Passaic River Basin

CLIMATE RESILIENCE PLANNING STUDY

CDM Smith

NJTPA

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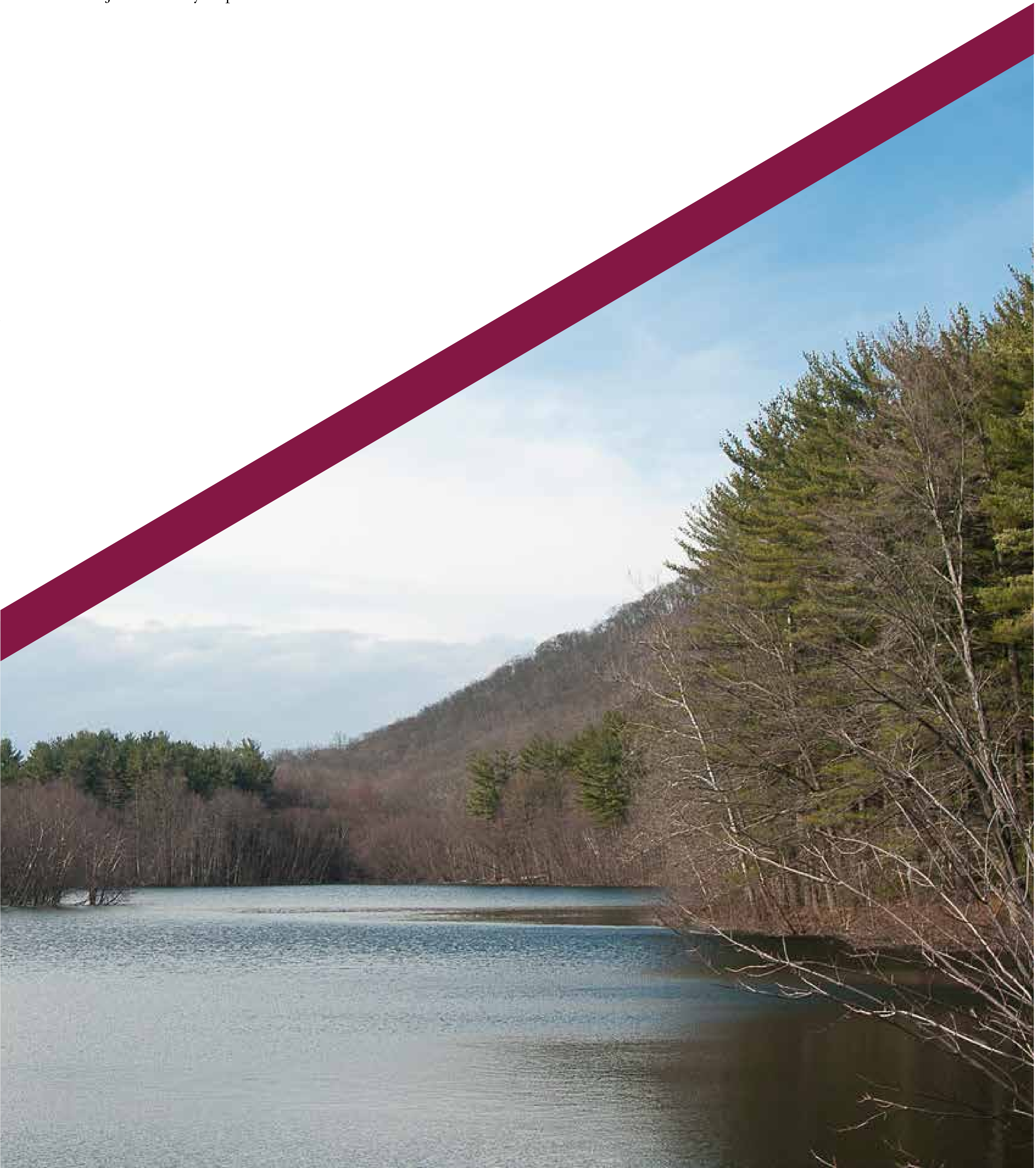

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Acronyms and Abbreviations

°F	degrees Fahrenheit
AADT	annual average daily traffic
ADA	Americans with Disabilities Act
ADCIRC	ADvanced CIRCulation model
BCA	benefit cost analysis
BMP	best management practice
CMIP5	Climate Model Intercomparison Project Phase 5
CSO	combined sewer outflow
DOT	department of transportation
DPW	Department of Public Works
EGIS	NJTPA Enterprise Geographic Information System
EJSCREEN	Environmental Justice Screening and Mapping Tool
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	global climate model
GI	green infrastructure
GIS	geographic information system
H&H	hydrologic and hydraulic
HEP	New York-New Jersey Harbor & Estuary Program
HMP	hazard mitigation plan
I&EM	incident and emergency management
IPCC	Intergovernmental Panel on Climate Change
ITS	intelligent transportation system
MPO	metropolitan planning organization
NACCS	North Atlantic Coast Comprehensive Study
NJDEP	New Jersey Department of Environmental Protection
NJDOT	New Jersey Department of Transportation
NJ OEM	New Jersey Office of Emergency Management
NJTA	New Jersey Turnpike Authority
NJTPA	North Jersey Transportation Planning Authority
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NYMTC	New York Metropolitan Transportation Council
O&M	operations and maintenance
OEM	Office of Emergency Management
PRB	Passaic River Basin
R&D	research and development
RAMPP	Risk Assessment, Mapping, and Planning Partners
RCP	representative concentration pathway
ROCC	regional operations coordination committee
RWIS	Road Weather Information System
SME	subject matter expert

SW	stormwater
TAC	technical advisory committee
TIM	traffic incident management
TIP	transportation improvement program
TRANSCOM	Transportation Operations Coordinating Committee
USACE	U.S. Army Corps of Engineers
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey

Executive Summary

The North Jersey Transportation Planning Authority (NJTPA) is the federally authorized Metropolitan Planning Organization (MPO) for the 13-county northern New Jersey region, home to 6.7 million people. It evaluates and approves projects in a Transportation Improvement Program (TIP), provides a forum for cooperative transportation planning, sponsors and conducts studies, assists county and city planning agencies and monitors compliance with air quality goals.

NJTPA's first step towards addressing climate change impacts in the region was the Climate Change Vulnerability and Risk of New Jersey's Transportation Infrastructure study (Cambridge Systematics 2012). The Passaic River Basin Climate Resilience Planning Study furthers NJTPA's efforts to address the challenges of climate change. This study focuses on potential impacts that climate change will have on transportation infrastructure located within the Passaic River Basin (PRB) of northern New Jersey. The outcome of the study is a compilation of measures or best management practices (BMPs) and recommendations that may reduce the vulnerability of a transportation asset to climate change and increase its resilience to existing and future heat or flooding events.

This study is one of a series of planning studies that assesses the potential for increasingly severe and frequent storm and heat events along with rising sea levels to impact natural and man-made systems, threaten lives and property, and disrupt travel. This study enables the region and state to devise sound, effective plans and policies that promote and implement practical, cost-effective resiliency measures. These measures will prepare the region's transportation system for the anticipated effects of climate change and minimize the economic impact of frequent and/or severe climate related events. They will help the state and region:

- Prepare for natural hazards and weather-related disasters through better understanding of what assets are most vulnerable to these events and which of those assets are most critical to the function of transportation networks and communities.
- Assess transportation networks to ensure evacuation routes and communication networks remain operable during severe storm and heat events.
- Develop resilient, innovative, and integrated solutions, climate adaptation strategies, and BMPs that reduce vulnerabilities and prevent or minimize damage to private property and public assets from damaging floods and other climate impacts.
- Prioritize the investment of resources and capital to not only identify which measures should be implemented in the near- or long-term but also deduce what climate adaptation strategies are most cost-effective from a societal perspective and in consultation with key stakeholders.
- Help communities and transportation providers recover from damaging storms and severe climate events.

Study Area

The PRB comprises 935 square miles within the states of New Jersey (approximately 785 square miles) and New York (150 square miles). The seven major tributaries are the Whippany River, Rockaway River, Pompton River, Pequannock River, Wanaque River, Ramapo River, and Saddle River. According to the 2010 U.S. Census and the 2017 American Communities Survey, about 2.5 million people live within the boundaries of the Passaic River Basin, with about 920,000 homes and business located within the floodplain. Much of the population is particularly vulnerable to disruptions caused by flooding, including low-income households, older residents, and minority communities traditionally underserved by the transportation system. Many residences and business located within the study floodplain have suffered from storm events, some to the extent of requiring property buy-outs. Despite the environmental challenges it faces, the PRB has economic importance as the home for businesses integrated into regional supply chain networks and as a source of the labor force for major employers in surrounding areas and the urban centers of Newark and New York City.

Study's Purpose

The PRB has had frequent minor to moderate flooding over the past 60 years and has been impacted by major floods over the past century, which resulted in extensive inundation, property damage, evacuation of people, and closure of primary and secondary roads and railways. Past and current land use decisions continue to exacerbate flooding and flood damage in the PRB. Development in the floodplain increases the likelihood of future property losses, threatens the economic stability of communities, and puts public health and safety at risk. The transportation network is a set of assets that continue to be threatened by the stressors of more frequent and severe weather events, thus impacting society's ability to respond to a flood event and mitigate loss to local and regional commerce and individual property. Therefore, NJTPA initiated a climate resilience planning study to evaluate the vulnerability of PRB transportation assets to climate change events and identification of adaptation strategies for agencies and municipalities to integrate resiliency into the transportation network.

Report Summary

The study commenced with the development of a geospatial database of assets (bridges, culverts, facilities, rail lines, roads, transit assets) within the PRB, review of county hazard mitigation plans (HMPs), and interviews with a technical advisory committee (TAC) to assist with identifying frequently flooded areas, historically vulnerable assets, and current management strategies. Simultaneously, the study evaluated which assets were vulnerable to existing and future flood and heat conditions. The study mapped both extreme heat events and extreme precipitation events for existing conditions and two future planning horizons, one in 2045 and one in 2080. TAC input aided in the selection of the planning horizons and flood event scenarios for this effort.

- **Extreme heat event** is defined as a day in which ambient temperature is equal to or greater than 90°F, in alignment with NJ TRANSIT's 2012 Resilience of NJ TRANSIT Assets to Climate Impacts Report. The number of extreme heat events is projected to increase from 15 days under baseline conditions to 20 days in 2045 and 31 days in 2080.
- **Extreme precipitation event** is defined as the annual maximum precipitation within a 4-day storm event, which is the time scale dataset required to model flood inundation extents. This timescale allows for the time (known as "time of concentration") it takes for runoff to be routed through the 937-square mile watershed and accumulate at the outlet. Two flood event scenarios were mapped, including the 25-year (NJDEP planning and permit requirements) and 100-year (representative of an extreme event).

Precipitation is projected to increase in frequency and severity due to climate change impacts. For example, a 4-day storm event producing 9.1 inches of rain has a historical recurrence interval of 100-years. By 2045, a storm event producing the same 9.1 inches of precipitation over 4-days has a projected recurrence interval of 54 years. This means that the likelihood of extreme events of a specific magnitude occurring in the future is predicted to increase compared to the recent past. The magnitude of projected changes, however, does vary based on the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emission scenario used. For example, 2080 projections of change for the 25-year, 4-day storm event range from an increase of 0.6 inches to 1.8 inches. The 2045 projected increases for the same event range from 0.6 inches to 1.6 inches.

- **Criticality** of an asset considers its importance to the following considerations: disaster management, evacuation, business continuity, economy, social aspects of the region, transportation demand, and carrying capacity.
- **Sensitivity** is the degree to which the asset is affected by the climate conditions. It comprises climate impact exposure and known predicted effects.
- **Adaptive capacity** is a determination of an asset's ability to accommodate flood and heat stress and return to normal after a disruption.

Once the transportation asset locations and climate scenarios (both flood and heat) were evaluated, a vulnerability assessment was performed to understand the current and future sensitivity and adaptive capacity of the transportation systems and components within the study basin. Vulnerability of a transportation asset is determined by quantifying its criticality, sensitivity, and adaptive capacity under the stress of various existing and future climate conditions.

Data collection and review of the study area's HMPs, available geographic information system (GIS) data, and existing reports and studies, complemented by TAC interviews and modeling results of existing and future heat and flood event scenarios were used to determine the location of transportation corridors and assets, establish criticality of an asset to the transportation system, and quantify vulnerability of an asset to heat and flooding stressors. At least 10 percent of the 3,245 transportation assets evaluated in the PRB study were determined to be highly vulnerable to existing and future heat and/or floods events.

In consultation with the TAC, 71 adaptation strategies were developed and identified for all transportation asset types evaluated within the PRB study area (bridges, culverts, facilities, rail, roads including bus routes, and transit rolling stock) and some adaptation strategies that may be applied on a regional level.

The strategies are designed to be incorporated into existing and future policy, design, and operations and maintenance (O&M) by asset owners and operators. The adaptation strategies are categorized into seven types:

1. Reduce Thermal Expansion
2. Use Heat-Resistant Materials
3. Prevent System Failure
4. Increase or Improve Stormwater Drainage
5. Increase Flood Protection
6. Reduce Flood Damage
7. Regionwide policies (for natural systems, community development, and technology)

The 71 adaptation strategies were further refined, in consultation with the TAC, to identify their applicability to three subareas where case studies were conducted. The subareas represent geographies that contain a range of critical, interconnected transportation assets that are particularly vulnerable to climate events and contain a suite of assets that are representative of the entire PRB asset portfolio (bridges, culverts, facilities, rail lines, roads, transit assets) and stakeholder diversity (county, state, and federal owner/operators). These three subareas are:

1. Subarea A: Parsippany, Pine Brook
2. Subarea B: Willowbrook "Spaghetti Bowl"
3. Subarea C: River Road/ Route 21 Corridor

Each asset type within the subarea was associated with a set of recommended adaptation strategies based on flood exposure and heat event factors, TAC input, and subject matter expert (SME) review. This screening process was used to screen out and select the best or most effective

Study's Purpose

- Identify assets highly vulnerable to existing and future flooding and heat events, considering climate change factors such as future temperature and flooding projections, storm surge, and sea level rise.
- Develop adaptation strategies and recommendations, in consultation with the TAC, to foster integration of resiliency into the northern New Jersey transportation network.

adaptation strategies for each asset. A sketch-level benefit cost analysis (BCA)[1] and transportation demand analysis were performed to further inform strategy implementation within each subarea.

A subset of adaptation strategies identified and evaluated in more detail in this study relates to upgrades to incident and emergency management (I&EM) and intelligent transportation systems (ITS). I&EM is an organized, planned, and coordinated effort to detect and respond quickly to incidents, and restore the affected infrastructure to its capacity. ITS technologies improve transportation safety, mobility, and operations. ITS includes applications that collect, process, and communicate data to ease congestion, improve traffic management, make roads safer, and enhance driver mobility.

The ITS and I&EM evaluation identified common adaptation strategies (based on those from the Federal Highway Administration [FHWA]) used for traffic management during flood events, such as active warning systems, traveler information (pretrip and dynamic road information), and traffic management and control (land or road closures, contraflow/reversible lane operations, signal timing, ramp metering, and variable speed limits).

Based on the TAC interviews and a review of existing ITS assets and procedures, the use of ITS in incident and emergency response within the study area generally follows established best practices. Most events are at least partially anticipated, and agencies have adequate time to mobilize forces. Most events are first addressed at the local level, but involve sufficient coordination between local, county, and state agencies so that an event's status can be elevated quickly if necessary. Agencies recognize that ITS applications and related systems can be enhanced to better support emergency and incident management, and this is reflected in the recommendations.

Recommendations

In consultation with the TAC, recommendations were developed to advance integration of resiliency into the PRB transportation network. The TAC identified the following approaches to aid in prioritization and implementation of resiliency measures:

- Create a stakeholder collaborative for a local corridor or subarea to coordinate a strategy to plan, fund, and implement adaptation strategies. Examples of regional collaboratives are the New York - New Jersey Harbor & Estuary Program (HEP) created by the EPA and the Paterson Smart collaborative headed by the Great Swamp Watershed Association. The TAC recommended a non-profit lead to bring together this collaborative, such as the Lower Raritan Watershed Partnership or Montclair State University Passaic River Institute. The collaborative should include transportation operators/owners, municipalities, and community representatives.

- Identify emergency routes and sole access points for incorporation into Hazard Mitigation Plans. Subsequently, prioritize assets that serve an emergency management function or response in the adoption and implementation of adaptation strategies. Also, prioritize major local roadways that have a sole access point not included this in study. Counties or municipalities performing this action could collaborate with FEMA Community Rating System user groups, such as Morris County.

- Facilitate implementing recommendations and engage local agencies and counties on I&EM. This should include pursuing redundancy projects for ITS and traffic signal systems. Refer to **Section 5** of this report for specific recommendations.

1 *Sketch-Level BCA* compares the implementation costs (construction and operation) to the monetized benefits (from the travel demand model [TDM] process) and the rehabilitation/repair cost savings.

The following recommendations should be performed as next steps and as a collaboration among the responsible agencies, operators, and other relevant stakeholders of each asset.

- Transportation agency owners and operators should use the study findings to provide justification and support in requests for funding to construct or rehabilitate an asset(s) to be resilient to existing and future climate scenarios. NJTPA already includes resiliency scoring criteria in evaluating proposed federally funded TIP projects and other relevant project proposals.
- Transportation agency owners and operators should continue to update and refine the vulnerability scoring of PRB assets as information becomes available. Data gaps should be addressed to the extent possible and the vulnerability scoring should be reevaluated. A current data limitation is the identification of evacuation routes within the PRB, not including NJ OEM coastal evacuation routes. Other data gaps are the elevation of the bridge segment suspended above the waterbody surface and the depth of the superstructures or entranceways below the bridges.
- The NJTPA and stakeholders should use study findings and data compilation to perform adaptation strategy analysis on other PRB subareas or at a finer geographic scale, as necessary. Study findings can also be applied to other basins, such as the Raritan River Basin and the Hackensack River Basin. The type of additional modeling and assessment required is project-specific.
- Transportation agency owners and operators should integrate vulnerability into asset management systems to track asset-specific vulnerability scores, rehabilitation need(s), and repair/reconstruction schedules. Current asset management systems include but are not limited to the NJDOT Bridge Management System and Morris County in-house roadway asset system.
- Transportation agency operators should develop and maintain an O&M plan that encompasses implementation, tracking, and roles of responsible parties for performing O&M adaptation strategies.
- Use the vulnerability assessment findings in current and future planning and design studies to inform the siting of new infrastructure and updates and improvements to existing infrastructure. Resiliency measures can be considered in an improvement project when repairing and upgrading infrastructure, such as retrofitting an asset to be compliant with the Americans with Disabilities Act and Passaic County's Green Infrastructure Plan.
- Prepare public outreach materials to communicate present and future risks of extreme heat and flood events to the transportation network and surrounding community. Provide stakeholder engagement materials to facilitate dialogue and inform decision-making for property buyouts due to flooding and implementation of green and gray infrastructure adaption strategies.
- Develop workshops for Department of Public Works (DPW) and other user/operators to provide educational opportunities to learn about resiliency and adaptation measures. Create a checklist or fact sheet to aid integration of vulnerability assessments and resilient adaptation measures. These next steps can be modeled after Complete Streets initiatives and supporting materials.

The following recommendations are to assist NJTPA and its partner agencies expand and build upon the data and modeling provided in this planning study.

- Evaluate the role of a supersaturated subsurface, due to excessive snowmelt and frequent precipitation events, in contributing to nuisance and severe flooding. Results of such a study could advise in location and design of green infrastructure strategies.
- Evaluate future land use changes under the NJDEP Blue Acres Program, county and municipal master plans, and similar studies, to refine the H&H model findings and inform the location and design of green infrastructure and flood protection infrastructure strategies. Update existing policy to consider incorporation of climate change projections in stormwater control plans.
- Refine H&H models of the state's watersheds that do not meet Tier 1 modeling approach requirements. Updated models can then be used to map the flood inundation footprint of current and future climate scenarios across a greater extent of the basin, region and state.
- Additional climate scenarios could be modeled to better represent an asset's lifespan and state of good repair. Also, the 500-year storm event is becoming a more common flood scenario to model, including EPA recommendations of flood resilience for water and wastewater utilities. Performance of additional modeling should supplement this study and not hinder taking action on the planning study's findings.

The TAC identified the following as opportunities for the stakeholders to enhance resiliency planning in northern New Jersey.

- Identify other critical watersheds (e.g., Raritan River Basin and Hackensack River Basin) and transportation hubs (e.g., Newark Airport and Port of Newark) and perform a complementary climate resilience planning study.
- Continuously update hazard mitigation plans, long-term combined sewer outflow control plans, green infrastructure plans, and other related planning documents to incorporate the most recent resilience planning studies.
- Evaluate stormwater retainage potential of local green infrastructure projects to advise in location and design of green infrastructure strategies.
- Map stormwater infrastructure and identify capacity potential to further optimize stormwater volume retainage capacity, with a specific focus on the segments of the PRB that are prone to excessive flooding and serve as a stormwater sink.
- Conduct a study to evaluate innovative, cutting edge adaptation strategy measures and BMPs not currently vetted on a planning scale. These would include research and development and academic evaluations. For example, innovative adaptation strategies to mitigate the heat island effect include painting parking lots white, creating "cooling walls" with water in terracotta pots, and creating a green canopy over major streets to provide shade. These strategies can be implemented as pilot studies to test the practicality of innovative climate solutions and enable owners/operators to be a leader in implementing innovative solutions.

Conclusion

The PRB climate resilience planning study highlights the importance and challenges of fostering a resilient transportation network not only in the PRB but also throughout northern New Jersey and neighboring area. The PRB has a documented history of flooding that is projected to increase in frequency and severity within the study planning horizons of 2045 and 2080. The occurrence of extreme heat events is projected to double by year 2080. At least 10 percent of the 3,245 transportation assets evaluated in the PRB study were determined to be highly vulnerable to existing and future heat and/or floods events. Seventy-one adaptation strategies were developed to aid integration of transportation resiliency measures into infrastructure planning, construction and rehabilitation, O&M, and policy-making. Adaptation strategy fact sheets present planning-level technical and financial considerations for each strategy. Further detailed study will be required in interpreting the results to more accurately evaluate assets, especially those in the high vulnerability category. In addition, as the science of climate change evolves, the assumptions used in this study should be reevaluated and updated on a periodic basis.

Section 1
Introduction

This section is an overview of the Passaic River Basin (PRB), history of New Jersey drainage basin flooding, planning process methodology for this study, and overall study objectives.

Passaic River Basin

The PRB comprises 935 square miles within the states of New Jersey (approximately 785 square miles) and New York (150 square miles). The seven major tributaries are the Whippany, Rockaway, Pompton, Pequannock, Wanaque, Ramapo, and Saddle Rivers. The New Jersey drainage basin is designated into three natural divisions based on topographic and hydrologic characteristics:

- **Upper PRB –** Mountainous area 10 to 15 miles wide at an average height of 1,300 feet above sea level, characterized by a series of parallel ridges flanking the westerly and northerly limits of the drainage basin. These ridges are deeply dissected by a series of steep-sided transverse valleys that produce relatively extreme high-velocity and high-volume runoff.
- **Central PRB –** Broad, flat valley 8 to 12 miles wide and approximately 30 miles long that lies between the Highlands Region and the Watchung Mountains to the south and east. It extends from the Great Swamp on the south through Chatham to Pompton Lakes in the Pompton Valley on the north.
- **Lower PRB –** From the Central PRB to the river mouth at Newark Bay is the approximately 23-mile tidal estuary. The river gradient is slight and broken by grade drops at Little Falls, Great Falls, and Dundee Dam. The area south of Dundee Dam is tidally influenced.

According to the 2010 U.S. Census and the 2017 American Communities Survey, the PRB contains about 2.5 million people and about 920,000 homes and business, with vulnerable populations (i.e., a community population with an above state average environmental justice demographic index[1]) residing throughout the basin. The USACE *FACT SHEET – Passaic River Mainstem and Tributaries, New Jersey* determined about 20,000 homes and businesses are located within the Passaic River floodplain.[2] The PRB has economic importance through the supply chain networks and transport of labor workforces between western and northern regional industries and suburban communities to eastern cities such as Newark and New York City.

1 The average of two demographic indicators: Percent Low-Income (percent of a block group's population in household income is less than or equal to twice the federal poverty level) and Percent Minority (percent of individuals in a block group who list their racial status as a race other than white alone and/or list their ethnicity as Hispanic or Latino). EPA Environmental Justice Screening and Mapping Tool (EJSCREEN), https://www.epa.gov/ejscreen.

2 U.S. Army Corps of Engineers (USACE). 2013. FACT SHEET – Passaic River Mainstem and Tributaries, New Jersey, https://www.nan.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/487436/fact-sheet-passaic-river-mainstem-and-tributaries-new-jersey/.

Study Area

The study area's geographic boundary encompasses parts of Bergen, Essex, Hudson, Morris, Passaic, Somerset, Sussex, and Union Counties, as shown in **Figure 1**.

Principal components of the study area's transportation infrastructure were evaluated for potential service disruption and damage from future climate events. These components are:

- Roadways (interstate highways, state highways, county routes, major roadways, evacuation routes)
- Bridges
- Rail lines (NJ TRANSIT rail and light rail lines, Metro-North Commuter Railroad rail lines)
- Transit (movable assets such as buses and rail cars)
- Culverts (connectors and pipelines from the U.S. Geological Survey (USGS) National Hydrography Dataset)
- Facilities (rail yards, intermodal facilities, rail stations, bus maintenance garages and depots, park-and-ride facilities)

History of Basin Flooding

The PRB has been impacted by major floods over the past century, resulting in extensive inundation, property damage, evacuation of people, and closure of primary and secondary roads and railways. Major flooding is a recurring source of disruption to the transportation system. Both regional and local transportation assets can be out of service for days, rendering the transportation system unreliable for long periods of time following a storm event. Due to this history of flooding and the expected reoccurrence of major flood events, the NJTPA identified the need to determine the vulnerability of transportation assets to the potential impacts of climate change, including increased flooding.[3]

Summary of Historic Flood Events

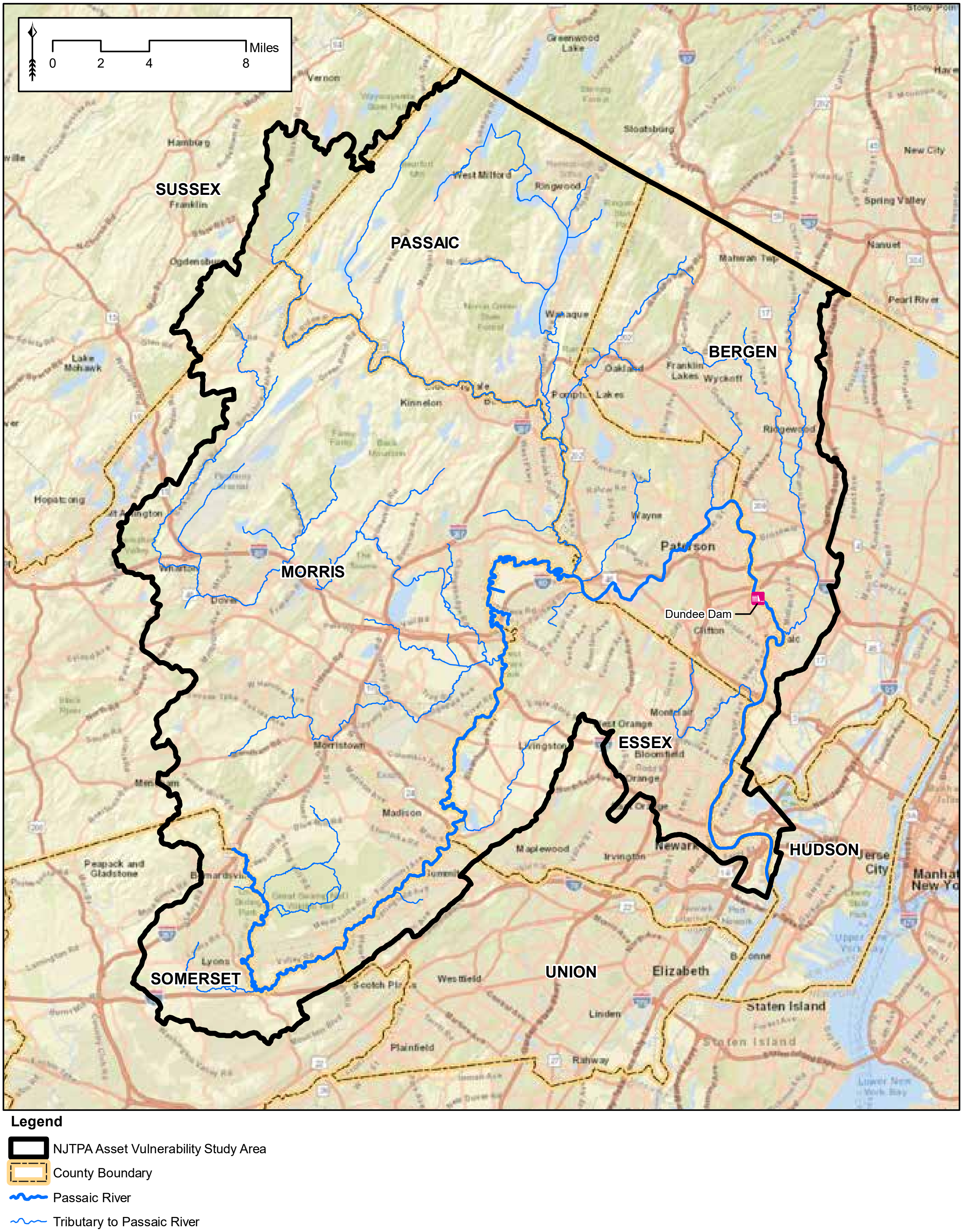
The record flood of October 1903 resulted in at least a 100-year flood event over most of the basin and caused one of the worst floods in the basin's history. The severity of flooding impacts was elevated due to the ground being supersaturated from 3 months of excessive rainfall prior to the storm's landfall in the basin. Some of the more recent floods in 1968, 1971, 1972, 1973, 1975 (two floods), 1984, 1992, 1999, 2005, 2007, 2010, and 2011 were sufficiently devastating to warrant federal disaster declarations. Flooding was exacerbated during the March 2010 nor'easter due to snowmelt contributions to increased stream flows for a period of 10 days to 2 weeks prior to storm landfall.

From August 27–30, 2011, the effects of Hurricane Irene resulted in inundated streams and peak streamflows exceeding the 100-year recurrence interval throughout New Jersey. Rainfall totals averaged more than 10 inches throughout the state combined with

"Since 1900, at least 26 lives have been lost in floods and the total loses are over $5.5 billion dollars. In addition to the flood damages that occur in over thirty-five municipalities in the basin, environmental damage from flooding has also occurred. Significant interruption to businesses and transportation has also resulted in hardship in the basin and region after each flood event. The flood of 1984 resulted in the loss of three lives and caused $642 million in damages (October 2006 dollars). Tropical Storm Floyd in September 1999 caused over $261 million in flood damages (October 2006 dollars). The April 2005 flood caused over $100 million dollars in damages in the basin. The April 2007 flood resulted in over 5,000 people being evacuated and caused $686 million (October 2006 dollars) in damages. The recent March 2010 and April 2011 nor'easters and August 2011 tropical storms all caused significant damages to the communities of the Passaic River Basin."[1]

3 Passaic County, New Jersey. 2012. Moving Passaic County: Transportation Element of the Passaic County Master Plan, Final Plan, http://www.passaiccountynj.org/About%20Us/A/transportation%20master%20plan.pdf.

Figure 1. Geographic boundaries of Passaic River Basin climate resilience planning study area



already saturated soils caused by excessive rainfall during the 3 weeks preceding storm landfall.[4]

The following year Superstorm Sandy impacted the tidally influenced section of the PRB, south of Dundee Dam (October 28–30, 2012). The storm surge inundated an extensive area of highly developed industrial, commercial, and residential neighborhoods in Newark, Kearny, and Harrison. The transit system (Port Authority of New York and New Jersey, NJ TRANSIT, Amtrak) was severely impacted and extensively damaged.[5]

During the course of this planning study, frequent precipitation events and the presence of supersaturated soils continued to impact the transportation system, disrupting mobility and operations in the PRB.

Land use decisions continue to exacerbate flooding and flood damage in the PRB. Development in the floodplain increases future property losses, threatens the economic stability of communities, and puts public health and safety at risk. Flood damage has been observed to be highest in the Central PRB, followed by the Lower PRB. Repeated flooding problems have been observed in the Central PRB due to extensive development in the floodplains, the amount of lowlands and meadowlands, and the flat stream slopes and topography and in the Lower PRB due to extensive development within the floodplain. Limited flooding has been observed in the Upper PRB due to the narrowness of the floodplains, steepness of stream channels, and intensive development. The Upper PRB is impacted by flash flooding and conveys floodwater to the Lower PRB; however, the volume of floodwater is attenuated by the natural storage within the Central PRB.[1,6]

Study Objectives

The PRB resilience planning study objectives are to:

- Assess existing and future vulnerability of transportation assets and corridors within the study area to flooding from extreme precipitation events, sea level rise and storm surge, and extreme heat stressors.
- Develop adaptation strategies that can be incorporated into existing and future policy, design, and O&M by asset owners and operators.
- Identify a subset of adaptation strategies and perform a sketch-level benefit cost analysis (BCA) of adaptation strategies that would protect transportation assets vulnerable to severe flood and heat events located within three critical study basin subareas.
- Assess ITS best practices in I&EM during severe weather events and develop recommendations to enhance existing emergency communication systems and practices.
- Engage with stakeholders to integrate their values and needs into the planning study.

The planning study objectives are an initial step to addressing the MPO's recommendations to perform a vulnerability assessment of transportation assets within the PRB, explore ITS options, and identify strategies to mitigate flooding and heat impacts.[7]

4 Watson, K.M, Collenburg, J.V., Reiser, R.G. 2013. Hurricane Irene and associated floods of August 27–30, 2011, in New Jersey. Scientific Investigations Report 2013-5234, https://doi.org/10.3133/sir20135234.

5 USACE. 2017. Draft Integrated Hurricane Sandy General Reevaluation Report & Environmental Assessment Passaic River Tidal Protection Area, New Jersey Coastal Storm Risk Management Feasibility Study, https://www.nan.usace.army.mil/Missions/Civil-Works/Projects-in-New-Jersey/Passaic-Tidal-Protection-Area/.

6 New Jersey Department of Environmental Protection (NJDEP). 2011. Report to the Governor: Recommendations of the Passaic River Basin Flood Advisory Commission, https://dspace.njstatelib.org//handle/10929/23294.

7 Passaic County, New Jersey. 2012. Moving Passaic County: Transportation Element of the Passaic County Master Plan, Final Plan, http://www.passaiccountynj.org/About%20Us/A/transportation%20master%20plan.pdf.

Study Limitations

The following summarizes the limitations of this planning study:

- Precipitation and temperature projections were downscaled and spatially averaged across the entire study basin, not locally.
- Precipitation projection outputs were processed based on data requirements for the Federal Emergency Management Agency (FEMA) hydrologic and hydraulic (H&H) models and evaluation process. The FEMA H&H models used are based on a 4-day storm event, which is the time, known as "time of concentration," it takes for the runoff to be routed through the 935-square-mile basin and accumulate at the outlet. A precipitation event with a shorter time frame was not modeled.
- Based on geographic limitations of the FEMA H&H studies and usability of models available within the PRB, three approaches were required to map existing and future annual-chance flood event scenarios. Due to budget and schedule limitations and usability limitations of the FEMA H&H models, portions of the Upper PRB and tributaries to the Central and Lower PRB were not modeled for flood inundation extents.
- GIS data limitations include:
  - Identification of evacuation routes used in addition to NJ OEM coastal evacuation routes.
  - Available bridge elevation data were based on lidar ground surface elevations that reflect the elevation of the bridge deck; bridge deck height above an elevated crossing and depth of the superstructure below the bridge are data gaps.
- While the vulnerability assessment was performed across the study basin, budget and project schedule limitations made it necessary to focus the adaptation strategy analysis to three selected PRB subareas.
- There was incomplete data to fully evaluate the vulnerability of some assets. This is notable if the vulnerability score for an asset is less than 3 or if the score for criticality, sensitivity, or adaptive capacity is zero.

Each limitation is discussed in more detail within the applicable section of this planning study. The compilation of data and information and presented methodology can be used to address planning study limitations and associated data gaps. This planning study also can be used to support future climate scenario modeling, vulnerability assessment, and/or adaptation strategy assessment for other PRB subareas or finer geographic scale, if necessary. The type of additional modeling and assessment required is project-specific.

The TAC participated in a series of interviews, meetings, and other engagement activities, including a survey, to supplement the data collection and analysis effort with local and institutional knowledge. The TAC comprised agencies and entities that manage, maintain, and operate the transportation network within the PRB, including NJ TRANSIT, New Jersey Department of Transportation (NJDOT), eight counties (Bergen, Essex, Hudson, Morris, Passaic, Somerset, Sussex, and Union), and City of Newark. It also comprised numerous stakeholders, including New Jersey Department of Environmental Protection (NJDEP), Rutgers University Office of the New Jersey State Climatologist, Transportation Operations Coordinating Committee (TRANSCOM), New Jersey Office of Emergency Management (NJ OEM), and New York Metropolitan Transportation Council (NYMTC) Mid-Hudson Transportation Coordinating Council.

Planning Process Methodology

NJTPA seeks to address the challenges of climate change through a series of planning studies to provide the foundation for sound, effective policies and integration of resiliency measures into the transportation planning process to prepare the New Jersey transportation system for potential climate change impacts. The outcomes of these efforts are designed to support the diverse planning, development, and infrastructure needs of NJTPA's member counties, municipalities, and state and federal transportation entities. This planning study focused on potential climate change impacts to transportation assets and infrastructure located in the PRB within New Jersey state boundaries.

The planning process comprised the four steps shown in **Figure 2** and summarized as follows:

Steps 1 and 2 included an existing and future vulnerability assessment. The vulnerability of each transportation asset was determined by using a set of criteria, developed for this study, quantifying its criticality, sensitivity, and adaptive capacity under the stress of various existing and future climate conditions. The criteria were applied to different asset classes, including bridges, culverts, facilities, rail lines, roads, and transit, and to determine the criticality for all assets. These criteria were based on the Federal Highway Administration (FHWA) 2017 Vulnerability Assessment and Adaptation Framework and the FHWA Vulnerability Assessment Scoring Tool.

Step 1: Vulnerability Assessment of the Area's Transportation Systems

The critical first step in determining future risk and vulnerability to climate change is understanding how transportation assets and plans have fared during past extreme weather events. Step 1 comprised evaluating NJDEP, NJDOT, NJTPA Enterprise Geographic Information System (EGIS), federal, state, local, and other data sources to identify and characterize existing transportation assets vulnerability to extreme flooding and heat events. This evaluation was supplemented by a review of hazard mitigation plans (HMPs) and the performance of Technical Advisory Committee (TAC) interviews. A GIS analysis was done to identify transportation assets vulnerable to existing storm conditions. In consultation with the TAC, there are two existing conditions for precipitation events: (1) existing 25-year precipitation event and (2) existing 100-year precipitation event.

Step 2: Projection of Future Climate Risks for the Passaic River Basin

Building upon the existing conditions assessment, Step 2 evaluated the risk and vulnerability of the transportation system based on climate change impacts. A range of global climate model projection datasets of future air temperature and precipitation, combined with H&H modeling and GIS analysis, were used to identify the transportation assets vulnerable to future extreme weather events. Sea level rise and storm surge factors were integrated into the analysis to evaluate future storm conditions. In consultation with the TAC, the 2045 and 2080 planning horizons were selected to assess the future 25-year (probability of occurrence is 4 percent in any given year) and 100-year (probability of occurrence is 1 percent in any given year) precipitation and heat events.

Step 3: Develop Adaptation Strategies for Prioritized Vulnerabilities

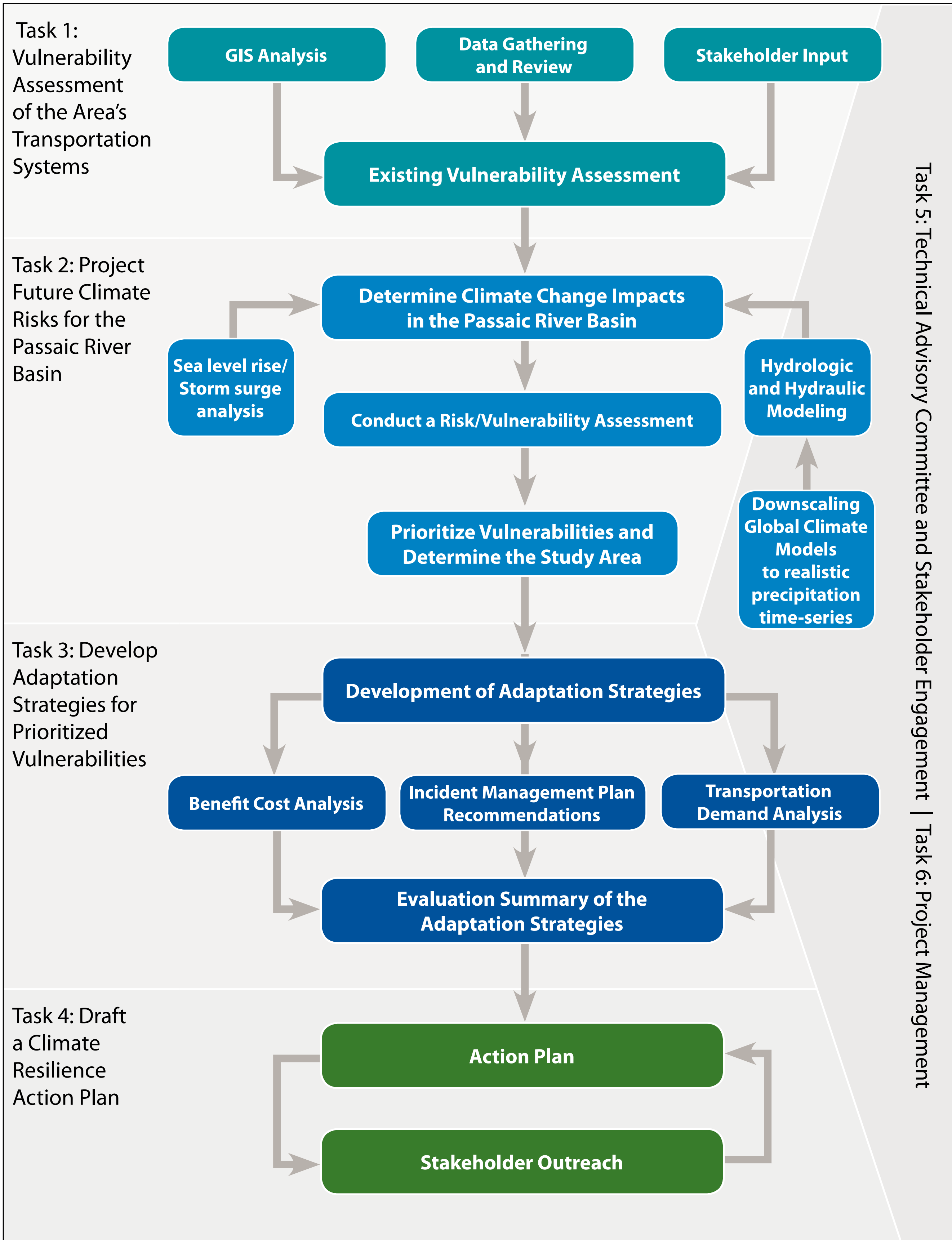
Step 3 commenced with the development of 71 adaptation strategies, which are applicable basinwide, based on literature review and consultation with subject matter experts and the TAC. Three critical transportation subareas were then identified, in consultation with the TAC, to identify a subset of adaptation strategies and perform a sketch-level BCA of transportation assets vulnerable to severe flood and heat scenarios located within each subarea.

Step 3 comprised a basinwide ITS analysis, including TAC interviews, to help identify strategies or best practices to improve incident response and emergency management during a severe climate event and develop recommendations for new or improved ITS.

Step 4: Draft Climate Resilience Planning Study

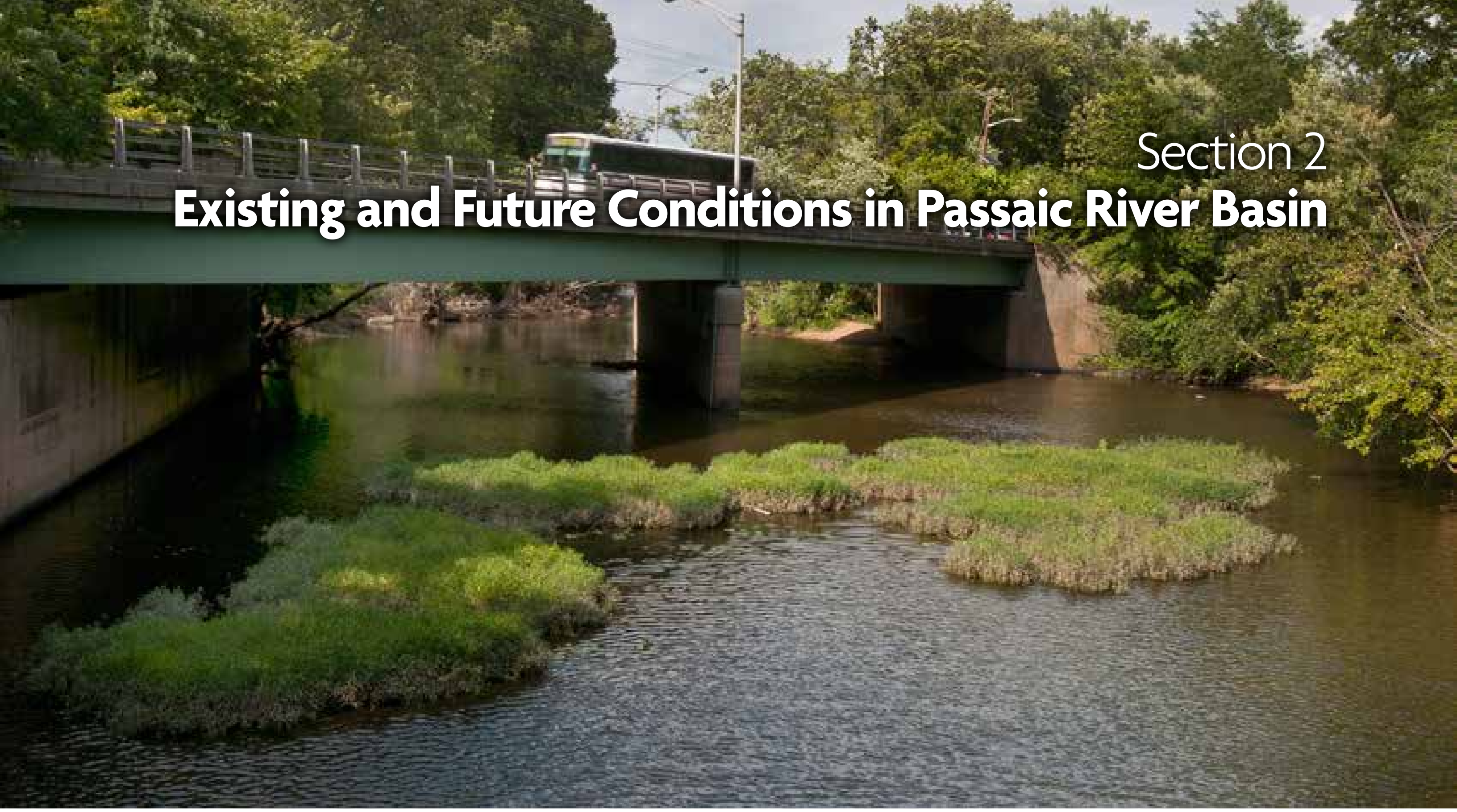
Step 4 compiled findings from Steps 1 through 3 to prepare the Passaic River Basin Climate Resilience Planning Study, including recommendations for further actions. This step included consultation with the TAC to ensure the recommendations were practical and implementable considering local practices and current and expected future resources.

