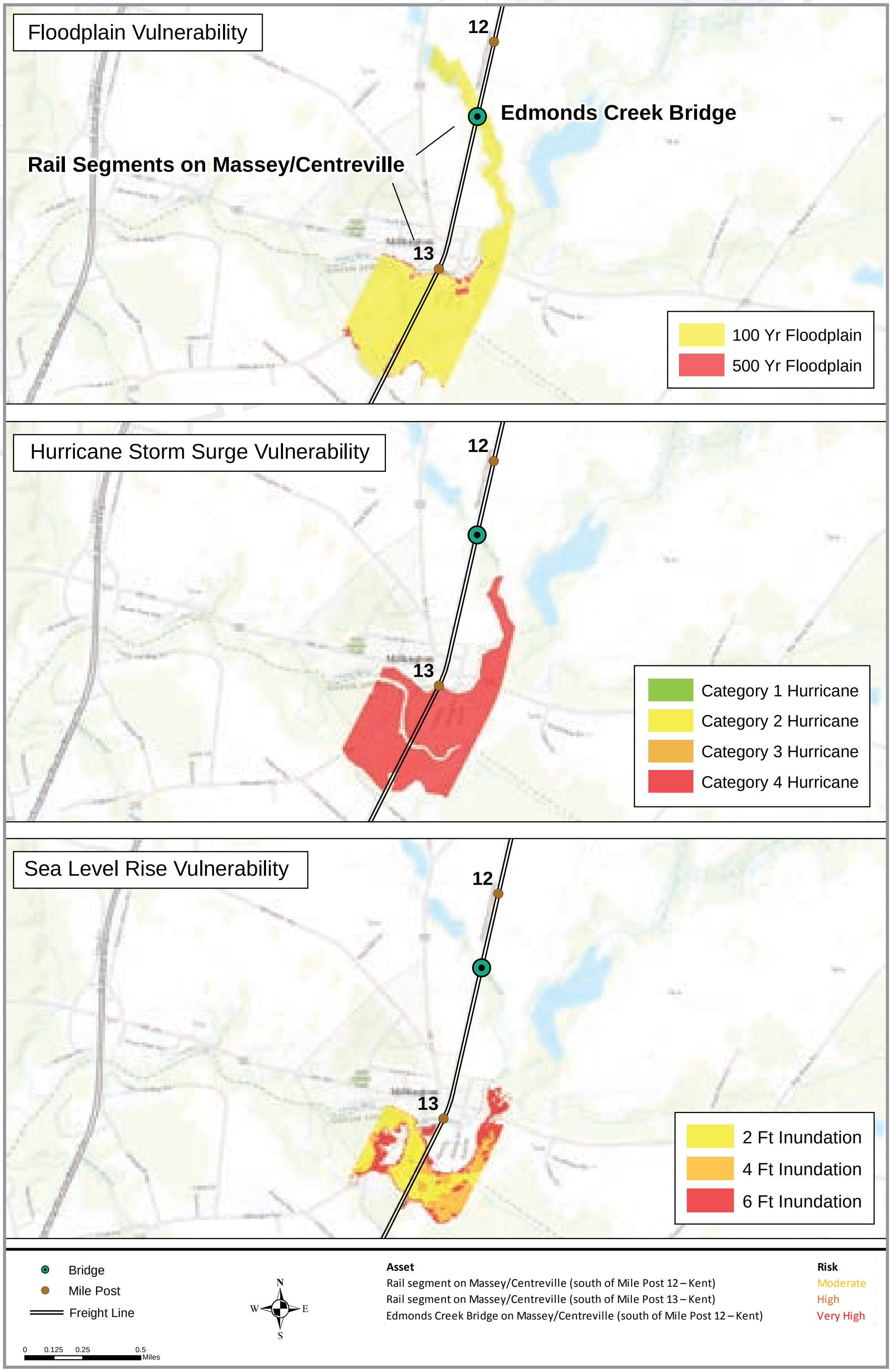
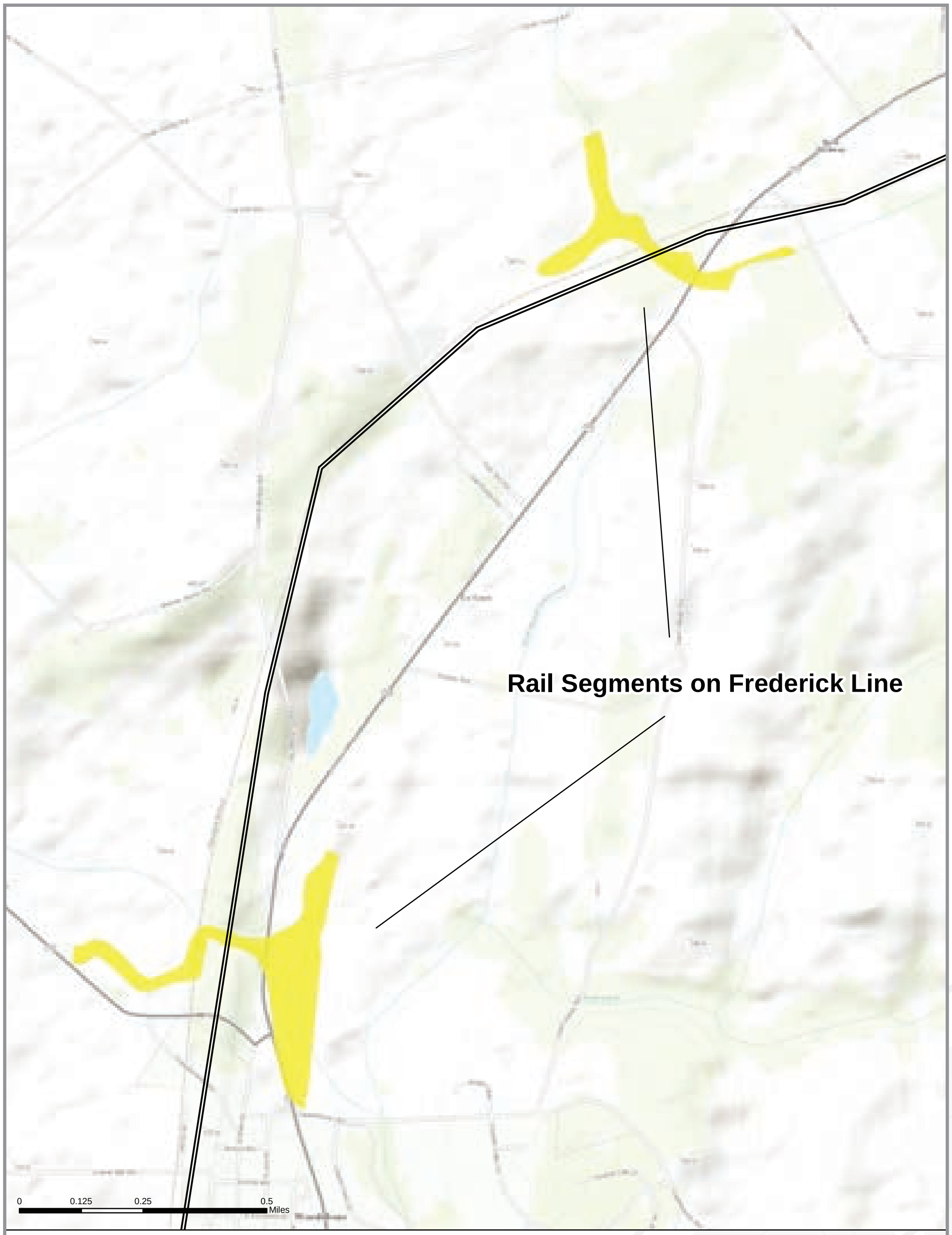