Figure 2. Workflow process for NJTPA climate resilience planning study for Passaic River Basin



Planning Study Organization

- **Section 1 – Introduction:** Overview of the PRB basin, history of basin flooding, planning process methodology, and overall study objectives. Document review performed under Step 1 was incorporated into this section.
- **Section 2 – Existing and Future Conditions in Passaic River Basin:** Evaluation of extreme heat and precipitation events for existing conditions and two future planning horizons: 2045 and 2080. Presentation of Steps 1 and 2 temperature and precipitation projections and heat and flood extent mapping.
- **Section 3 – Vulnerability Assessment:** Identification of transportation assets that were ranked to be highly vulnerable to existing and future heat and flood event scenarios using the FHWA Vulnerability Assessment and Adaptation Framework as part of Step 3.
- **Section 4 – Adaptation Strategy Assessment:** Development and assignment of 71 measures or best management practices (BMPs) that can reduce the vulnerability of a transportation asset and increase its resilience to heat or flooding events. Assignment of the 71 measures or BMPs to highly vulnerable assets identified as part of Step 3. Case studies, including recommended adaptation strategies and sketch-level BCA, of selected subareas—Subarea A: Parsippany/Pine Brook, Subarea B: Willowbrook "Spaghetti Bowl," and Subarea C: River Road/Route 21 Corridor.
- **Section 5 – Intelligent Transportation Systems and Incident and Emergency Management:** Detailed evaluation of ITS and I&EM through document review and stakeholder interviews. Development of recommendations to upgrade PRB emergency communication systems and ITS to improve transportation safety, mobility, and operations.
- **Section 6 – Conclusions:** Summary of major study findings, recommendations to continue advancing the integration of resiliency into the PRB transportation network, and opportunities to enhance resiliency planning in northern New Jersey.



Section 2
Existing and Future Conditions in Passaic River Basin

Climate Change in New Jersey's Passaic River Basin

The state of New Jersey's geographic location results in highly variable weather patterns influenced by wet, dry, hot, and cold airstreams. The PRB resides in the New Jersey's Northern and Central Climate Zones, which are summarized below:

- **Northern Climate Zone:** Comprises elevated highlands and valleys that are part of the Appalachian Uplands. This zone normally exhibits a colder temperature regime than other climate regions of the state. During winter, average temperatures can be more than 10 degrees Fahrenheit (°F) cooler than in the state's Coastal Zone. Annual snowfall averages 40 to 50 inches. Average number of freeze-free days is 163. During the warm season, thunderstorms are primarily responsible for precipitation, with twice the number of thunderstorms occurring compared to the Coastal Zone, where the nearby ocean helps stabilize the atmosphere.
- **Central Zone:** Comprises a northeast-southwest orientation, running from New York Harbor and the lower Hudson River to the great bend of the Delaware River near Trenton. This zone is densely populated by urban locations with a high concentration of paved surfaces that result in warmer temperatures and contribute to the "heat island" effect. During the warm season, temperatures above 90°F are commonly observed for 15 to 20 days. During the cool season, the average number of freeze-free days is 179.

Measurable precipitation falls on approximately 120 days of the year. Fall months are usually the driest with an average of 8 days with measurable precipitation. Other seasons average between 9 and 12 days per month with measurable precipitation. Average annual precipitation ranges from about 40 inches along the southeast coast of New Jersey to 51 inches in north central parts of the state. Many areas average between 43 and 47 inches. Most areas receive 25 to 30 thunderstorms per year, with fewer storms near the coast than farther inland.[1]

Climate change is occurring in the northern New Jersey region and will continue resulting in increased temperatures; increased precipitation; more frequent droughts; increased intensity, duration, and frequency of extreme storms; and sea level rise.

1 Rutgers University Climate Lab. n.d. "The Climate of New Jersey." Available at https://climate.rutgers.edu/stateclim_v1/njclimoverview.html.

The following impacts from Superstorm Sandy are identified in the New Jersey HMP.

NJ Transit Rail System

- NJ Transit's Rail Operations Center was engulfed in water that damaged backup power supply systems, the emergency generator, and the computer system that control the movement of trains and power supply.
- Numerous downed trees across the rail system caused damage to overhead wires and signal wires.
- There were rail washouts across the system, including on the North Jersey Coast Line.
- Several rail stations were flooded, including Hoboken Terminal (a key multimodal regional transportation hub).

NJ Transit Bus System

- Power outages in local communities resulted in the loss of traffic control devices critical to safe operation.
- Downed tree limbs and power lines made many roads impassable.
- Nine of NJ Transit's bus garages operated on backup generator power for an extended time period.

NJ Transit Light Rail System

- Newark Light Rail sustained flooding in Newark Penn Station and major debris damage between Newark Penn and Branch Brook Park stations.

According to the New Jersey state climate summary by National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information,[2] annual temperature has increased approximately 3°F since the beginning of the twentieth century. Declines in the number of extreme cold days (minimum temperatures below 0°F) have occurred since the early 1990s. The years 2004 to 2014 observed annual total precipitation approximately 8 percent above average of the past century's average; the number of extreme precipitation events also were above this average. Annually the state experiences at least one coastal storm; however, some years have documented 5 to 10 storm events. The number of tidal flood days also has increased due to sea level rise and land subsidence[3] factors. These changes in climate conditions expose vulnerabilities of the transportation network, impacting the function of specific transportation assets and negatively affecting the transportation network's operations. NJTPA planning studies and county HMPs document how the transportation system has been, and will continue to be, impacted by extreme temperatures and storm events. The following table lists findings from those documents:

Severe Storm Events
• Major wind events caused trees to fall, resulting in roadway and railway closures, power outages, and temporary relocation of citizens throughout the Township Montclair
• Flooding resulted in asset closure and damage during Hurricane Irene. For example, portions of the Conrail system in the City of Clifton were closed, portions of I-287 collapsed in Morris County, and road closures occurred at U.S. 46 in Essex County, I-80, State Route 20, State Route 23, U.S. 202, and U.S. 64 in Passaic County. Some roads remained flooded into early September
• Flood waters overflowed the riverbank, resulting in inaccessibility by emergency vehicles, including the industrial area in the Township of Livingston
• Heavy precipitation and associated flooding resulted in loss of assets; for example, the flooding at the Township of Livingston municipal garage resulted in the loss of vehicles and equipment and in the Town of Harrison resulted in damage to traffic signal control cabinets
• Deposition of vegetative and anthropogenic debris, such as experienced by the City of Newark during Hurricane Sandy
• Bridges were overtopped by floodwater, including bridges over the East Branch Rahway River in the Township of Livingston. Frequent closures of the Third River Bridge in Township of Belleville were necessitated
• Coastal storms and heavy precipitation events impacted underground rail, such as the City of Newark Light Rail
• Insufficient capacity of existing stormwater pumping stations and associated stormwater infrastructure contributed to flooding, such as experienced by the Township of West Caldwell and Township of West Orange
• Infrastructure, particularly asphalt roads, damaged due to the application of salt and intermittent freezing and warming conditions
Extreme Temperatures
• Extreme temperatures affected railroad tracks and suspended roadways, including bridges, by causing the steel to shrink or buckle
• Extreme heat events caused "brown-outs" due to increased energy usage from air conditioners, appliances, etc.
• Extreme cold temperature events caused power interruption from heavy snowfall, ice storms, etc.
• Extended power outages due to limited availability of backup power resulted in critical facilities and infrastructure being inoperable

2 National Oceanic and Atmospheric Administration (NOAA). n.d. NOAA State Climate Summaries, New Jersey. Available at https://statesummaries.ncics.org/chapter/nj/.

3 Land subsidence is the gradual settling or sudden sinking of the Earth's surface. Land subsidence and rising water combine to cause sea level rise.

The following sections discuss the assumptions and methodology for modeling existing and future extreme heat and flood events, considering sea level rise, storm surge, increased temperature, and precipitation projections. In consultation with the TAC, the annual occurrence storm events and future planning horizon models were determined upfront to support development of heat and precipitation projections and identification of climate change factors (such as sea level rise and storm surge values).

Storm Event Frequency (occurring in given year):

- 25-year storm has a 4% chance (or 1-in-25 chance)
- 50-year storm has a 2% chance (or 1-in -50 chance)
- 100-year event has a 1% chance (or 1-in-100 chance)

* A specific storm event can occur multiple times in a one-year period. Annual chance of occurrence does not mean the storm event will only occur once, rather indicates the probability of occurrence.

During an in-person TAC meeting on December 6, 2017, two precipitation events were selected for evaluation: 25-year precipitation event and 100-year precipitation event. The 25-year precipitation event corresponds to roadway design standards established by NJDOT.[4] The 100-year precipitation event was used to represent a severe storm event scenario and is typically used for flood insurance rate mapping by FEMA. In addition, the TAC selected two future planning horizons to evaluate climate change impacts: 2045 and 2080. The 2045 planning horizon complements existing 2045 capital plans and other planning documents issued by transportation agencies. The year 2080 represents a longer-term time frame that coincides with the expected useful life of many transportation assets being built or upgraded today.

Climate Change Factors

Projections of future heat and precipitation events, sea level rise, and storm surge were determined to model existing and future conditions within the PRB. These assumptions are summarized below and detailed in **Appendix A, Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Event** and **Appendix B, Projections for Sea Level Rise and Storm Surge.**

Heat Event and Precipitation Event Projections

Heat event and precipitation event projections used in this study were determined based on the World Climate Research Programme Climate Model Intercomparison Project Phase 5 (CMIP5) dataset.[5]

The CMIP5 dataset was used for the Fifth Assessment Report (AR5) Synthesis Report: Climate Change 2014 published by the Intergovernmental Panel on Climate Change (IPCC). IPCC is the United Nations body for assessing the science related to climate change and is the most widely accepted overview of the state of knowledge on the science of climate change. It includes projections of temperature and precipitation through the end of the twenty-first century using a range of global climate models. The IPCC projections were downscaled and spatially averaged across the entire study basin. Localized differences in precipitation and temperature patterns were not evaluated in detail, which is a limitation of the study.

The IPCC global climate models use four Representative Concentration Pathway (RCP) scenarios that base climate impacts on radiative forcing values. Radiative forcing is the net amount of energy the earth absorbs from the sun. Greenhouse gases increase the amount of solar radiation in the atmosphere, which results in an increase of the net radiative forcing of the earth—this is known as greenhouse effect. The RCP value indicates the level of radiative forcing assumed in the climate model to be reached by the year 2100. For example, RCP 2.6 is the rising radiative forcing that results in 2.6 watts per square meter by the year 2100. The four RCP scenarios are labeled: 2.6, 4.5, 6.0, and 8.5, representing four assumed radiative forcing levels of year 2100. Generally, higher numbers indicate greater assumed future greenhouse gas emissions and, consequently, larger anthropogenic climate change impacts. However, downscaled climate models may have some variation on this trend as presented with the study RCP 2.6 scenario for precipitation projections found in the results subsection.

For this study, heat events and precipitation events are defined as:

- **Heat events** are days when the ambient temperature is equal to or greater than 90°F. This is in alignment with NJ TRANSIT's 2012 Resilience of NJ TRANSIT Assets to Climate Impacts Report.
- **Precipitation events** are annual projected maximums and were used to model flood inundation extents. For this study, 4-day storm events were modeled, which is the time, known as "time of concentration," it takes for the runoff to be routed through the 935-square-mile watershed and accumulate at the outlet.

4 NJDOT Roadway Design Manual, https://www.state.nj.us/transportation/eng/documents/RDM/.

5 CMIP is a collaborative effort involving climate modeling groups from around the world. CMIP promotes a standard set of model simulations used to evaluate how realistic climate models are in simulating the recent past; provide projections of future climate change on two time scales (near term and long term); and understand factors responsible for differences in projections. For more information, go to https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5.

Heat Event Projections Results

The decade 2001–2010 was the hottest on record, and the current decade is on the way to exceeding it, with the period 2013–2017 registering as the hottest five-year period on record. This trend is expected to continue. For the analysis presented here, extreme heat events are defined as days in which the daily maximum temperature is equal to or above 90˚F. The number of days equal to or above 90°F projected by the global climate models for the two planning horizons (2045 and 2080) were compared to a historical baseline from 1950 to 1999 to quantify how much more frequently the basin may expect this type of extreme event in the future. **Table 1** presents the relative likelihood and representative total number of days of exceeding 90°F in the 2045 and 2080 planning horizons for each RCP scenario.

Table 1. Relative Likelihood and Representative Number of Days Exceeding Daily Maximum Temperature of 90°F

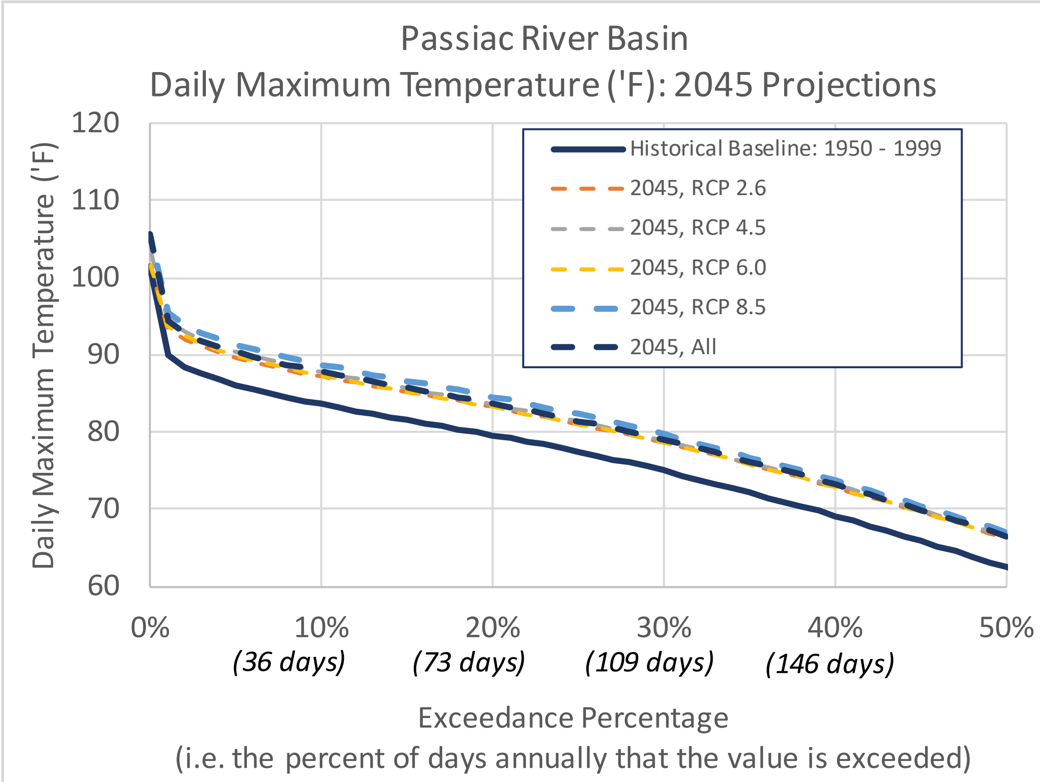
Global Climate Model Representative Concentration Pathway (RCP) Scenario	Planning Horizon (year)	
	2045	**2080**
RCP 2.6	15 days	15 days
RCP 4.5	18 days	26 days
RCP 6.0	15 days	33 days
RCP 8.5	26 days	62 days
RCP, All	20 days	31 days

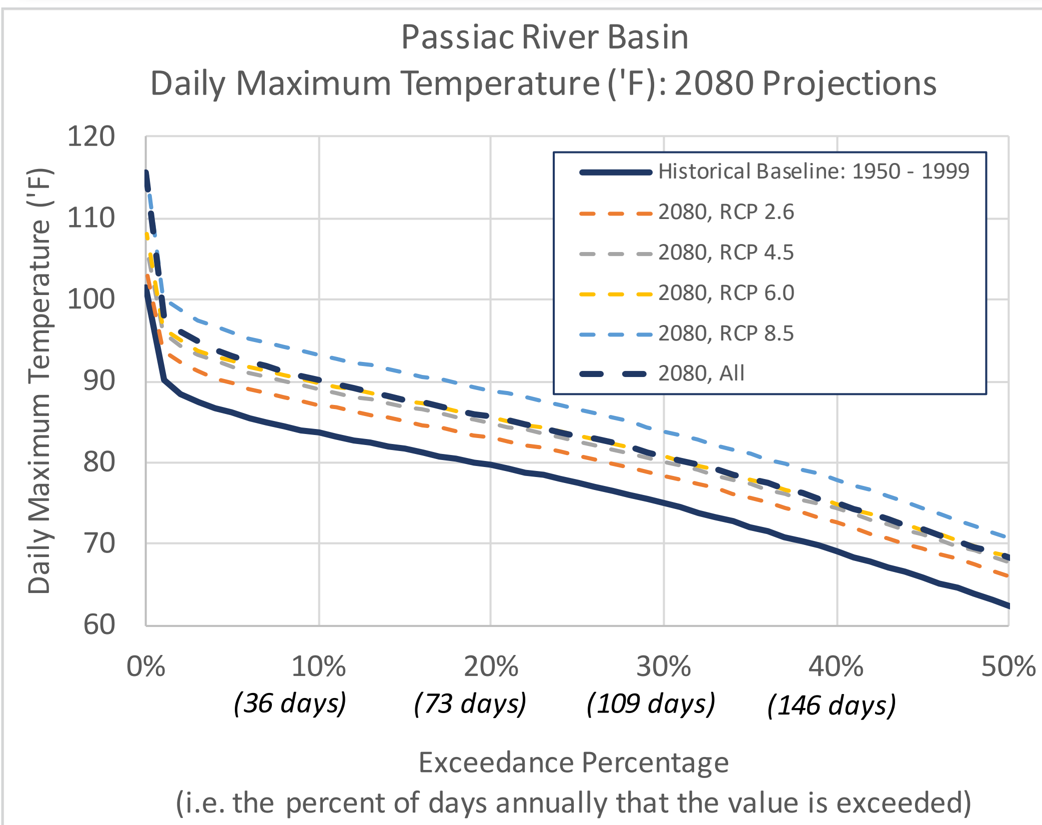
The results of this analysis are summarized with percentile plots (**Figure 3**) showing levels of consensus among models, within each RCP category separately and pooled together (All), for the two future planning horizons (2045 and 2080). **Figure 3** summarizes the modeled daily maximum temperature projections, for both planning horizons. Results show an upward shift in daily maximum temperatures from the historical baseline for the full range of daily temperatures. The results also demonstrate the variability in projections due to future emissions assumptions (RCP scenarios), with the worst-case scenario (RCP 8.5) projecting approximately 6 degrees higher than the best-case scenario (RCP 2.6), for the 2080 planning horizon. Much less variability is observed across the projection ensembles for the shorter 2045 planning horizon.

Findings show that 1 out of 50 years (2 percent probability of occurrence) in the historical hindcast period (1950–1999) had at least 15 days with maximum temperatures over 90°F. Conversely, the global climate model projection RCP All scenario predicts an approximately 95 percent chance of the same number of extreme heat days occurring in 2080.

At 100% level of consensus, the models are certain there will be an increase in the total number of days over 90°F. At the highest end of the projection spectrum (1-percent level of consensus), global climate models project extreme heat days in the range of 60–100 days per year for 2080, a double increase compared to the same percentile level for the historical baseline period.

Figure 3. Daily maximum temperature projections: Full range of temperatures





Precipitation Event Projections Results

Based on the study model, precipitation events occurring within the PRB are generally projected to increase in intensity and frequency for both planning horizons (2045 and 2080). **Table 2** shows the recurrence interval and storm size associated with the selected extreme storm events.

Table 2. Projected Changes in 4-Day Storm Event Recurrence Intervals

Storm Size (inches)	Reported Historical Recurrence Interval (years)	Projected Future Recurrence Interval, All (years)	Projected Future Recurrence Interval, RCP 2.6 (years)	Projected Future Recurrence Interval, RCP 4.5 (years)	Projected Future Recurrence Interval, RCP 6.0 (years)	Projected Future Recurrence Interval, RCP 8.5 (years)
2045 Planning Horizon						
3.7	2	2	2	2	1	1
4.4	5	4	4	3	3	3
5.6	10	6	8	6	6	6
6.6	25	14	19	12	11	14
7.9	50	27	37	24	20	34
9.1	100	54	64	47	33	70
2080 Planning Horizon						
3.7	2	1	2	1	1	1
4.4	5	3	4	3	3	3
5.6	10	6	7	6	6	5
6.6	25	14	14	13	18	13
7.9	50	27	16	28	36	30
9.1	100	53	33	58	70	54

There is consensus across global climate models that storm events will increase in magnitude in the future (**Figure 4**). For example, a 4-day storm event producing 9.1 inches of rain has a historical recurrence interval of 100 years or a 1-percent annual chance of occurrence. In 2045, this annual chance of a storm event producing the same 9.1 inches of precipitation over 4 days approximately is doubled, or is twice as likely (projected recurrence interval of 54 years) for the global climate model projection RCP All scenario.

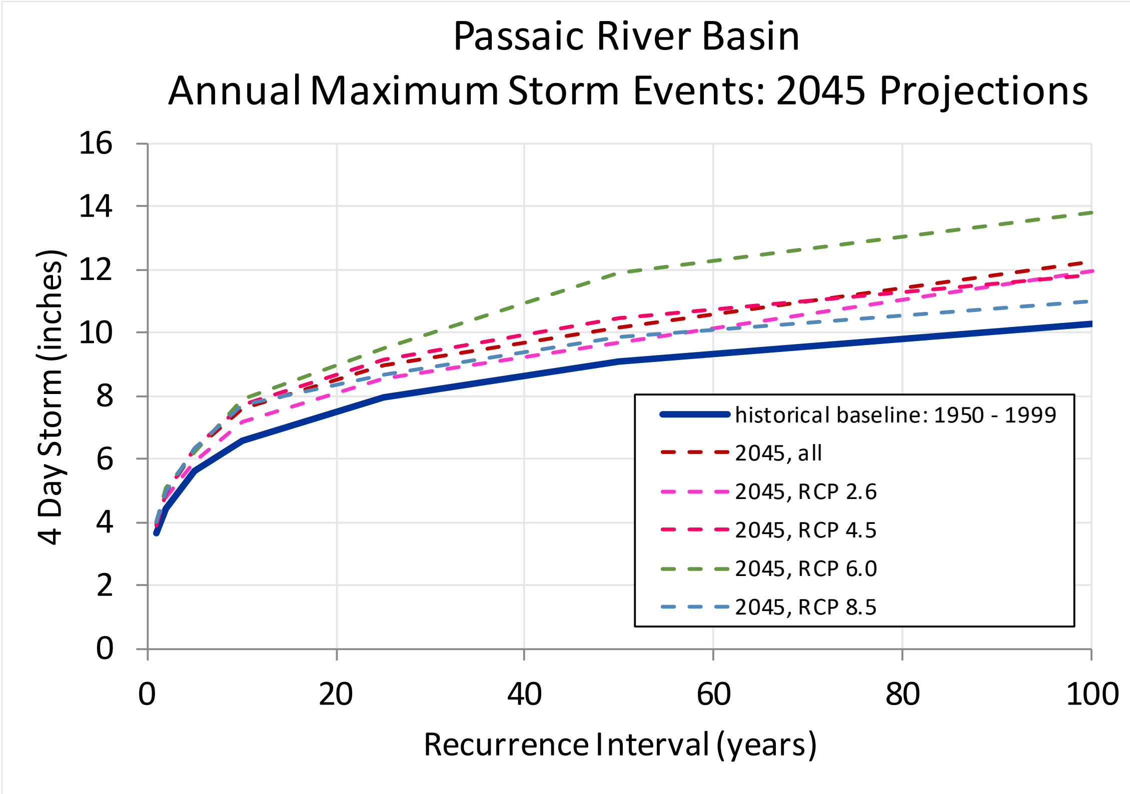
This means that the likelihood of extreme events of a specific magnitude occurring in the future is predicted to increase compared to the recent past. The magnitudes of projected changes do vary across models and model ensembles. For example, 2080 projections of the changes in the 25-year 4-day storm range from an increase of 0.6 inch to an increase of 1.8 inches, across the five ensembles. The 2045 projected increases for the same 25-year event range from 0.6 inch to 1.6 inches. The data are shown in **Figure 4** and **Appendix A, Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Events**.

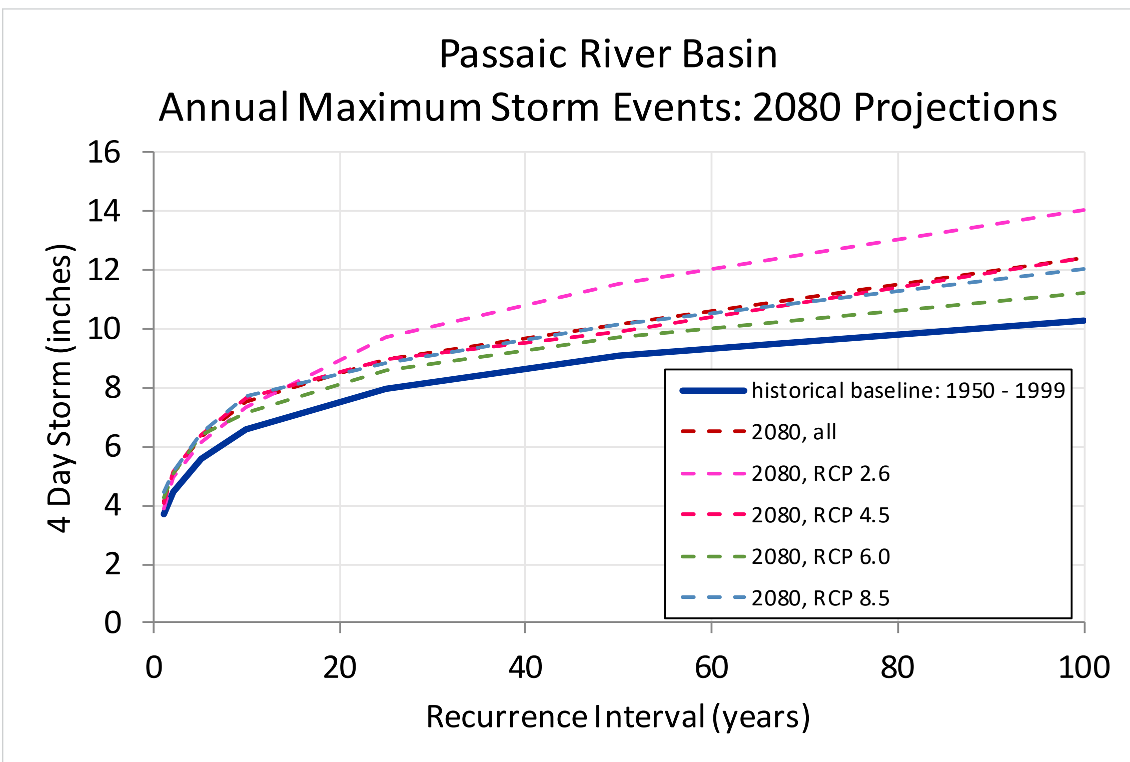
Based on the heat and precipitation event projections, three climate change scenarios were selected to model under each planning horizon:

- Planning Horizon 2045 Conditions: 25-year precipitation event (All RCP scenario); 100-year precipitation event (All RCP scenario); and one heat event (All RCP scenario)
- Planning Horizon 2080 Conditions: 100-year (All RCP scenario); 100-year precipitation event (RCP 2.6 scenario); and one heat event (All RCP scenario)

The All RCP projection scenario was primarily used for modeling purposes to reduce bias that may be present in one given set of global climate models. In addition, the results of the global climate model downscaling showed that the 2080 25-year event was similar in size to the 2045 25-year event. Therefore, a second 100-year event was chosen in place of the 25-year event for 2080. The 2080 100-year events encompass the All RCP scenario and the ensemble of the RCP 2.6 models. The RCP 2.6 scenario projection yielded the highest amount of rainfall for a 1-percent annual storm event.

Figure 4. Annual maximum 4-day storm event projections





Sea Level Rise and Storm Surge

Two major causes of sea level rise are melting of land-based ice such as glaciers and ice sheets and thermal expansion caused by warming of the ocean. Globally, sea level rose 0.7 inches per decade and has risen by approximately 1.3 inches per decade over the last 20 years. Sea level rise in New Jersey is rising faster than the global average due to land subsidence (sinking), including parts of the PRB study area. In the twentieth century, sea level rose by 12 to 14 inches in New Jersey, with the higher levels observed in areas of compactable sediments susceptible to subsidence and groundwater withdrawal.[6]

Higher sea levels mean that storm surges push water farther inland, which may impact roadways, bridges, railway, and other transportation infrastructure in the study area. Land subsidence, the loss of surface elevation due to removal of subsurface support, also contributes to higher flood depths. Land subsidence varies by location (local land subsidence) due to local groundwater levels, soil types, depth to bedrock, and other geophysical factors.

- **Storm surge**[8] is the amount of water, combined with the effect of normal tides, which is pushed towards the shore during a storm. The height of the storm surge is driven by many variables, such as the strength, size, and direction of the storm. Specifically, storm surge models are run for many storms. The storm parameters are used to determine the probability of storm surge events (10 percent, 2 percent, 1 percent, and 0.2 percent annual chance magnitudes). The results are a series of GIS points that are combined to create a stillwater elevation surface.
- **Stillwater elevation**[8] is the flood levels, not including the effects of waves but including storm surge and astronomic tide.
- **Sea level rise**[8] is caused by the melting of land ice in places such as Greenland and Antarctica, the thermal expansion of ocean water caused by increased temperatures, and changes in land water storage.

USACE and NOAA Sea-Level Change Curve Calculator computes six potential sea level rise curves for tide gauge locations across the United States. The models use existing historical tide gauge data as a baseline and calculate future sea level rise values based on different RCP scenarios from global climate models. The Sandy Hook, NJ gauge was used as the basis for establishing sea level change in the study area. The gauge has geographic proximity and similarities in vertical land movement (land subsidence or uplift) to the study area. The NOAA Intermediate High sea level rise projection was used to reflect a “middle of the road” planning approach.

Storm surge is the rise of water above tide levels that occurs during storms such as hurricanes, tropical storms, and nor’easters. The extent of coastal flooding is determined by three general factors:

1. Nature of the storm’s intensity, duration, and path;
2. Astronomical tide conditions at the time the storm surge reaches the shore; and
3. Land surface topography and sediment bed bathymetry (floor of a waterbody) of a particular area, which affect the timing and passage of storm surge.

Flood levels, not including the effects of waves but including storm surge and astronomic tide, are referred to as stillwater elevation. The 100-percent annual chance stillwater elevation data from the 2015 USACE North Atlantic Coast Comprehensive Study (NACCS) were used for this study and represent a flood elevation that is expected to occur in a given year. The stillwater elevations are based on detailed ADvanced CIRCulation model (ADCIRC)[7] storm surge models (high-fidelity, coupled wave, and storm surge models) from NACCS and represent the best science and engineering available on the topic. The results are shown in **Table 3**.

Table 3. Sea Level Rise and Stillwater Elevation Results for Tier 1 and 2 Hydraulic and Hydrologic Model Analysis

Planning Horizon (year)	Sea Level Projections (feet)	100% Stillwater Elevation[1] (feet NAVD88*)
2045	2.2	4.95
2080	4.82	

[1] Tier 1 and 2 H&H model stillwater elevation is applicable to the 2045 and 2080 planning horizons
* NAVD 88 = North American Vertical Datum of 1988

6 Miller, K.G., Kopp R.E., Browning, J.V., and Horton, B.P. 2014. Sea-level rise in New Jersey fact sheet. Available at https://geology.rutgers.edu/images/stories/faculty/miller_kenneth_g/Sealevelfactsheet7112014update.pdf.

7 The ADvanced CIRCulation model (ADCIRC) is a two-dimensional, depth-integrated, barotropic time-dependent long wave, hydrodynamic circulation model used to evaluate storm surge impacts.

8 Definitions per FEMA https://www.fema.gov/media-library-data/20130726-1541-20490-3376/frm_p1still.pdf and https://data.femadata.com/NationalDisasters/Hurricane%20Sandy/RiskMAP/Public/Public_Documents/Workmaps/Fact_Sheet_NJ_Storm_Surge.pdf.

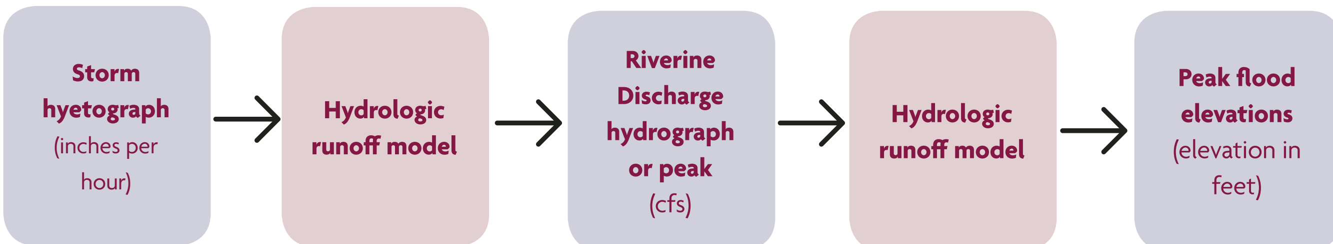
Planning Study Flood Event Scenarios

Computer modeling of hypothetical storm events allows engineers to provide planners and stakeholders with estimates of flooding depths and their associated probability for transportation assets in a study area. H&H information that is available within the PRB study area was used to:

1. Evaluate the existing flood risks
2. Approximate flood risks associated with future precipitation and storm surge scenarios

Figure 5 shows a basic schematic of the H&H modeling process. There are no statewide detailed H&H model coverages available and the available hydraulic model within the study had limited accessibility. This study made the best use of the limited available data and models, as discussed below.

Figure 5. Schematic of H&H modeling process



2012 Passaic River Basin Detailed Study

In December 2012, Risk Assessment, Mapping, and Planning Partners (RAMPP) presented FEMA Region 2 with an H&H study of the PRB.[9]

The 2012 study included an evaluation of riverine discharge using hydrologic runoff[10] modeling of the 935-square-mile PRB. The study also supported the detailed flood hazard mapping of a 41.2-mile reach of the Passaic River, which replaced prior detailed study of the Passaic River from 1978. Because of geographic limitations of RAMPP's detailed flood hazard mapping, the FEMA Region 2's 2017 Coordinated Needs Management Strategy database documenting 690 miles of detailed riverine study and 217 miles of approximate study was used to support the analysis. FEMA's National Flood Hazard Layer geodatabase includes flood hazard areas depicting the flood extents for detailed study (AE Zone) and approximate study (A Zone). The FEMA Region 2 study is documented in flood insurance studies spread across Sussex, Passaic, Morris, Essex, Somerset, Union, and Bergen Counties.

Details of the RAMPP and FEMA studies are in **Appendix C, Sources and Recommended Framework for Hydrologic and Hydraulic (H&H) Modeling.**

- **H&H models** provide estimates of flooding depths and the associated probability of specific assets to be impacted by floodwaters during a predefined, hypothetical storm event. Hydrologic models reflect the stormwater runoff over a defined area and hydraulic models analyze the behavior of water through water conveyance systems such as stormwater channels and storm sewers.
- **Storm hyetograph** is a time series of rainfall intensity distributed over the duration of an observed or hypothetical storm event.
- **Riverine discharge** refers to flow in a river which rises during and immediately following a storm event.

Based on the geographic limitations of the FEMA H&H studies and usability of models available within the PRB, three approaches were required to map existing and future annual-chance flood event scenarios:

1. Tier 1 method established flood risk within the 41.2-mile reach of the Central and Lower PRB
2. Tier 2 method established flood risk within the Upper PRB and tributaries to the Central and Lower PRB
3. Coastal area analysis established flood risk at the mouth of the Passaic River, adjoining Newark Bay

9 FEMA Region II, Task Order HSFE02-09-J-0001 for Passaic River Watershed Hydrologic & Hydraulic Study, New Jersey. FEMA Contract No. HSFEHQ-09-D-0369. Prepared by RAMPP, a joint venture of Dewberry, URS, and ESP. December 2012.

10 Hydrologic runoff analysis refers to an estimate of the riverine discharge associated with a particular storm hyetograph. The runoff model represents the area of the contributing watershed and simulates the amount of rainfall that either (a) infiltrates into the soil or (b) "runs off" and accumulates in the rivers. The model is based on the physical characteristics of the watershed and is often calibrated based on observed data. The output of the model is a set of riverine discharge hydrographs. Often only the discharge from the hydrologic runoff analysis is reported.

The geographic extent of each flood risk characterization approach is shown in **Figure 6**. These approaches are summarized in the subsequent subsections and details provided in **Appendix C** and **Appendix D, Geographic Information Systems Hydrologic and Hydraulic (H&H) Modeling Processing**.

Tier 1 Methodology for Establishing Flood Risk

The Tier 1 methodology covers a 41.2-mile reach of the Central and Lower PRB for which detailed hydraulic profiles and hydrologic runoff models were available from the 2012 FEMA study.

Those models were run using the flood depth profiles for 25-year and 100-year storm. The Tier 1 approach is the most comprehensive analysis for establishing the flood elevation for the existing and future annual-chance flood event scenarios.

Figure 7 shows the increase in flood depth and extent of inundation for the existing, 2045 and 2080 100-year storm event within the Tier 1 area. Therefore, all assets located within the modeled flood scenario extent of the Central and Lower PRB were able to be evaluated for vulnerability to flood events.

Tier 2 Methodology for Establishing Flood Risk

The Tier 1 area is a small fraction of the total amount of stream reaches in the study area (41 of 1,976 miles of streams in the basin as identified by the National Hydrologic Database). Therefore, a second methodology (Tier 2) was established to evaluate flood inundation depths and extents in targeted areas of the study area.

The project team applied the Tier 2 methodology on a representative sample of assets for which there is a detailed FEMA study (spanning 40 years) but no readily accessible hydraulic model is available to be used to determine future climate conditions. Therefore, the Tier 2 hydraulic analysis used available H&H modeling datasets nearest to a targeted asset to develop flood elevations for each storm event scenario and subsequently generate the flood hazards in defined Tier 2 focus areas of the study area (shown in **Figure 6**).

This approach links the hydraulic dataset within Tier 2 focused areas to the detailed hydrologic runoff modeling from the 2012 FEMA study that was updated with future climate scenarios. The datasets required for this approach were not digitized and could not be performed for all the assets in the study area due to project-specific constraints.

The criteria used to prioritize a representative sample of asset locations in the study area are as follows:

- Assets are not within the proximity of the 41.2-mile reach of the Central and Lower PRB covered under Tier 1.
- Location must be identified as impacted by the riverine flooding in of one of the effective detailed FEMA studies.
- Sample is geographically representative of the stakeholders' political boundaries (counties, townships, population density).
- Sample is geographically representative of the hydrologic boundaries (subbasins).
- Range of transportation assets falls within the sample areas, if possible, to evaluate the flood risk across asset class.
- Areas include those that have been qualitatively identified as areas of concern or at risk from flooding by the TAC, county HMPs, and drainage management system output GIS layer (see **Section 3, "Data Sources"**).

The Tier 2 approach calculated elevation of flood inundation extents based on the river station at each asset to determine if the asset would be inundated during a specific flood event. The calculated flood inundation extent could be not extrapolated for the entire Tier 2 area due to topographic changes, non-transportation asset structures along the river (such as residential and commercial buildings), and other features that effect the river hydraulics not represented in available H&H models.

Within the Tier 2 areas, 4,245 assets were evaluated for vulnerability to climate scenarios including 1,476 point locations along evacuation routes. Of these asset locations, 1,117 flood during the existing 100-year event, 1,263 asset locations flood under the 100-year (2045, RCP All) and 1,471 asset locations flood under the 100-year (2080, RCP 2.6) event. The total number of assets evaluated for each climate scenario is dependent upon the flood extent (footprint) of each scenario and whether transportation assets were located within this extent.

Figure 6. Passaic River Basin potential flood risk characterization areas. This figure shows the area of the study basin where Tier 1, Tier 2, and coastal analysis methodology was applied.

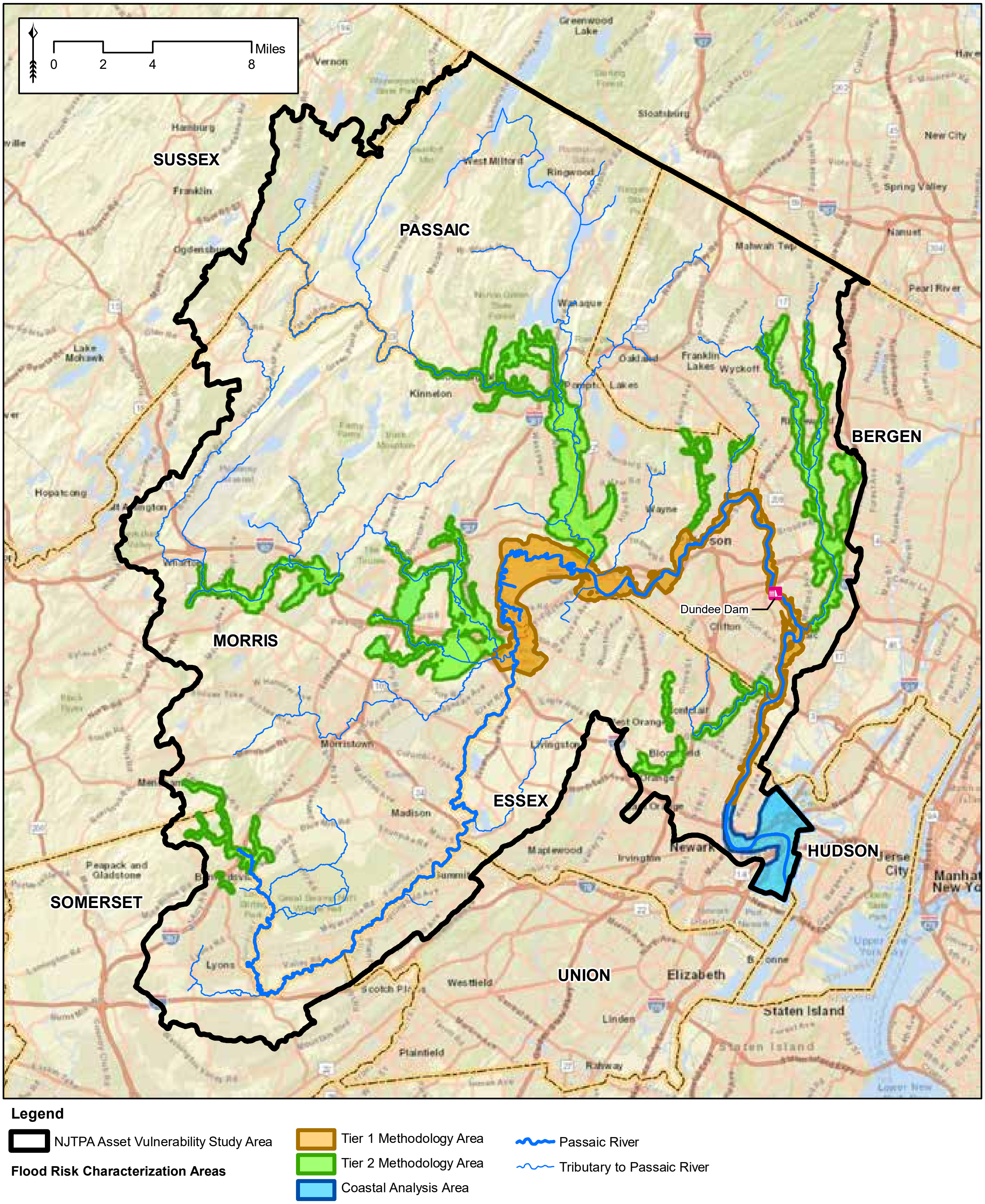
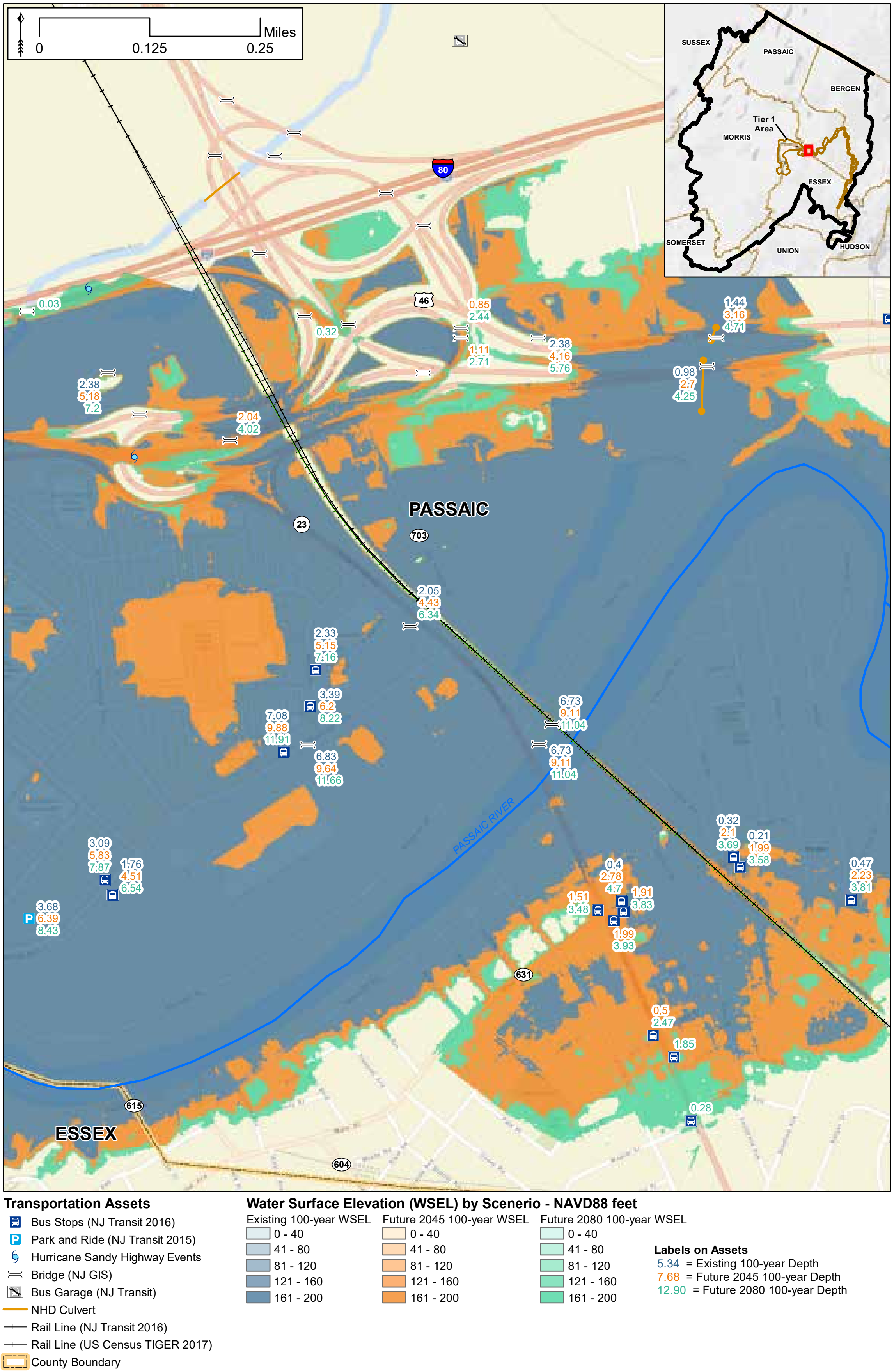


Figure 7. Flood depth level at select assets for the existing, 2045, and 2080 100-year storm event. This figure shows the increase in flood depth and extent of inundation over time for the existing, 2045, and 2080 100-year storm event within the Tier 1 area.