Figure E-7 Freight Rail Floodplain Vulnerability



- Bridge
- Mile Post
- Freight Line
- 100 Yr Floodplain
- 500 Yr Floodplain

Asset	Risk
Rail Segment west of Cash Smith Rd and Woodsboro Pike on Frederick Line	High

Figure E-8 Freight Rail Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability

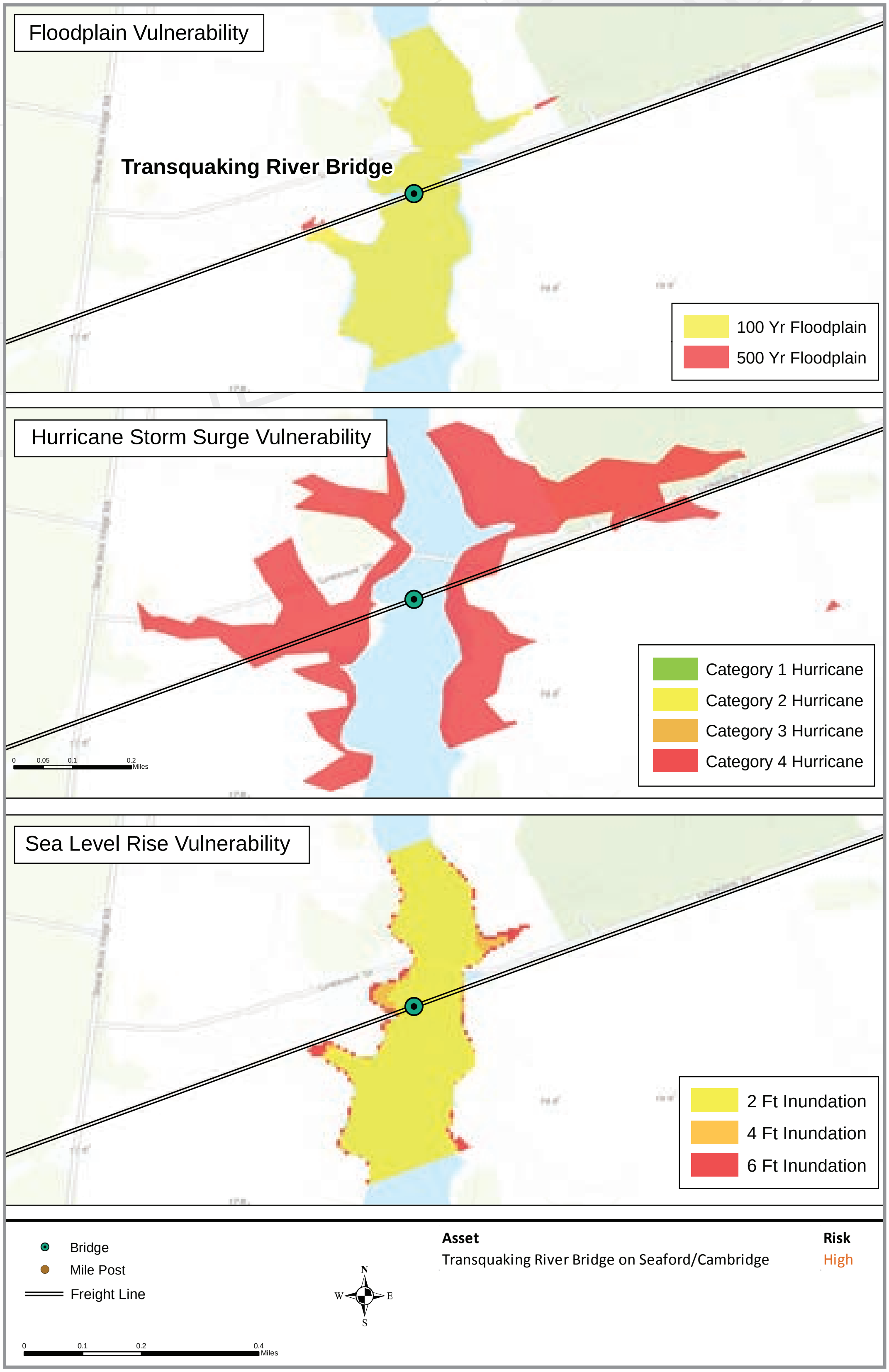


Figure E-9 Freight Rail Floodplain, Hurricane Storm Surge, and Sea Level Rise Vulnerability

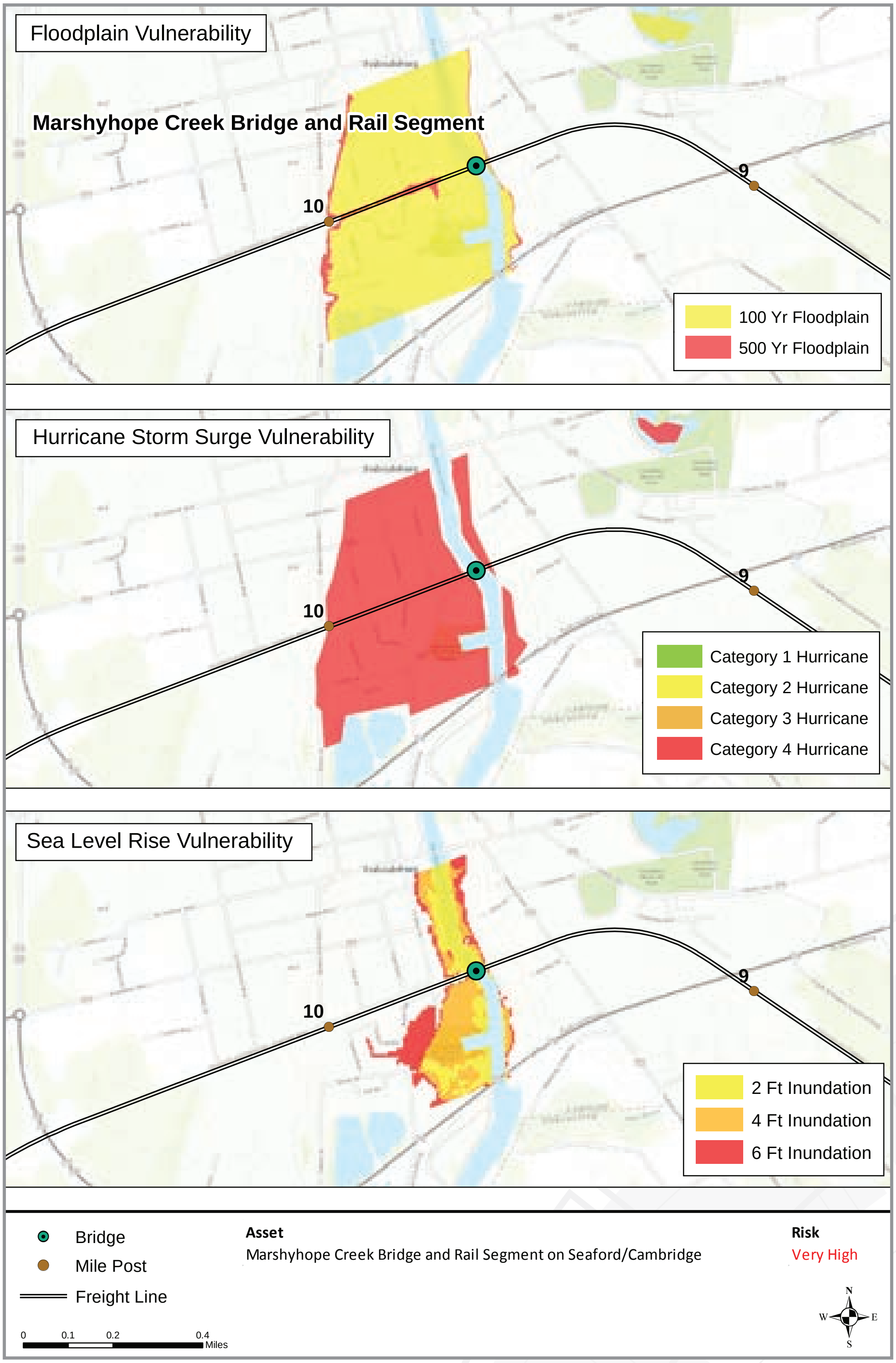