Coastal Area Analysis

A separate process to evaluate the potential flooding impacts at the mouth of the Passaic River near the coast was developed because there are no H&H models available, such as those used for the Tier 1 and Tier 2 methodologies. In this area of the river, as shown in **Figure 6**, a linear superposition (bathtub model) approach was applied. This approach takes the predicted sea level rise and adds it to stillwater elevation results and then uses the topography and elevation of the ground surface to determine the locations where assets will be subjected to flooding. It does not consider additional riverine flooding from inland stormwater runoff because the coastal flooding impacts are orders of magnitude greater.

In a coastal area, storm surge coincident with the 25-year and 100-year riverine flooding events is lower than the 25-year and 100-year stillwater elevation, respectively, because the storm events that drive the most extreme flooding conditions (riverine flooding events) are not the same storm events that drive the most extreme coastal storm surge conditions (stillwater elevations). Since it is coastal storm surge, and not precipitation-driven riverine flooding, that dominates flooding in the area at the mouth of the Passaic River, the 25-year and 100-year stillwater elevations were used as shown in **Table 4**. This is the same source of information used to determine the 1-year (100 percent) stillwater elevation of 4.95 feet shown in **Table 3**. **Figure 8** is a representation of the flood inundation depth and extent in the coastal area under the year 2045 scenario.

Table 4. Sea Level Rise and Stillwater Elevation Results Used for Coastal Area Analysis

Stillwater Scenarios	Sea Level Rise Projections (feet)	Stillwater Elevation (feet NAVD88)	Stillwater Elevation + Sea Level Rise (feet NAVD88)
25-year stillwater	n/a	10.66	10.66
100-year stillwater	n/a	13.35	13.35
25-year + sea level rise 2045	2.20	10.66	12.86
100-year + sea level rise 2080	4.82	13.35	18.17

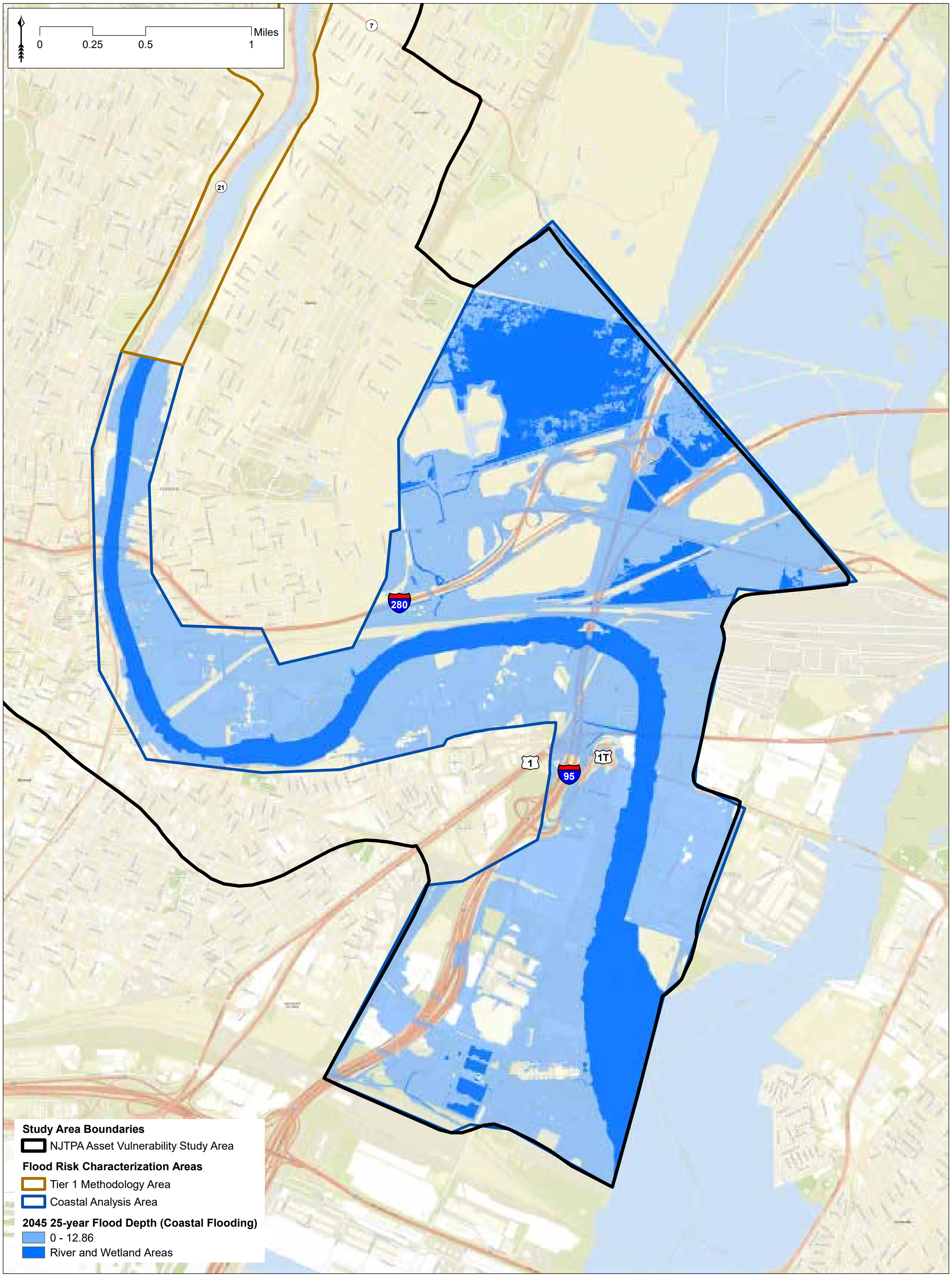
The initial results between the 25-year and 100-year 2045 events and the two 2080 100-year events (All RCP versus RCP 2.6) differed by fractions of an inch. Therefore, only one value for each future year was incorporated into the analysis.

Existing and Future Conditions

The existing and future vulnerability assessment scenarios developed for the study basin and discussed in this planning study include:

- Existing 25-year precipitation event
- Existing 100-year precipitation event
- 2045 25-year precipitation (All RCP) + 1-year stillwater elevation (NACCS 100-percent annual chance) + 2045 sea level rise NOAA intermediate-high)
- 2045 100-year precipitation (All RCP) + 1-year stillwater elevation (NACCS 100-percent annual chance) + 2045 sea level rise (NOAA intermediate-high)
- 2080 100-year precipitation (RCP 2.6, to show the worst-case scenario) + 1-year stillwater elevation (NACCS 100-percent annual chance) + 2080 sea level rise (NOAA intermediate-high)
- 2080 100-year precipitation (All RCP) + 1-year stillwater elevation (NACCS 100-percent annual chance) + 2080 sea level rise (NOAA intermediate-high)
- 2045 heat events (20 days over 90°F)
- 2080 heat events (31 days over 90°F)

Figure 8. Representation of flood inundation depth and extent in the coastal area under 25-year storm event at the 2045 planning horizon with consideration of 2.20 feet of sea level rise.



Once the transportation asset locations were mapped and climate scenarios (both flood and heat) were evaluated, a vulnerability assessment was performed to understand the current and future sensitivity and adaptive capacity of the transportation systems and its components within the study basin. The vulnerability assessment was conducted as follows:

- Reviewed available data sources to determine and map transportation corridors and assets in conjunction with existing and future climate scenarios in the project-specific geospatial database.
- Established criteria by which to evaluate the criticality of an asset to the transportation system, and quantify vulnerability sensitivity and adaptive capacity of an asset to heat and flooding stressors.
- Conducted TAC interviews to further refine the evaluation criteria for the *criticality*, *sensitivity*, and *adaptive capacity* of transportation assets within their jurisdictions.
- Assessed level of *vulnerability* (as measured by the criticality, sensitivity, and adaptive capacity) for PRB transportation assets using the FHWA Vulnerability Assessment and Adaptation Framework. Vulnerability of a transportation asset is determined by quantifying its criticality, sensitivity, and adaptive capacity under the stress of various existing and future climate conditions.

Data Sources

The vulnerability assessment encompassed data collection and review of the study area's HMPs, available GIS data, and existing reports and studies, complemented by TAC interviews and modeling results of existing and future heat and flood event scenarios. The following sections summarize data resources reviewed. A compilation of the study data resources is provided in **Appendix E, Data Sources Reference Table and Study Geospatial Database Schema**.

- **Criticality** of an asset considers its importance to the following considerations: disaster management, evacuation, business continuity, economy, social aspects of the region, transportation demand, and carrying capacity.
- **Sensitivity** is the degree to which the asset is affected by the climate conditions. It comprises climate impact exposure and known predicted effects.
- **Adaptive capacity** is a determination of an asset's ability to accommodate flood and heat stress and return to normal after a disruption.
- **Vulnerability** of a transportation asset is determined by quantifying its criticality, sensitivity, and adaptive capacity under the stress of various existing and future climate conditions.

Review of Existing Reports and Studies

Several studies, reports, and evaluations related to climatic hazards in the study area and throughout New Jersey were reviewed. The following resources were used to support development of the vulnerability assessment methodology:

- NJTPA Plan 2045, Connecting New Jersey, NJTPA Regional Transportation Plan
- FHWA Vulnerability Assessment and Adaptation Framework, 3rd Edition, FHWA-HEP-18-020, December 2017
- U.S. Department of Transportation (USDOT) Vulnerability Assessment Scoring Tool, June 2015
- HMPs for Bergen, Essex, Hudson, Morris, Passaic, Somerset, Sussex, and Union Counties[1] and New Jersey's statewide HMP[2]

All counties in the study area have HMPs that outline current and future hazards to the region; hazards include current and potential flood hazards relative to assets in the study basin. The team reviewed these plans to inform performance of the vulnerability assessment. Compiled information included establishing what potential extreme heat and flood risks may affect transportation assets, criticality of asset function (serve an emergency function), and current and recommended adaptation strategies.

GIS Data

GIS data were obtained from a variety of sources, including EPA's Environmental Justice Screening and Mapping Tool (EJSCREEN), NJTPA, NJDEP, NJDOT, NJ OEM, TAC county representatives, U.S. Department of Homeland Security, and New Jersey Geographic Information Network. These datasets primarily provided asset locations and corridors. NJDOT's 2016 Drainage Management System ranking was used to identify roadway closures due to flooding.

In general, the GIS data for commuter and freight rail and road assets, including support facilities, were comprehensive. Road and rail assets identified to be highly vulnerable to a flood event in the TAC interviews or the HMPs were highlighted and incorporated into the analysis. Road and rail GIS layers were broken further into network segments so specific areas of flooding could be evaluated. No sole access routes[3] for county, state, or interstate roadways were identified, and therefore sole access routes were not evaluated as part of this planning study.

A GIS layer showing evacuation routes was used to determine the emergency function of a transportation asset. Evacuation routes were primarily determined based on information from NJ OEM Coastal Evacuation Maps and supplemented by review of HMPs and TAC interviews. Roadways were designated as serving an emergency function if located within one-quarter mile of an emergency facility (shelters, hospitals, police stations) and as identified from review of the HMPs and TAC interviews. One-quarter mile was selected as a reasonable representation of roadways that would likely be used to access an emergency facility.

Annual Average Daily Traffic (AADT) counts along roadway segments were converted into GIS and used to determine where high volumes of traffic occur (high volumes of traffic correlate to increased maintenance). The National Bridge Inventory compiled and maintained by FHWA offers a comprehensive dataset identifying conditions of the nation's bridges. The inventory offers AADT counts for trucks, which influences the amount of wear and tear on a bridge's

1 Bergen County Hazard Mitigation Plan (2015), https://meri.njmeadowlands.gov/downloads/BC%20Plan_ALL.pdf; Essex County Hazard Mitigation Plan (2015), http://www.essexsheriff.com/wp-content/uploads/2016/10/Mitigation-Plan-Essex-Sheriff.pdf; Hudson Hazard Mitigation Plan (2015), http://www.hudsoncountynj.org/all-hazard-mitigation-plan/; Morris County Hazard Mitigation Plan (2015), https://oem.morriscountynj.gov/mitigation/; Passaic County Hazard Mitigation Plan (2015), http://www.passaiccountynj.org/government/departments/office_of_emergency_management/hazard_mitigation_plan.php; Somerset County Hazard Mitigation Plan (2015), https://www.co.somerset.nj.us/government/public-health-safety/hazard-mitigation/hazard-mitigation-plan; Sussex County Hazard Mitigation Plan (2016), https://www.sussex.nj.us/documents/sheriff/pdm/20160412/2016-Sussex-County-Draft-Plan.pdf;Union County Hazard Mitigation Plan (2015), http://ucnj.org/public-safety/2015-hazard-mitigation-plan-update/.

2 State of New Jersey Hazard Mitigation Plan (2014), http://ready.nj.gov/mitigation/2014-mitigation-plan.shtml.

3 Sole access routes are roadways that have a single entranceway and terminate with no outlet.

decking and structure. Other factors considered in the bridge assessment include structure type, age of the structure, vertical clearance, and bridge deck area. This information helped analyze the vulnerability of bridges and potential replacement costs. There are, however, bridge data limitations. Depth of the superstructure below the bridge and scour criticality[4] were not available for this vulnerability assessment. These data are important for evaluating bridge sensitivity to a flood event and subsequent impacts. The vulnerability assessment for bridges can be refined by stakeholders or NJTPA if the information becomes available.

Available information for all transportation assets studied includes location and elevation. The elevations were determined using lidar-derived digital elevation model surfaces. The spatial resolution of the digital elevation models is 1 meter. Vertical accuracy is approximately 15 to 20 centimeters in root mean square error. The horizontal accuracy for the model was not provided.

Modeling results of existing and future conditions, in conjunction with GIS display of culvert locations, were used to analyze where water levels may exceed road surfaces and whether water flows from events may exceed the culvert's capacity to convey the floodwaters. These data helped establish the vulnerability of roadways and culverts and analysis of potential replacement costs.

Technical Advisory Committee Interviews

Interviews with the TAC were conducted with representatives from each county in the study area (Bergen, Essex, Hudson, Morris, Passaic, Somerset, and Union), City of Newark, NJDEP Bureau of Dam Safety, and NJ TRANSIT.

A questionnaire was used to conduct the interviews and standardize the data collection process. The primary questions focused on identifying the transportation corridors and assets located within the representative's geographic or organizational area and determining which corridors or assets are critical to operations of the larger transportation system and which corridors or assets may be vulnerable to current and future climate conditions.

Evaluating Transportation Asset Vulnerability

Vulnerability of a transportation asset is determined by quantifying its criticality, sensitivity, and adaptive capacity under the stress of various existing and future climate conditions.

Figure 9 shows the process to quantify vulnerability. Criticality of an asset considers its importance to the following considerations: disaster management, evacuation, business continuity, economy, social aspects of the region, transportation demand, and carrying capacity. Sensitivity is the degree to which the asset is affected by the climate conditions. It comprises climate impact exposure and known predicted effects. Adaptive capacity is a determination of an asset's ability to accommodate flood and heat stress and return to normal after a disruption.

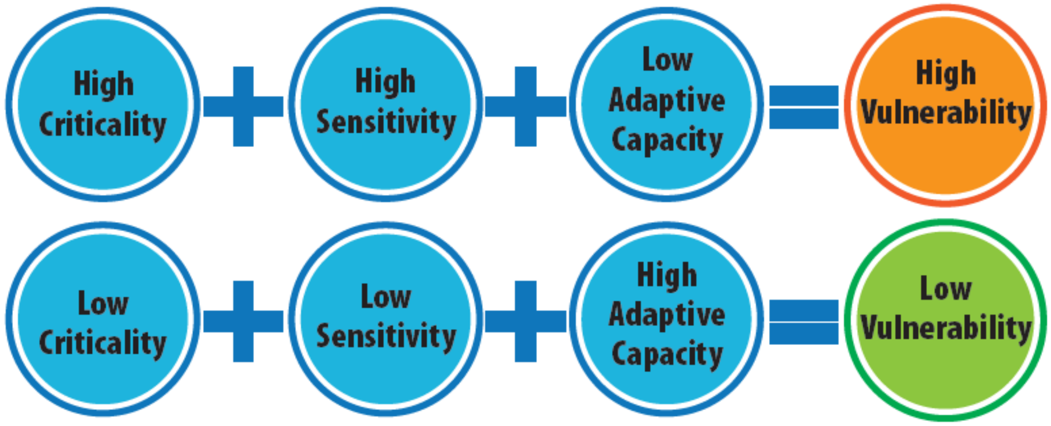
A set of criteria was developed for quantifying sensitivity and adaptive capacity for different asset classes (bridges, culverts, facilities, rail lines, roads, transit) and criticality for all assets.[5] These criteria were based on the FHWA Vulnerability Assessment and Adaptation Framework, FHWA Vulnerability Assessment Scoring Tool, and study team's subject matter expertise.

The framework developed to quantify vulnerability criteria is based on the framework recommended by FHWA, an

4 As defined in FHWA Report No. FHWA-PD-96-001, "a scour critical bridge is one with abutment or pier foundations which are rated as unstable due to (1) observed scour at the bridge site or (2) a scour potential as determined from a scour evaluation study."

5 Transportation assets in this study are categorized as bridges, including road and rail bridges; facilities, including administrative, maintenance, stations, parking, and bus depots; rail, including rail track; roads, including evacuation routes or serve an emergency function (within one-quarter mile of an emergency facility); and transit assets, including all rolling stock such as buses and rail cars.

Figure 9. Representation of vulnerability determination



indicator-based vulnerability assessment approach that provides a relatively cost-efficient way to quantify and rank vulnerability of transportation assets using available data. FHWA states this approach "offers practitioners a big picture understanding of system-wide vulnerabilities and identifies where additional resources could be used to further distinguish asset-specific vulnerabilities."

Under the PRB study framework, quantitative data on assets (asset elevation, geographic location) serve as indicators for evaluating potential vulnerabilities to current and projected climate conditions. The indicators are specific to asset classes (bridges, culverts, facilities, rail lines, roads, transit) and, depending on the nature of the assets in that class and available data, focus on asset-specific sensitivity and adaptive capacity factors for each climate stressor evaluated (extreme heat events, extreme precipitation events, sea level rise, storm surge).

Three criteria were added together to quantify vulnerability: criticality, sensitivity, and adaptive capacity. Each criterion has a set of indicators with an assigned a value between 1 and 10 (1 = low, 5 = medium, 10 = high). The indicators for criticality of all asset classes are:

1. Asset is identified as a critical transportation asset.
2. Magnitude of connections or ridership volume.
3. If the asset is classified as an evacuation route.

To quantify sensitivity and adaptive capacity, different indicators were identified for each asset class. The scores were assigned for each indicator based on a sensitivity level on a scale of 1 to 10 (same scale as criticality) and on an adaptive capacity scale of 1 to 10 (1 = high, 5 = medium, 10 = low), the reverse of criticality and sensitivity. The highest score from any one indicator for each category—criticality, sensitivity, or adaptive capacity—is the rating for the category. Scores for individual indicators within each vulnerability assessment category were not added together, and an asset that triggered multiple criticality indicator ratings cannot get a score higher than 10. This method was chosen in order to not skew results for a class of assets that may have more available indicators in a given category than other classes of assets.

The overall score of each vulnerability criteria were added, resulting in the total vulnerability score for an asset (see **Figure 9**). The total possible score for any single asset is between 3 and 30; the higher the score, the more vulnerable the asset is to the climate scenario analyzed. An important assumption when analyzing these scores is if a total score is lower than 3, then it indicates there were incomplete data to conduct the full vulnerability assessment. It does not indicate there a lower vulnerability. The detailed criteria used to conduct the vulnerability assessment are in **Appendix G, Process for Evaluating Criticality, Sensitivity, and Adaptive Capacity of Assets**.

Vulnerability Assessment Assumptions

The quantity and quality of available data to assess vulnerability of transportation assets varied between asset categories and within a category. Thus, certain assumptions were made.

- **Bridges**
  - Each county government entity is responsible for inspecting and maintaining its bridges. Some county public works departments indicated they have routine inspection and maintenance programs for their bridges.
  - Bridges within the project area boundaries receive timely inspections and routine and preventive maintenance.
- **Rail**
  - If a rail crossing intersected a stream or water body, it was assumed a bridge was located along the length of rail track.
- **Roads**
  - Evacuation route mapping was used as the key criticality indicator for the study area's roadway data. Because evacuation routes result in a roadway being highly critical, it is assumed all assessed evacuation route roadways are critical. No further criticality analysis was conducted.
- **Transit**
  - Bus routes on critical roadways are included in the road category rather than the transit category.
- **Data Gaps**
  - Additional vulnerability indicator data gaps were identified for each asset category. Those data gaps are listed in **Table 5**. The data gaps have been built into the existing GIS database and, if populated, can refine the results of future vulnerability assessments in the region.

Table 5. Vulnerability Assessment Indicator Data Gaps for Asset Classes

Asset Class	Indicator Data Gaps
Bridges	• Preventative plan for cooling movable bridges • Detour length • Disruption duration • Depth of the bridge's superstructure below the deck surface (depth of bridge cross section) • Scour criticality • Truck traffic volume • Bridge condition ratings
Culverts	• Culvert length • Culvert dimensions at inlet and outlet
Facilities	• Previous heat damage • Disruption duration • Preventative maintenance and preservation practices
Rail	• Delay ratio • Preventative rail plan • Emergency response plans • Disruption duration • Preventative maintenance and preservation practices • Rail design • Ballast type • Presence of electric signals
Roads	• Previous heat damage • Disruption duration • Detour length • Preventative maintenance and preservation practices • Pavement surface material and type • Truck traffic volume
Transit	• Delay ratio • Priority for assistance • Disruption duration

Vulnerability Assessment Results

The vulnerability assessment score is instrumental in identifying assets that may experience service disruptions during extreme heat and flooding events. The score is the first step to ranking and prioritizing the assets for adaptation strategies.

A total of 3,245 transportation assets were evaluated for the vulnerability assessment, giving a combination of 22,920 scores. Approximately 10 percent (2,920) of these asset and scenario combinations resulted in a vulnerability score greater than or equal to 21 out of 30. **Table 6** shows the results of the existing and future vulnerability assessment by climate scenario and transportation asset.

Table 6. Transportation Assets Assessed for Vulnerability to Flood and Heat Scenarios

Asset Class	Sea Level Rise Projections (feet)
Bridge	406
Culvert	1,520
Facilities	637
Rail	230
Road	452
Transit	Transit assets include all rolling stock such as buses and rail cars
Total	**3,245**

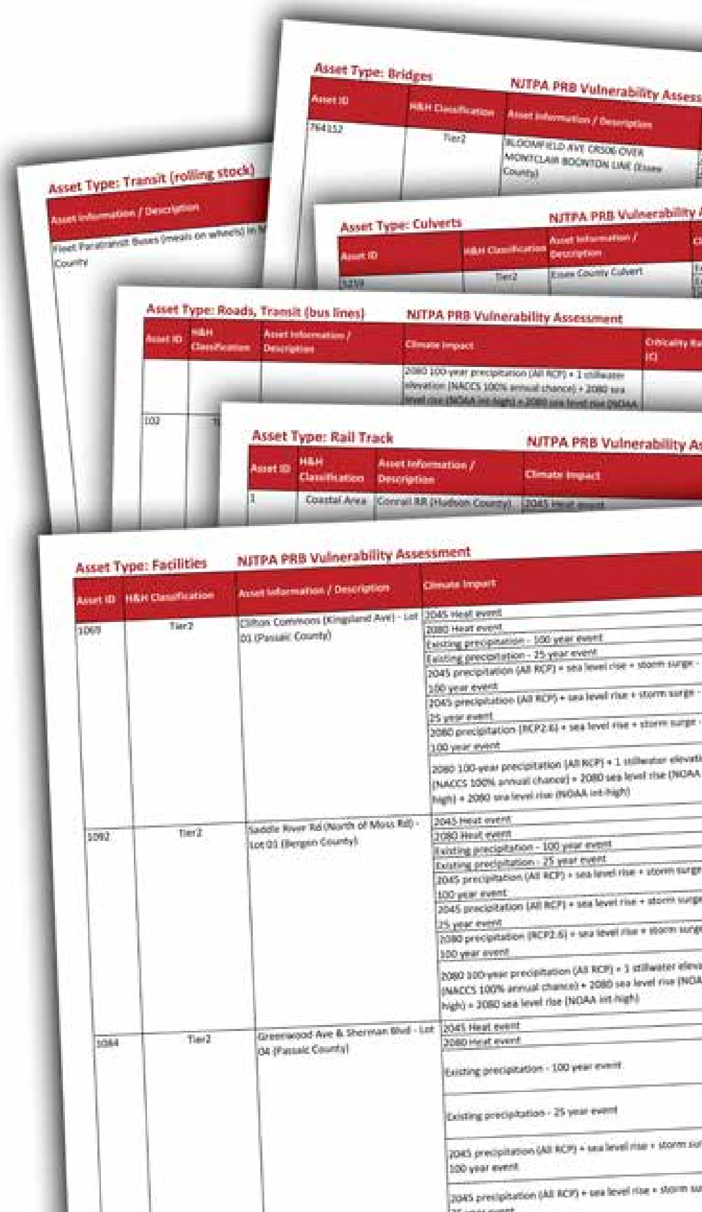
The vulnerability assessment results are summarized in **Appendix H, Results of the NJTPA PRB Vulnerability Assessment**. Each matrix includes a unique GIS identification number (Asset ID), H&H classification that reflects the methodology used to determine flooding extents (Tier 1, Tier 2, Coastal Area); asset information and description; and quantification (or ratings) of asset criticality, sensitivity, and adaptive capacity.

The asset ID is a key piece of information that will differ for each asset evaluated in the planning study. In some cases, the asset information and description are the same for multiple assets, which is due to the limitation in the extent of the data available in GIS. In these cases, refer to the asset ID to distinguish between assets with the same or similar descriptions. The indicators that triggered criticality, sensitivity, and adaptive capacity ratings are included to provide reasoning for the ratings. The overall vulnerability rating is then calculated in the final column. **Figure 10** is a screenshot of the vulnerability matrix template. **Figures 11** through **18** are maps showing the vulnerability results.

When reviewing the vulnerability assessment results, assumptions and indicator triggers were considered. For bridges, for example, the flood level might not reach the top of the bridges, but it may inundate the bridge's approaches, leading to bridge closure or damage due to rising waters and debris carried by the floodwaters. The same may be true if floodwaters reach the bottom chord of the superstructure, often several feet below the road deck of the bridge structure.

A data limitation is the available bridge elevation data are based on lidar that reflects the elevation of the bridge deck. The sensitivity score reflects this elevation against the determined floodwater elevations, which may not fully reflect the true

Figure 10. Screenshot of vulnerability assessment matrix



vulnerability of a given bridge. An opportunity for further analysis for bridge owners and operators is to survey the bridges for height of their superstructures or entryways and to reevaluate the vulnerability based on these updated elevations.

Subject matter expertise should be leveraged when interpreting the results to more accurately evaluate assets, especially those in the high vulnerability category. Examples of high vulnerability assets are provided below along with their vulnerability scores to provide for further detail on how vulnerability ratings were established by the study team.

Examples of Highly Vulnerability Assets

Bridge spanning Pompton River, Morris County, New Jersey

The bridge in Morris County at NJ Route 23 over Pompton River (Asset ID 1619151) has a vulnerability score of 30 (the highest possible score). This score puts the bridge in the high vulnerability range for all six flooding climate scenarios. (The bridge received a score of 21 for the heat scenarios). The bridge is located on an emergency evacuation route, giving it a criticality rating of 10. It was constructed in 1935 and reconstructed in 1986 with a low navigational channel clearance over Pompton River, giving it a sensitivity rating of 10. The bridge has three lanes in each direction. It has a total length of 343 feet and a deck area of 37,717 square feet. Based on FHWA guidance, the bridge's total replacement cost is about $16,972,533 (2018 US$), giving it a low adaptive capacity rating of 10 in accordance with established criteria used to conduct the vulnerability assessment are in **Appendix G, Process for Evaluating Criticality, Sensitivity, and Adaptive Capacity of Assets**.

Mountain View-Wayne Station in Passaic County, New Jersey

Mountain View-Wayne Station in Passaic County on the Montclair-Boonton Line (Asset ID 1055) was identified as a high vulnerability asset with a score of 30 for all six flooding climate scenarios. (The station received a score of 20 for heat scenarios). The station was identified as a critical asset in the county's HMP, giving it a 10 rating for criticality. The HMP identified performance issues and service disruptions during past extreme events; the station was impacted by 100- and 500-year flood events, putting this asset in the high sensitivity category with a 10 rating. If the station is affected by an extreme event, it will directly affect the station's performance, functionality, or usability, which puts the station in the low adaptive capacity category with a rating of 10. Station replacement costs are not available.

Figure 11. Existing 25-year precipitation event

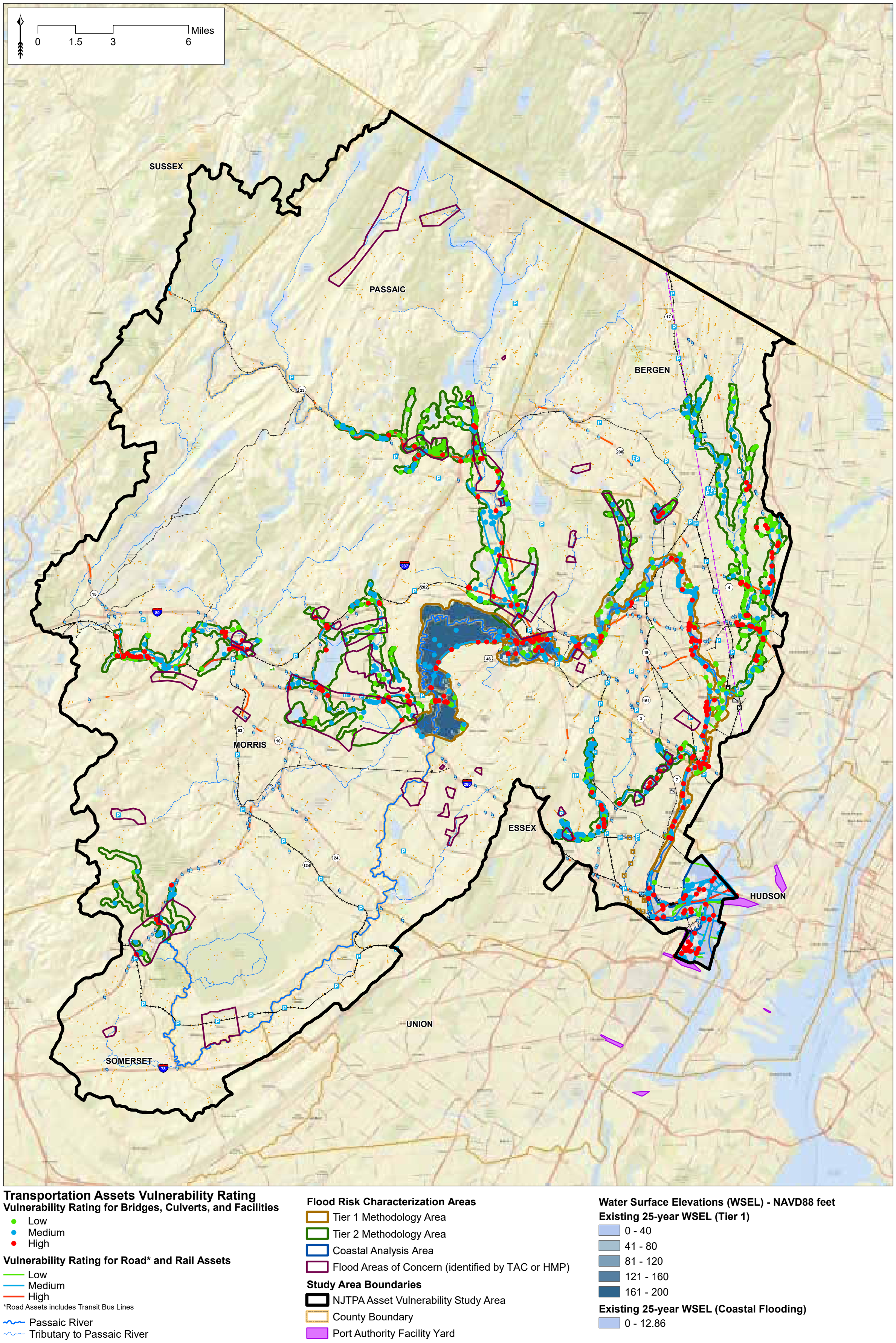
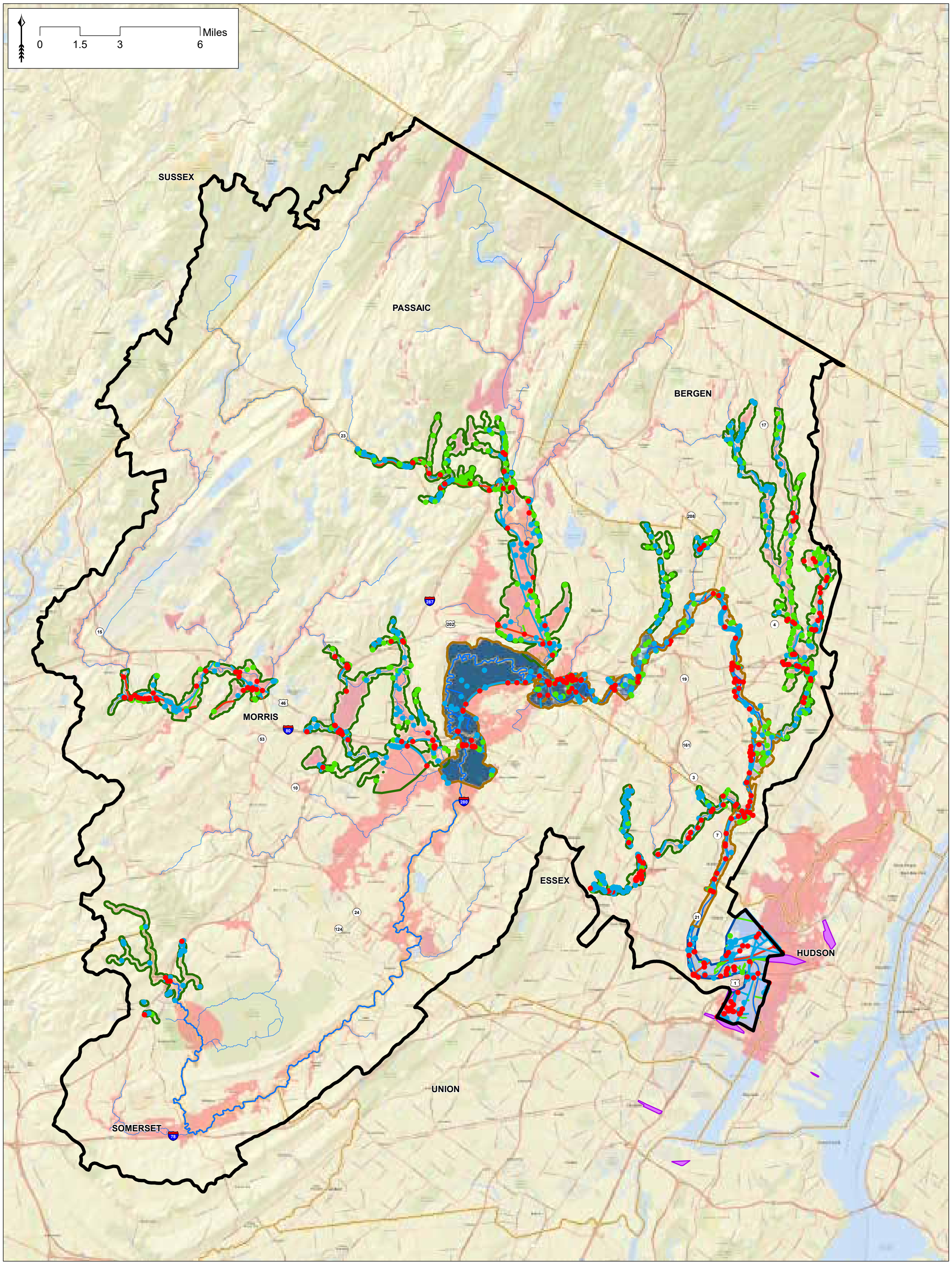


Figure 12. Existing 100-year precipitation event



Transportation Assets Vulnerability Rating

Vulnerability Rating for Bridges, Culverts, and Facilities
- Low
- Medium
- High

Vulnerability Rating for Road* and Rail Assets
- Low
- Medium
- High

*Road Assets includes Transit Bus Lines

- Passaic River
- Tributary to Passaic River

Flood Risk Characterization Areas
- Tier 1 Methodology Area
- Tier 2 Methodology Area
- Coastal Analysis Area

Study Area Boundaries
- NJTPA Asset Vulnerability Study Area
- County Boundary
- Port Authority Facility Yard
- FEMA Effective Flood Zone

Water Surface Elevations (WSEL) - NAVD88 feet

Existing 100-year WSEL (Tier 1)
- 0 - 40
- 41 - 80
- 81 - 120
- 121 - 160
- 161 - 200

Existing 100-year WSEL (Coastal Flooding)
- 0 - 12.86

Figure 13. 2045 25-year precipitation (All RCP) + 1 stillwater elevation (NACCS 100-percent annual chance) + 2045 sea level rise (NOAA intermediate-high)

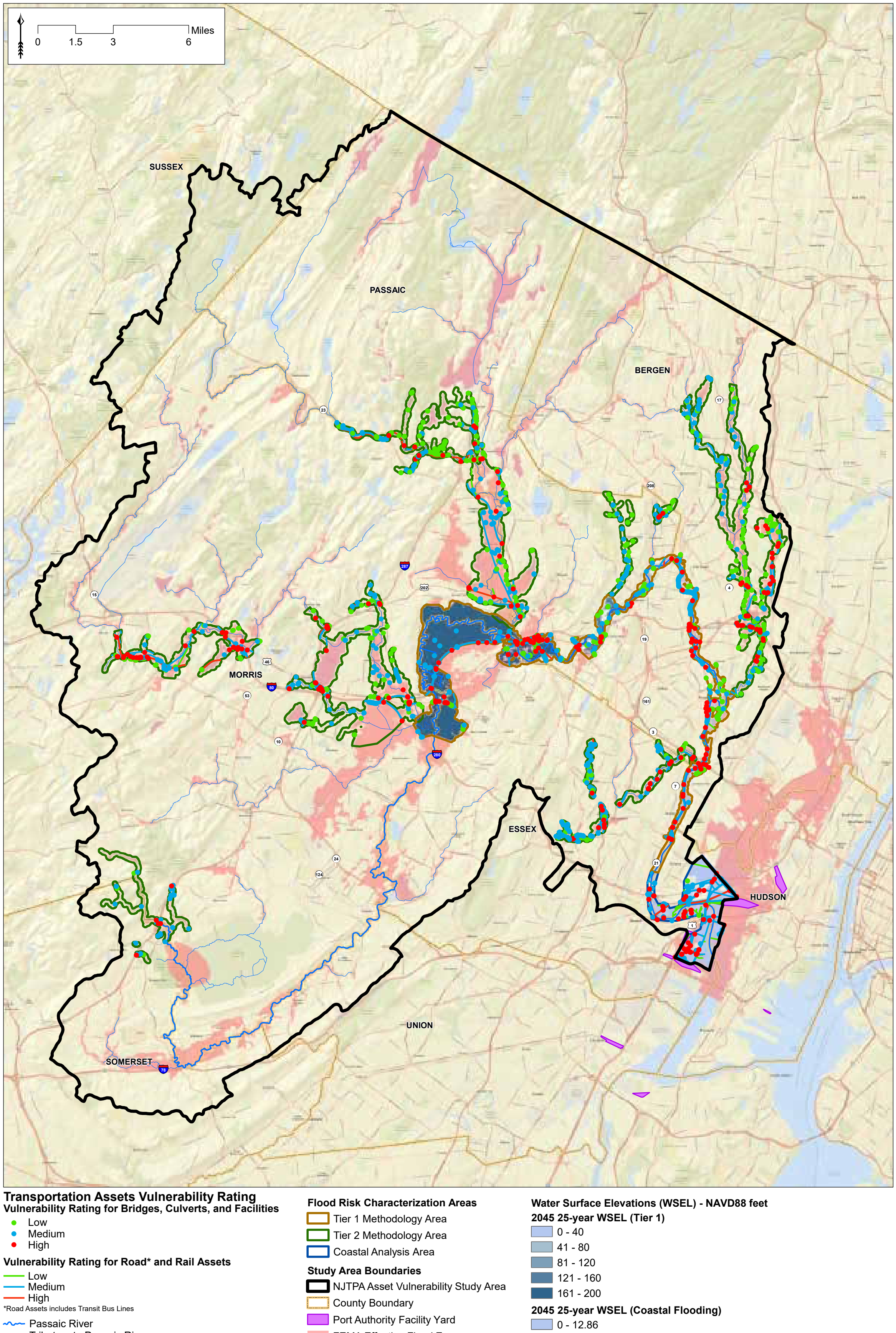


Figure 14. 2045 100-year precipitation (All RCP) + 1 Stillwater Elevation (NACCS 100-percent annual chance) + 2045 sea level rise (NOAA intermediate-high)