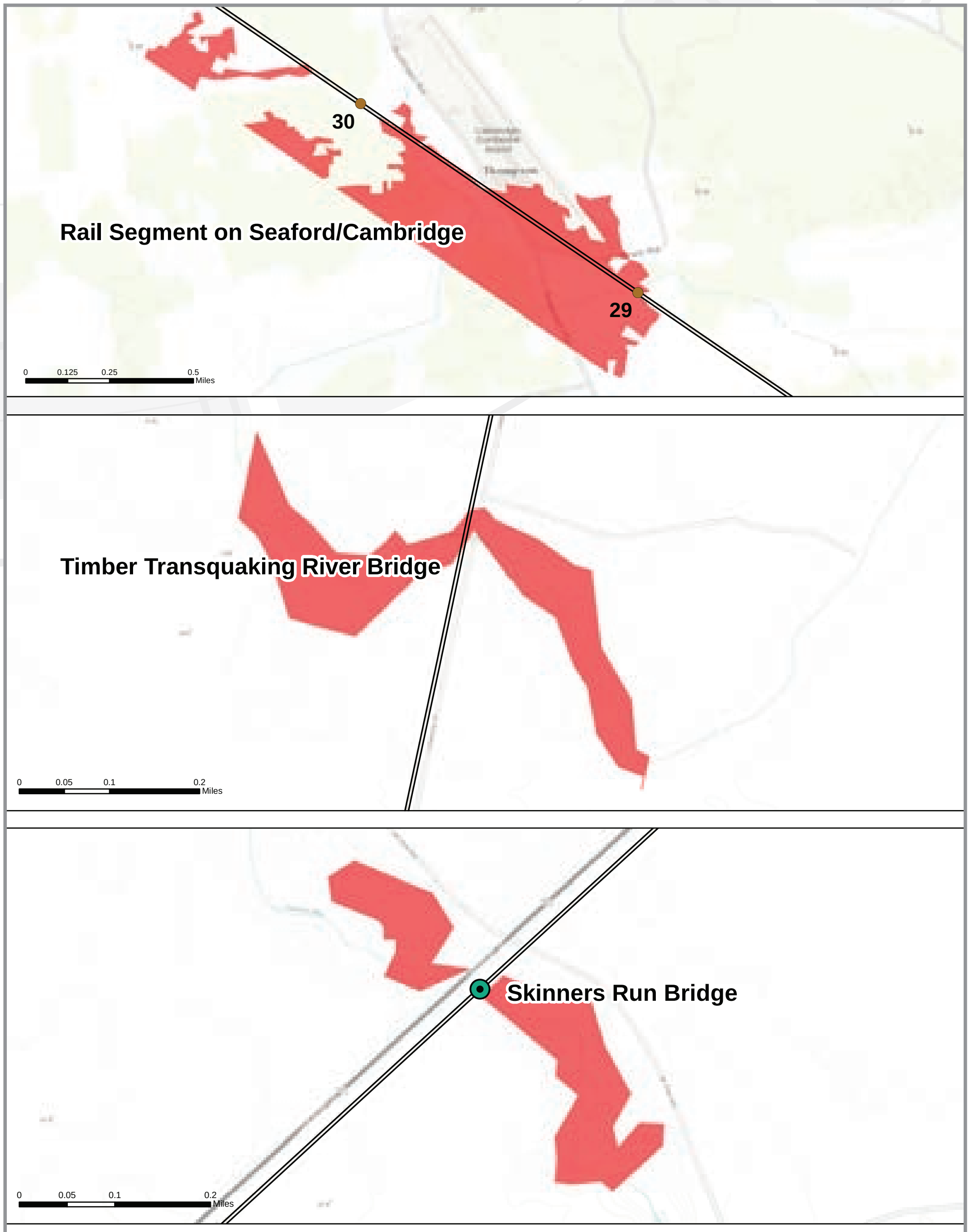


Figure E-10 Freight Rail Hurricane Storm Surge Vulnerability



- Bridge
- Mile Post
- Freight Line
- Category 1 Hurricane
- Category 2 Hurricane
- Category 3 Hurricane
- Category 4 Hurricane

Asset	Risk
Rail Segment at Bucktown Road Grade Crossing on Seaford/Cambridge	High
Timber Bridge over Transquaking River on Seaford/Cambridge	High
Rail Segment at Skinners Run Bridge on Seaford/Cambridge	High

N W E S

Appendix F
Overview Vulnerability Maps

Figure F-1 Sensitive Locations and Assets Inundated due to Flooding Events

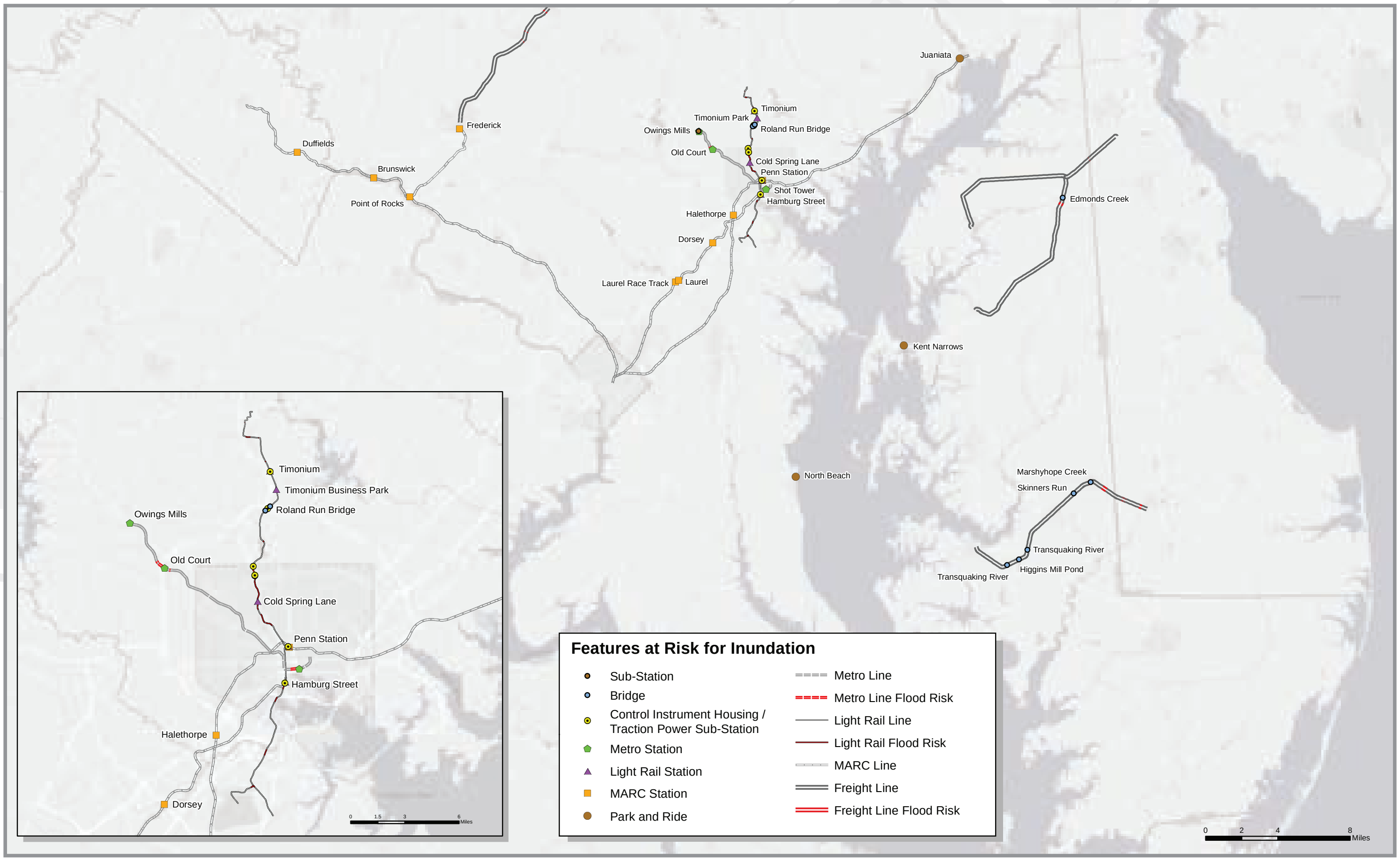


Figure F-2 Sensitive Locations and Assets Inundated due to Hurricane Storm Surge

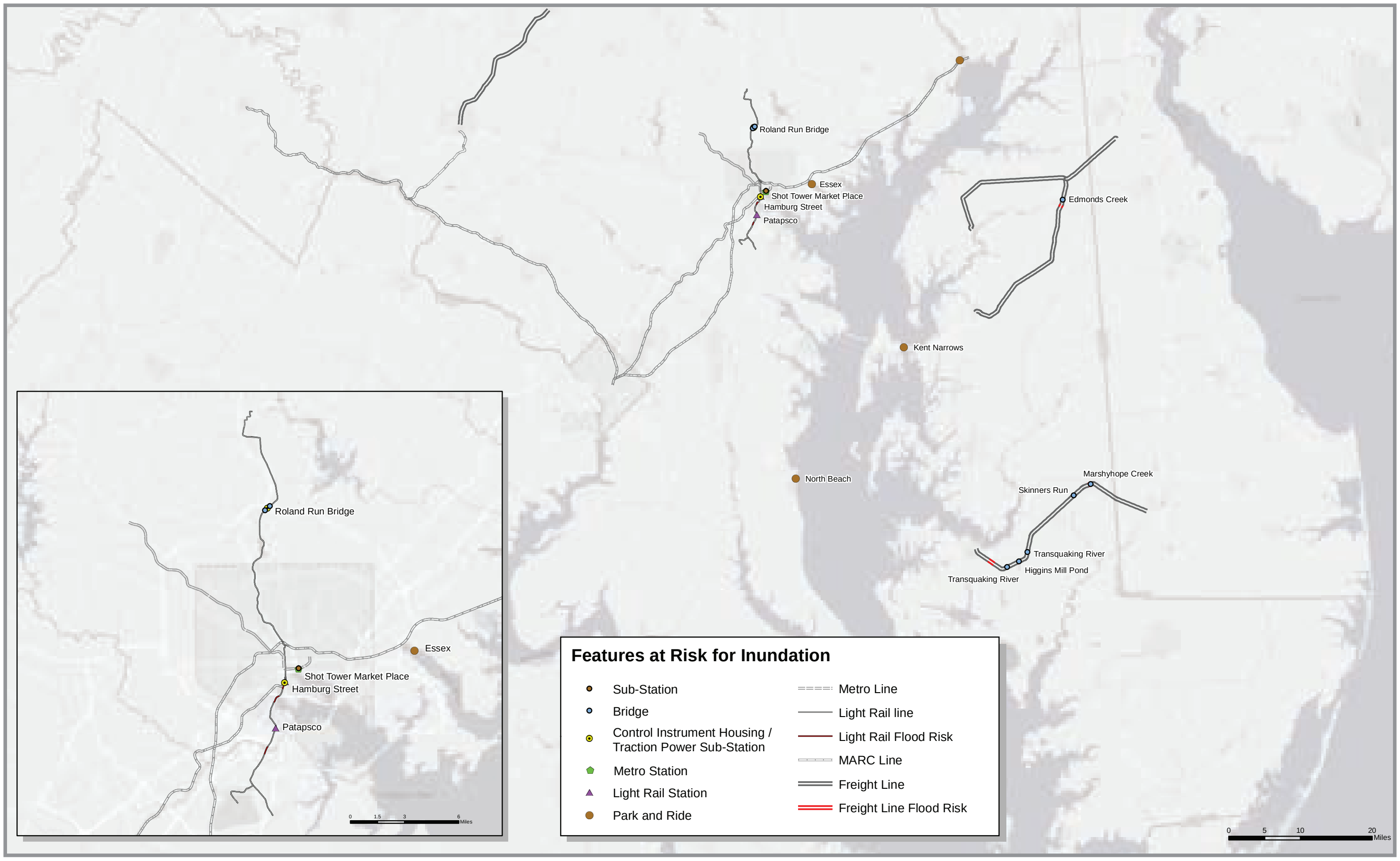
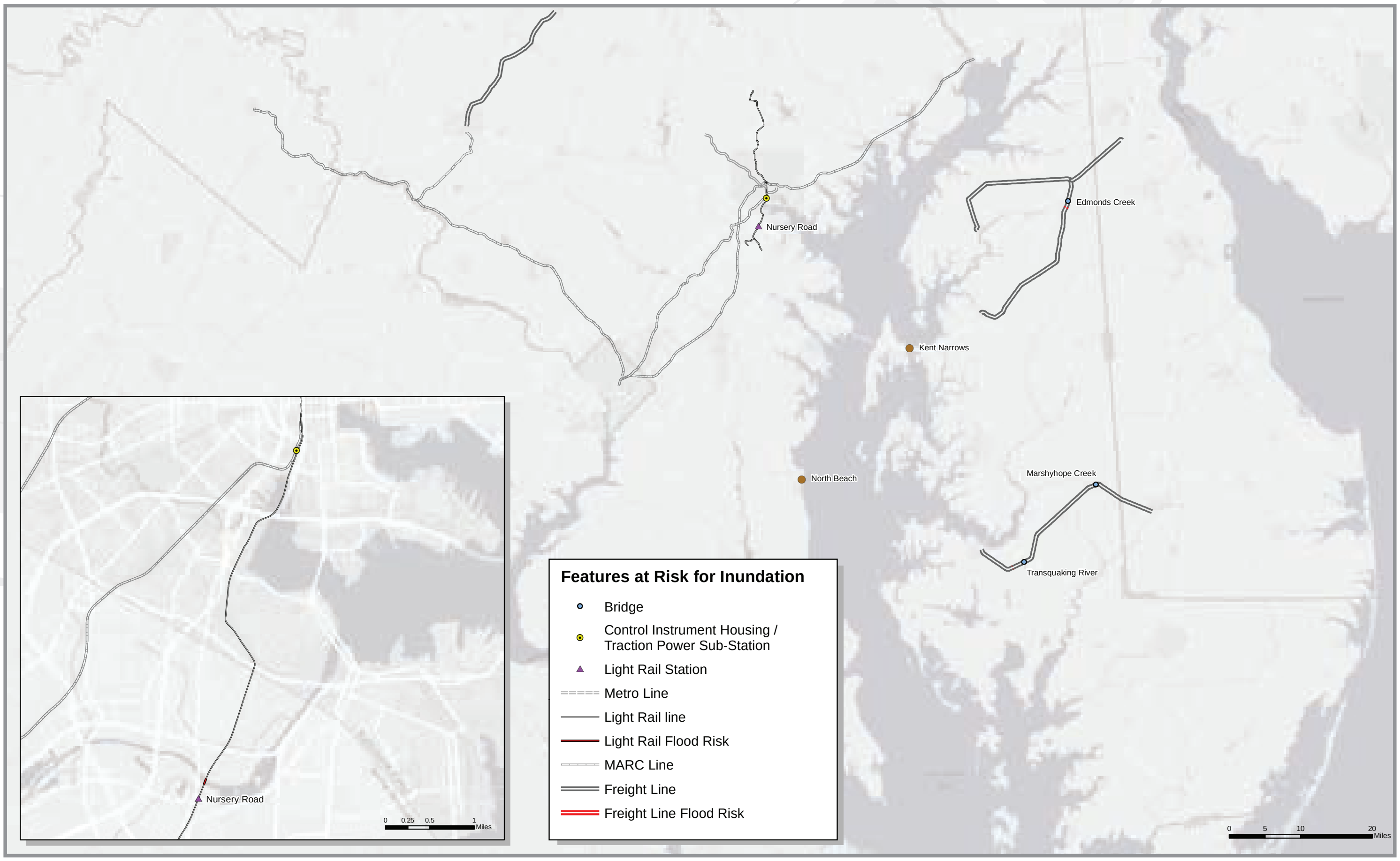