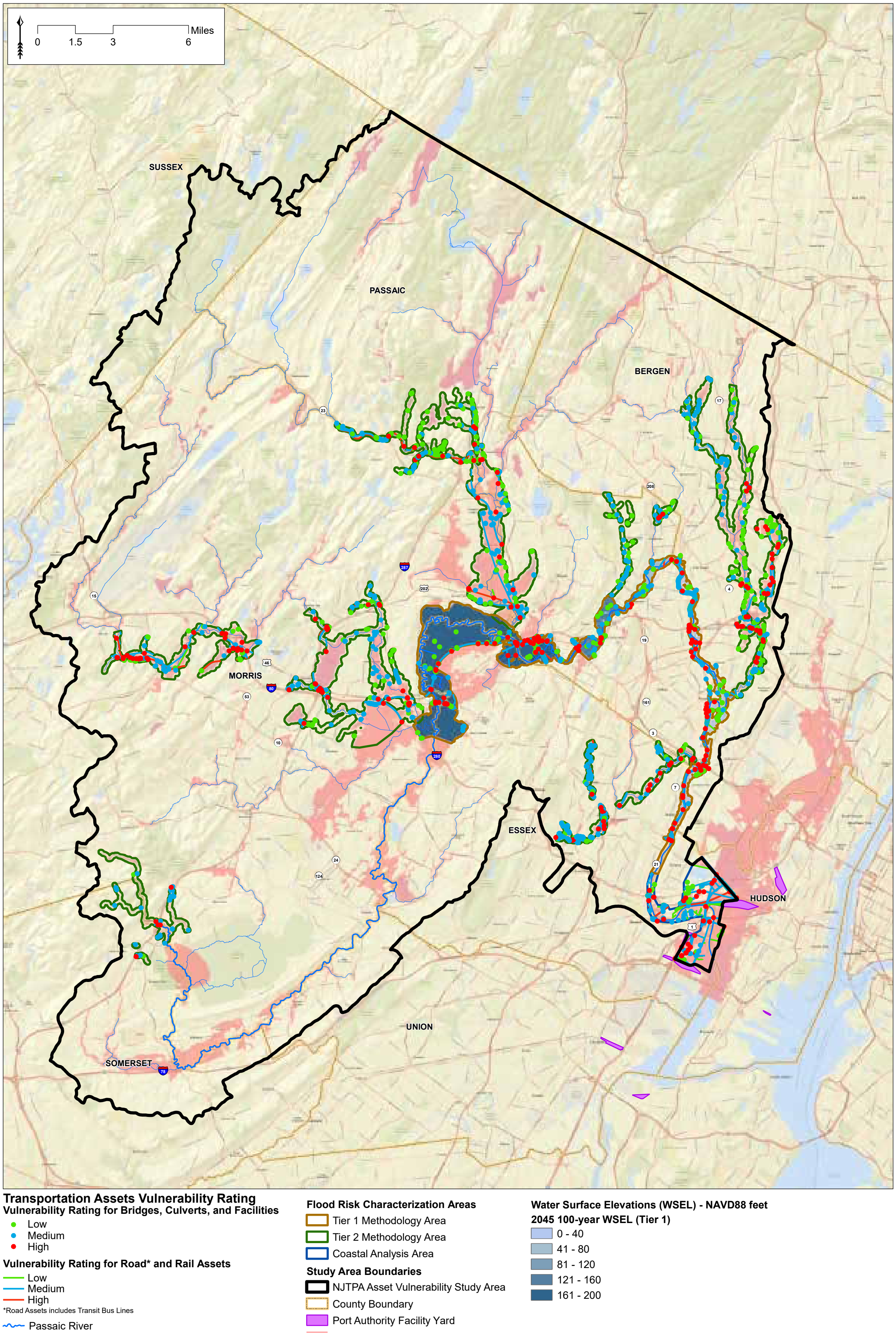


Figure 15. 2080 100-year precipitation (RCP 2.6, to show the worst-case scenario) + 1 stillwater elevation (NACCS 100-percent annual chance) + 2080 sea level rise (NOAA intermediate-high)

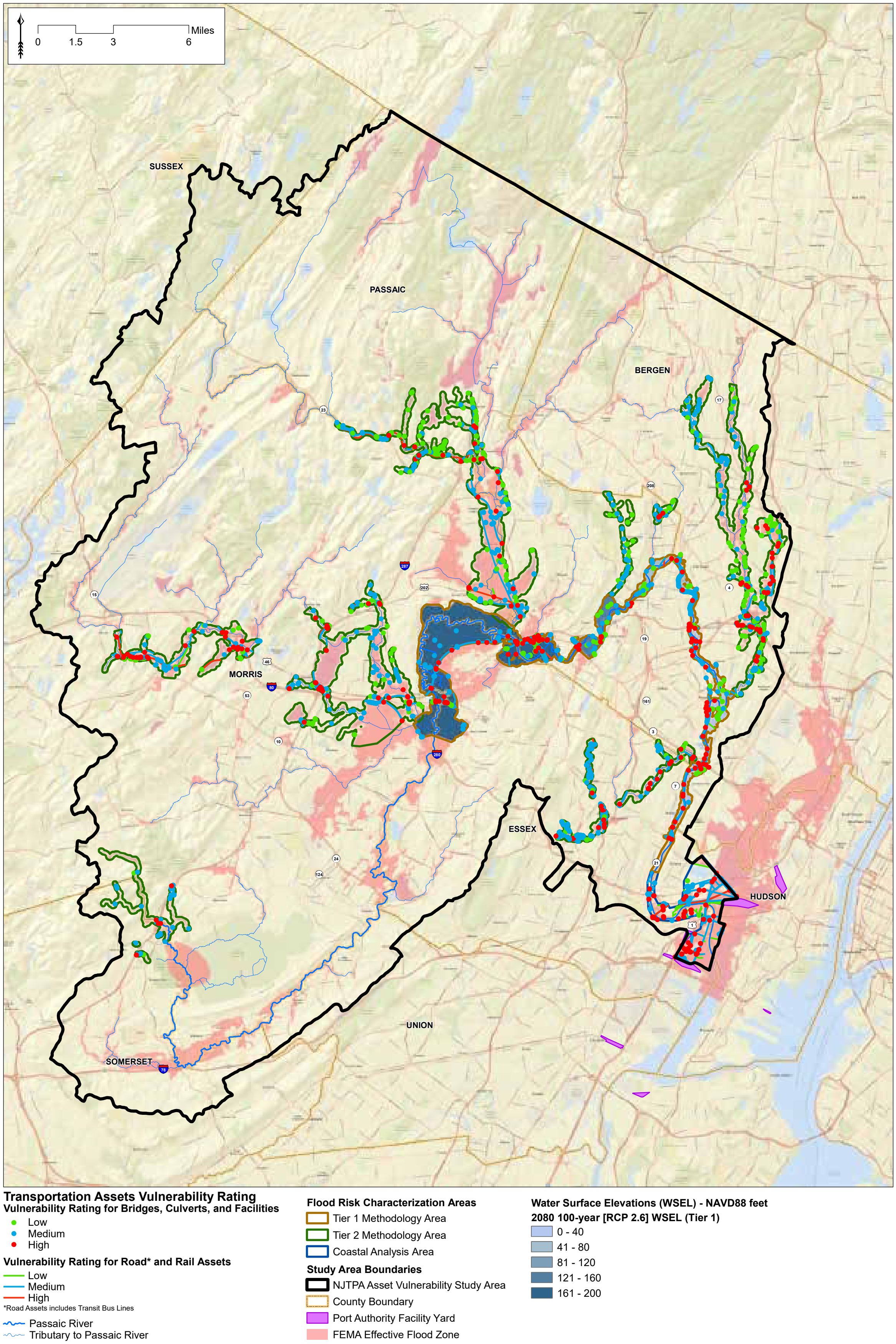


Figure 16. 2080 100-year precipitation (All RCP) + 1 stillwater elevation (NACCS 100-percent annual chance) + 2080 sea level rise (NOAA intermediate-high)

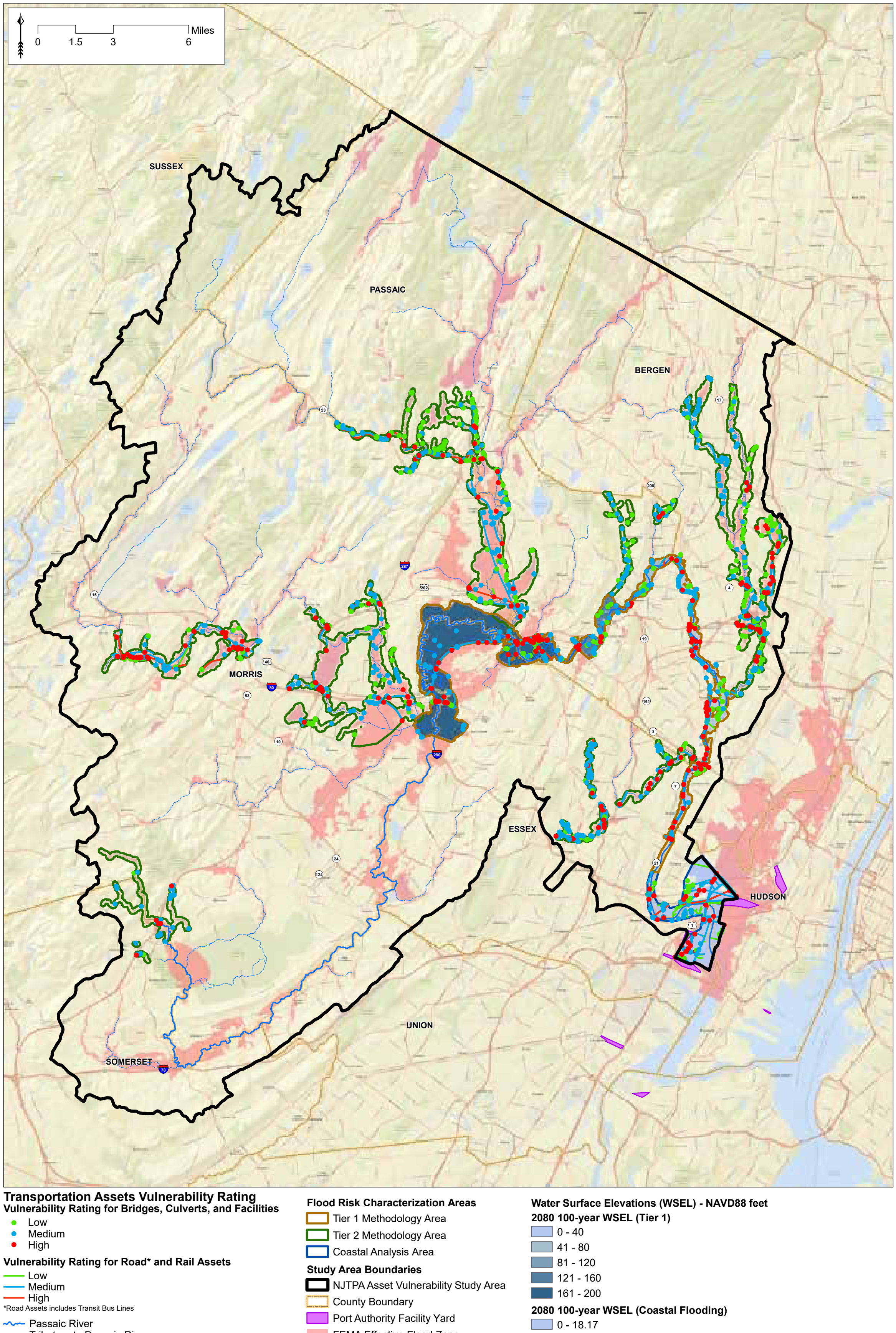
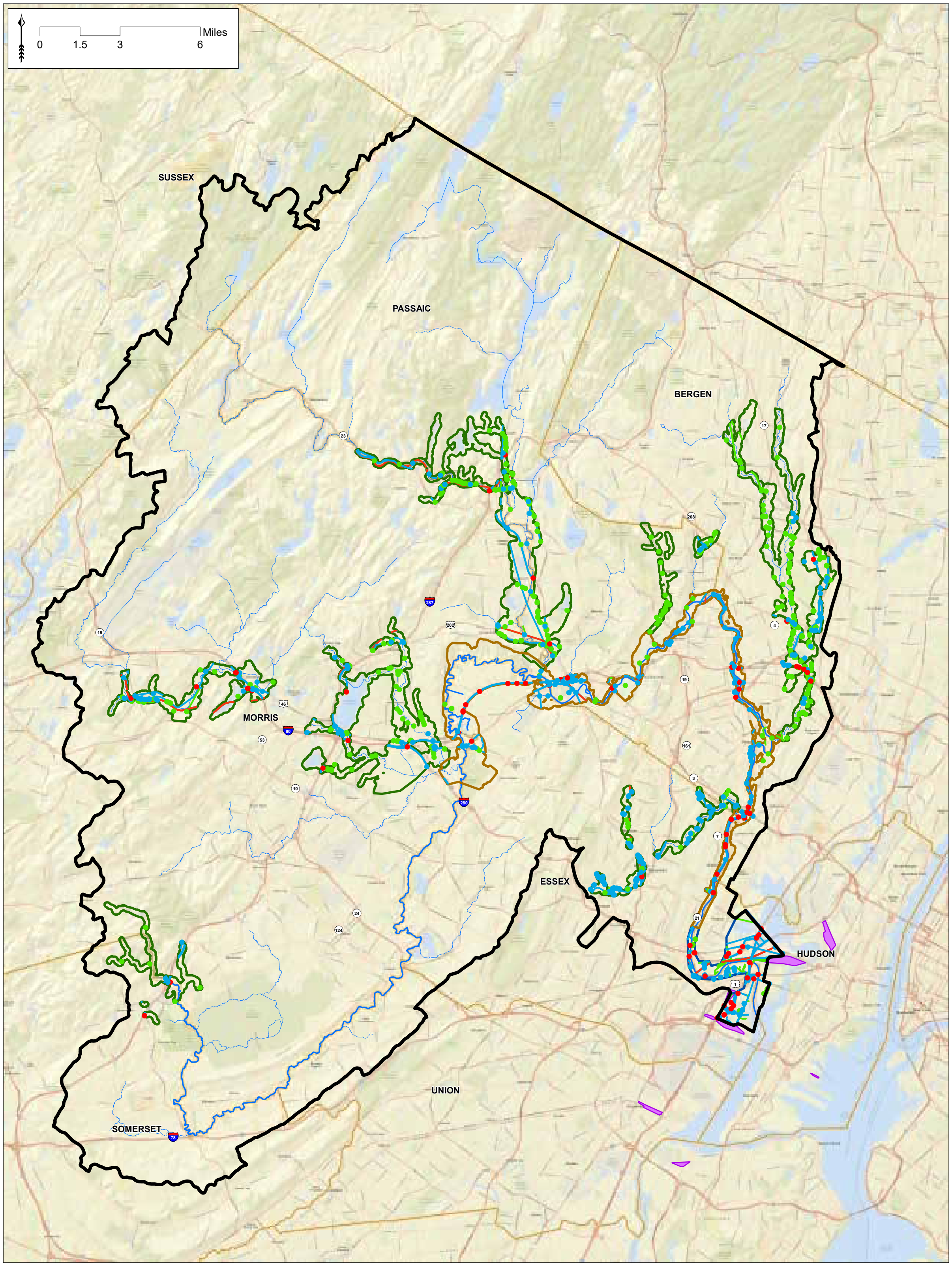


Figure 17. 2045 heat events



Transportation Assets Vulnerability Rating

Vulnerability Rating for Bridges, Culverts, and Facilities
- Low
- Medium
- High

Vulnerability Rating for Road* and Rail Assets
- Low
- Medium
- High

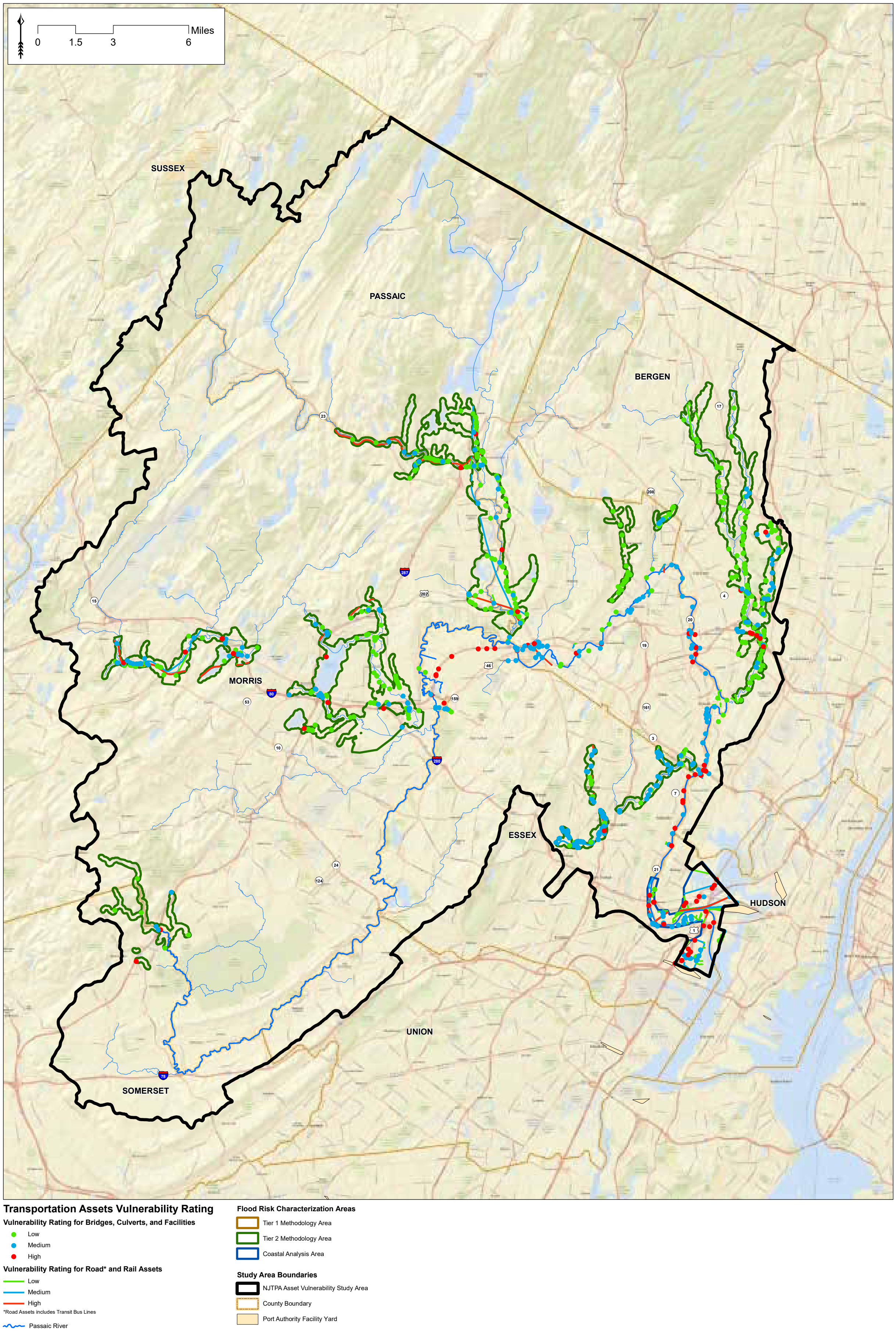
*Road Assets includes Transit Bus Lines

- Passaic River
- Tributary to Passaic River

Flood Risk Characterization Areas
- Tier 1 Methodology Area
- Tier 2 Methodology Area
- Coastal Analysis Area

Study Area Boundaries
- NJTPA Asset Vulnerability Study Area
- County Boundary
- Port Authority Facility Yard

Figure 18. 2080 heat events



Section 4
Adaptation Strategy Assessment

The vulnerability assessments conducted in **Section 3** evaluated and quantified the potential for future travel disruptions and damages to transportation assets caused by extreme precipitation events, sea level rise, storm surges, riverine flooding, and heat stresses. Subsequently, the project team performed an adaption strategy assessment to identify measures or BMPs that can reduce the vulnerability of a transportation asset and increase its resilience to heat or flooding events. These measures or BMPs are a way for the asset to "adapt" to existing and future climate hazards by allowing it to remain functional during a climatic event or to resume operations quickly after an event.

As part of this study, the vulnerability of 3,245 transportation assets was evaluated based on the criticality, sensitivity, and adaptive capacity of each asset. Approximately 10 percent of these assets were determined to be highly vulnerable to 2045 and 2080 heat and/or flooding conditions. Since the vulnerability assessment was performed across the study basin, budget and project schedule limitations made it necessary to focus the next level of analysis on three subareas of the PRB: Subareas A, B, and C. This section presents how three subareas in the PRB were selected for further evaluation as a representative sampling of the entire basin and for understanding how to identify and select adaptation strategies that would make the region more resilient to climate impacts. The process involved assessing or screening numerous adaptation strategies to identify the most effective, practical climate adaptation strategies for the basin.

This section is organized as follows:

- **Adaptation Strategy Assessment Process:** A compilation of asset-specific and regional-level adaptation strategies were developed for all transportation asset types evaluated within the PRB study area (bridges, culverts, facilities, rail, roads including bus routes, and transit rolling stock). A screening process was then implemented by which adaptation strategies were assessed so that the most effective strategies are assigned to the vulnerable transportation assets.
- **Selection of Subareas:** Process for selecting three transportation subareas in consultation with the TAC for further adaptation strategy evaluation. The objective was to select specific geographies that contain a range of critical, interconnected transportation assets that are particularly vulnerable to climate events and to ensure the subareas selected are representative of the entire PRB.
- **Subarea Adaptation Analysis:** Presents the location, history of flooding, summary of the climate scenarios for floods events, identified adaptation strategies for highly vulnerable and critical assets, and strategy implementation consideration for each of the three subareas.

Adaptation Strategy Assessment Process

The adaptation strategies were vetted for applicability to the specific geographic context of the PRB and are selected to be practical for the owners and operators in the area. However, they may also be applied beyond the bounds of the geographical boundaries of this project.

Adaptation strategies that can be implemented in the short term will inherently aid in mitigation of nuisance flooding. The Increase or Improve Stormwater Drainage (SW) strategies are most applicable to addressing nuisance flooding or urban flooding events. Green infrastructure (GI) is a component of some of the SW strategies. Implementation of GI for stormwater management aligns with regional plans, including Passaic County's Green Infrastructure Plan (http://njbikeped.org/learn-about-passaic-county-green-infrastructure-plan/).

Identification and Development of Adaptation Strategies

Seventy-one adaptation strategies were developed and identified for all transportation asset types evaluated within the PRB study area (bridges, culverts, facilities, rail, roads including bus routes, and transit rolling stock) and some adaptation strategies that may be applied on a regional level. The strategies are designed to be incorporated into existing and future policy, design, and O&M by asset owners and operators. They were developed by researching options identified in literature,[1] consulting with subject matter experts, and integrating TAC input from a webinar on October 22, 2018.

Table 7 shows the final list of the identified adaptation strategies. The type of climatic event (heat and/or flooding) and the implementation project stage (policy, design, and/or O&M) for each adaptation strategy are presented. The adaptation strategies are categorized into seven types:

- Reduce Thermal Expansion
- Use Heat-Resistant Materials
- Prevent System Failure
- Increase or Improve Stormwater Drainage
- Increase Flood Protection
- Reduce Flood Damage
- Regionwide Policies – split into the subcategories of natural systems, community development, and technology

The regionwide policies would be executed on a county, regional, or statewide level and not a corridor or asset level. The policies would lead to new regulations, standards, or incentives that would enable or require the public and private sectors to construct low-impact projects or protect valuable resources.

The result of the implementation of these policies would not only improve climate resiliency of the region, such as improved hydrologic outcomes through land use strategies that reduce the extent of impervious surfaces and stormwater runoff, but also provide additional co-benefits. These co-benefits could include improved environmental and health outcomes by reducing sprawl, and thereby preserving forests, farms, greenfields, marshes, and wetlands; increasing transit ridership; reducing overall vehicle miles traveled; reducing demand for parking, resulting in lower pollutant levels, cleaner air, and fewer greenhouse gas emissions; and improving health outcomes by enabling more active lifestyles.

Each adaptation strategy in **Table 7** is further developed with summaries presented in **Appendix I, Adaptation Strategy Fact Sheets**. These adaptation strategy summaries are a user-friendly reference resource for transportation asset owners and operators to address the vulnerability of assets under their jurisdiction.

1 Sources of adaptation strategy research include "Post Hurricane Sandy Transportation Resilience Study in NY, NJ, and CT," https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/hurricane_sandy/; "New Haven Commercial Industrial Toolkit," https://circa.uconn.edu/new-haven-commercial-industrial-toolbox/; "Mainstreaming Climate Change Adaptation Strategies into New York State Department of Transportation's Operations: Final Report, October 31, 2011," https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-08-09_synthesisfinalReport1.pdf; "DC Climate Adaptation Plan," https://ddot.dc.gov/sites/default/files/dc/sites/ddot/publication/attachments/ddot_climate_adaptation_plan.pdf; "Caltrans - Addressing Climate Change Adaptation in Regional Transportation Plans: A Guide for California MPOs and RTPAs, February 2013," http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/FR3_CA_Climate_Change_Adaptation_Guide_2013-02-26_.pdf.

Table 7. List of Adaptation Strategies

Adaptation Strategy Identification	Adaptation Strategy	Applicable Event Type		Project Stage
		Heat	Flood	
Reduce Thermal Expansion (TE)				
TE1	Design rail tracks for higher maximum temperatures in replacement or new rail infrastructure	•		Design, O&M
TE2	Lower speeds and use shorter trains to shorten braking distance and to allow for lighter loads to reduce track stress in extreme heat events	•		O&M
TE3	Use bridge joints that can accommodate exceptional thermal expansion	•		Design
TE4	Monitor sagging of large suspension bridges during extreme heat	•		O&M
TE5	Increase seat lengths of expansion joints and/or the range of finger joints in bridges	•		Design
TE6	Monitor for temperatures of assets and heat-related impacts by installing sensor systems	•		Design, O&M
TE7	Conduct regular maintenance and restore infrastructure previously impacted by heat events	•		O&M
Use Heat-Resistant Materials (HR)				
HR1	Establish design standards for higher maximum temperature	•		Policy
HR2	Incorporate design standards for higher maximum temperature	•		Policy
HR3	Use heat-resistant materials, including heat-resistant asphalt, concrete or painted roadways	•		Policy, Design
HR4	Overlay or rebuild roads with new or more rut-resistant asphalt or concrete	•		Design, O&M
HR5	Encourage construction of green roofs to cool buildings through evaporation/transpiration of vegetated surfacing	•		Policy, Design
HR6	Plant trees and other vegetation to shade assets	•	•	Design
Prevent System Failure (SF)				
SF1	Install energy system back-up such as generators, batteries, or other alternate sources of power during an emergency or long power outage	•	•	Design, O&M
SF2	Modernize the electric grid to allow for "islanding"/micro-grids and encourage the construction of alternative energy systems/use of renewable energy sources as the primary energy source	•	•	Design
SF3	Incorporate redundant power and communication lines and systems	•	•	Design
SF4	Develop procedures and plans for when peak power demand exceeds capacity during heat events	•		Policy
SF5	Construct temporary floating bridges in cases where permanent bridges are damaged		•	Design, O&M
SF6	Upgrade emergency communication systems and ITS (see Section 5 for details)	•	•	Policy, Design

Table 7. List of Adaptation Strategies

Adaptation Strategy Identification	Adaptation Strategy	Applicable Event Type		Project Stage
		Heat	Flood	
SF7	Protect fuel supplies along evacuation routes and near shelters		•	Policy, Design
SF8	Develop new critical use transportation facilities outside future flooding levels		•	Policy, Design
SF9	Develop and use redundant evacuation routes to allow for faster movement out of flooded areas		•	Policy, O&M
SF10	Bury utilities wherever feasible		•	Policy, Design
Increase or Improve Stormwater Drainage (SW)				
SW1	Construct stormwater retention or detention basins		•	Design
SW2	Install internal drainage system using basins and sump pumps		•	Design, O&M
SW3	Install green infrastructure: bioretention ponds, bioswales, and rain gardens		•	Design
SW4	Install green infrastructure: pervious pavements		•	Design
SW5	Install green infrastructure: tree planting		•	Design
SW6	Maintain buffer or clear zone between edge of highways/rail lines/power lines and adjacent tree belts/woodlands to minimize damage and obstruction caused by falling trees and limbs		•	Design
SW7	Conduct routine maintenance of culverts and storm sewers to remove sediment and improve stormwater conveyance		•	O&M
SW8	Increase capacity of stormwater infrastructure and drainage system		•	Design
SW9	Remove obstacles within streams and rivers to allow a higher capacity of flow in high precipitation events		•	O&M
SW10	Enlarge culverts to increase the capacity		•	Design
SW11	Upgrade bridge deck and road drainage systems to manage a higher capacity of stormwater		•	Design
SW12	Replace culverts with bridges		•	Design
SW13	Ensure bridge openings and culverts are clear for appropriate flood management		•	O&M
SW14	Dredge rivers/lakes/streams to aid in the conveyance of floodwaters		•	O&M
Increase Flood Protection (FP)				
FP1	Anchor tanks to resist flood loads and buoyancy forces from floodwaters		•	Design, O&M
FP2	Anchor and secure rolling stock during flooding events		•	O&M

Table 7. List of Adaptation Strategies

Adaptation Strategy Identification	Adaptation Strategy	Applicable Event Type		Project Stage
		Heat	Flood	
FP3	Relocate rolling stock assets outside of areas prone to flooding or storm surge		•	Policy, O&M
FP4	Incorporate dry floodproofing: Installing flood-resistant barriers or impermeable elements at structure's openings to prevent interior flooding and to resist flood loads		•	Design
FP5	Incorporate wet floodproofing: Install flood openings and water-resistant materials to allow building to withstand some exposure to floodwaters and the associated loads/ pressures		•	Design
FP6	Elevate existing structures		•	Design
FP7	Construct catchment devices upstream of bridges to catch floating debris and minimize effect of debris and ice floes on bridges		•	Design
FP8	Elevate critical mechanical and electrical equipment		•	Design
FP9	Protect and restore wetlands to protect infrastructure		•	Policy, Design
FP10	Construct and raise protective dikes, bulkheads, berms, and levees, including tide gates as necessary		•	Design
FP12*	Incorporate a higher base flood elevation in design changes as needed		•	Policy, Design
FP13	Deploy temporary barriers to protect critical assets during flooding events		•	O&M
FP14	Reconstruct transportation assets at a less vulnerable location		•	Policy, Design
FP15	Install sensors along or within assets to monitor for water level and changing conditions		•	Design, O&M
Reduce Flood Damage (FD)				
FD1	Protect bridge piers and abutments with riprap		•	Design
FD2	Alter, upgrade, or retrofit bridge movement system (e.g., bearings) to prevent excessive lateral or vertical displacement due to buoyancy forces or water pressure		•	Design, O&M
FD3	Retrofit/replace/relocate existing bridges for new scour conditions		•	Design, O&M
FD4	Monitor bridge for scour and other conditions that could undermine a bridge's structural integrity during a flooding event		•	O&M
FD5	Use of vegetation or earthwork to stabilize river and stream embankments and provide riverine buffers		•	Design, O&M
FD6	Ensure roadway and rail tracks are clear of rocks, debris, and downed vegetation		•	O&M
FD7	Use moisture-resistant materials that are more resilient to flooding conditions		•	Policy, Design

Table 7. List of Adaptation Strategies

Adaptation Strategy Identification	Adaptation Strategy	Applicable Event Type		Project Stage
		Heat	Flood	
FD8	Use new asphalt/concrete mixtures able to withstand flood conditions		•	Policy, Design
FD10	Improve temporary and permanent erosion control standards of construction sites		•	Policy, Design, O&M
FD11	Conduct regular maintenance and restore infrastructure that was previously impacted from flooding events		•	O&M
FD12	Construct permanent floating bridges to withstand changes in water levels		•	Design
Regionwide (RW) Protection: Natural Systems				
RW1	Require low-impact development and green infrastructure strategies to retain and infiltrate precipitation on site for new and redevelopments		•	Policy
RW2	Preserve and enhance the tree canopy to reduce urban heat island effects and reduce emissions from cooling loads	•		Policy
RW3	Protect, expand, and restore natural systems and vegetative buffers along inland waterways		•	Policy
Regionwide (RW) Protection: Community Development				
RW4	Develop relocation, retreat, and/or evacuation plans		•	Policy
RW5	Limit or prohibit development in floodplains to protect life, property, and floodplain function		•	Policy
RW6	Encourage “Smart Growth” approaches and “Complete Streets” principles to counter suburban sprawl, decrease energy use, reduce parking demand, reduce emissions, and promote resilience; such as walkable, livable, compact development	•	•	Policy
RW7	Promote Transit-Oriented Development, including compact, mixed-use development and affordable housing within walkable, multimodal “Complete Streets”	•	•	Policy
Regionwide (RW) Protection: Technology				
RW8	Research and incorporate emerging technologies in design policies and standards	•	•	Policy, Design

*FP11: Establish a higher base flood elevation and FD9: Install pavement grooving and cross-sectional sloping to encourage drainage of water out of the roadway and provide traction were removed per TAC and subject matter expert input. See **Appendix A, Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Event** for more detail.

Each adaptation strategy summary includes:

- Brief description of the adaptation strategy
- Technical, implementation, and financial considerations for the strategy
- Applicable asset type (bridges, culverts, facilities, rail, roads including bus routes, transit rolling stock)
- Applicable event type(s) (heat or flooding)
- Recommended project stage for implementation (policy, design, O&M)
- Parties assigned to consider implementation of adaptation strategies, such as the county or state agency
- Range of project time frame (less than 1 year, 1 to 5 years, less than 5 years, 5 to 10 years, or over 10 years)

- Magnitude of project cost to implement strategy on an asset, relative to other adaptation strategies, based on adaptation strategy research and experience of SMEs:
  - $ – Requires a relatively low investment of capital and/or resources
  - $$ – Requires a moderate amount of investment of capital and/or resources
  - $$$ – Requires a high amount of investment of capital and/or resources
  - $$$$ – Requires a very high amount of investment of capital and/or resources
- Project co-benefits or benefits beyond adapting to the heat or flood event:
  - Reduce greenhouse gas emissions – Strategies that reduce greenhouse gas emissions. Greenhouse gases are gases that traps heat in the atmosphere and contributes to climate change. This reduction could be achieved by either eliminating a source of greenhouse gas or by more efficient operation of assets.
  - Improve water quality – Strategies that could have the potential to improve water quality of the surrounding ecosystem by using natural treatment or by preventing pollutants to enter local water supply.
  - Improve air quality – Strategies that help improve air quality either by eliminating or reducing sources of air pollutants, or by using natural processes that assist with the improvement of air quality.
  - Improve or create greenspace – Strategies that improve existing greenspaces or create new naturalized areas. Greenspaces are vegetated open spaces that are either natural or man-made and that can be open to the public and offer recreational opportunities.
  - Improve aesthetic and visual qualities – Strategies that improve the aesthetics and visual qualities of a community. These are areas or assets that are visually pleasing that help enhance community character and quality of life.
  - Improve localized ecosystem – Strategies that help conserve local environments and help foster the growth and improvement of the vegetation and wildlife. This is achieved by protecting and improving existing natural areas.
  - Improve safety and reduce potential for loss of life – Strategies that help protect the lives by limiting potential sources of danger or loss of life during an extreme heat or extreme flooding event. This can include strategies that allow communities to evacuate in a timely manner or provide greater protection of heat- or flood-prone areas.
  - Reduce loss of property or substantial property damage – Strategies that may reduce the damage of property and other transportation assets in an area during an extreme heat or extreme flooding event. This can include strategies that protect transportation assets and surrounding properties.
  - Reduce negative business impacts from disruptions in transportation service – Strategies that may help businesses to stay open or return to normal operations during or after an extreme weather event. These strategies either prevent complete system failure or allow for a quick recovery. These strategies could limit impacts to key commuting corridors and supply chain transportation routes.

- Maintain cultural resource – Strategies that can help protect important cultural resources that are vital to a community's character and preserve the local heritage. These include archaeological resources, historic resources, or cultural landscapes.
- Contribute to Smart Growth initiatives – Strategies that contribute to Smart Growth initiatives that help protect a community's health and natural environment by means of efficient, low-impact development and conservation.

Assignment of Adaptation Strategies to Transportation Assets

The PRB study geospatial database was used to identify the flood exposure of an asset and whether the asset was impacted by a heat event, based on adaptation strategy factors presented in **Table 8**. The compilation of applicable adaptation strategies assigned by the geodatabase to assets in each subarea and to the entire study basin are presented in **Appendix J, Screening Results: Assigning Adaptation Strategies for the Benefit Cost Analysis** and as an Excel spreadsheet compilation in **Attachment I**, respectively.

Each asset type is associated with a set of recommended adaptation strategies based on application of adaptation strategy factors (**Table 8**) using the geodatabase, TAC input, and SME review. This screening process was used to screen out and select the best or most effective adaptation strategies for each asset, based on the information available for this study. For example, if a bridge asset has a minor level of flooding, the appropriate adaptation strategy may not be to raise the bridge (and all associated roadways and ramps) but rather to reinforce the structural integrity of the bridge to ensure it may remain functional. The objective of this screening process is to provide the transportation owner and operator with a process of developing a reasonable range of adaptation strategies and to focus the BCA scope for this study.

Two meetings were held with the TAC to present and discuss adaptation strategies and assignment factors (October 22, 2018, and November 1, 2018). The TAC members provided input based on the local context of the three subareas further evaluated for adaptation strategy assessment, the TAC's individual jurisdictional priorities, and the feasibility of implementing specific adaptation strategies. TAC input on the adaptation strategies was incorporated in the technical, implementation, and financial considerations presented on the adaptation strategy fact sheets in **Appendix I**. Input that reduced the number of strategies under consideration included considering only design and O&M strategies that have been thoroughly tested and reasonably assumed to be within current operational budgets and scope. Therefore, innovative, cutting-edge adaptation strategy measures and BMPs not vetted on a planning scale were not considered in the assessment.

The study team's SME reviewed and eliminated adaptation strategies if there was overlap or redundancy among more than strategy and evaluated the local context using Google Maps and Google Maps Street View to ground truth implementation of the strategies.

Bridge on County Route 613 (Two Bridges Road) over Passaic River, Essex County (Asset ID 070M060)

The following is an example of how the adaptation strategy screening process was conducted. It applies to a bridge within Subarea B, Willowbrook "Spaghetti Bowl" located on County Route 613 and comprises of two distinct bridge decks spanning across the Passaic River in Essex County. This bridge was identified as a critical transportation asset in the county HMP and serves as an emergency route. The flood level (for a 100-year storm event in both the 2045 and 2080 planning horizons) for this bridge is greater than 5 feet above the bridge's deck. As shown in **Table 9**, through the TAC and SME review process, only three out of the eight flood adaptation strategies were applicable and carried forward to the next step of the study, the sketch-level BCA.

Table 8. Assignment of Adaptation Strategies to Transportation Assets

Event Type	Asset Type	Adaptation Strategy Assignment Factor	Applicable Adaptation Strategy (defined in Table 8)	Notes
Flooding	Roads and related bridges, culverts	Flood level >0 feet above evacuation route and related assets (bridges or culverts)	SF9, SW8, SW9, SW10, SW11, SW12, FP6, FP10, FP13, FP14, FP15, FD (all), RW4	Portion of evacuation route is inundated and therefore need to elevate entire route, find an alternate route, or mitigate potential future flood inundation.
Flooding	Rail and related bridges, culverts	Flood level >0 feet above rail and related assets (bridges or culverts)	SF9, SW8, SW9, SW10, SW11, SW12, FP6, FP10, FP13, FP14, FP15, FD (all), RW4	Portion of railway is inundated, potentially resulting in oversaturation of soils, degrading of railbed support structures, and erosion.
Flooding	Roads	Flood level >0.5 feet above asset	SF6, SF9	A road hazard warning (or possible closure) is warranted. According to FEMA, 6 inches of water is enough to lose control of an automobile and possibly stall, and 2 feet can lift and carry (mobilize) an automobile.[1,2.]
Flooding	Bridges	Flood level 0 to 15 feet below asset	FP7, FP15, FD1, FD2, FD3, FD4, FD10, FD11	Bridge is not overtopped but possibly has enough flooding that damage from floating debris, surface water flow, and wave action is a concern.
Flooding	Bridges	Flood level >5 feet below asset	FP7, FP15, FD1, FD2, FD3, FD4, FD11	Low flood levels that may create buoyancy forces that damage the bridge bearing systems. At this level, water is likely reaching the bottom of the girders, which may trap air under the bridge, leading to buoyancy forces uplifting the bridge deck. (Bridges outside seismic zones, like New Jersey, generally rely on their weight to remain stable.)
Flooding	Bridges	Flood level >15 feet below asset	No adaptation strategy is recommended	At a flood level 15 feet or less below the asset, an impact from flooding is less likely; therefore, no strategy recommended, as the asset is expected to perform as designed.
Heat + Flooding	Rail	Flood level >0 feet and impacted by a heat event	TE1, HR2, HR3	Heat-related adaptation strategies when flooding mitigation strategies are being employed.
Heat	Rail	Impacted by a heat event	TE2, TE6, TE7, HR1, HR6	Rail "sun kinks" and other track bulking incidents due to extreme heat event, resulting in speed restrictions and derailments.
Heat	Bridges, Roads	Impacted by a heat event	TE3, TE4, TE5, TE6, TE7, HR1, HR2, HR3, HR4, HR6, SF3	Contraction or expansion of bridge joints and stress on bridges, as well as softening, cracking, rutting, buckling, or potholing of roadways due to extreme heat event.

[1] https://www.fema.gov/media-library-data/1519151123644-898c2e76649767da9538c8aa3bcac9a0/2018_Flood_Safety_Awareness_Toolkit.pdf
[2] https://www.weather.gov/safety/flood-turn-around-dont-drown

Table 9. Flood Adaptation Strategy Assessment for Bridge Asset ID 070M060

Adaptation Strategy Identification	Adaptation Strategy	Included in BCA (Y/N)	Rationale for Inclusion or Exclusion from BCA
FP7	• Construct catchment devices upstream of bridges to catch floating debris and minimize effect of debris and ice floes on bridges	No	• TAC feedback indicated that this was not a strategy determined to be fully tested in the study area
FP15	• Install sensor systems along or within assets to monitor for water level and changing conditions	No	• SME review determined that this strategy could reasonably be achieved within current operational budgets and scope and therefore unlikely to add substantially to the costs in the BCA
FD1	• Protect bridge piers and abutments with riprap	Yes	• SME review determined that this strategy is feasible for this asset and within the local context
FD2	• Alter, upgrade, or retrofit bridge movement system (e.g., bearings) to prevent excessive lateral or vertical displacement due to buoyancy forces or water pressure	Yes	• SME review determined that this strategy is feasible for this asset and within the local context for the purpose of the BCA
FD3	• Retrofit/replace/relocate existing bridges for new scour conditions	No	• SME review determined that this strategy is similar or redundant to FD4, which is better suited for this asset for the purpose of the BCA
FD4	• Monitor bridge for scour and other conditions that could undermine a bridge's structural integrity during a flooding event	Yes	• SME review determined that this strategy is similar or redundant to FP15 and more appropriate for this asset for the purpose of the BCA
FD10	• Conduct regular maintenance and restore infrastructure that was previously impacted from flooding events	No	• SME review determined that this strategy could reasonably be achieved within current operational budgets and scope and therefore unlikely to add substantially to the costs in the BCA
FD11	• Construct permanent floating bridges to withstand changes in water levels	No	• TAC feedback indicated that this was not a strategy determined to be fully tested in the study area

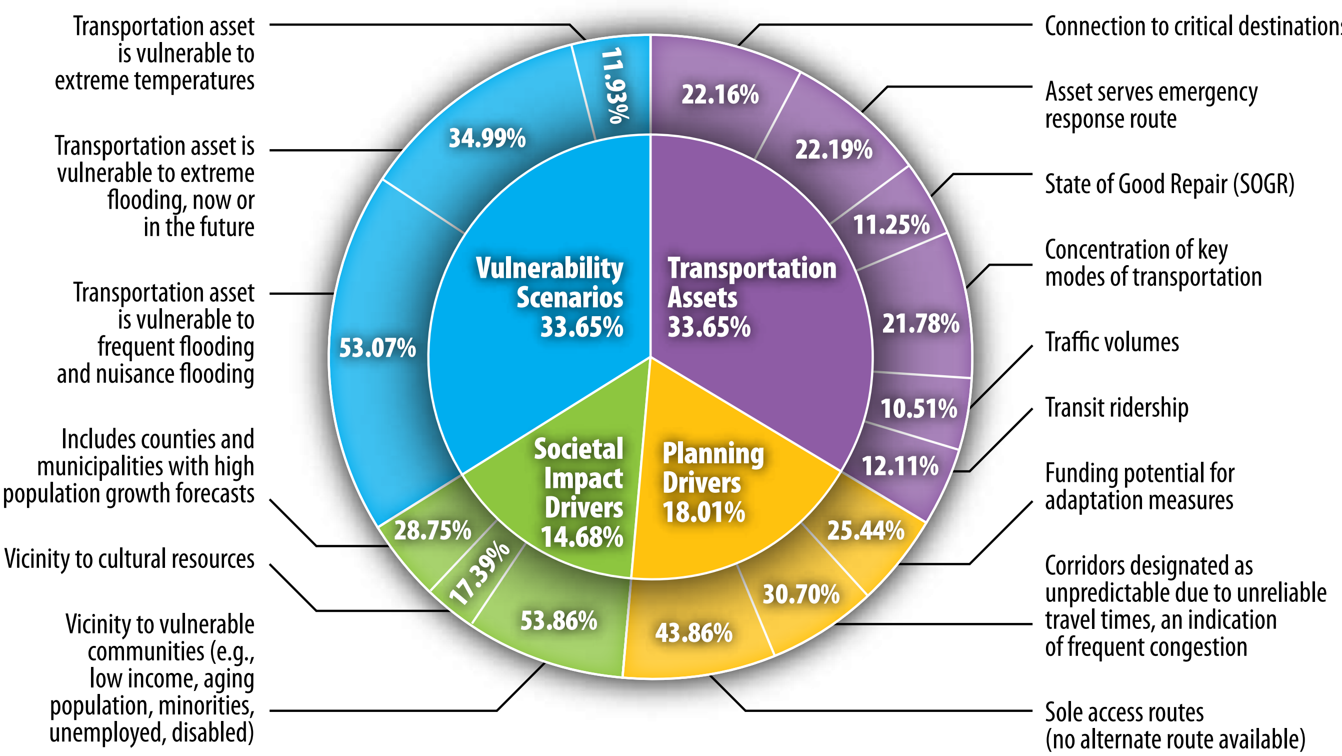
Selection of Subareas

A process that encompassed critical and highly vulnerable transportation subareas based on the findings from the vulnerability assessment was developed for selecting three subareas areas.

The objective was to select specific geographies that contain a range of critical, interconnected transportation assets that are particularly vulnerable to climate events and to ensure that the subareas selected are representative of the entire PRB asset portfolio (a concentration of bridges, culverts, facilities, rail lines, roads, transit assets) and stakeholder diversity (county, state, and federal owner/operators).

Since the vulnerability assessment was performed across the study area, prioritization criteria were identified to assist in selecting the three study subareas.

Figure 19. TAC survey results of subarea prioritization criteria



Subarea Selection Methodology

Ten subareas were identified for consideration of a detailed adaptation strategy assessment and sketch-level BCA. The prioritization criteria were developed based on a review of documents focused on study area planning initiatives and transportation vulnerability frameworks, including:

- Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure[1]
- Plan 2045, Connecting North Jersey, NJTPA Regional Transportation Plan[2]
- Resilience of NJ TRANSIT Assets to Climate Impacts3
- 2013–2015 Climate Resilience Pilot Program: Outcomes, Lesson Learned, and Recommendations4
- Climate Change Vulnerability Framework

1 Cambridge Systematics. 2012. Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure, https://www.camsys.com/publications/case-studies/climate-change-vulnerability-and-risk-assessment-new-jersey%E2%80%99s.

2 NJTPA. 2017. Plan 2045, Connecting New Jersey, NJTPA Regional Transportation Plan, https://apps.njtpa.org/plan2045/draftplan.html.

3 https://www.adaptationclearinghouse.org/resources/resilience-of-new-jersey-transit-nj-transit-assets-to-climate-impacts.html.

4 FHWA. 2016. 2013–2015 Climate Resilience Pilot Program: Outcomes, Lesson Learned, and Recommendations, https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/index.cfm.

Table 10 shows the 16 prioritization criteria within four categories: planning drivers, transportation asset function, societal impact drivers, and vulnerability scenarios.

Following development of the prioritization criteria, a survey was created for TAC members to weigh the various selection criteria and offer input on the importance of each in selecting the three selected subareas. The survey was performed using multicriteria decision analysis software, Expert Choice. For each decision criteria category and metric, the TAC members were asked to decide which of two criteria sets, such as "connection to critical destinations" or "asset serves emergency response route" they consider more important and by what degree (equal, moderately, strongly, very strongly, extremely).

Prioritization Results

Based on survey results, five prioritization criteria were rated as low importance (less than 20-percent priority rating). These criteria include state of good repair, traffic volumes, transit ridership, vicinity to cultural resources, and transportation asset is vulnerable to extreme temperatures. The remaining prioritization criteria were used with the vulnerability assessment to determine the three study subareas. The results of the multicriteria decision analysis survey are shown in **Figure 19**.

GIS shapefiles were developed for prioritization criteria identified to be of high importance (greater than 20-percent priority rating) and overlaid with the existing and future flood inundation extents modeled. Ten potential subareas within the PRB were initially identified to contain a high concentration of transportation assets that were determined to be highly vulnerable to future severe climate events and met several prioritization criteria, as shown in **Figures 19** through **29**. **Table 6** shows the prioritization criteria identified and total number of transportation assets designated with high and medium vulnerability within each potential subarea. The TAC provided feedback on these 10 subareas at an in-person meeting held on July 17, 2018, and subsequently, the committee selected three subarea geographic extents for further evaluation:

- **Subarea A, Parsippany/Pine Brook:** Subarea A encompasses Subarea 6 in **Table 11**. No modifications to the geographic extent of the subarea was made.
- **Subarea B, Willowbrook Spaghetti Bowl:** Subarea B encompasses Subarea 5 (**Table 11**) and commuter rail and road "pinch-points" in Subarea 8 (**Table 11**), located directly north, to evaluate a larger extent of the Route 23 and NJ TRANSIT/Conrail corridor.
- **Subarea C, River Road/Route 21 Corridor:** Subarea C encompasses Subareas 2 and 4 (**Table 11**) to evaluate a larger extent of the Route 21 Corridor.

The TAC's selection was based on which subareas best represented the multiple classes of transportation assets within the PRB study area and therefore would inform the full climate resilience plan by providing a mix of asset types (bridges, culverts, evacuation routes, rail, and facilities) and geographic diversity (assets located within the Upper, Central, and Lower PRB).

The three subareas (Subareas A through C) selected for further evaluation are shown in **Figure 31** and described below. **Table 12** provides a breakdown of the 337 transportation assets that were determined to be highly vulnerable (vulnerability assessment score greater than or equal to 21 out of 30) to future severe climate events within the three selected subareas.

Table 10. Subarea Prioritization Criteria

Design Criteria Category	Decision Criteria Metrics	Metrics Definitions
Transportation Assets	Connection to critical destinations	Corridor connects to destination identified as high employment and/or population density
	Asset serves emergency response route	Corridor/subarea is identified as a component of a municipal/county/state evacuation response route, including roadways to shelters and public emergency response staging areas. Evacuation routes are critical prior to, during, and after a storm event for emergency preparation, response, and recovery operations
	State of good repair	Transportation asset is identified as slated for state of good repair maintenance or repair work within the Plan 2045 planning horizon
	Concentration of transportation key modes	Subarea includes a confluence of assets that carry multiple transportation modes, corridors, and assets (such as a combination of roadway, airport, and transit) and consider key transportation routes (interstate truck freight and rail freight corridors)
	Traffic volume	Corridor is ranked high in annual AADT
	Transit ridership	Corridor is ranked high in daily ridership
Planning Drivers	Funding potential for adaptation measures	Transportation asset is identified as a future project to be funded in the Plan 2045
	Corridors designated as unpredictable due to unreliable travel times (an indication of frequent congestion)	Corridors designated with unreliable travel times frequently exhibit unpredictable conditions; for example, where speeds regularly drop far below normal
	Location of current infrastructure TIPs	Subarea contains at least one infrastructure TIP
	Sole access routes (no alternate route available)	County route corridor does not have a viable alternate route option during roadway closure
Societal Impact Drivers	Vicinity to vulnerable communities (low income, aging population, minorities, unemployed, disabled)	Corridor and/or subarea serves vulnerable communities identified during TAC interviews and supplemented by EJSCREEN
	Vicinity to cultural resources (historic Central Railroad of New Jersey Terminal in Liberty State Park)	Subarea encompasses cultural resources identified during TAC interviews as vulnerable to climate change impacts
	Includes counties and municipalities with high population growth forecasts	Subarea encompasses counties and/or municipalities identified to have and projected to have high population growth between 2015 and 2045
Vulnerability Scenarios	Transportation asset is vulnerable to frequent flooding and nuisance flooding	Transportation asset is vulnerable to frequent storm events and nuisance flooding
	Transportation asset is vulnerable to present or future extreme flooding	Transportation asset is currently vulnerable to extreme storm events or will be vulnerable to climate change
	Transportation asset is vulnerable to extreme temperatures	Transportation asset is currently vulnerable or will be vulnerable to extreme temperatures (above 90°F) from climate change

Table 11. Prioritization Criteria and Number of Transportation Assets Designated with High and Medium Vulnerability within Each Subarea

			Planning Driver			Transportation Asset or Function		Societal Driver		Vulnerability Assessment[1]			
										2080 100-year Flood Event		2080 Heat Event	
Subarea Number	Subarea Name	County	TIP-funded Routes	Unreliable Route LOTTR Ratio >1.5	Extreme Delay Route Ratio >75%	Connection to Critical Destinations	Emergency & Evacuation Routes	High Population Growth	Vulnerable Populations (EJ) Demographic Index>State Avg	# of Assets Ranked High	# of Assets Ranked Medium	# of Assets Ranked High	# of Assets Ranked Medium
1	Newark/Hudson County Coastal Analysis	Essex, Hudson	•	•	•	•	•	•	•	32	110	39	52
2	River Road/Route 21 Corridor	Bergen, Essex, Passaic		•	•	•	•	•	•	23	67	0	5
3	Saddle River/Route 80, GSP Corridor	Bergen	•	•	•		•		•	13	39	5	9
4	McLean Blvd/ Route 80, 46, GSP Corridor	Bergen, Passaic	•	•	•	•	•	•	•	12	17	1	4
5	Willowbrook "Spa-ghetti Bowl"/Route 80, 46, 23	Essex, Morris, Passaic	•	•	•	•	•	•	•	33	105	1	4
6	Parsippany, Pine Brook/Route 80, 46	Morris	•	•	•	•	•		•	25	69	2	21
7	Dover/Route 46, 15	Morris	•	•			•		•	17	24	2	20
8	Wayne/Route 202	Morris, Passaic	•	•		•	•	•	•	11	74	2	12
9	Kinnelon, Bloomingdale/ Route 23	Morris, Passaic	•	•			•		•	12	106	2	12
10	Paramus/Route 17, GSP	Bergen	•	•	•		•		•	14	17	1	16

[1] Total number of assets considers multiple segments of roadways and rail tracks as one asset per corridor.
Avg = average; Blvd = boulevard; EJ = environmental justice; GSP = Garden State Parkway; LOTTR = level of travel time reliability; TIP = transportation improvement project; y = year;

Table 12. Highly Vulnerable Assets within Each Critical Subarea

Asset Type	Subarea A Parsippany/Pine Brook	Subarea B Willowbrook Spaghetti Bowl*	Subarea C River Road/Route 21 Corridor	Total
Bridges	26	38	38	102
Roads (including bus routes)	96 segments from 7 roadways	39 segments from 5 roadways	74 segments from 7 roadways	209 segments
Culverts	3	5	4	12
Rail tracks (including rolling stock)	0	7 segments from 2 rail lines	5 segments from 3 rail lines	12 segments
Facilities	0	2	0	2
Total	**125**	**91**	**121**	**337**

* Includes commuter rail and road "pinch-points" in Wayne Township located directly north of the "Spaghetti Bowl" to evaluate a larger extent of the Route 23 and NJ TRANSIT/Conrail corridor in the adaptation strategy assessment.

Figure 20. Ten Highly Vulnerable and Critical Subareas in the Passaic River Basin