Figure F-3 Sensitive Locations and Assets Inundated due to Sea Level Rise



Appendix G
MTA Climate Change Policy

Figure G-1 Policy Name: Incorporating Climate Change and Sea Level Rise Information into the Maryland Transit Administration's (MTA) Capital Planning Process 2010

Policy Name: Incorporating Climate Change and Sea Level Rise Information into the Maryland Transit Administration's (MTA) Capital Planning Process

2010

Policy Description: MTA will utilize DNR/MDP's "Lead by Example" policy guidance on coastal erosion, coastal storm and sea level rise adaptation and response planning strategies in an evaluation of existing infrastructure and future proposed projects in the MTA's capital planning program.

Lead Agency: Maryland Transit Administration (MTA)

Supporting Agencies: Maryland Department of Transportation (MDOT), Department of Natural Resources (DNR) and Maryland Department of Planning (MDP)

Implementation Process:

- The MTA Environmental Planning Division (EPD) of the Office of Planning will lead the effort to evaluate vulnerability of MTA-owned infrastructure to sea level rise and periodic inundation from storm surge.
- The MTA will procure GIS capability as a tool for evaluating existing and proposed infrastructure vulnerability to sea level rise and storm inundation.
- All proposed MTA capital projects undergo an environmental feasibility analysis to identify any environmental fatal flaws or constraints. The MTA Environmental Planning Division (EPD) of the Office of Planning will use "Lead by Example" policy guidance to assess project vulnerability related to sea level rise.
- Using documentation provided by DNR on projected sea level rise and potential areas of inundation, all new MTA capital projects and those currently in the planning and preliminary engineering phase will be evaluated on vulnerability to sea level rise and storm inundation.
- Using documentation provided by DNR on projected sea level rise and potential areas of inundation, existing MTA-owned infrastructure such as rail lines, bus and rail yard and shops, and other facilities will be evaluated on vulnerability to sea level rise and storm inundation. Adaptation measures will be identified to address infrastructure vulnerability.

Progress in 2010

- The MTA initiated procurement of GIS capability to assist in completing the *Assessment of Infrastructure Vulnerability* report and assessment of project vulnerability to sea level rise and storm inundation. Full implementation of the GIS is anticipated by December 2010.
- The MTA has initiated discussion with SHA on data sharing and accessing GIS layers related to sea level rise and storm inundation.

Figure G-1 Policy Name: Incorporating Climate Change and Sea Level Rise Information into the Maryland Transit Administration's (MTA) Capital Planning Process 2010

Maryland Transit Administration
Incorporating Climate Change and Sea Level Rise Information

Deliverables for 2011

- In 2011, using documentation provided by DNR, MTA will begin development of a draft *Assessment of Infrastructure Vulnerability* report. The draft report will be provided to MDOT, DNR and MDP for review and comment before being finalized.
- With full implementation of GIS capability in 2011, EPD will immediately begin to incorporate assessment of vulnerability into its environmental feasibility analysis for new projects.

Future Actions:

- DNR/MDP's "Lead by Example" policy guidance will be integrated in development of all new capital projects proposed in the MTA's capital program. The MTA will address the siting and design of all capital planning and infrastructure projects in areas vulnerable to sea level rise or increased storm surge.
- Existing MTA-owned infrastructure such as rail lines, bus and rail yard and shops, and other facilities will be evaluated on vulnerability to sea level rise and storm inundation. Adaptation measures will be identified to address infrastructure vulnerability.