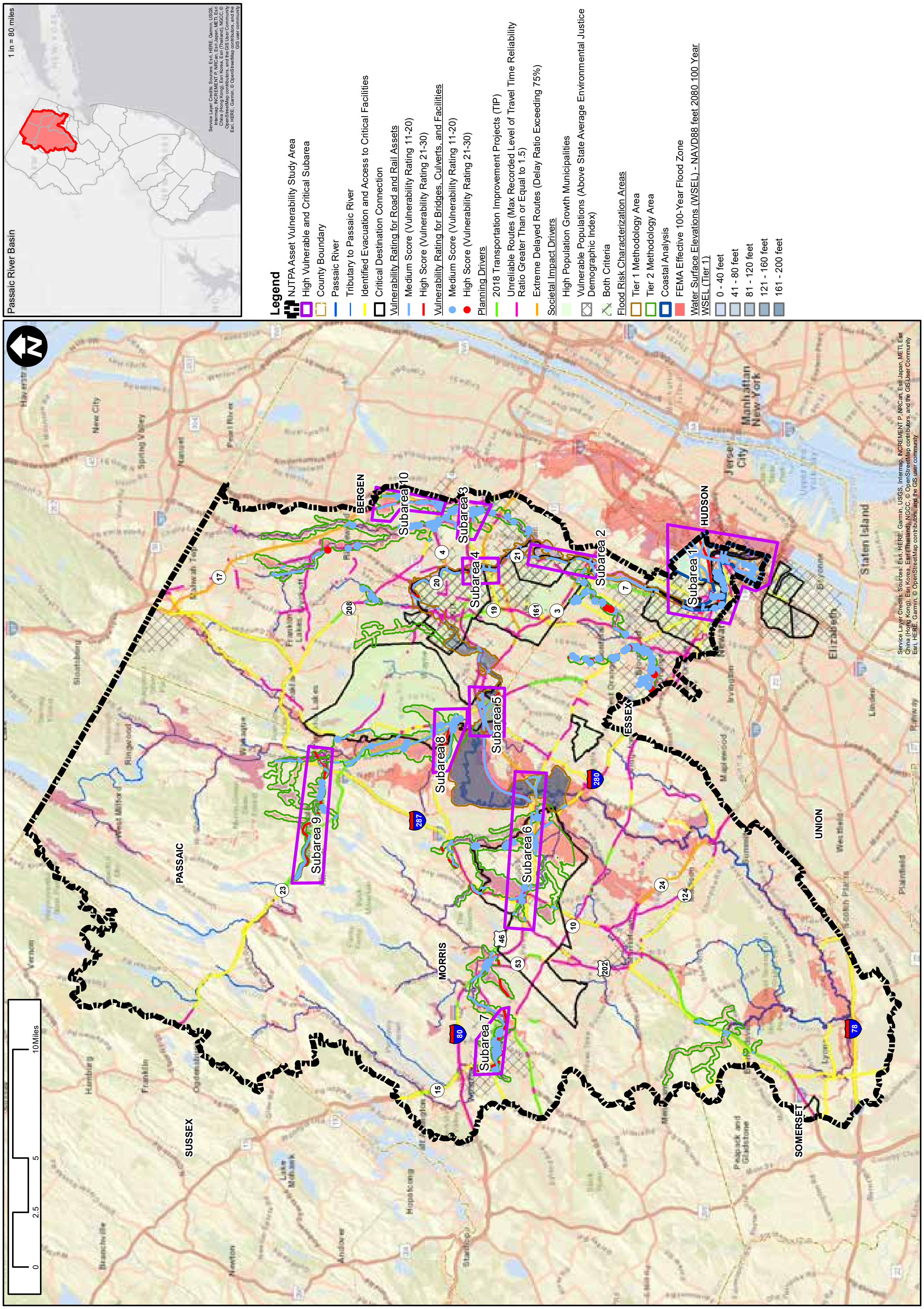


Figure 21. Subarea 1: Newark/Hudson County Coastal Analysis

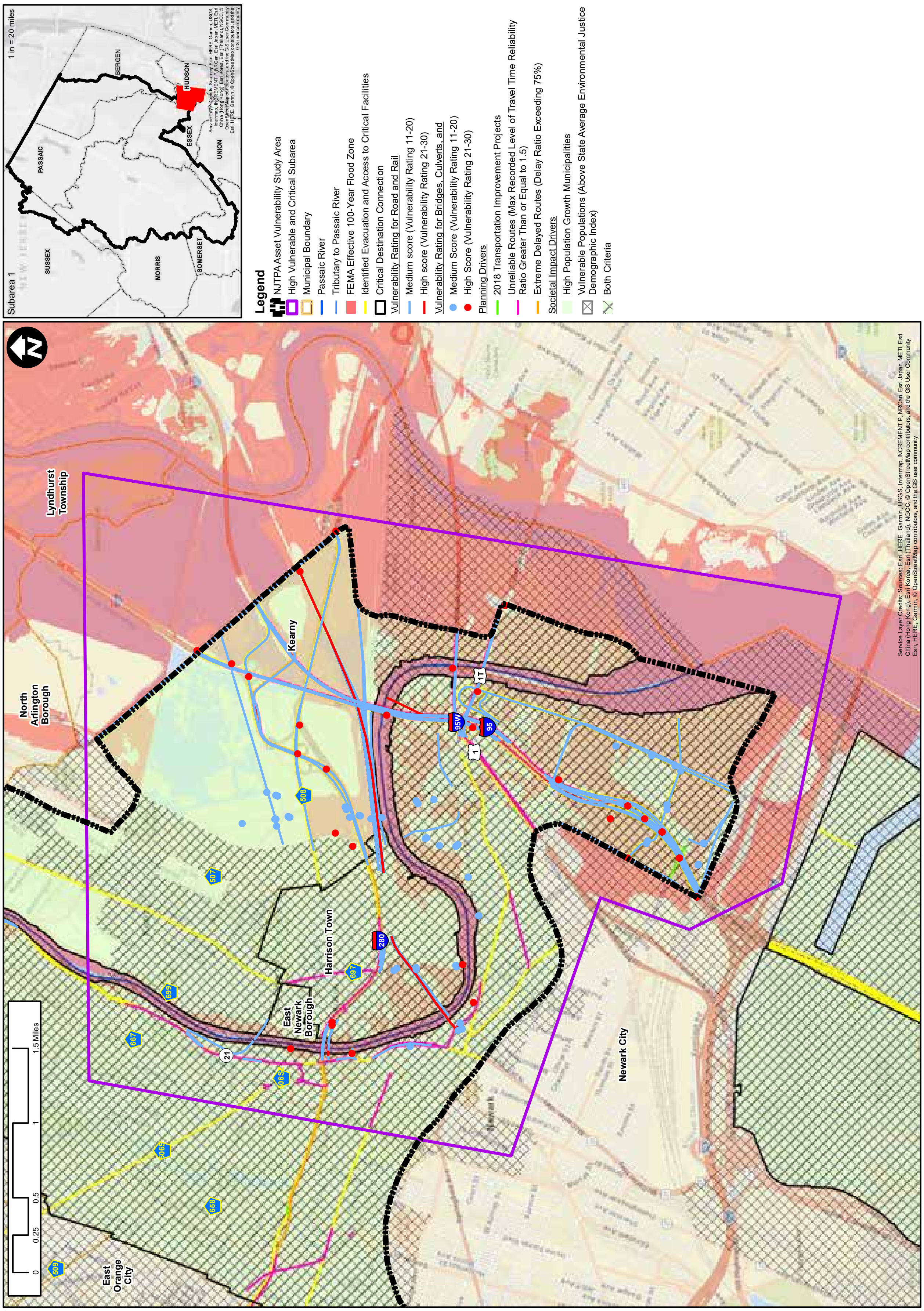


Figure 22. Subarea 2: River Road/Route 21 Corridor

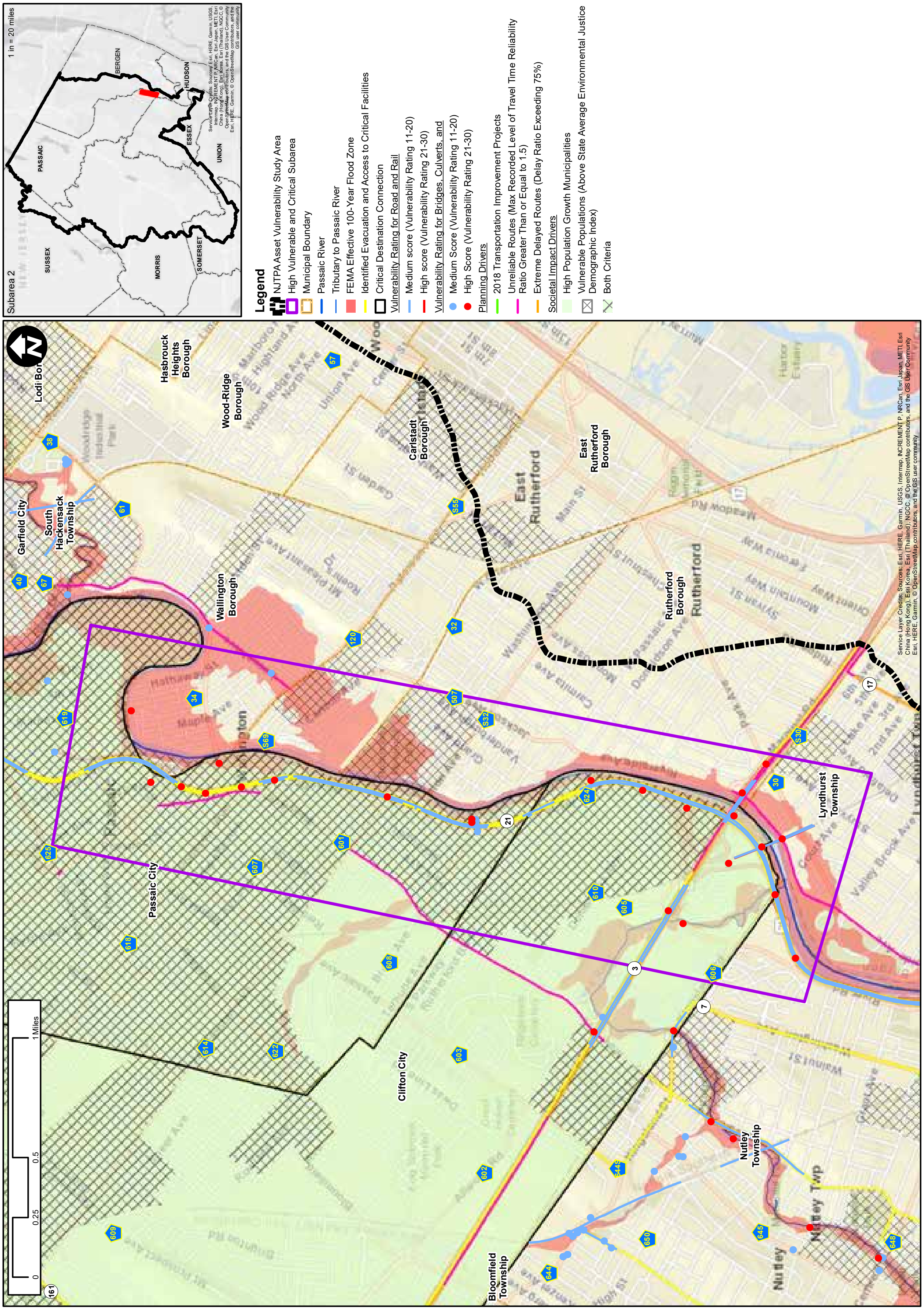


Figure 23. Subarea 3: Saddle River/Route 80, GSP Corridor

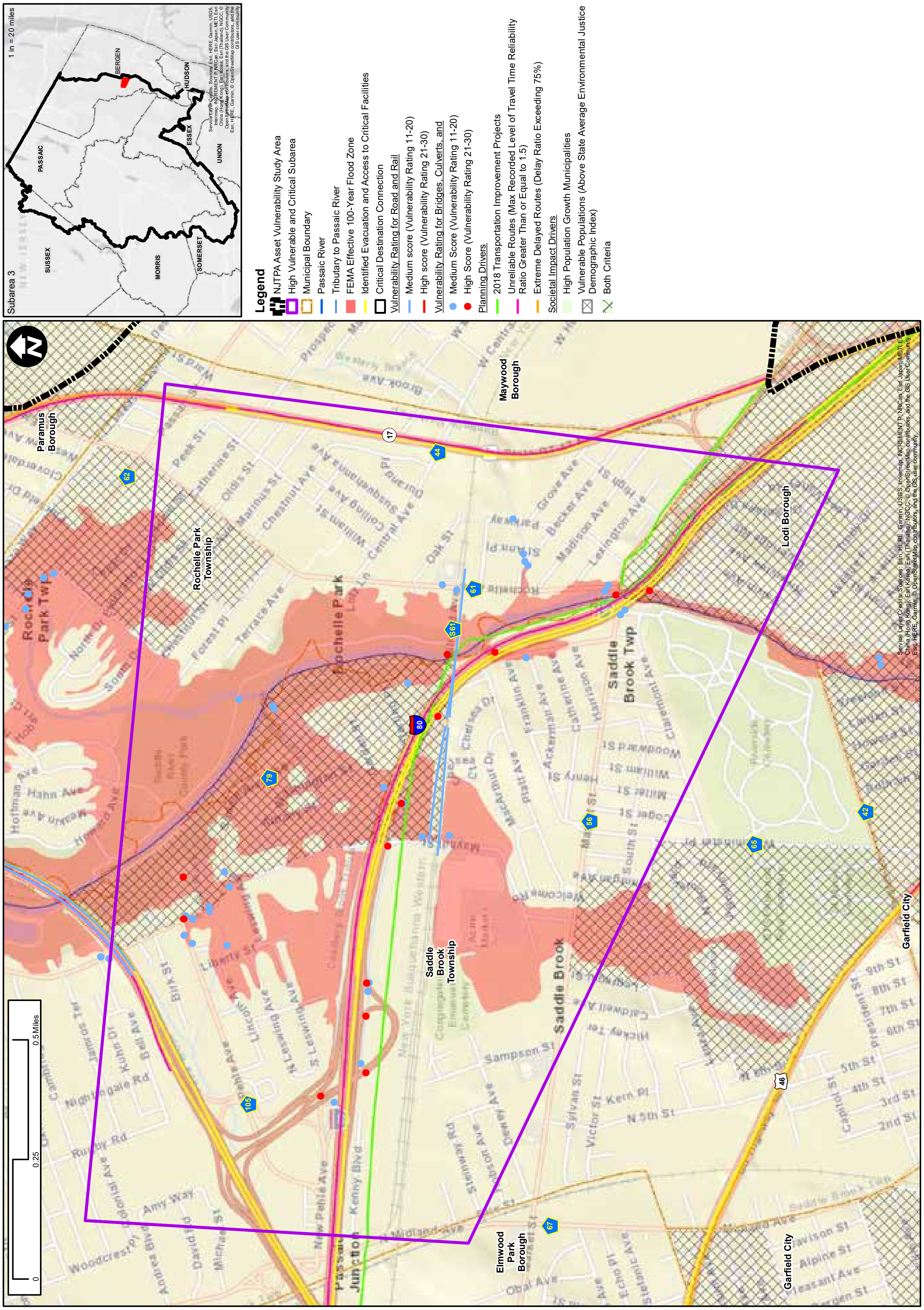


Figure 24. Subarea 4: McLean Blvd/Route 80, 46, GSP Corridor

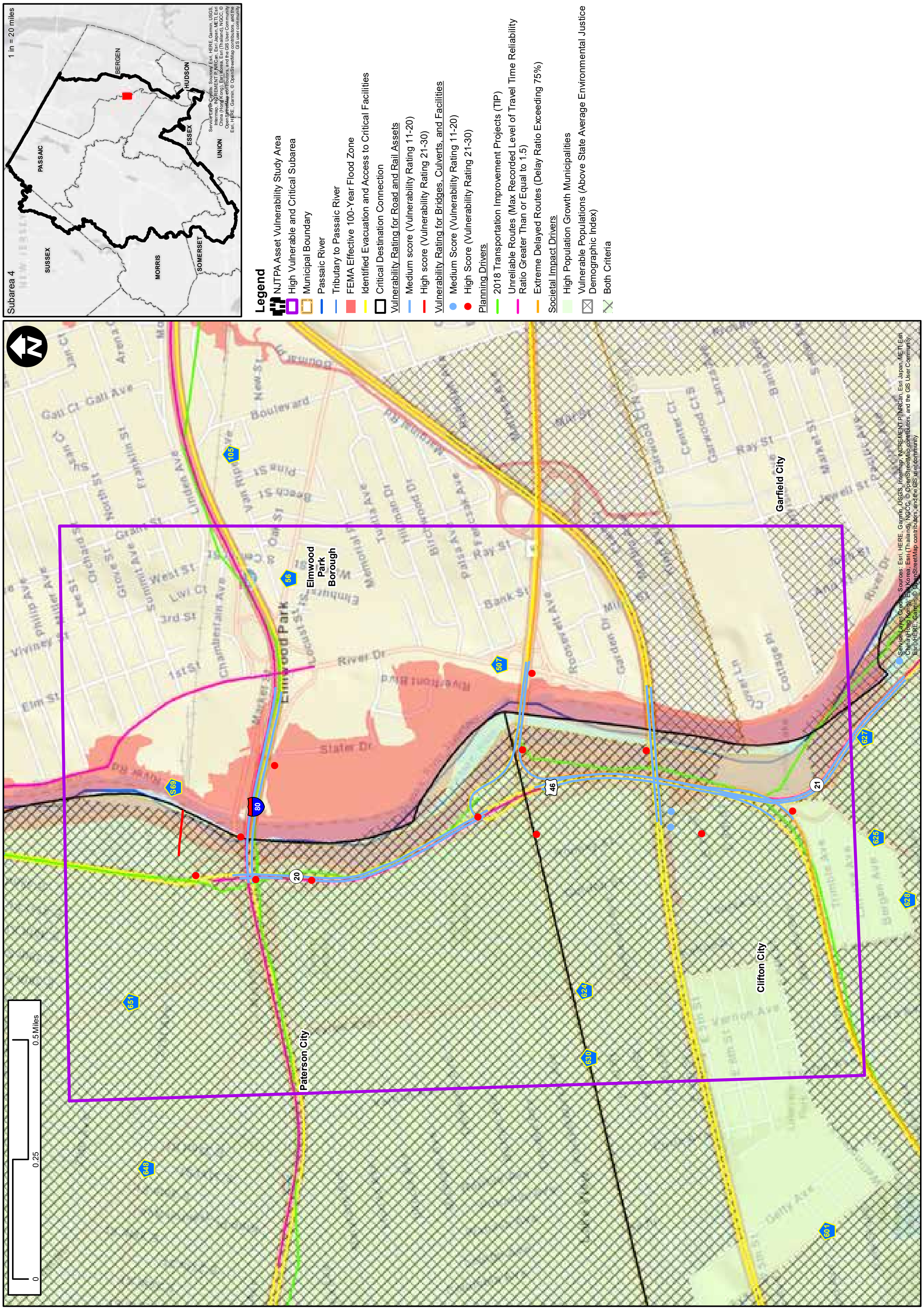


Figure 25. Subarea 5: Willowbrook Spaghetti Bowl/Route 80, 46, 23

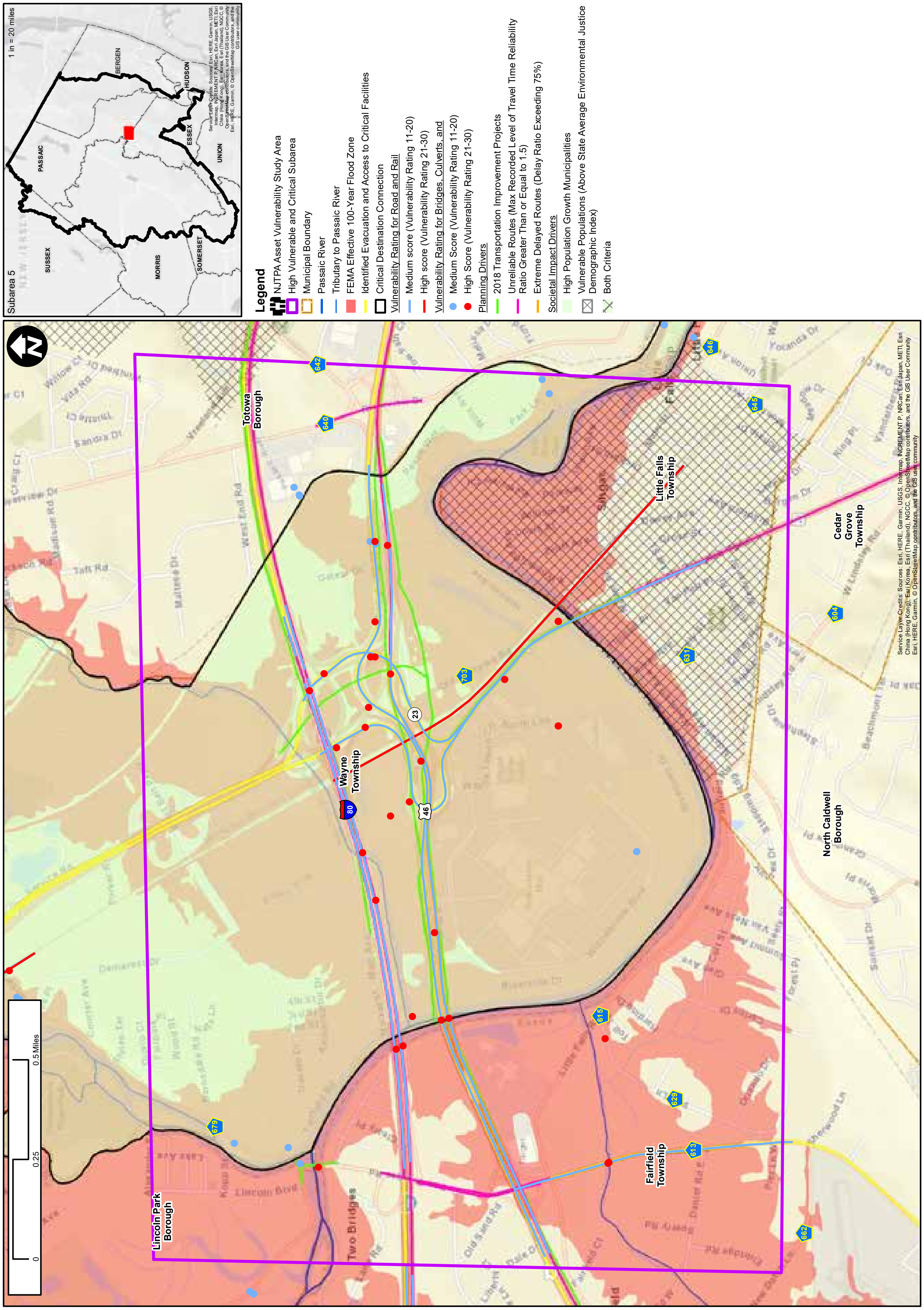


Figure 26. Subarea 6: Parsippany, Pine Brook/Route 80, 46

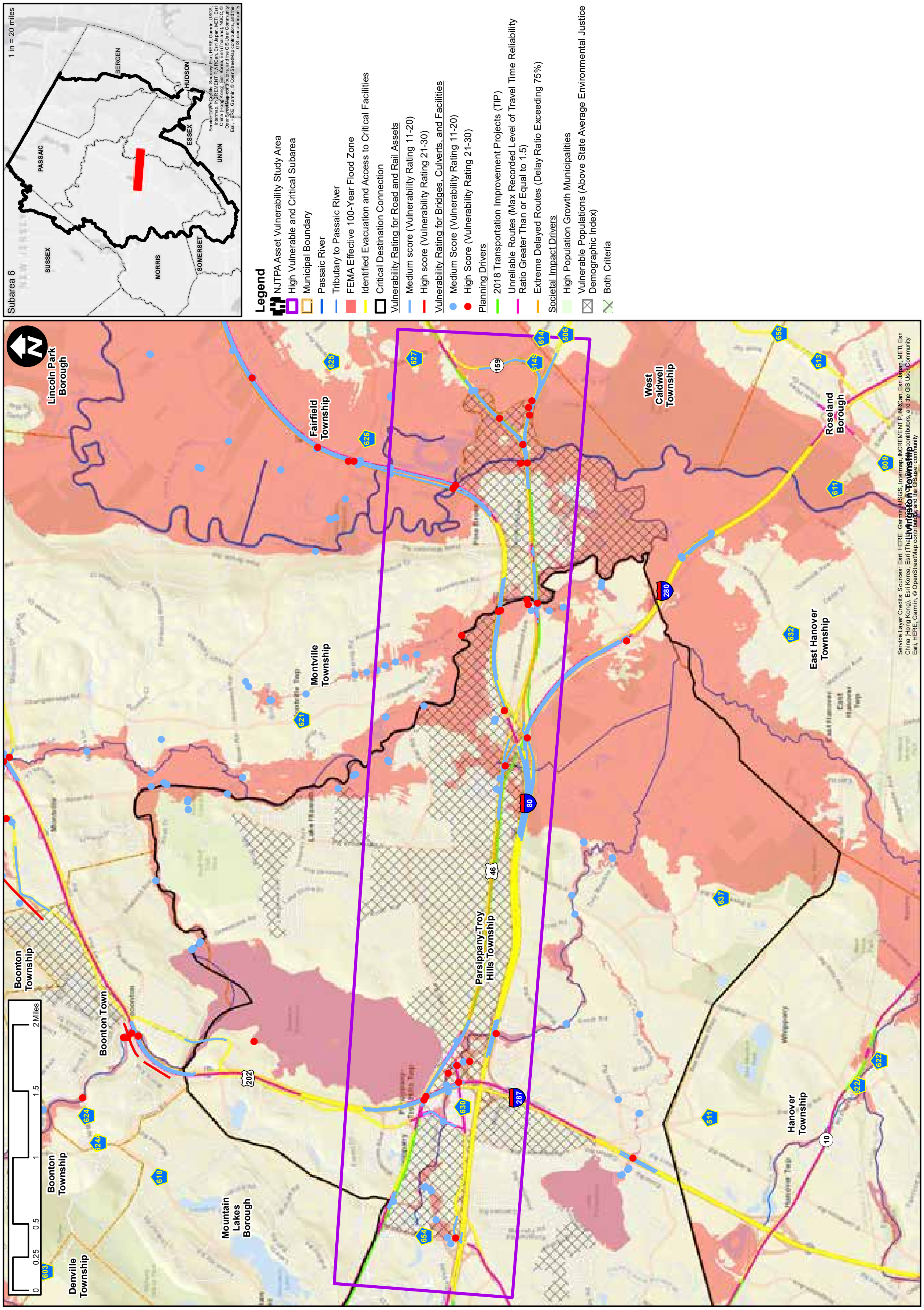


Figure 27. Subarea 7: Dover/Route 46, 15

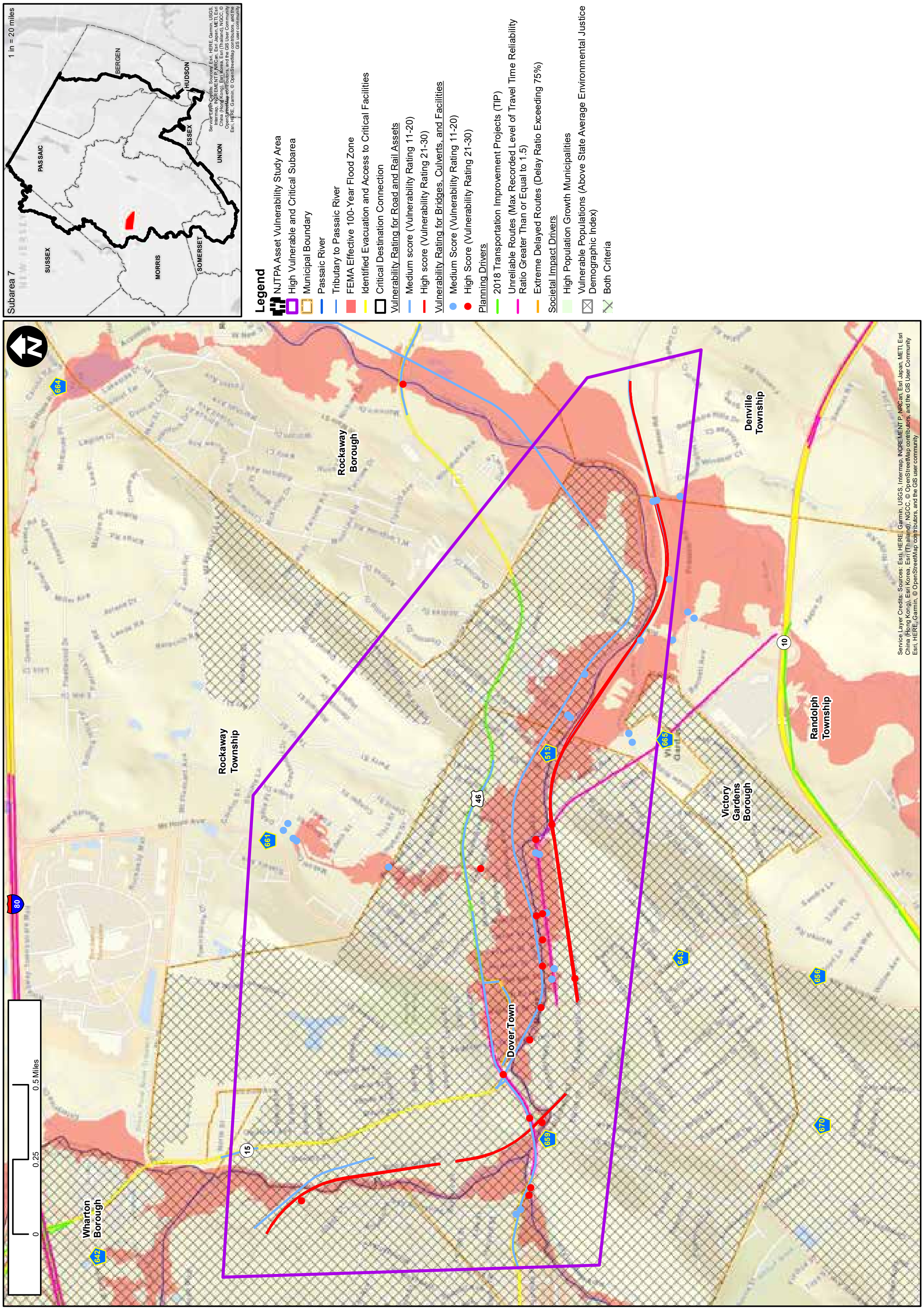


Figure 28. Subarea 8: Wayne/Route 202

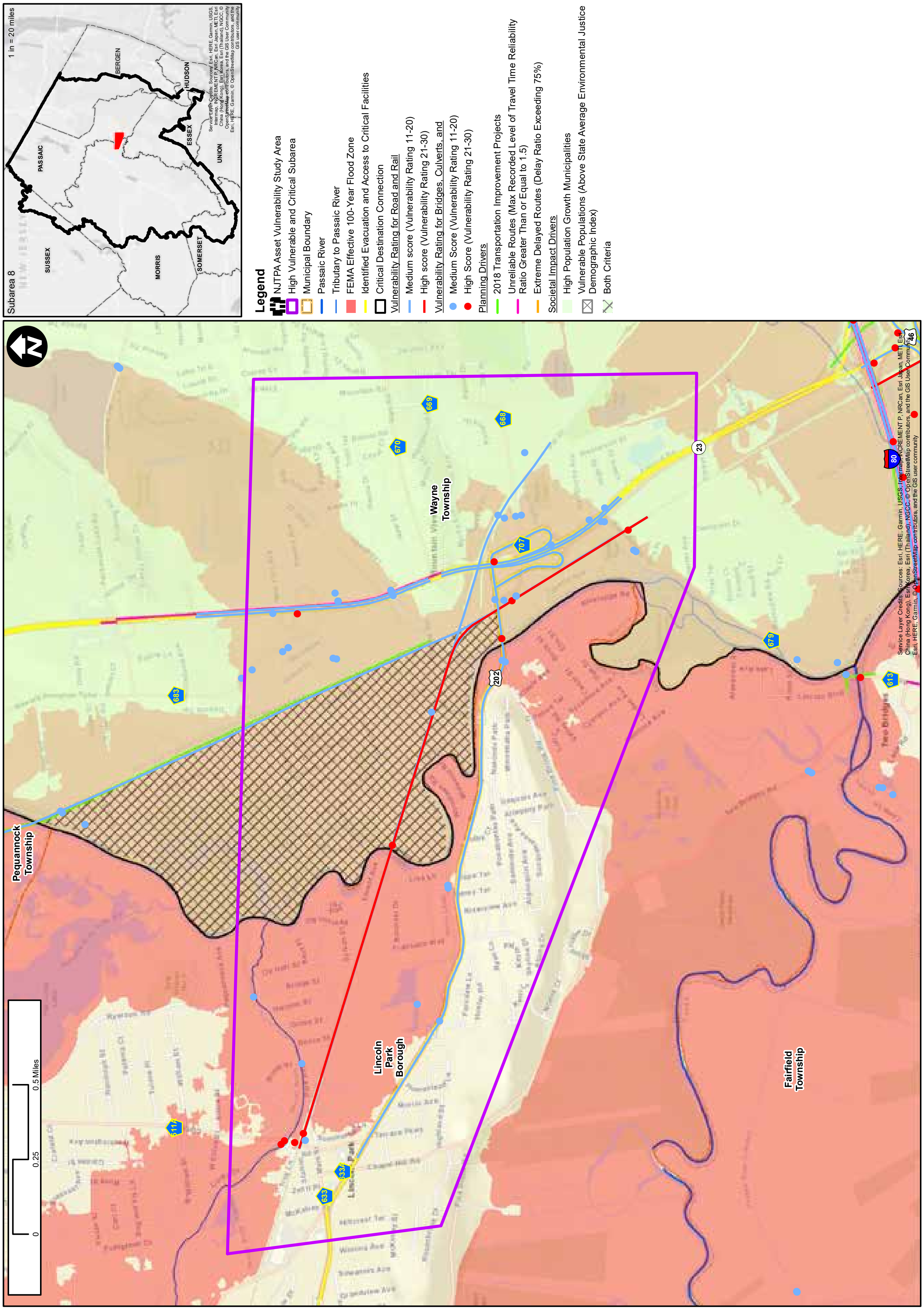


Figure 29. Subarea 9: Kinnelon, Bloomingdale/Route 23

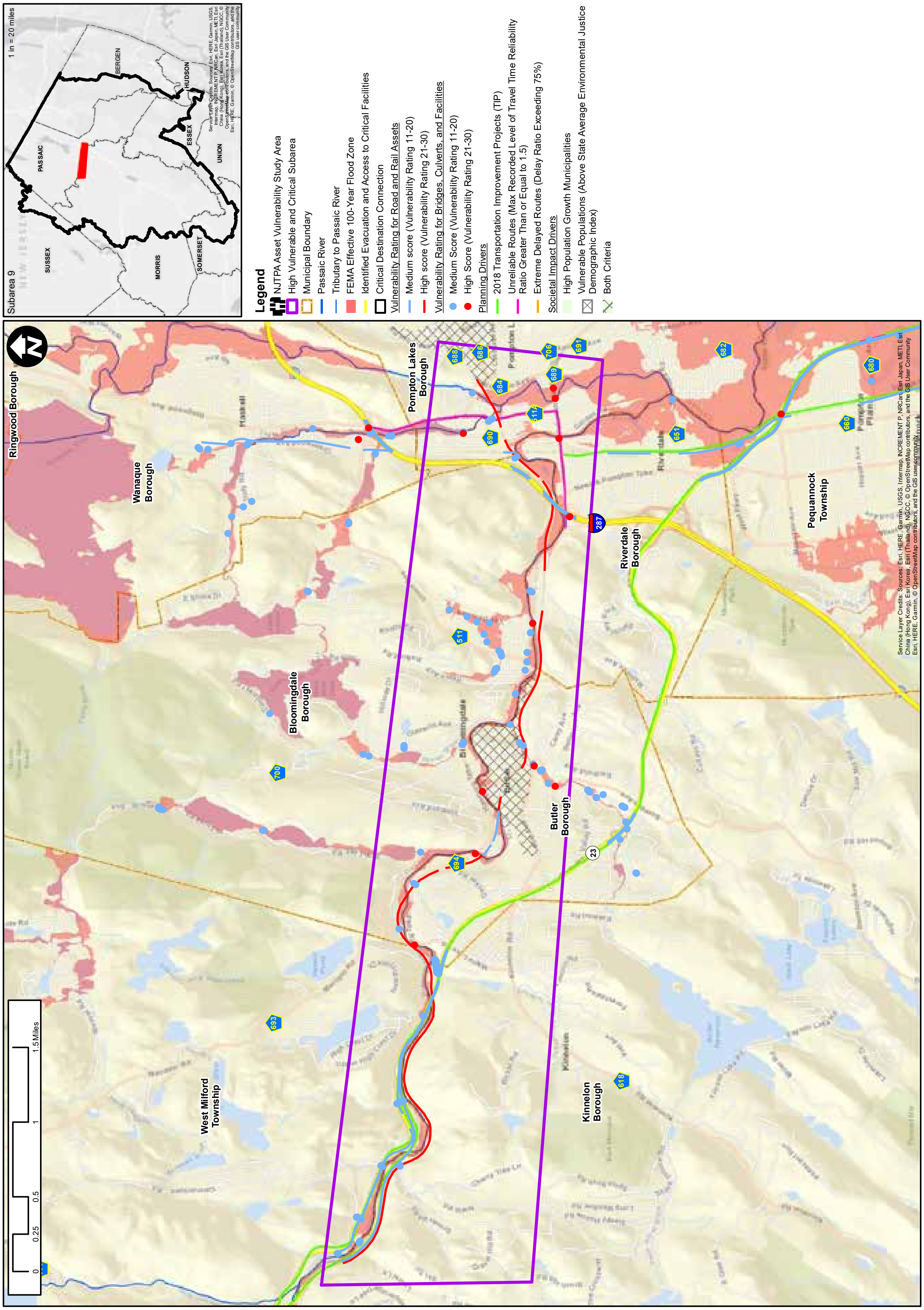


Figure 30. Subarea 10: Paramus/Route 17, GSP

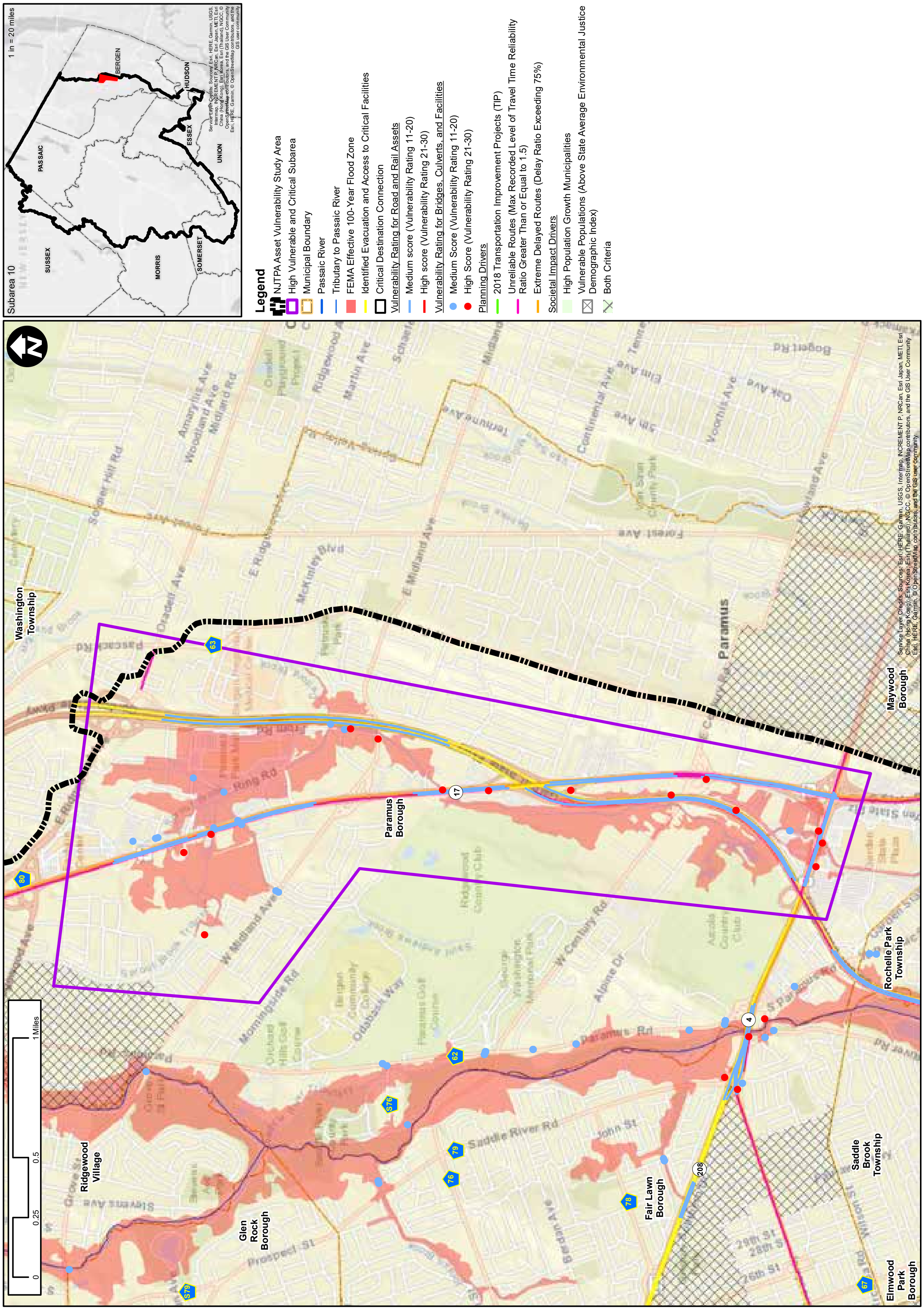
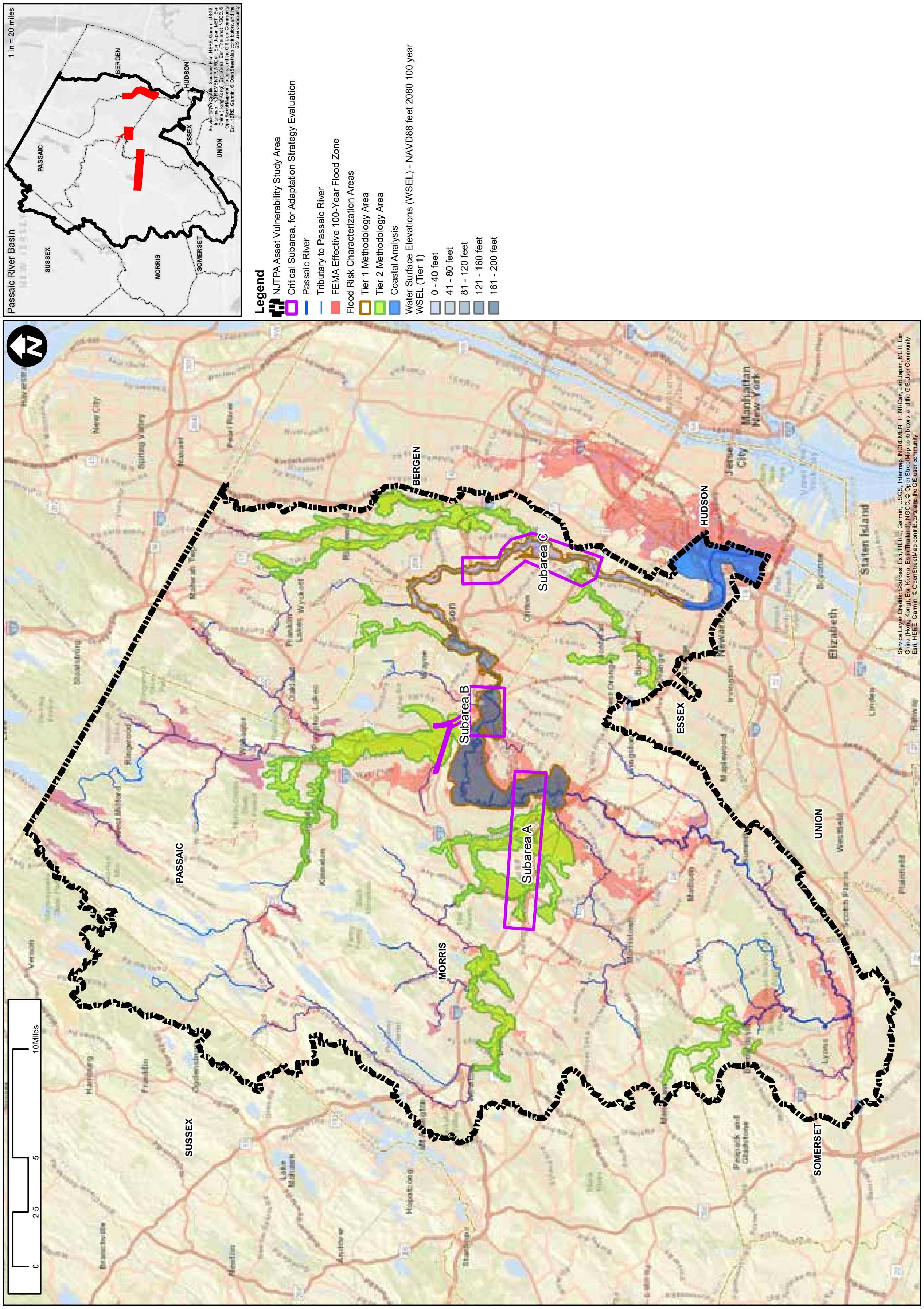


Figure 31. Critical Subareas for Adaptation Strategy Evaluation



Subarea Adaptation Analysis

Subarea A: Parsippany/Pine Brook

Location

The Parsippany/Pine Brook Subarea is bounded within portions of Essex and Morris Counties to include the intersections of Interstates 80, 280, and 287 and Routes 46 and 202. More specifically, the subarea runs along the Interstate 80 and Route 46 corridor, from Route 202/Littleton Road (County 630) and Cherry Hill Road (County 654) in Parsippany to the west and Oak Road (County 614/Route 159) in Fairfield to the east; with boundaries that extend within 1 mile north of this corridor and approximately one-quarter mile south. Four municipalities in Essex and Morris Counties are represented in this subarea: Parsippany-Troy Hills Township, Montville Township, Fairfield Township, and West Caldwell Township. The transportation network (1) serves as a major highway node of regional and national significance to the movement of goods and people; (2) serves as evacuation routes and access to critical emergency facilities; (3) contains connections to critical destinations (employment hubs located to the south in Morristown and east to the City of Newark and New York City); (4) services vulnerable populations; and (5) includes 2018 TIP-funded projects. Segments of Interstates 80, 280, and 287; Routes 46 and 202; and County Road 630 have been identified as having both unreliable travel times and extreme delays. Subarea A and transportation assets that were determined to be highly vulnerable to future severe climate events are shown in **Figures 32** through **37.**

History of Flooding and Climate Scenario Summary

The project team interviewed county stakeholders and reviewed county HMPs to understand the impact that flooding has had on the transportation assets in the region. The Morris County HMP identified the following areas with a history of frequent flooding: Parsippany south of Route 46, the Lake Hiawatha neighborhood, and along the Rockaway River and Troy Brook tributaries. Flooding is this subarea has the potential to impact major highways. The Essex County HMP emphasizes the natural geography of Fairfield acting as a large natural storage to floodwaters from both the Passaic and Pompton Rivers. As a result, approximately 70 percent of property and structures in Fairfield are located within the FEMA-identified Special Flood Hazard Area, an area where the National Flood Insurance Program regulations must be enforced and where the mandatory purchase of flood insurance applies. In addition, while outside of this subarea, stakeholders from Passaic County identified portions of Interstate 80 as experiencing heavy flooding during Hurricane Irene, recalling the event as having forced cars off the road and created the need to detour traffic as far north as Interstate 287.

Figures 32 through **37** presents flood level ranges for the 100-year flood event in the 2045 and 2080 planning horizons modeled to occur at Subarea A transportation assets. Flood level ranges modeled at each asset (including bridges, culverts, and roadways) were the same for the 2045 and 2080 planning horizons, with the following exceptions:

- Two Bloomfield Avenue bridges crossing a tributary of the Rockaway River (Asset IDs 1400431 and 1400432). The flood level ranges at these two assets for the 100-year flood event in 2045 is 0.0 to 5.0 feet below the asset and in 2080 is 0.0 to 0.5 feet above the asset.

This change in flood elevation between the two planning horizons indicates a likely increase in flooding impacts in this area.

The portion of Subarea A that is identified to have a flood level greater than 5.0 feet above assets under the future 100-year flood event are primarily located on/near Route 46 in the vicinity of the Passaic River along the Fairfield Township and Montville Township border. Flood levels ranging from 0.5 to 5.0 feet above an asset were identified throughout Subarea A on/near Route 46 just south of the Boonton Reservoir, at the Route 80 and Route 280 interchange, in the vicinity of the Rockaway River, and at the intersection of Route 159 (Bloomfield Avenue). Route 80 near John Street Park and Christopher Columbus Highway has assets with flood levels ranging from 0.5 to 5.0 feet above an asset under these climate scenarios. Mobility in these areas will likely be affected during extreme flood events.

In addition, transportation assets within the selected subarea are vulnerable to an extreme heat event. All roadway assets were determined to be vulnerable to extreme heat. Eight bridges were identified to be highly vulnerable to an extreme heat event, as shown in **Figures 32** and **33**. Of these eight bridges, only two were determined to be vulnerable to flood levels ranging 0.5 to 5.0 feet above the asset. These bridge locations are:

- Interstate 80 bridge crossing the Passaic River (Asset ID 1415157)
- Route U.S. 46 bridge crossing the Passaic River (Asset ID 1410159)

A summary of the highly vulnerable and critical assets for Subarea A is presented in **Appendix L, Assigned Adaptation Strategies and Associated Costs for the Benefit Cost Analysis.**

Adaption Strategies for Highly Vulnerable and Critical Assets

Subarea A has transportation assets that were determined to be highly vulnerable to both heat and flooding events; these assets were evaluated for potential adaptation strategies to reduce the vulnerability. The assets include approximately 96 road segments (along seven roadways), 5 bus lines, 26 bridges, and 3 culverts. A summary of the applicable adaptation strategies for highly vulnerable and critical assets in Subarea A is summarized in subsection "Subarea Recommended Adaptation Strategies" and presented in **Appendix L.**

Adaptation Strategy Implementation Considerations

Subarea A includes major highways with limited access issues, therefore localized road closure is not anticipated to prevent commuter transport to nearby destinations or outside of the subarea. It has a high volume of truck traffic and the eastern end is dominated by industrial activity. Impacts to assets in this area could have a significantly negative economic impact to the state and regional supply chain. Some redundancy currently exists in the highway system as Route 46 and Interstate 80 run along a similar geographic corridor and may adequately provide detours, though these roadways are determined to be high traffic areas. Interstate 280, a highly congested route, does not include any redundancy. Route 46 has commercial access and businesses along the roadway that would make the construction of berms and elevation of this segment of the roadway challenging.

Challenges may include construction activities that may temporarily disrupt access to local businesses and places of employment and longer travel times post construction due to roads reconfigured around berms or limits on business access to elevated ramps.

Figure 32. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Bridge Assets

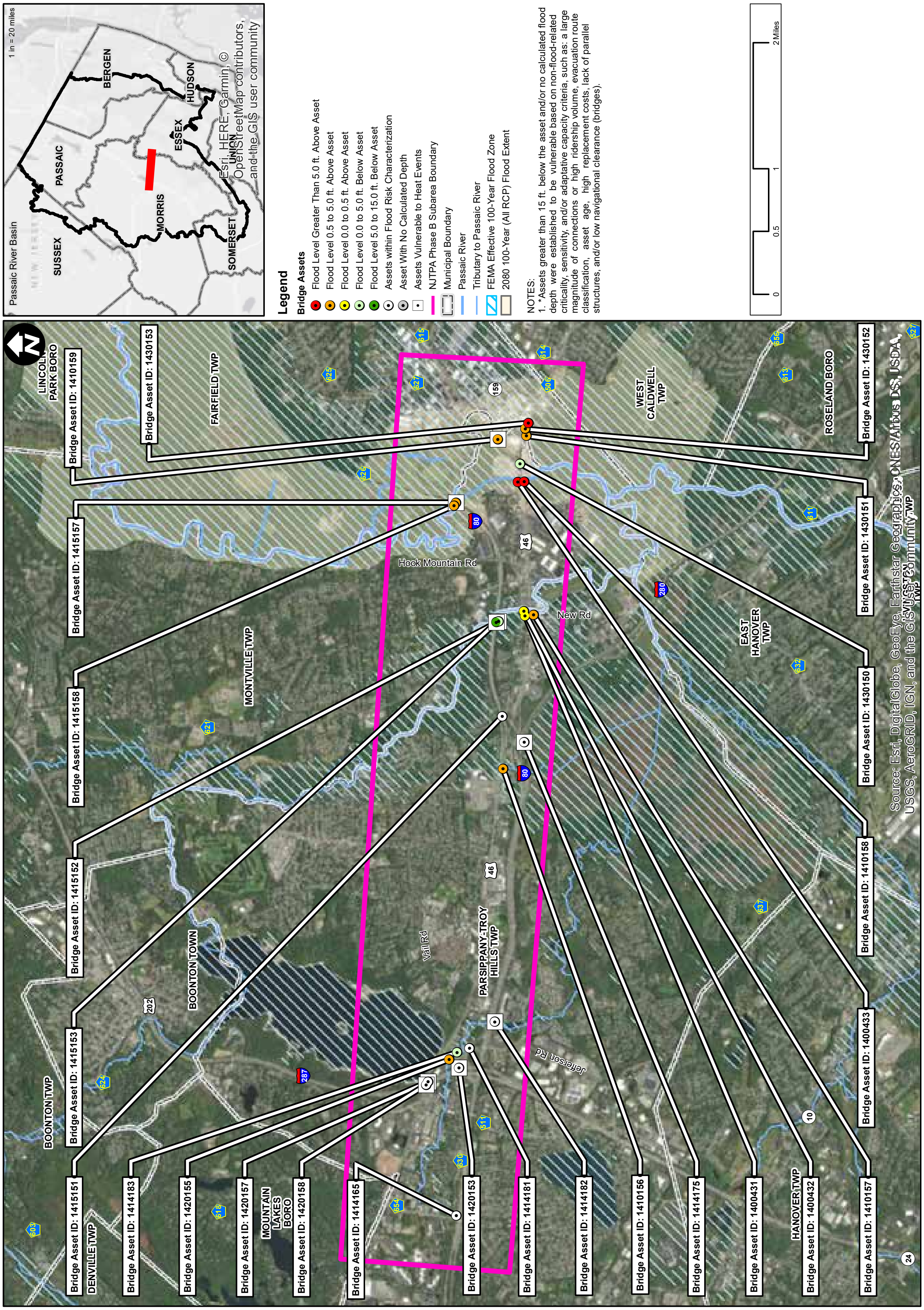


Figure 33. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Bridge Assets

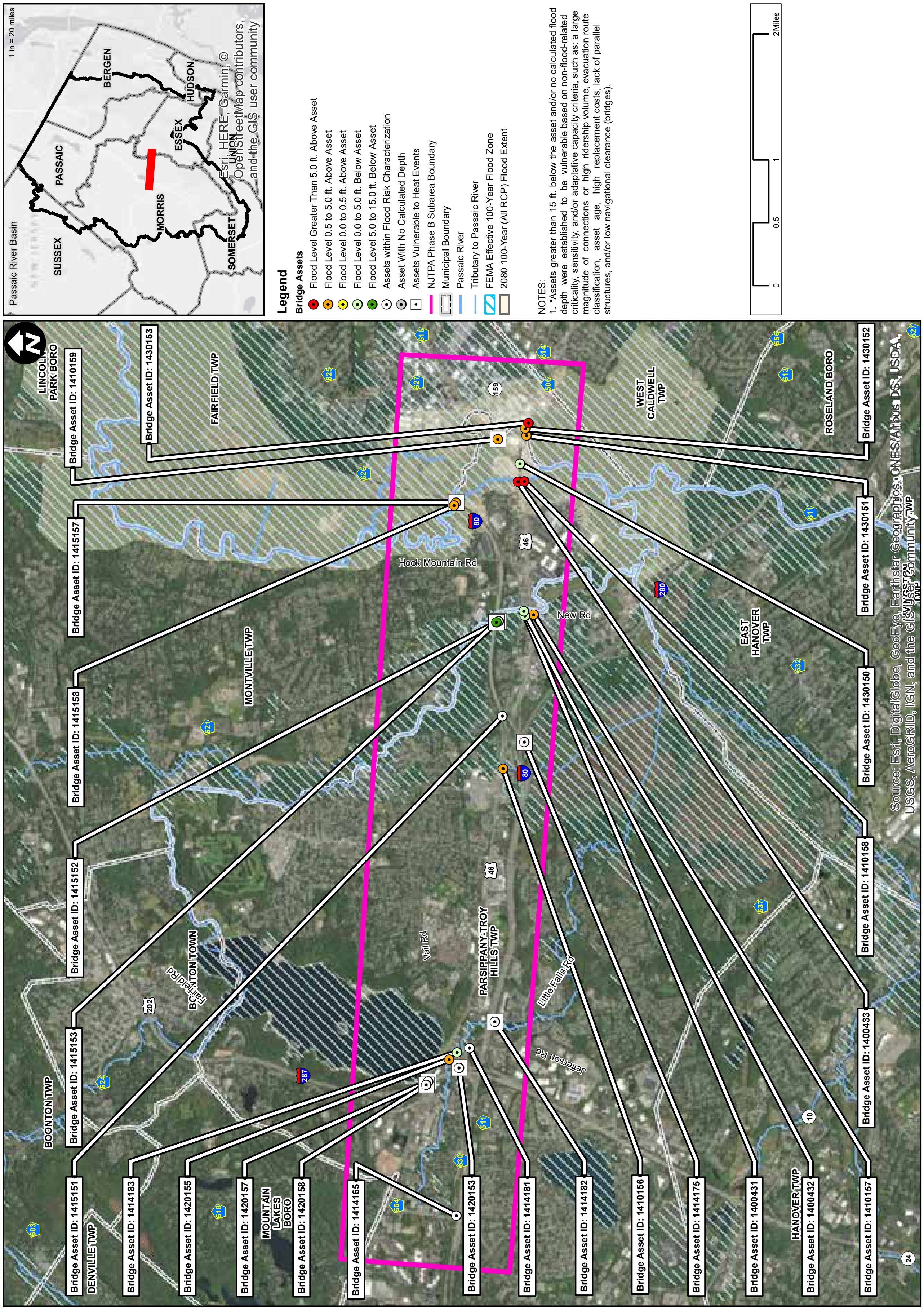


Figure 34. Vulnerable Assets to 2045 100-Year (All RCP) Flood Events: Culvert Assets

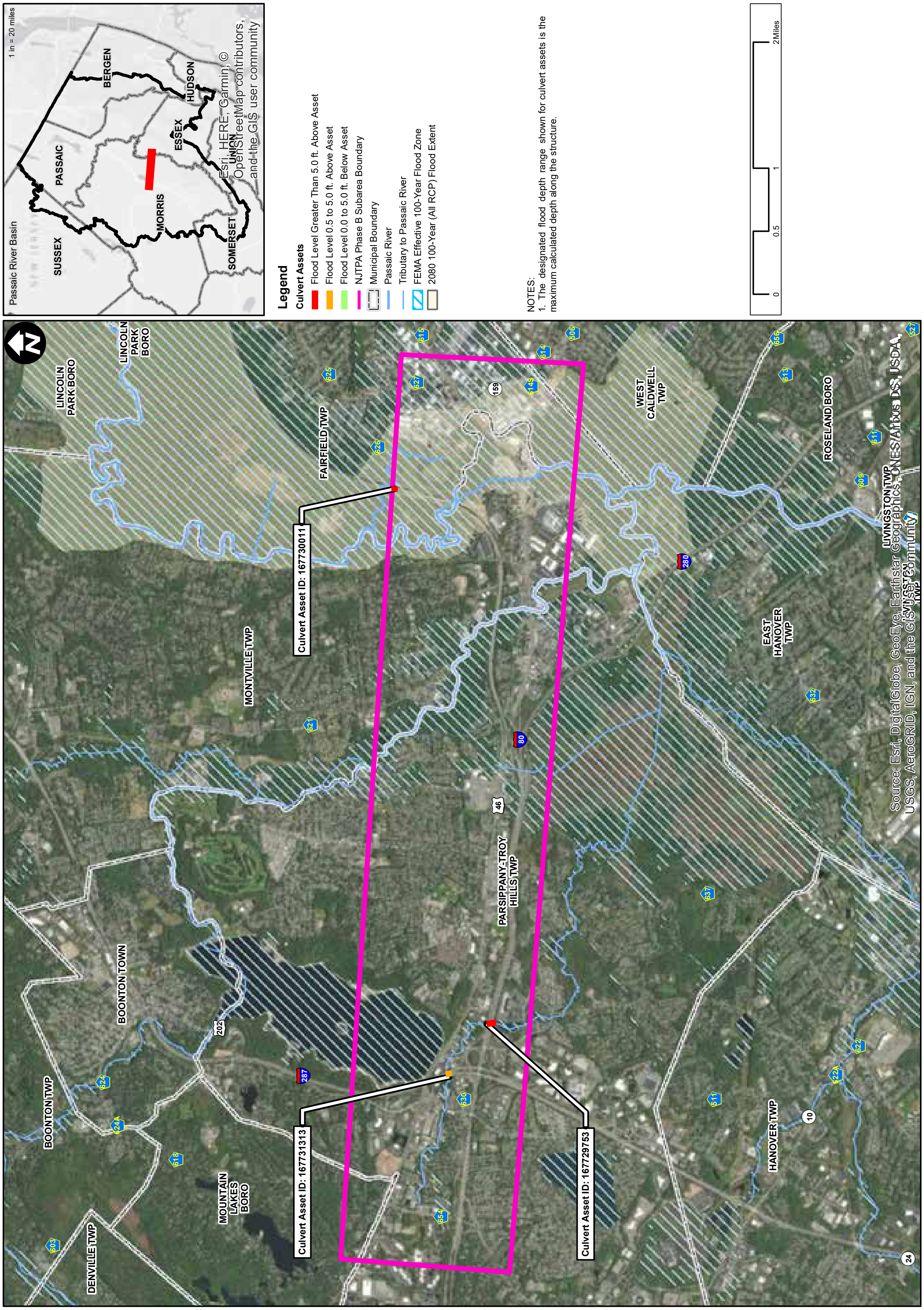


Figure 35. Vulnerable Assets to 2080 100-Year (All RCP) Flood Events: Culvert Assets

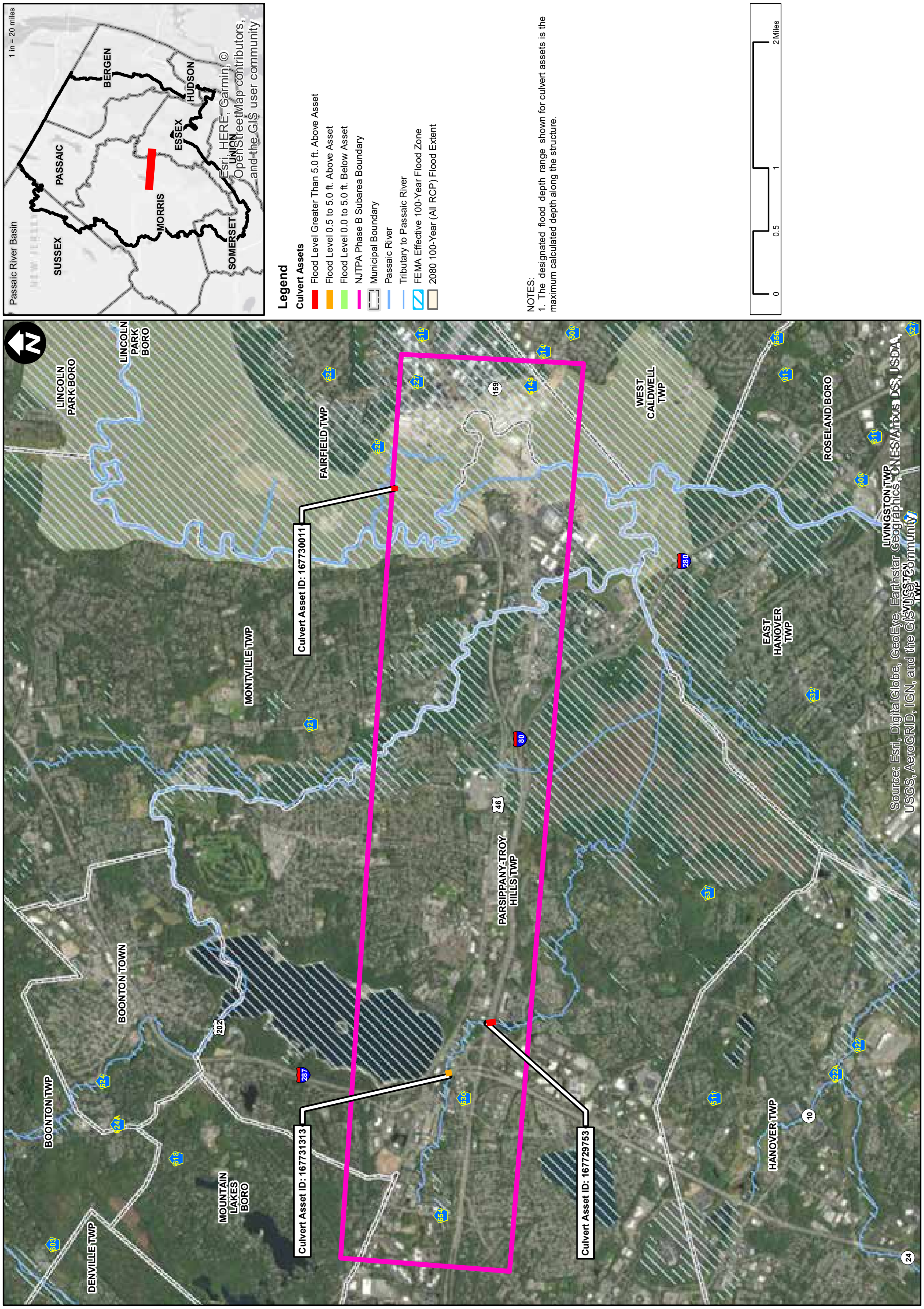


Figure 36. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Roadway Assets

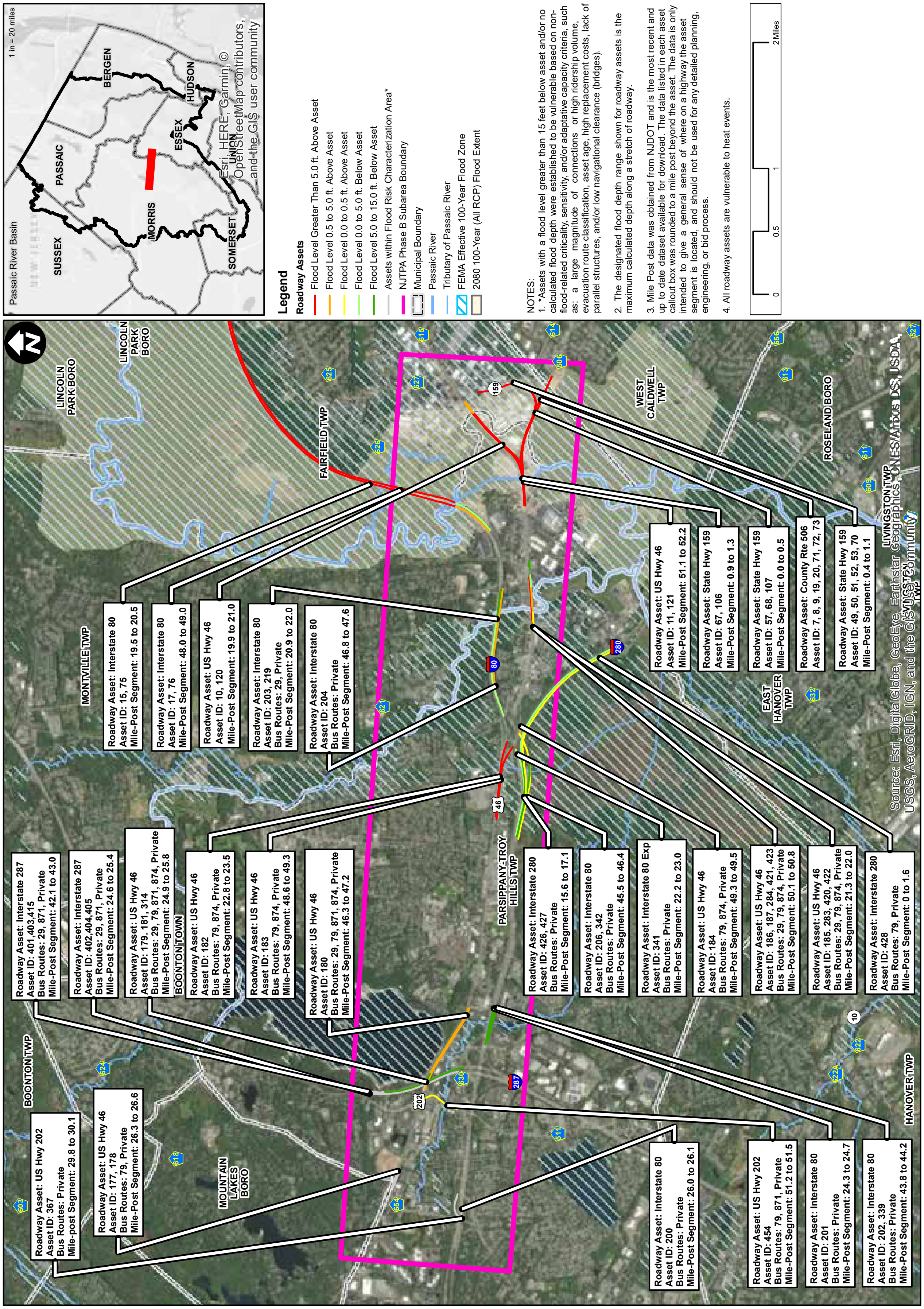
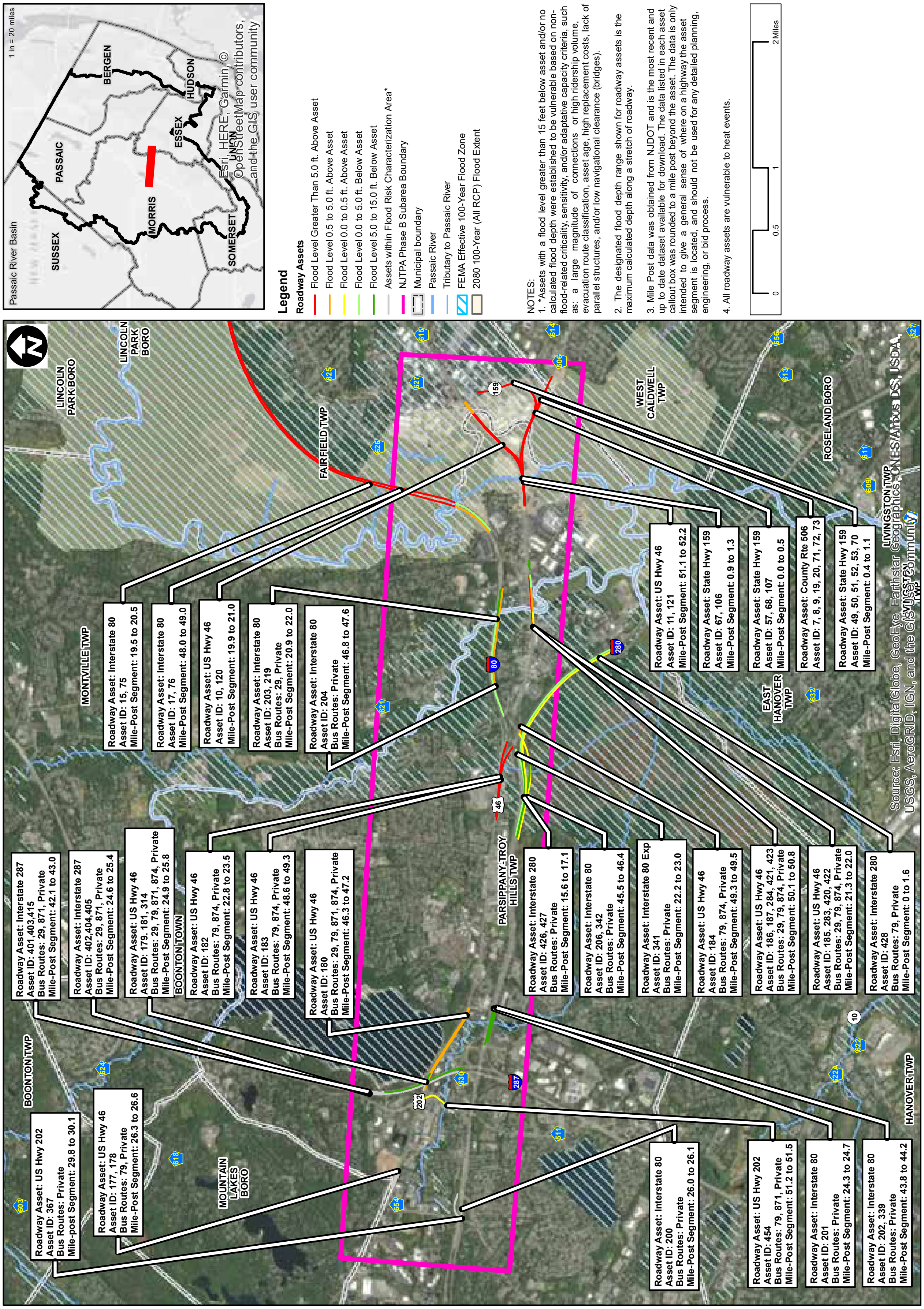


Figure 37. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Roadway Assets



Subarea B: Willowbrook "Spaghetti Bowl"

Location

The Willowbrook Spaghetti Bowl Subarea B is located at the intersections of Interstate 80 and Routes 23 and 46. Based on feedback provided by the TAC, the commuter rail and road "pinch-points" in the township of Wayne Township located directly north of the Spaghetti Bowl were included to evaluate a larger extent of the Route 23 and NJ TRANSIT/Conrail and Eerie Lackawanna corridors in the adaptation strategy assessment. It includes the portion of Route 23, south of its intersection with Newark-Pompton Turnpike in Wayne and the segments of the Montclair-Boonton Rail Road Line up to Beaver Brook Road in Lincoln Park. County road segments within this subarea include Passaic Avenue (County 613), Little Falls Road (County 615), Pier Lane (County 629), Main Street (County 631), Riverview Drive (County 640), Fairfield Road (County 679), and Old Turnpike Road (County 703).

Seven municipalities in Essex, Morris, and Passaic Counties are represented in the subarea: Cedar Grove Township, Fairfield Township, Borough of Lincoln Park, Little Falls Township, Borough of North Caldwell, Borough of Totowa, and Wayne Township. Most of the subarea is within the FEMA-mapped floodplain due to the confluence of the Passaic River and its tributaries. The transportation network in this subarea connects to critical destinations (Willowbrook Mall, the Lincoln Park and Mountain View-Wayne train stations, and employment hubs to the east) and serves an area currently experiencing high population growth and having vulnerable populations, serves as evacuation routes and access to critical emergency facilities, and includes 2018 TIP-funded projects. These transportation routes have been identified as having both unreliable travel times and extreme delays. Subarea B and transportation assets that were determined to be highly vulnerable to future severe climate events are shown in **Figures 38** through **47**.

History of Flooding and Climate Scenario Summary

The project team interviewed county stakeholders and reviewed county hazard mitigations plans to understand the impact historical flooding has had on the transportation assets in the subarea. The location of assets determined to be vulnerable to flooding impacts fell within the existing and future flood inundation extents modeled for the study. Passaic County stakeholders have identified all the major highways in the region as having experienced frequent flooding events in the past and in multiple locations along each roadway. These major highways include Routes 23 and 46 and several other local, arterial roadways, including Newark-Pompton Turnpike, Alps Road, West Belt Parkway, Riverview Drive, and Mountainview Boulevard. The Passaic County HMP emphasizes the impacts from frequent flooding at these roadways due to the Passaic River and its tributaries. Little Falls and Wayne are the two municipalities that comprise a substantial portion of the subarea; both have been identified as having flooding challenges from heavy rainstorm events in the past.

Figures 38 through **47** present flood level ranges for the 100-year flood event in the 2045 and 2080 planning horizons modeled to occur at Subarea B transportation assets. Flood level ranges modeled at each asset (including bridges, culverts, roadways, railways, and facilities) were the same for the 2045 and 2080 planning horizons, with the following exceptions:

- Montclair Boonton rail line bridge over the Pompton River (Asset ID 1663163)
- Pedestrian bridge in the vicinity of Montclair Boonton rail line and Fairfield Avenue (Asset ID 1604172). The GIS dataset labels Asset ID 1604172 as "pedestrian bridge over Route 23;" however, the aerial shows this asset located at the Fairfield Avenue crossing over the Montclair Boonton Railroad.

The flood level ranges at these two assets for the 100-year flood event in 2045 is 0.0 to 5.0 feet below the asset and in 2080 is 0.0 to 0.5 feet above the asset. This change in flood elevation between the two planning horizons indicates a likely increase in flooding impacts in this area. A majority of transportation assets within Subarea B have a flood level greater than 5.0 above assets under the future 100-year flood events, including significant segments of Routes 80, 46, and 23; segments of the Erie-Lackawanna; Conrail and Montclair Boonton railways; approximately 40 percent of bridges, and all culverts. In addition, approximately 27 percent of bridges and large segments of Route 23 and the Conrail Railroad in the vicinity of Route 703 and the Spaghetti Bowl roadway network were identified to have flood levels ranging from 0.5 to 5.0 feet above an asset under these climate scenarios. The flood level range modeled at the Lincoln Park Transit Facility is 0.0 to 0.5 feet above the asset. Mobility in these areas will likely be affected during extreme flood events.

In addition, transportation assets within the selected subarea are vulnerable to an extreme heat event. All roadway and railway assets are vulnerable to extreme heat. Seven bridges were identified to be highly vulnerable to an extreme heat event, as shown in **Figures 38** and **39**. Of these seven bridges, two were determined to be vulnerable to flood levels ranging 0.5 to 5.0 feet above the asset and an additional two vulnerable to flood levels greater than 5.0 feet above the asset. These bridge locations are:

- Vulnerable to flood levels 0.5 to 5.0 feet above the asset
  - Route U.S.-46 bridge crossing a branch of the Passaic River (Asset ID 1606178)
  - County Route-613 crossing over Deepavaal Brook (Asset ID 0700096)
- Vulnerable to flood levels greater than 5.0 feet above the asset
  - Interstate-80 bridge crossing the Passaic River and Fairfield Road (Asset ID 0726155)
  - Route U.S.-46 bridge crossing the Passaic River (Asset ID 0722157)

A summary of the highly vulnerable and critical assets for Subarea B is presented in **Appendix L, Assigned Adaptation Strategies and Associated Costs for the Benefit Cost Analysis**.

Adaption Strategies for Highly Vulnerable and Critical Assets

Subarea B has transportation assets that were determined to be highly vulnerable to heat and flooding events; these assets were evaluated for potential adaptation strategies to reduce the vulnerability. They include approximately 39 road segments along 5 roadways and 13 bus routes, 38 bridges and 5 culverts, 7 rail segments and associated rolling stock on 2 different rail lines, and 2 train stations. A summary of the applicable adaptation strategies for highly vulnerable and critical assets in Subarea B is summarized in subsection "Subarea Recommended Adaptation Strategies" and presented in **Appendix L, Assigned Adaptation Strategies and Associated Costs for the Benefit Cost Analysis**.

Adaptation Strategy Implementation Considerations

Presently, sections of Route 23 are frequently closed due to minor flooding events, and this is expected to continue under future climate stressors. Route 23 also has commercial access and businesses along the road, which would make berms and roadway elevation challenging. However, a majority of the interstate highways in Subarea B are elevated; therefore, the types of assets identified to be the most vulnerable to flooding are bridges, culverts, and facilities. During the November 2018 TAC meeting, NJDOT indicated that transportation projects are planned for the Spaghetti Bowl within the next 5 years, including repair and/or construction of ramps and culverts, that may provide an opportunity to implement some adaptation strategies in the near term.

Figure 38. Tier 1 Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Bridge Assets

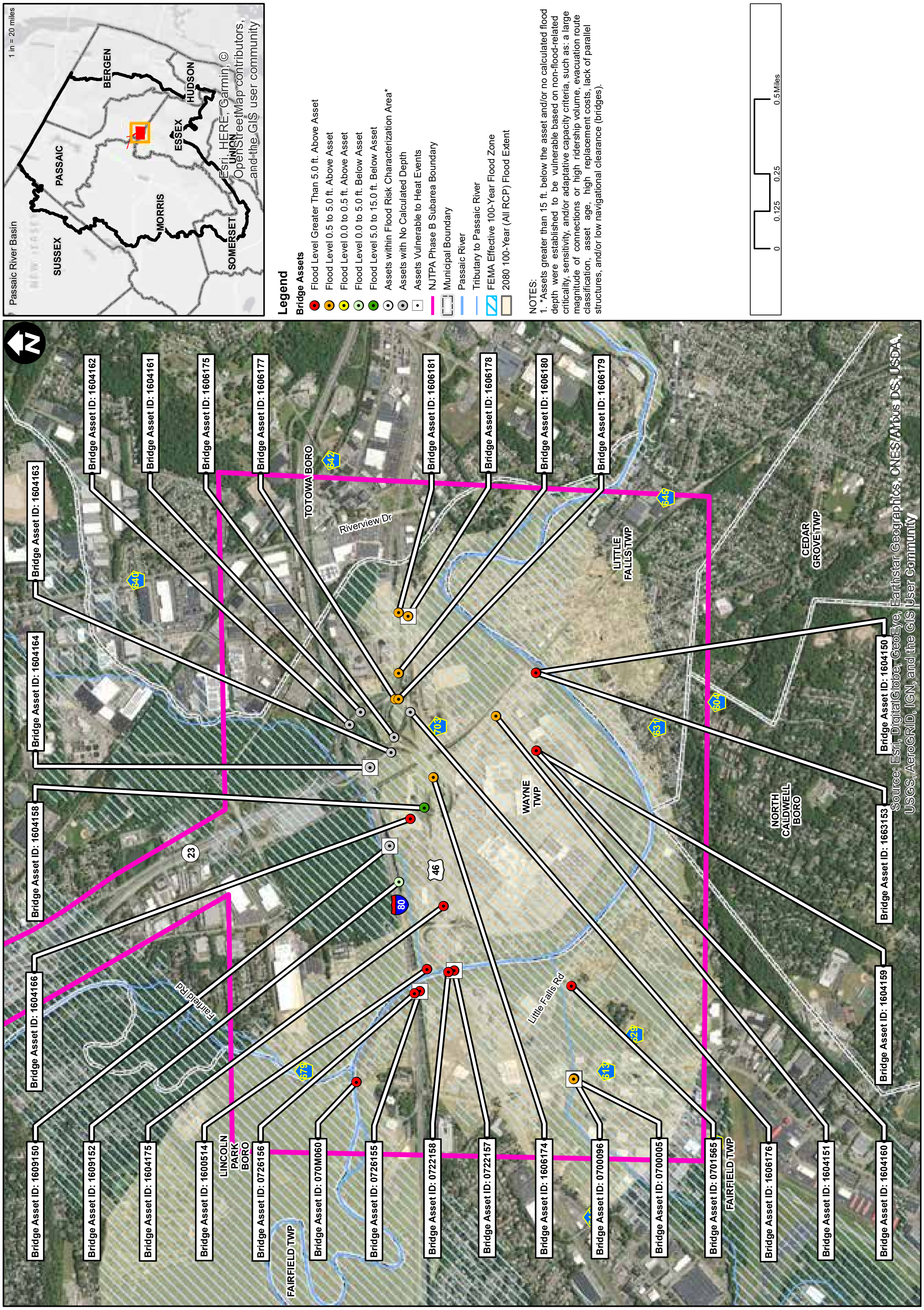


Figure 39. Tier 2 Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Bridge Assets

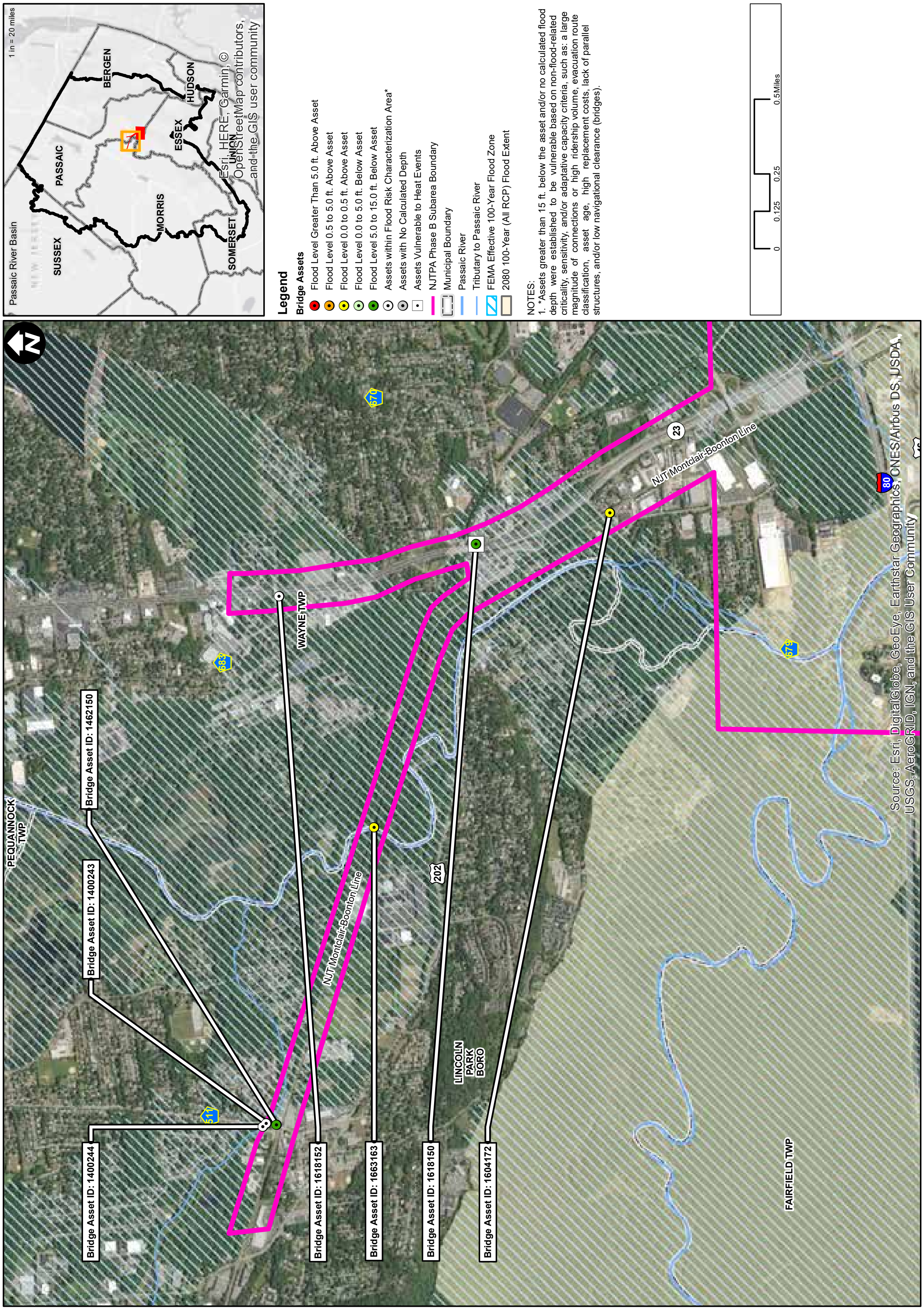


Figure 40. Tier 1 Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Bridge Assets

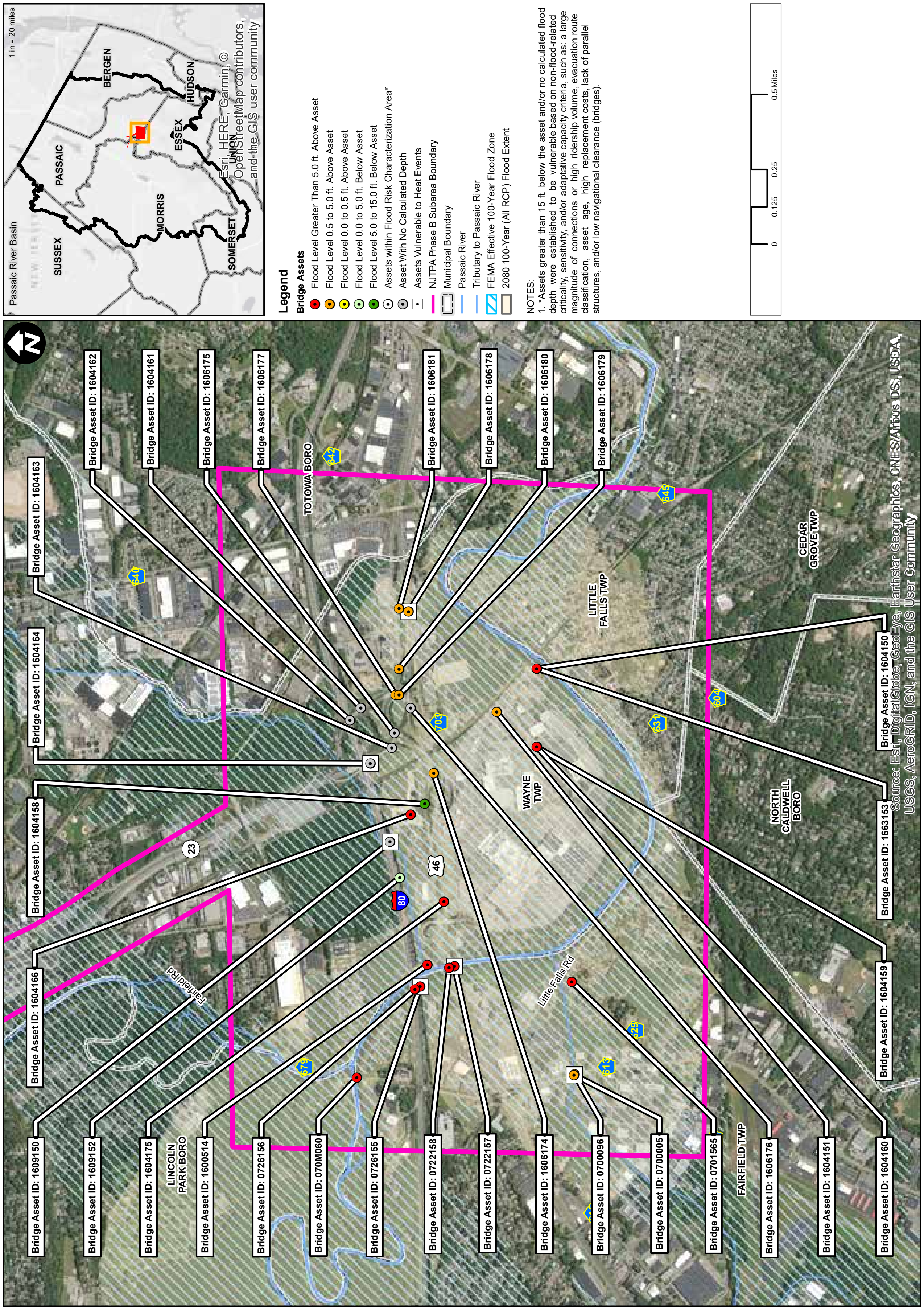


Figure 41. Tier 2 Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Bridge Assets

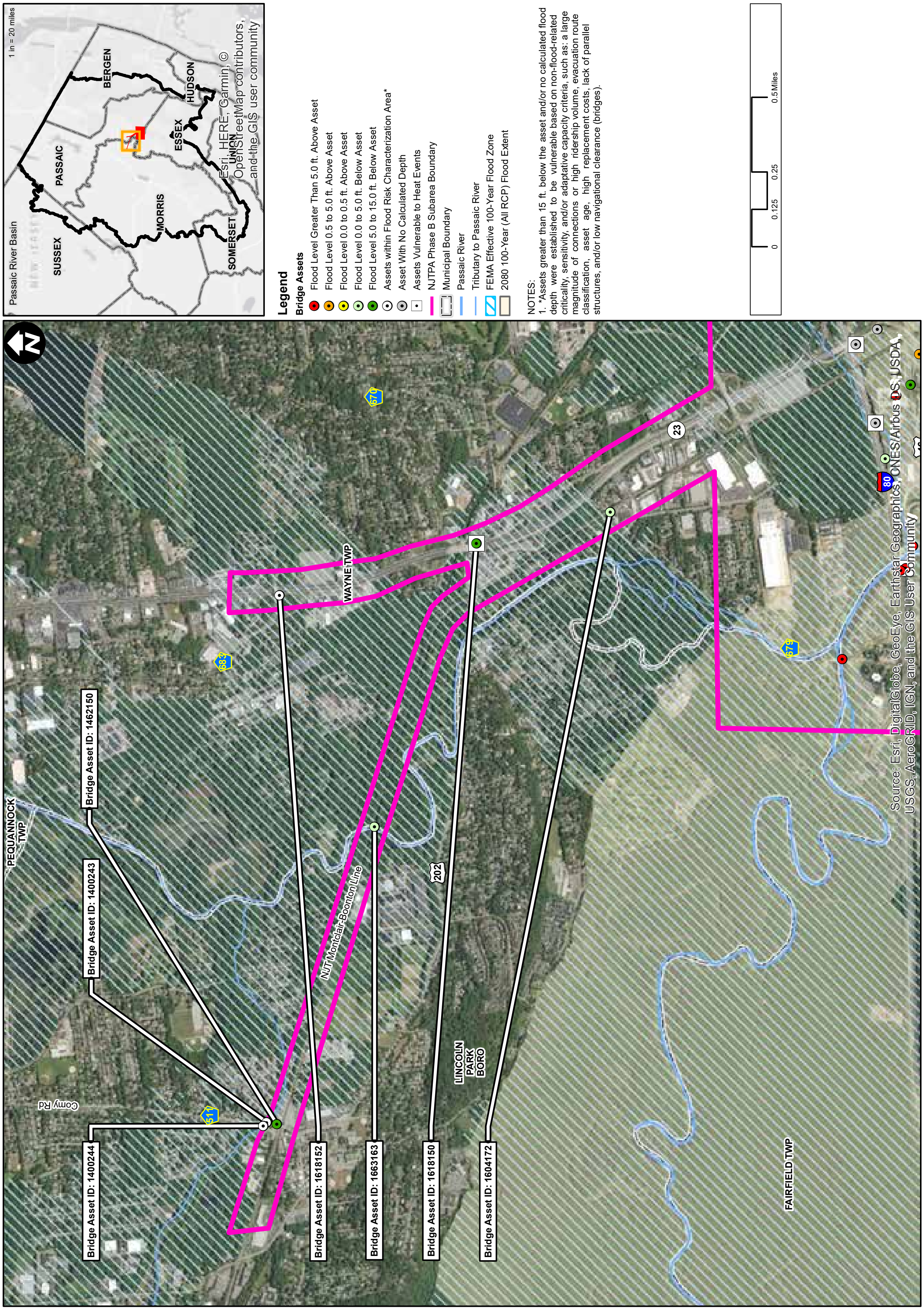


Figure 42. Vulnerable Assets to 2045 100-Year (All RCP) Flood Events: Culvert Assets

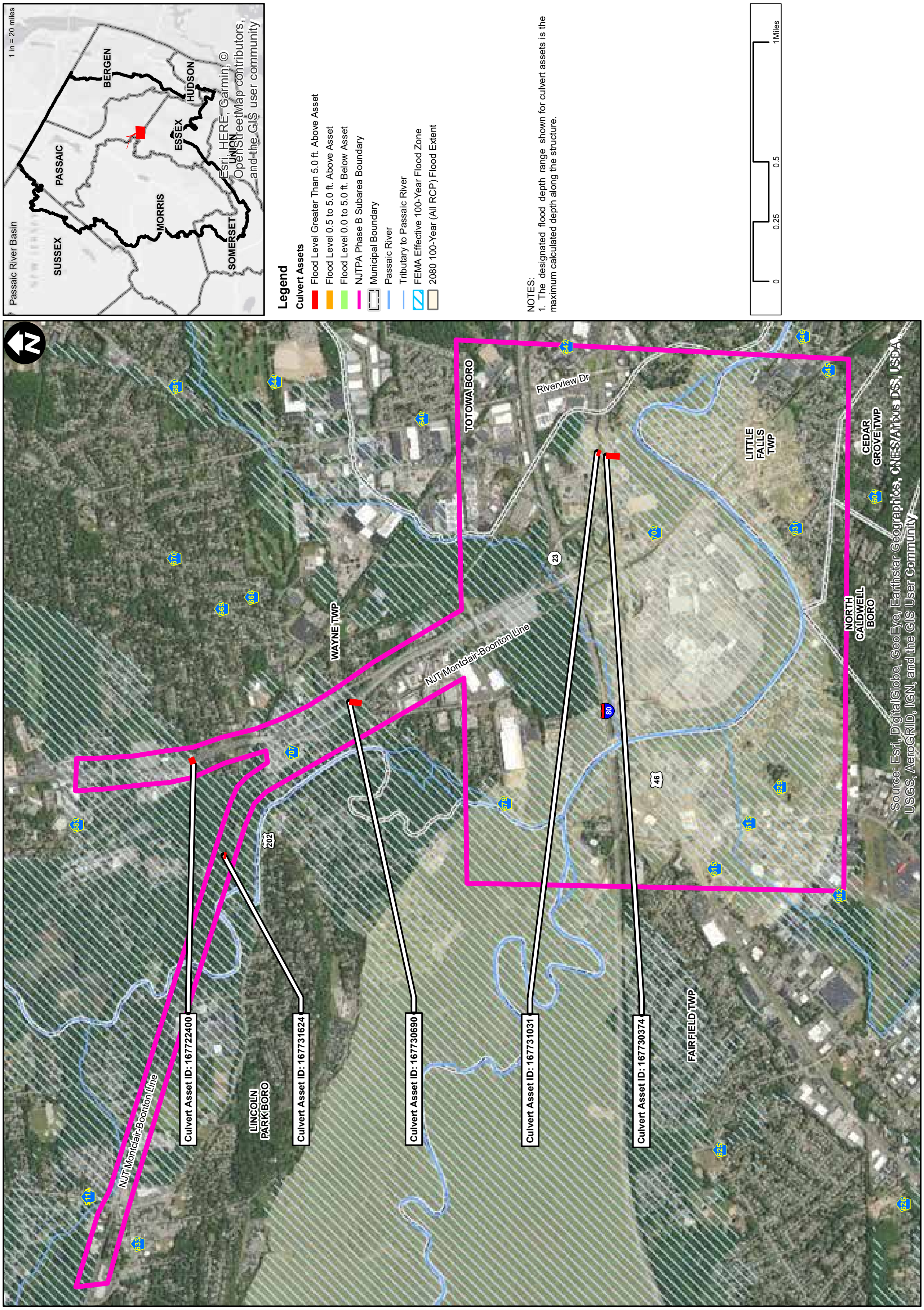


Figure 43. Vulnerable Assets to 2080 100-Year (All RCP) Flood Events: Culvert Assets

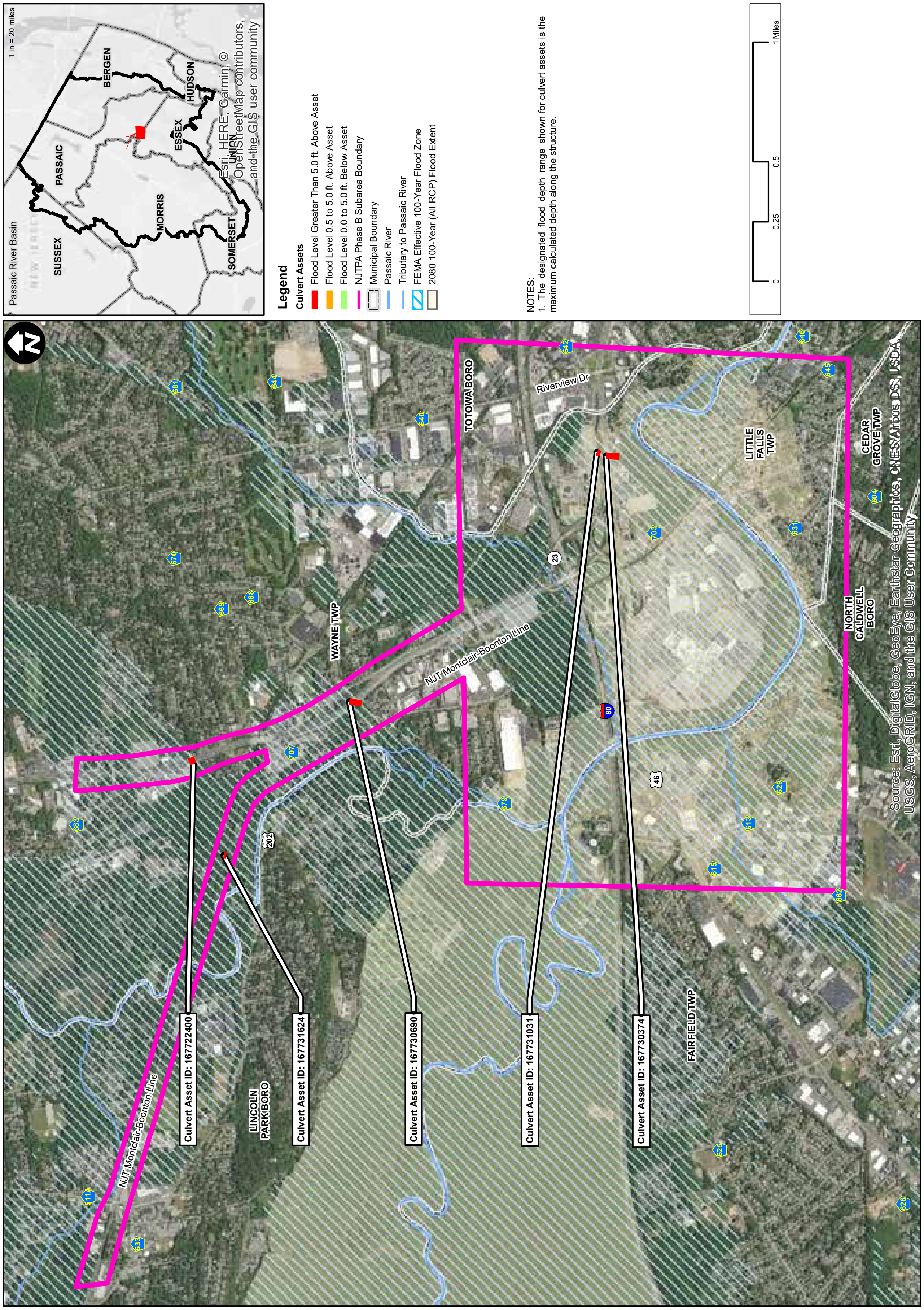


Figure 44. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Roadway Assets

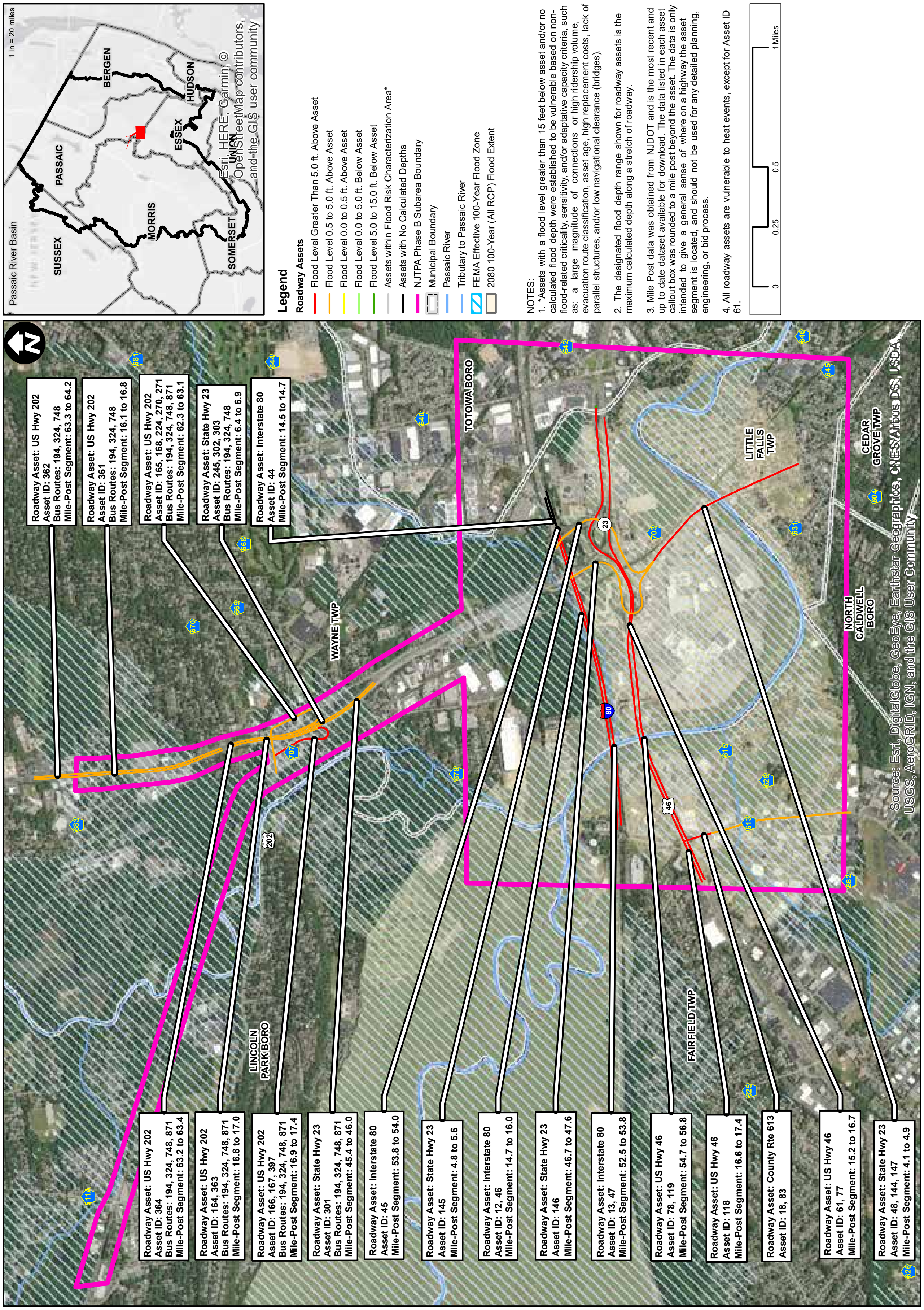


Figure 45. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Roadway Assets

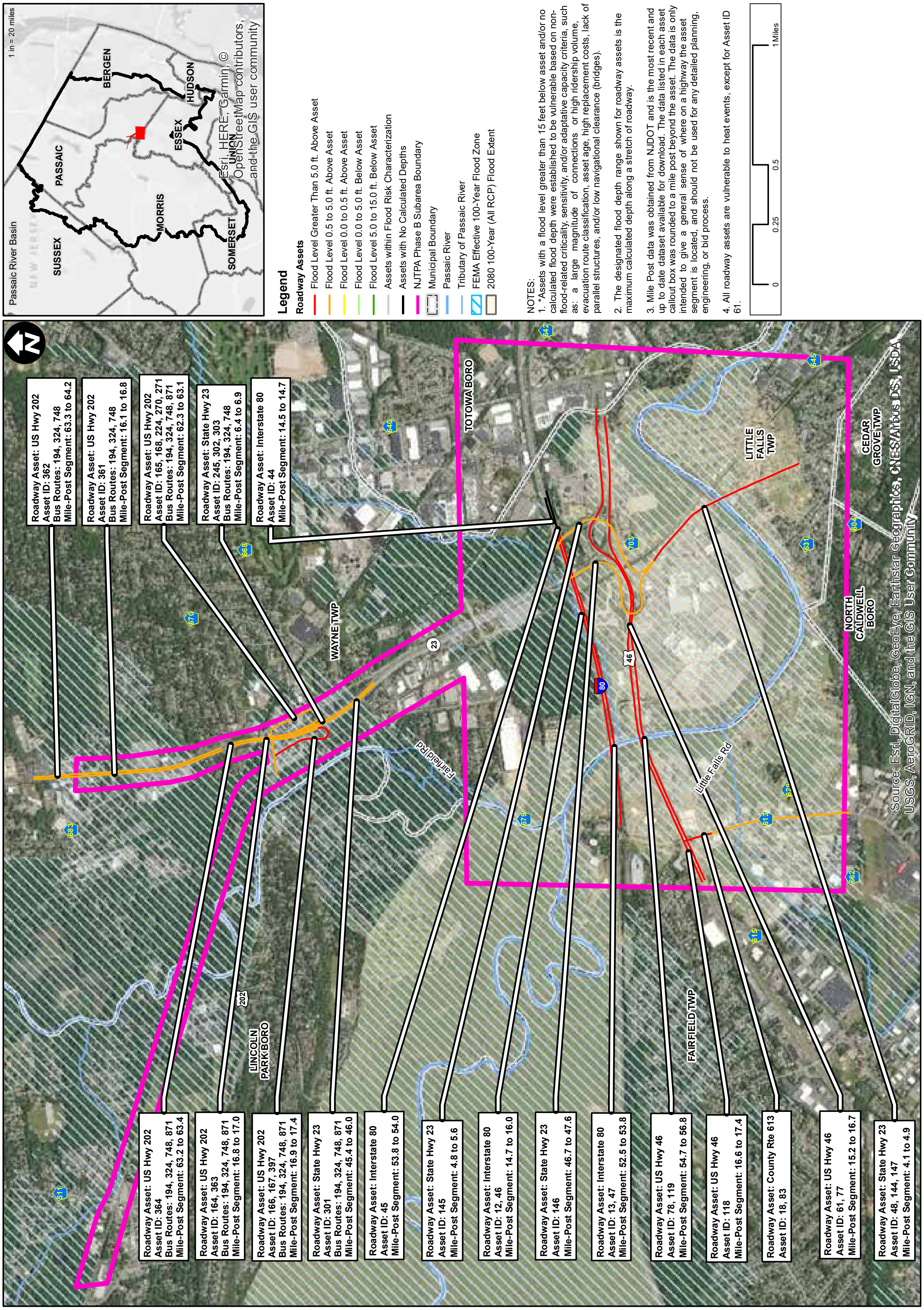


Figure 46. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Rail and Facility Assets

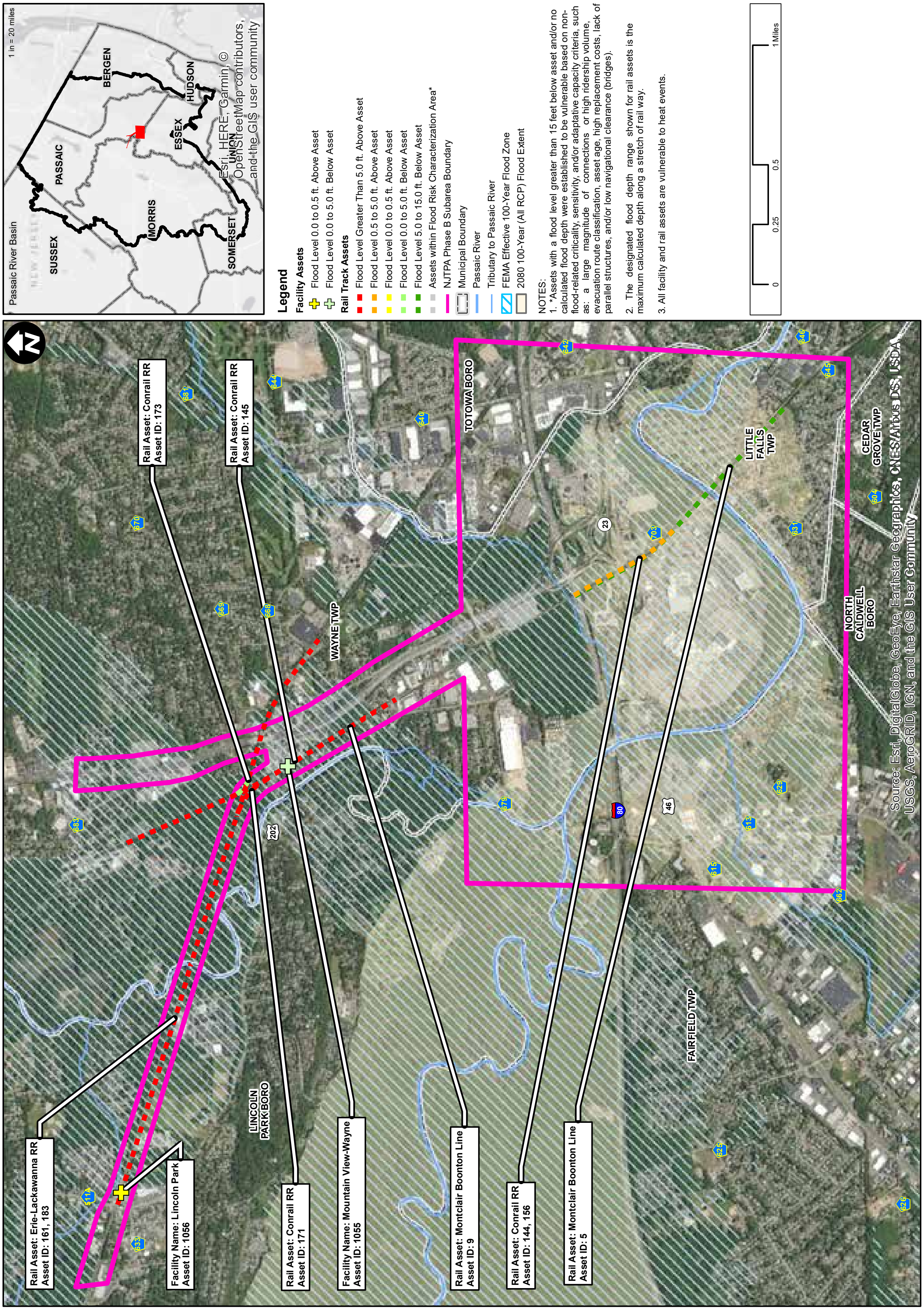
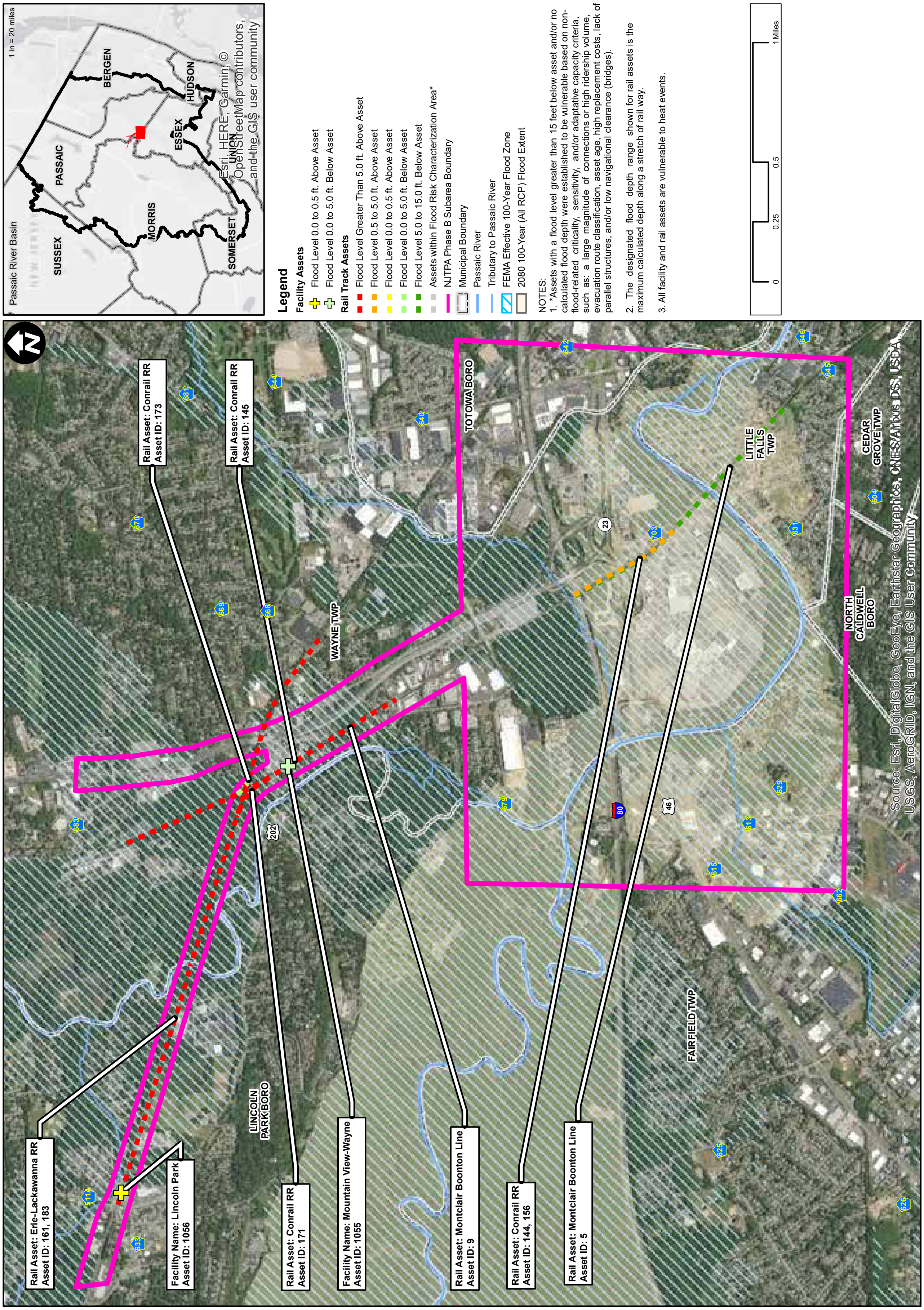


Figure 47. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Rail and Facility Assets



Subarea C: River Road/Route 21 Corridor

Location

Based on feedback provided by the TAC, two proposed subareas in Bergen, Essex, and Passaic Counties were shifted and combined into one subarea (Subarea C) to capture high ridership bus routes. River Road/Route 21 Corridor is located along the Passaic River, from the border of Essex and Passaic Counties to the south and from the intersection of Interstate 80 and Route 21 to the north. Subarea C contains portions of 10 municipalities in Bergen, Essex, and Passaic Counties: Clifton City, Borough of East Rutherford, Borough of Elmwood Park, Garfield City, Lyndhurst Township, Nutley Township, Passaic City, Paterson City, Borough of Rutherford, and Borough of Wallington. Municipalities in Passaic County are identified as high-population growth areas. Route 21 is the defining feature of the subarea and an important north-south arterial highway connecting Passaic and Bergen Counties with other major regional highways and the City of Newark (a major center of employment and transportation node). Other vital, regional highways within the subarea include Interstate 80; Garden State Parkway; and Routes 3, 7, 20, and 46. The subarea transportation network contains connection to critical destinations (employment hubs south and west in the cities of Newark, Clifton, and Paterson and east in New York City); provides evacuation routes and access to critical emergency facilities and services used by vulnerable populations; and includes 2018 TIP-funded projects. These roadways have been identified as having both unreliable travel times and extreme delays. Subarea C and transportation assets that were determined to be highly vulnerable to future severe climate events are shown in **Figures 48** through **55**.

History of Flooding and Climate Scenario Summary

The project team interviewed county stakeholders and reviewed county hazard mitigations plans to understand the impact historical flooding has had on the transportation assets in the region. The location of assets determined to be vulnerable to flooding impacts fell within the existing and future flood inundation extents modeled for the study. Passaic County stakeholders have identified all the major highways in the region as having experienced some flooding event in the past. They identified all the bridges crossing the Passaic River in Paterson (within the subarea) as becoming inundated during major flood events, creating an island out of the city and making evacuation difficult. They also identified portions of the Passaic River south of the Dundee Dam as having experienced heavy impact from both fluvial and tidal flood events in the past. Low-lying areas along 8th Street in Passaic City were identified in detail by the Passaic County HMP. According to the Passaic HMP, flooding is known to occur near the most northern terminus of the subarea where Interstate 80 intersects the Passaic River. Additionally, both the Passaic County and Essex County HMPs referenced frequent flooding as occurring along the Third River, a tributary of the Passaic River that flows through the most southern portion of Clifton and northern portion of Nutley. The Essex County HMP also references River Road in Nutley as being subject to frequent flooding during heavy rain events.

Figures 48 through **55** presents flood level ranges for the 100-year flood event in the 2045 and 2080 planning horizons modeled to occur for Subarea C transportation assets. Flood level ranges modeled at each asset (including bridges, culverts, roadways, railways, and facilities) were the same for the 2045 and 2080 planning horizons, with the following exceptions:

- Near the Route 21 overpass over Monroe Street in Passaic, New Jersey (roadway Asset IDs 24 and 25). The flood level range in 2045 is 5.0 to 15.0 below the asset and in 2080 is 0.0 to 5.0 feet below the asset.

This change in flood elevation between the two planning horizons indicates a likely increase in flooding impacts in this area.

The portions of Subarea C that are identified to have a flood level greater than 5.0 feet above assets under the future 100-year flood event are primarily located on/near roadway crossings of the Passaic River along the Routes 20 and 21 (Mclean Boulevard) and River Road corridors, including on/near Route 80 (Christopher Columbus Highway), Route 46, and the Garden State Parkway river crossings. In addition, segments of Mclean Boulevard identified to have a flood level greater than 5.0 feet above the roadway are at the conjunction of Route 46 and Route 21, and approximately from the end of Slate Street to Washington Place in the City of Paterson.

Culverts identified to have a flood level greater than 5.0 feet above assets are located at:

- Monroe Street in the vicinity of the Route 21 overpass and 1st Street directly south of Monroe Street in the City of Passaic
- County Road 624 (River Road) under Route 21 overpass in the City of Paterson
- Third River beneath Route 3 in Clifton, New Jersey. Recent construction of the Route 3 corridor in this area may have included repair/rehabilitation of this culvert

Most railway evaluated in Subarea C was identified to have flood levels greater than 5.0 feet above the rail under the 100-year flood event. These include the New York Susquehanna and Western Railway, NJ Transit Main Line, Bergen County Line and Port Jervis Line, Earie-Lackawanna Railroad, and Conrail Railroad. Mobility at these areas will likely be affected during extreme flood events.

In addition, transportation assets within the selected subarea are vulnerable to an extreme heat event. All roadway assets are vulnerable to extreme heat. A total of 14 bridges were identified to be highly vulnerable to an extreme heat event, as shown on **Figures 48** and **49**. Of these 14 bridges, only two were determined to be vulnerable to flood levels ranging 0.5 to 5.0 feet above the asset and one bridge is vulnerable to flood levels greater than 5.0 feet above the asset. These bridge locations are:

- Vulnerable to flood levels 0.5 to 5.0 feet above the asset
  - Interstate 80 ramp ID A crossing an access road (Asst ID 0225150)
  - Route 21 ramp IDs 3, 5, and 7 (Asset ID 1603154)
- Vulnerable to flood levels greater than 5.0 feet above the asset
  - Garden State Parkway/Route 46/River Road ramps and connections adjacent to the Passaic River at Dundee Lake (Asset ID 361582T)

A summary of the highly vulnerable and critical assets for Subarea C is presented in **Appendix L, Assigned Adaptation Strategies and Associated Costs for the Benefit Cost Analysis**.

Adaption Strategies for Highly Vulnerable and Critical Assets

Subarea C has transportation assets that were determined to be vulnerable to heat and flooding events; these were evaluated for potential adaptation strategies to reduce vulnerability. They include 74 road segments along 7 roads and 12 bus lines, 38 bridges, 4 culverts, and 5 rail segments and associated rolling stock along 3 different rail lines. A summary of the applicable adaptation strategies for highly vulnerable and critical assets in Subarea C is summarized in Subarea Recommended Adaptation Strategies Subsection and presented in **Appendix L, Assigned Adaptation Strategies and Associated Costs for the Benefit Cost Analysis**.

Adaptation Strategy Implementation Considerations

This subarea includes mixed-use development, including residential, industrial, and commercial. The area west of the Passaic River includes environmental justice communities that heavily rely on bus lines to access businesses located along highways and to commute to nearby cities, including Newark, Hoboken, and New York City. The area south of the Dundee Dam needs to consider sea level rise and storm surge during adaptation strategy implementation since this area of the Passaic River is tidally influenced. Storm surge could create additional backflow if culvert sizes are increased. Rehabilitation and other types of stormwater management improvements performed along the riverbank and in-water at this part of the Passaic River could present toxicity and environmental concerns due to nearby industry and segments of the Passaic River designated as Superfund sites. Intrusive activities, such as excavation, may require a hazardous waste management plan and other NJDEP and EPA requirements.

Figure 48. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Bridge Assets

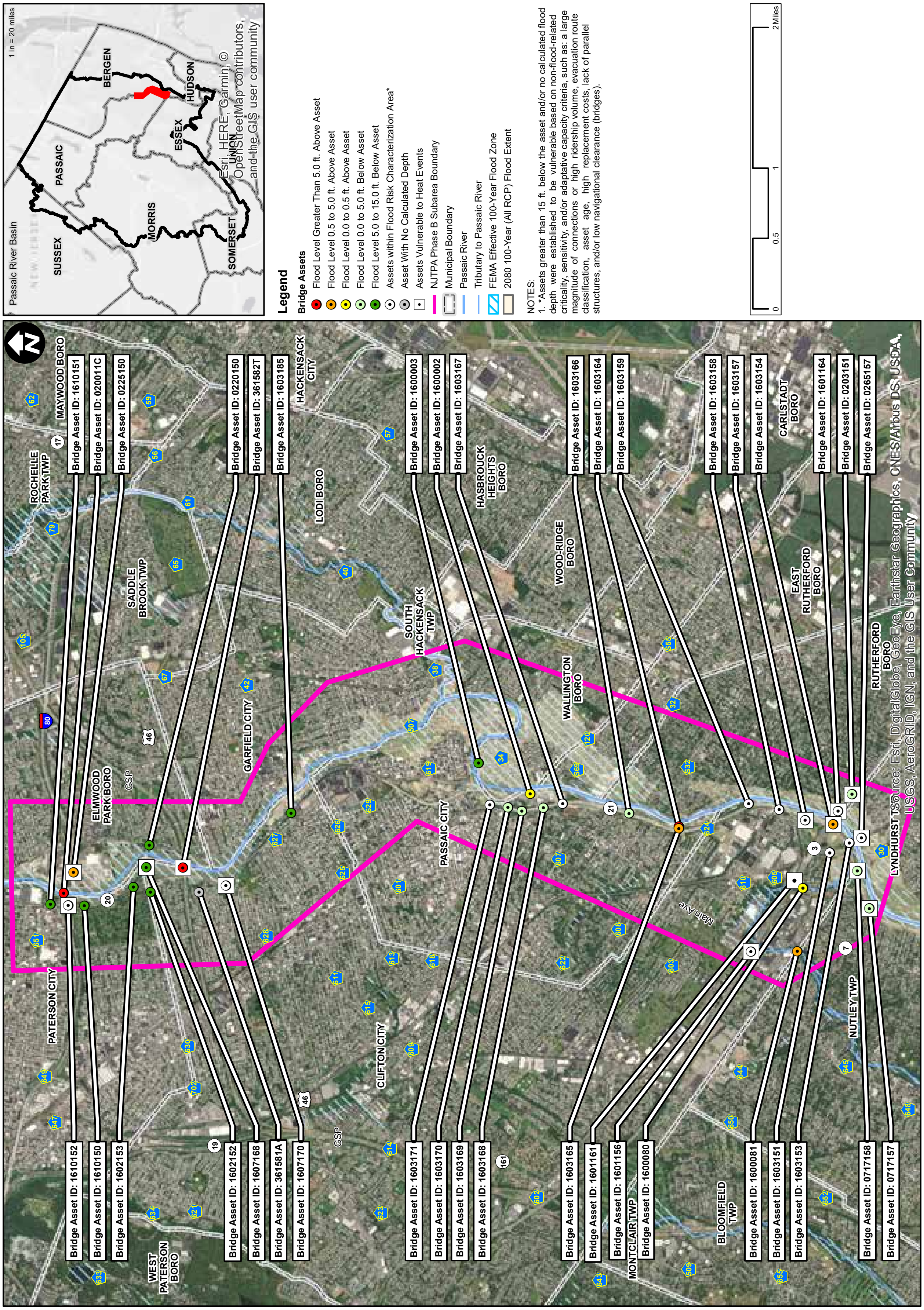


Figure 49. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Bridge Assets

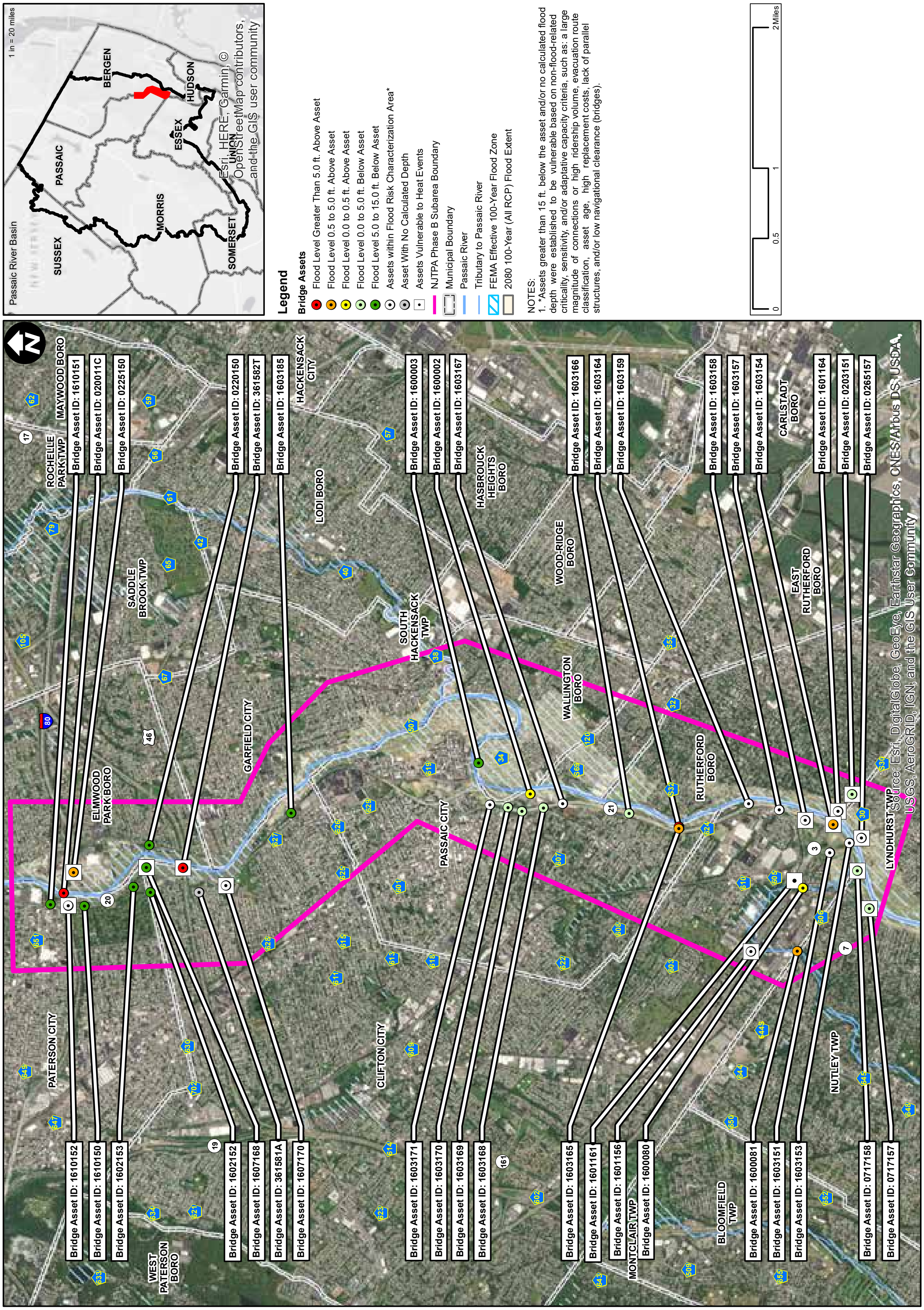


Figure 50. Vulnerable Assets to 2045 100-Year (All RCP) Flood Events: Culvert Assets

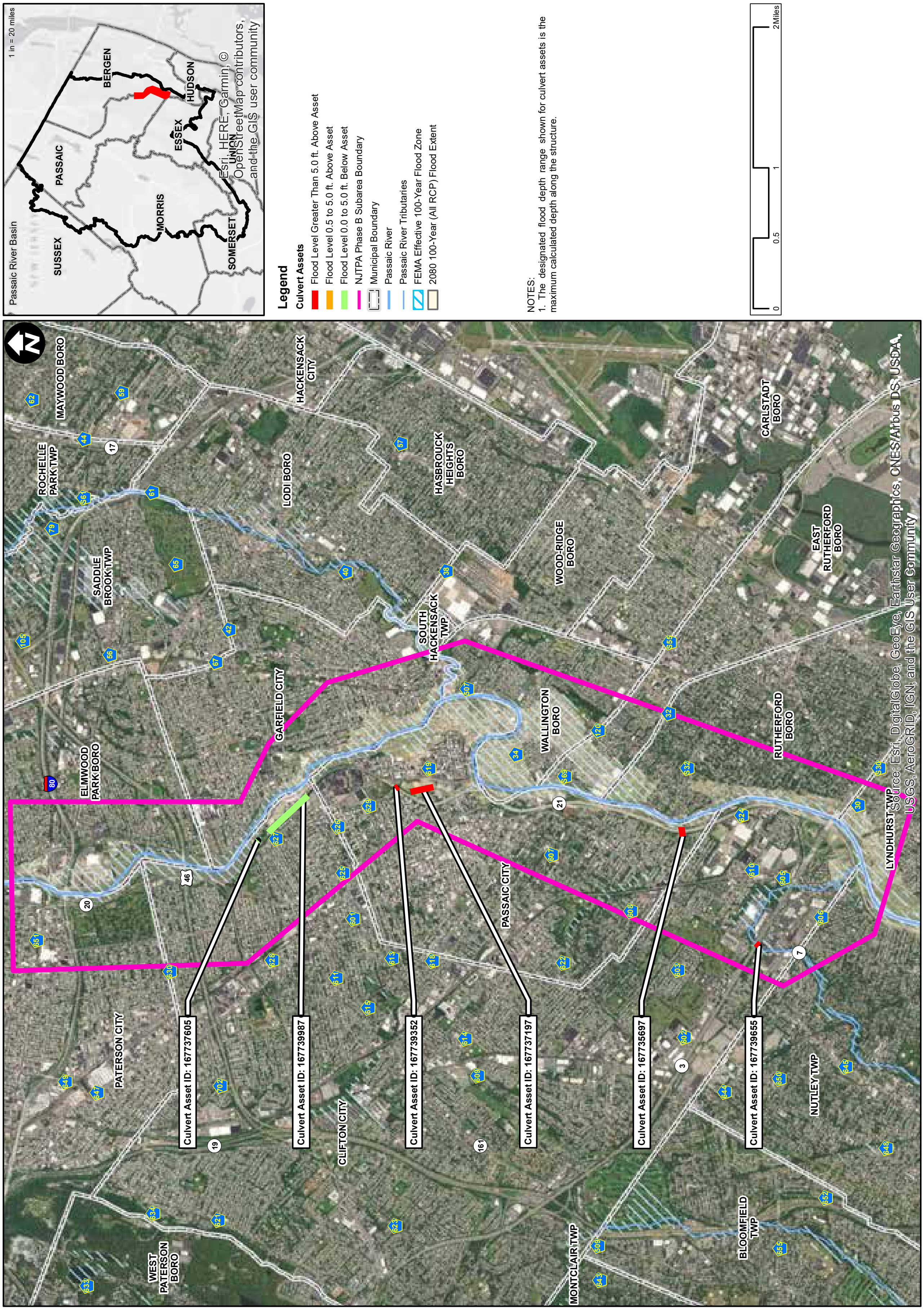


Figure 51. Vulnerable Assets to 2080 100-Year (All RCP) Flood Events: Culvert Assets

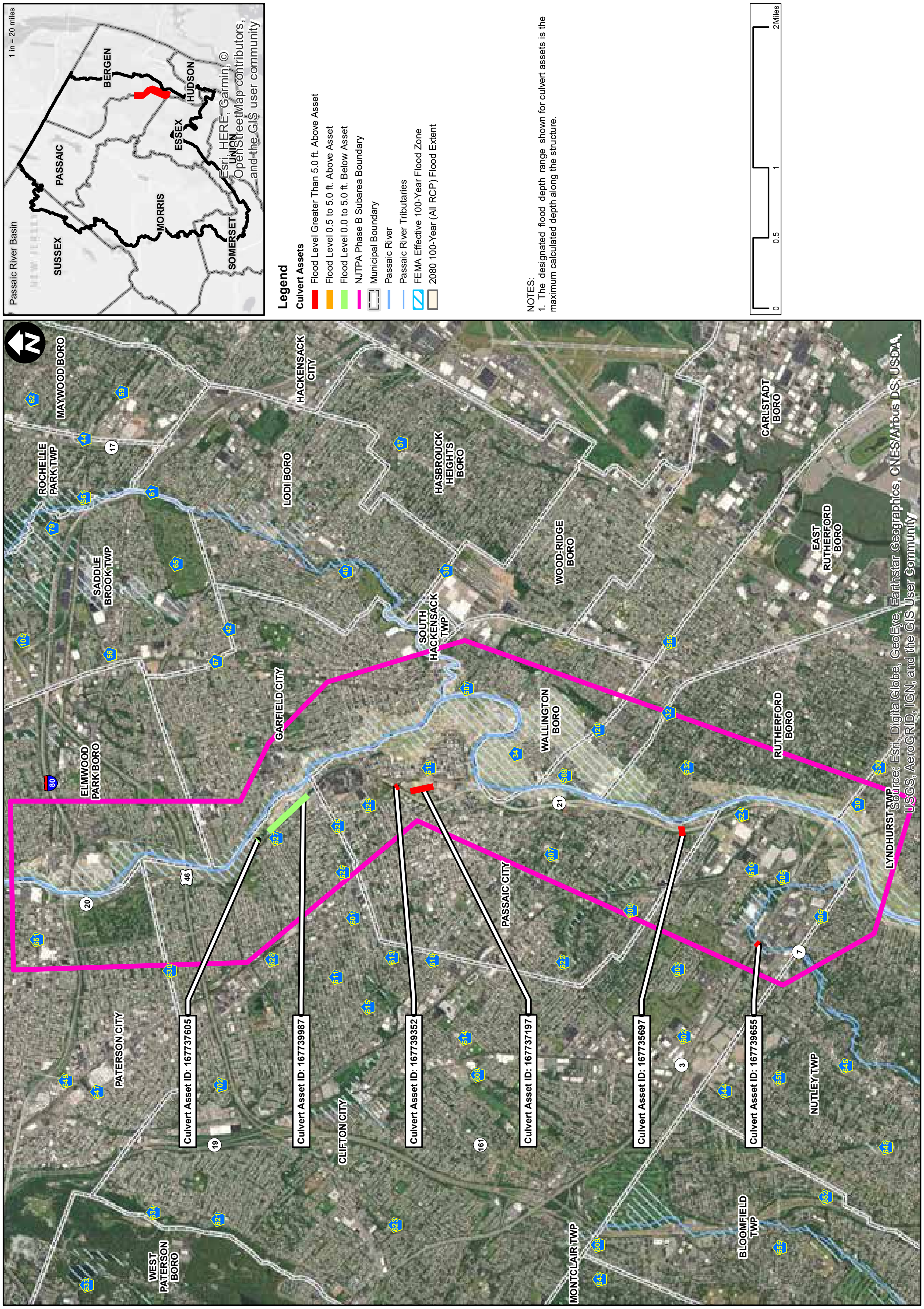


Figure 52. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Roadway Assets

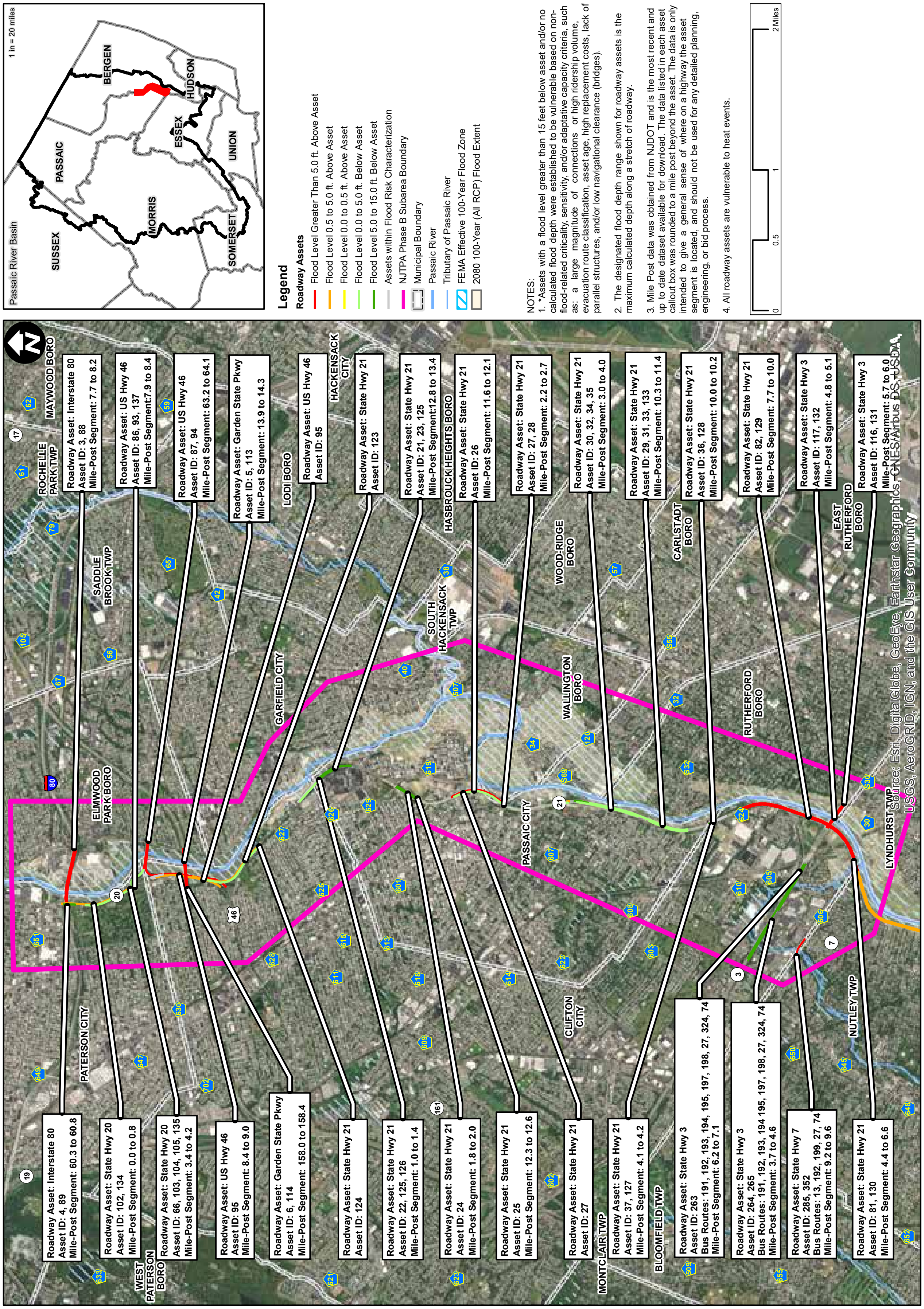


Figure 53. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Roadway Assets

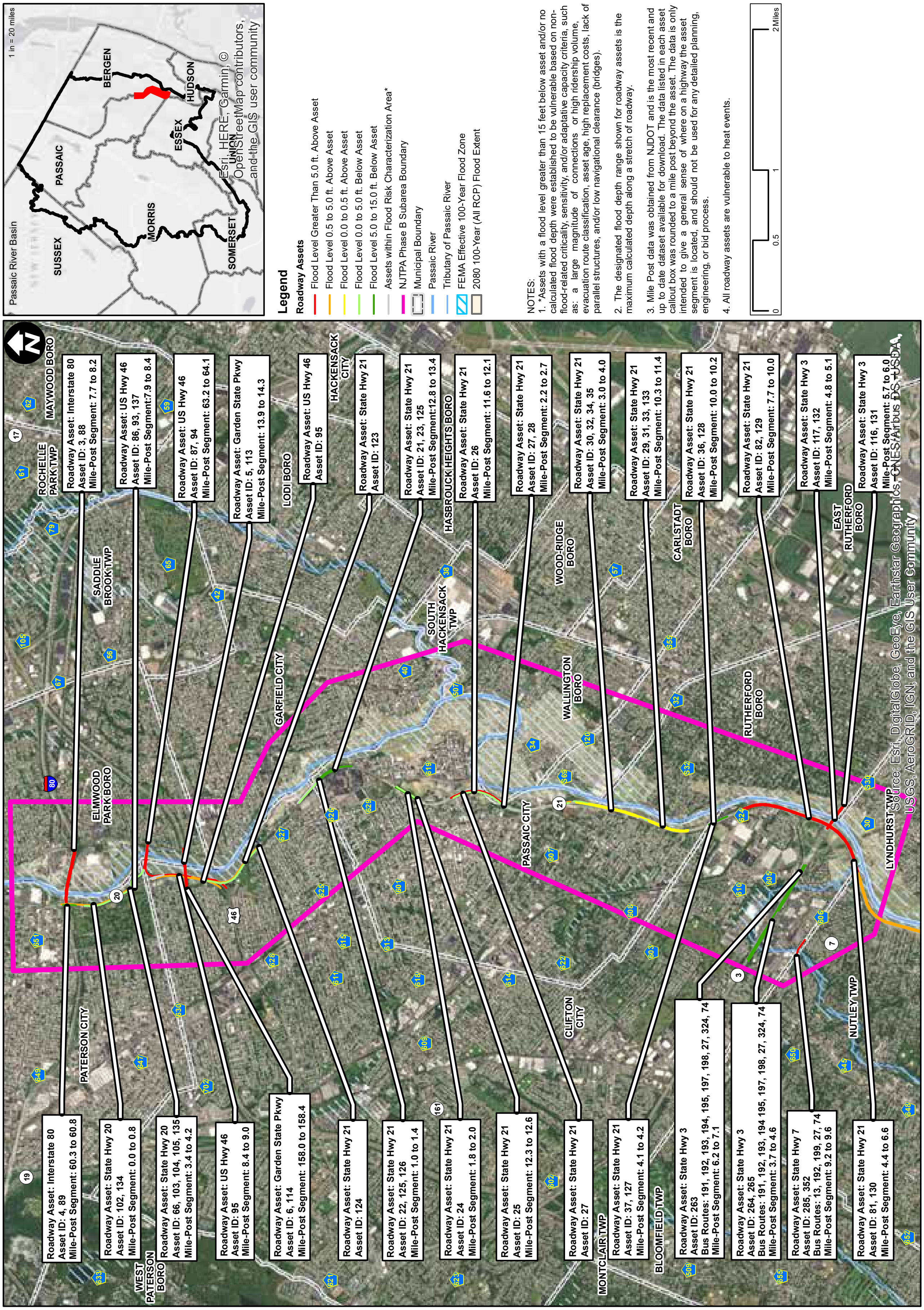


Figure 54. Vulnerable Assets to 2045 100-Year (All RCP) Flood & Heat Events: Rail Assets

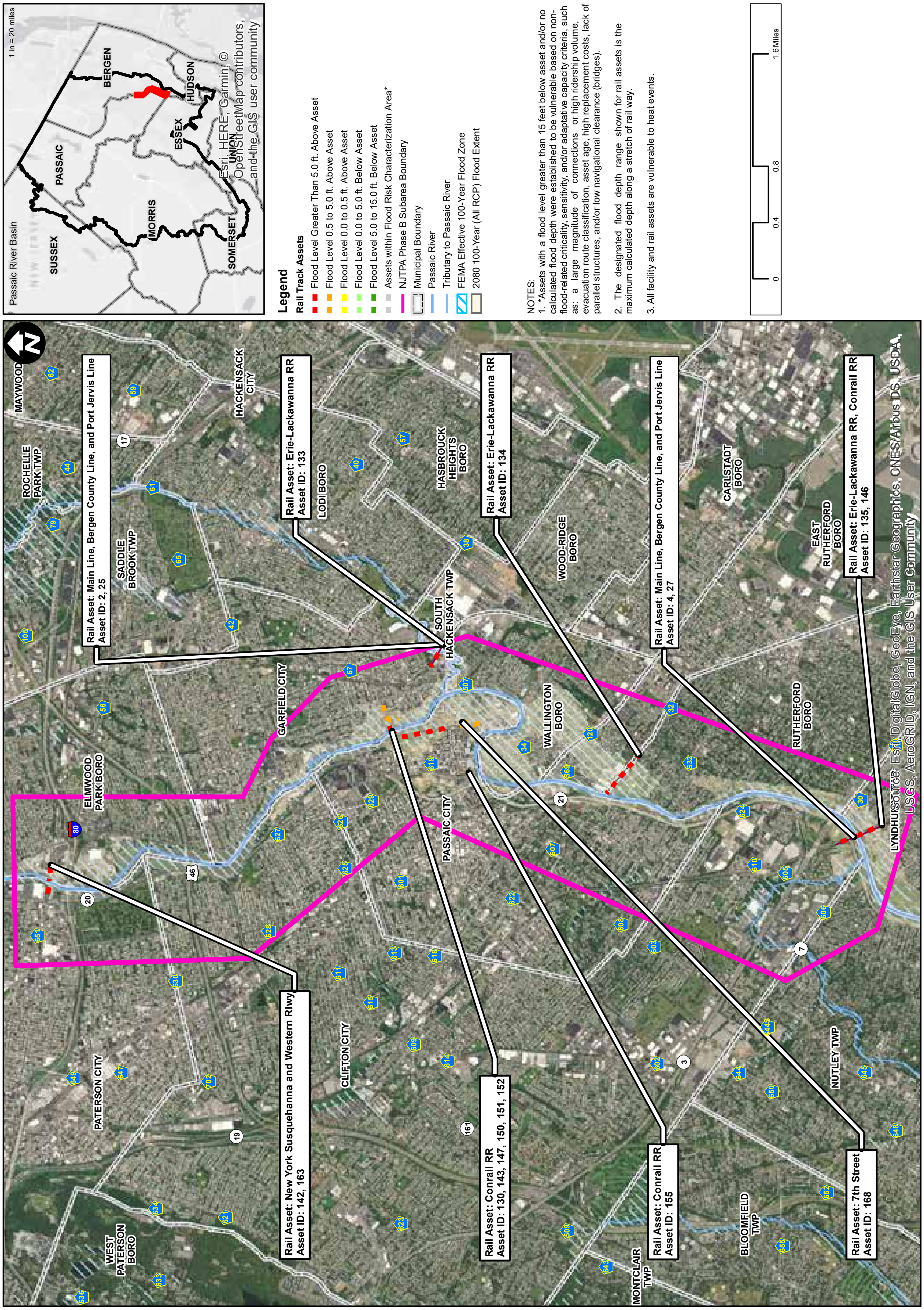


Figure 55. Vulnerable Assets to 2080 100-Year (All RCP) Flood & Heat Events: Rail Assets

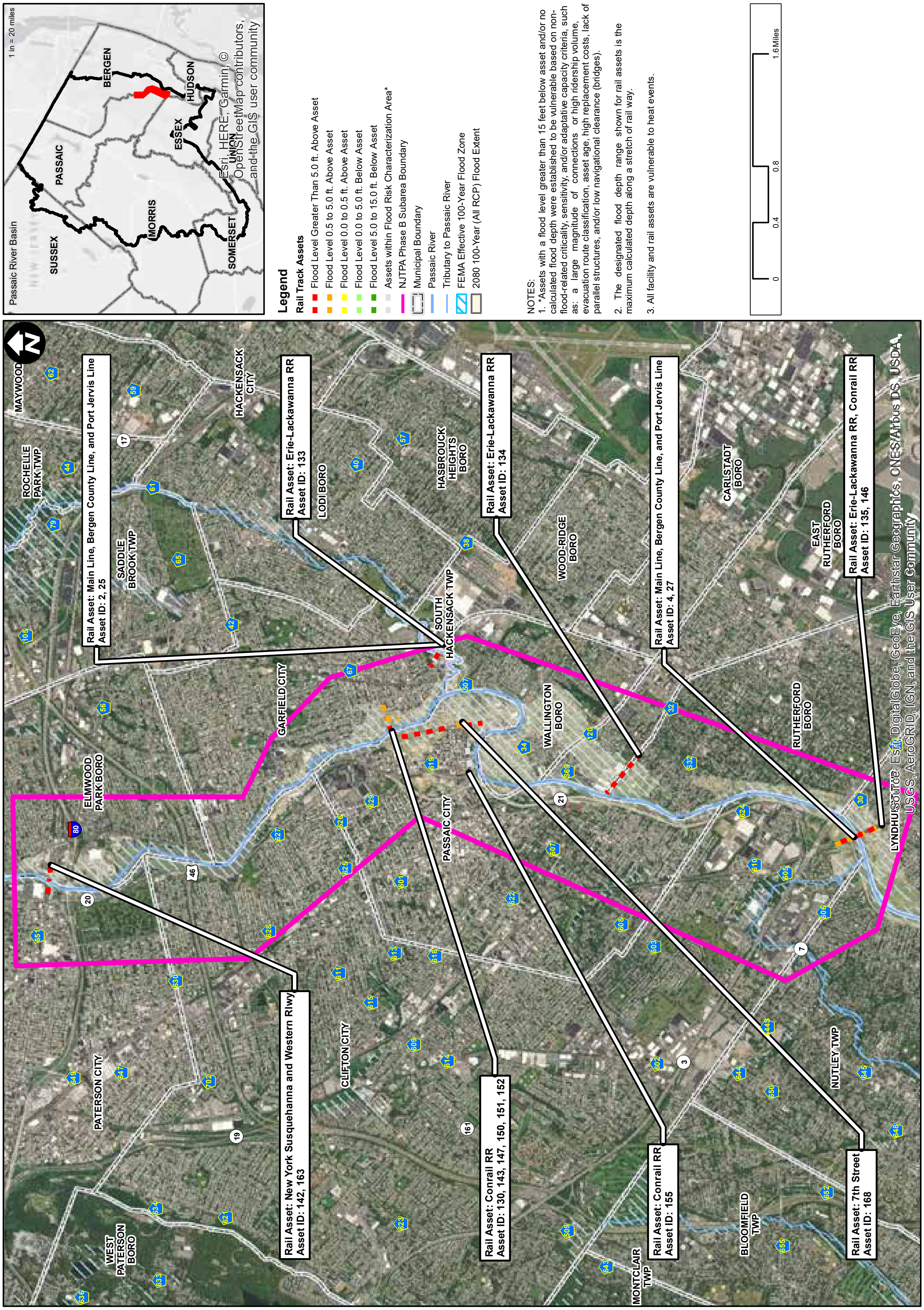


Table 13. Subarea Recommended Adaptation Strategies

Asset	Flood Vulnerability	Heat Vulnerability
Bridges	• FD1: Protect bridge piers and abutments with riprap. • FD2: Alter, upgrade, or retrofit bridge movement system (e.g., bearings) to prevent excessive lateral or vertical displacement due to buoyancy forces or water pressure. • FD4: Monitor bridge for scour and other conditions that could undermine a bridge's structural integrity during a flooding event. • FD11: Conduct regular maintenance and restore infrastructure that was previously impacted from flooding events.	• TE5: Increase seat lengths of expansion joints and/or the range of finger joints in bridges. • TE6: Monitor for temperatures of assets and heat-related impacts by installing sensor systems
Roads	• SW8: Increase capacity of stormwater infrastructure and drainage system • SW11: Upgrade bridge deck and road drainage systems to manage a higher capacity of stormwater. • FD6: Ensure roadway and rail tracks are clear of rocks, debris, and downed vegetation. • FD8: Use new asphalt/concrete mixtures able to withstand flood conditions. • FD10: Improve temporary and permanent erosion control standards of construction sites. • FD11: Conduct regular maintenance and restore infrastructure that was previously impacted from flooding events. • FP10: Construct and raise protective dikes, bulkheads, berms, and levees, including tide gates as necessary. • FP15: Install sensor systems along or within assets to monitor for water level and changing conditions.	• HR3: Use heat-resistant materials, including heat-resistant asphalt, concrete, or painted roadways. • HR4: Overlay roads with new or more rut-resistant asphalt. • HR6: Plant trees to shade assets; plant locations to be balanced against safety protocols. It is proposed that this strategy is applied to 10 percent of the roadway length. • SF3: Incorporate redundant power and communication lines and systems. • TE6: Monitor for temperatures of assets and heat-related impacts by installing sensor systems.
Culverts	• SW10: Enlarge culverts to increase the capacity. • SW12: Replace culverts with bridges.	—
Rail	• SW8: Increase capacity of stormwater infrastructure and drainage system • SW11: Upgrade bridge deck and road drainage systems to manage a higher capacity of stormwater. • FP10: Construct and raise protective dikes, bulkheads, berms, and levees, including tide gates as necessary. • FP15: Install sensor systems along or within assets to monitor for water level and changing conditions. • FD6: Ensure roadway and rail tracks are clear of rocks, debris, and downed vegetation. • FD10: Improve temporary and permanent erosion control standards of construction sites. • FD11: Conduct regular maintenance and restore infrastructure that was previously impacted from flooding events.	• HR6: Plant trees to shade assets; plant locations to be balanced against safety protocols. It is proposed that this strategy is applied to 10 percent of the roadway length. • SF3: Incorporate redundant power and communication lines and systems. • TE1: Design rail for higher maximum temperatures in replacement or new rail infrastructure. • TE2: Lower speeds and use shorter trains to shorten braking distance and to allow for lighter loads to reduce track stress in extreme heat events. • TE6: Monitor for temperatures of assets and heat-related impacts by installing sensor systems.
Facilities	• FP5: Incorporate wet flood-proofing: install flood openings and water-resistant materials to allow building to withstand some exposure to floodwaters and the associated loads/pressures. • FP8: Elevate critical mechanical and electrical equipment. • FP15: Install sensor systems along or within assets to monitor for water level and changing conditions.	• TE6: Monitor for temperatures of assets and heat-related impacts by installing sensor systems.
PRB Basinwide	• FD5: Use of vegetation or earthwork to stabilize river and stream embankments and provide riverine buffers (along the entire length of the Passaic River and tributaries). • SW1: Construct stormwater retention basins • SW2: Install internal drainage system using basins and sump pumps. • SW3: Install green infrastructure: bioretention ponds, bioswales, and rain gardens (especially for the more urban). • SW4: Install green infrastructure: pervious pavements. • FP9: Protect and restore wetlands to protect infrastructure (for coastally influenced parts of the river). • FP10: Construct and raise protective dikes, bulkheads, berms, and levees, including tide gates as necessary (for coastally influenced parts of the river).	—

Sketch-level Benefit Cost Analysis

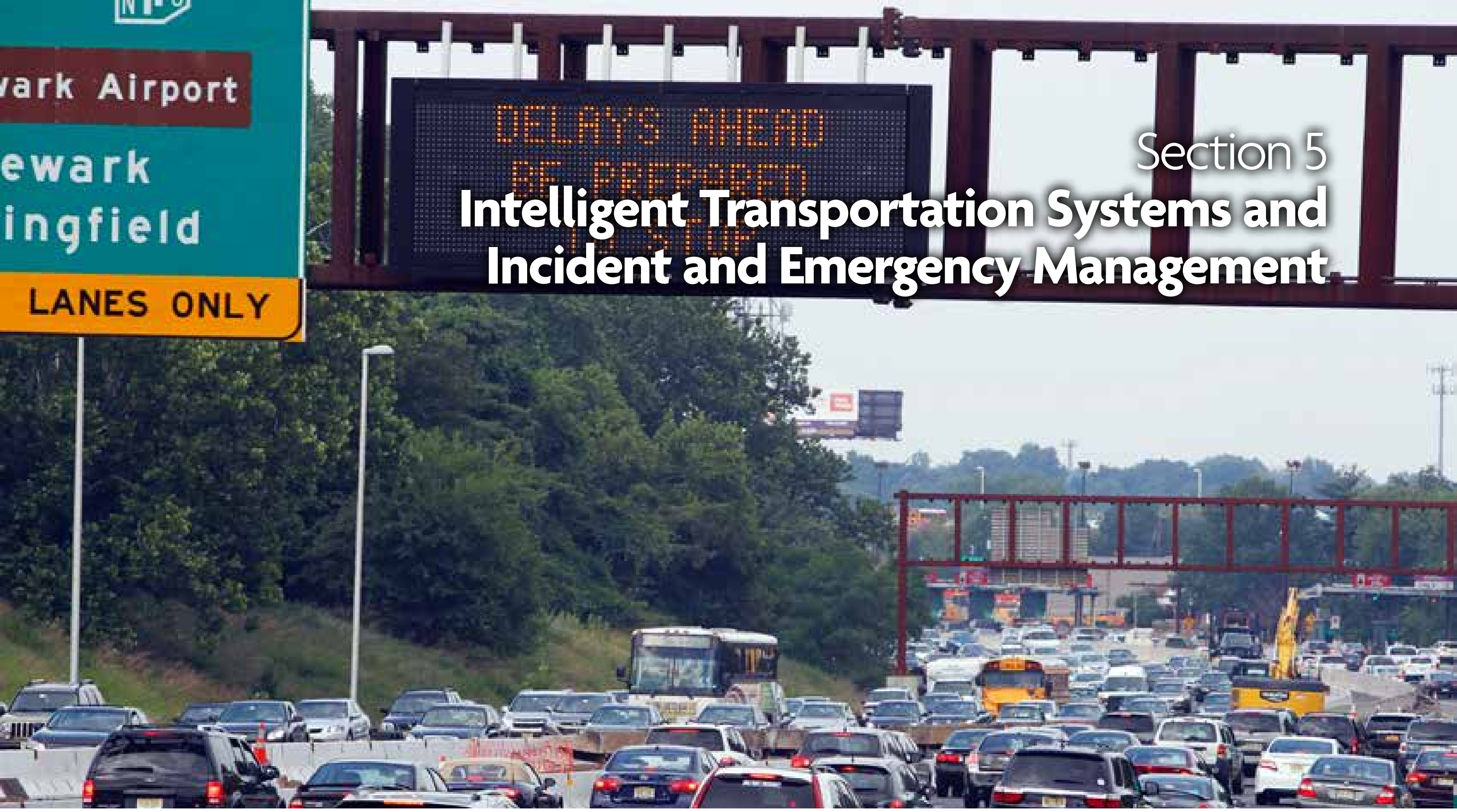
A single-run of a sketch-level BCA was conducted that compares the costs to implement the recommended adaptation strategies for the assets in each subarea to the economic benefits (details in **Appendices K** and **L**). In general, a BCA is not the sole basis of the decision-making process but plays a supporting role to assist in investments decisions and is a useful tool to compare a few strategies to each other. It is not uncommon for public spending to be based on the need to protect the health and safety of the public or to improve the economy without the expectation that there will be an economic payback. This BCA approach follows USDOT procedures and guidelines. The guidelines outline how to evaluate improvement scenarios, address implementation costs, and quantify cost-saving benefits. Of these tasks, the quantification of benefits is typically the most challenging. As such, USDOT outlines what can be included in the calculation and how to quantify monetary values (time, vehicle operating cost, accidents, emissions).

This BCA considers the infrastructure life cycle and evaluates how the proposed adaptation strategies mitigate impacts on transportation assets that would otherwise incur costly damages and/or disrupt travel as a result of a severe climate event. Implementing adaptation strategies comprises two implementation costs: initial construction and subsequent O&M. Resultant cost-savings comprise two types of benefits: agency cost savings (or benefits) and transport users' benefits (such as avoided accidents or reduced travel time). This sketch-level BCA only compares two scenarios for each of the three subareas:

- Do-Nothing Scenario – reflects conditions in which no adaptation strategies are implemented and an extreme climate event disrupts vulnerable assets. Under this scenario, it is assumed that transportation assets are damaged or destroyed, warranting repair or replacement, and is unavailable for public use.
- Build Scenario – represents implementation of all assigned adaptation strategies within each subarea that would avoid transportation asset damages and travel disruptions.

The results of the sketch-level BCA indicate that it is not economically prudent to implement the comprehensive package of adaptation strategies across the array of assets for any of the three subareas. However, this BCA had a limited scope, and should not be the determinant factor regarding further development of any of the adaptation strategies. Ideally, additional BCA iterations will be conducted based on the work presented in **Appendix L**. Additional benefits, and examples of these benefits, beyond the purview of this study that may be considered in a future BCA include:

- Health and safety benefits – protecting the public from harm of a climate event, providing access to emergency services after an event
- Property value benefits – proximity to green spaces, flood mitigation on private properties
- Environmental benefits – cleaner surface water as a result of green infrastructure, less noise due to a berm or flood wall
- Quality of life – access to amenities, reduced traffic delays due to infrastructure repairs
- Regional economy benefits – improving movement of freight, creating construction and long-term employment to maintain new infrastructure



Section 5
Intelligent Transportation Systems and Incident and Emergency Management

Introduction

One of the adaptation strategies identified and evaluated in more detail as part of this study is the upgrading of emergency communication systems and Intelligent Transportation Systems (ITS). ITS technologies improve transportation safety, mobility, and operations and includes applications that collect, process, and communicate data to ease congestion, improve traffic management, make roads safer, and enhance driver mobility.

Incident and Emergency Management (I&EM) is an organized, planned, and coordinated effort to detect and respond quickly to incidents and restore the affected infrastructure to its capacity. All operating agencies occasionally are required to address an emergency situation. To be effective, I&EM will involve communities, agencies, and human and material resources, including ITS. ITS technologies improve emergency management by providing transportation and public safety agencies with the ability to communicate and coordinate operations and resources in real-time.

ITS supports the data collection required for effective coordination of changing transportation system conditions and allows for the real-time implementation of operational and logistical strategies with other agencies and transportation partners. It also provides voice, data, and video communications that allow agencies to share information on the status of an emergency, operational conditions of transportation facilities, and location of emergency response resources.

Traveler Information & Traffic Management during Weather Events

ITS assets, such as dynamic message signs, portable changeable message signs, camera surveillance systems, and controlled traffic signals, are used to improve traffic operations and safety, including during flood events. As part of the Road Weather Management Program, FHWA reviewed strategies used by transportation authorities in anticipation of or in response to severe weather conditions. FHWA identified the most common strategies used for traffic management during flood events—active warning systems, traveler information, and traffic management and control.

Active Warning Systems

Active warning systems are designed to warn drivers of unsafe travel conditions through a section of roadway. For example, the Oregon DOT installed a flood warning system on Highway 101. The system comprises a level sensor at the low point in the road connected to a series of static warning signs with beacons on top of the signs. The flashing beacons are activated when flood conditions are imminent. The system transmits water level data to Oregon DOT district offices so that maintenance personnel can respond when conditions warrant. As part of this study, a flood warning system managed by a NJ transportation authority was not identified.

Traveler Information

Pretrip Road Information

Pretrip road information disseminates information about current and forecasted weather and pavement conditions to travelers before they initiate their trip. This information informs and influences travelers' choice of travel mode, departure time, or route.

Dynamic Road Information

Dynamic road information gives travelers real-time information and alerts about existing or developing weather and pavement conditions. The messages change dynamically to reflect current or forecasted conditions. The information is typically communicated through dynamic message signs, highway advisory radio, text alerts, or in-vehicle displays.

Traffic Management and Control

Lane or Road Closures

Lane and road closure information involves limiting vehicle access to specific sections of roadway; access can be restricted to specific structures (such as bridges or causeways), passes, or entire sections of roadway.

Contraflow/Reversible Lane Operations

Contraflow/reversible lane operations involve operating sections of highway as a contraflow or reversible lane facility. Traffic is temporarily directed to travel in the direction opposite the normal flow. These operations are generally reserved for large-scale evacuations and where a large volume of traffic needs to be cleared from an area in a short time.

Signal Timing

Signal timing involves designing new signal timing coordination plans to improve progression and account for reductions in travel speeds during inclement weather conditions. Timing plans can be implemented by operators in a control center or automatically, based on field measurements of weather conditions.

Ramp Metering

Ramp metering uses special timing plans to account for lost freeway capacity, slow travel speeds, and increased start-up time at ramp control signals. Strategies include limiting traffic flow entering the freeway or increasing ramp capacities during inclement weather.

Variable Speed Limits

Variable speed limits set new speed limits or speed restrictions in response to weather conditions, typically through variable speed advisory signs displayed on dynamic messaging signs.

Intelligent Transportation Systems Assets

NJDOT began installing ITS systems on interstates, freeways, and state highways in 1992. In 2004, NJDOT established a shared, high-speed, redundant fiber connection network (Dense Wave) with the New Jersey Turnpike Authority (NJTA), which provides IT networking and shared services with other agencies.

NJDOT has two high-tech traffic operations centers that use ITS infrastructure to manage the flow of traffic on highways and coordinate responses to traffic incidents. Combined they are the focus for all transportation operations in the state:

1. Central Dispatch Unit co-located in 2004 with the New Jersey State Police and NJDEP to assist the traffic operations centers in coordinating work assignments to respond to incidents; and
2. NJ Statewide Traffic Management Center, in Woodbridge, NJ, which provides a seamless transportation system through a 24/7 operations center jointly operated by NJDOT, NJTA, and New Jersey State Police.

Within these operations centers, the agencies share a common command floor to facilitate an expeditious and comprehensive response to situations that may impede the free flow of traffic. One center manages coverage in the southern half of the state. Counties situated within the Passaic River Basin, including Bergen, Essex, Hudson, Hunterdon, Middlesex, Morris, Passaic, Somerset, Sussex, Union, and Warren, are provided coverage by the other center.

Responsibilities of the traffic operations centers include:

- Monitoring and operating NJDOT's ITS technology, including traffic cameras, dynamic messaging signs, and computerized traffic signals and participating with the New Jersey State Police in activating Amber Alert and Silver Alert programs.
- Managing the flow of traffic on the highways and providing coordinated response for traffic incidents statewide through detection, verification, response, and recovery.

Incident and related travel time notifications are available on the 511 website, www.511NJ.org, which was designed to complement the 511NJ telephone service. It provides an easy, user-friendly way for commuters to see where incidents, accidents, congestion, and events like weather and construction are happening before they leave their workplace or home.

The Road Weather Information System (RWIS) is a network of meteorological and pavement sensors located along the highway system. RWIS stations are typically located in locations strategic to the owning agency. They are commonly placed at or near high-value bridges and sections of highway with known weather issues and, because they are costly, are spread geographically to cover large portions of the agency's jurisdiction. RWIS provide real-time road pavement and weather information and critical observations for forecasts. NJDOT maintains the RWIS.

An optimization opportunity for RWIS is integration of rain gages and flood monitoring systems. NJDEP maintains a website on rainfall data acquisition, which makes available for download data obtained from the National Weather Service (NWS) Multisensor Precipitation Estimator. Multisensor Precipitation Estimator technology uses a combination of rain gages and radar to estimate rainfall totals in near real-time for a 2.5-mile grid area. During storm events, users can access the latest rain total estimates every 30 minutes after the hour. NJDOT and NJDEP have the opportunity to collaborate and share gauge data to be better informed on asset vulnerability and aid in identification of applicable adaptation strategies.

- **Dynamic messaging signs**, both permanent and portable, are vital components of ITS in communicating with motorists on the road. These signs provide the traveling public with warnings pertaining to traffic congestion, crashes, incidents, construction, and speed restrictions.
- **511NJ** is a free phone and web service that consolidates traffic and transportation information into a one-stop resource for commuters and motorists in New Jersey. 511NJ provides motorists information about accidents, incidents, and unusual delays on New Jersey interstates and state highways, New Jersey Turnpike, Garden State Parkway, Atlantic City Expressway, and bridge and tunnel crossings. It offers real-time traffic and travel information 7 days a week, 365 days a year. In addition, 511NJ broadcasts Amber Alerts and other emergency messages. TRANSCOM operates and maintains the 511 system for New Jersey.

Stakeholder Interviews

Together with NJTPA, CDM Smith identified key agencies and conducted interviews with emergency management personnel. The interviews focused on ITS, incident management, and emergency management in the region. Interviews were conducted by phone in September and October 2018 and January 2019. The interviews are summarized below.

Bergen County

The Bergen County OEM role in flood events is primarily organizational—facilitating coordination between agencies. Municipal police and fire agencies are first responders to flood events, along with NJDOT, for flooding on the interstate. NJDOT and local police handle large events, with local police departments and the county's sheriff office having a major role.

In Bergen County, representatives mentioned that the county has a robust trunked radio system and does not believe communications during flood events are an issue. Approximately 13 of the roughly 70 municipalities in Bergen County have their emergency response personnel dispatched through the county's dispatch system; there are some interoperability problems with the radio system in a few towns. Bergen County's OEM owns dynamic messaging systems, cameras, and portable changeable message signs, which it loans to municipalities. The county acquired some camera trailers that can be moved around.

The main problem the county faces is getting people to evacuate in advance of the floods. The county has an automated telephone system that provides alerts to homes in areas anticipated to flood, and it uses social media (Facebook, Twitter) to post alerts. Possible contributions to the lack of compliance to evacuate include previous false alarm alerts.

Morris County

Similar to Bergen County, the Morris County OEM role in flood events is primarily organizational—facilitating coordination between agencies. OEM has access to some ITS devices owned by other agencies and has a countywide interoperability radio system and automated notification system accessible to all of municipalities within the county. Municipal police and fire agencies are first responders to flood events, along with NJDOT for flooding on the interstate. Morris County OEM is well-equipped with barricades and portable changeable message signs, and most municipalities are self-sufficient and able to handle most flood events. In circumstances where the county cannot support the municipalities, the county elevates requests for support to NJDOT.

While the OEM functions during business hours, activation of the Emergency Operations Center is relatively rare (three to four times a year). Emergency Operations Center activations occur when a large storm is pending and there is enough advance warning so responses can be planned ahead.

New Jersey Department of Transportation and Transportation Operations Coordinating Committee

For the interview with NJDOT, TRANSCOM was included, as TRANSCOM plays a key role in incident and emergency response in the study area. TRANSCOM is a coalition of 16 transportation and public safety agencies in the New York-New Jersey-Connecticut region. It was created in 1986 to provide a cooperative, coordinated approach to regional transportation management. TRANSCOM provides tools to monitor real-time traffic and highway operations in the tri-state area around New York City. TRANSCOM uses multiple data sources, including relationships with highway and transit agencies throughout the metropolitan region to facilitate interagency communication. This is accomplished through real time incident data integration into a single database source made available to the agencies. TRANSCOM also directly contacts agencies to relay information to their operations center.

NJDOT does not have a formal preplanning process for flood events within the PRB. Flood events are addressed as part of other existing response plans, and NJDOT coordinates prestaging of ITS equipment as needed. Prior to emergency events like flooding, NJDOT regional maintenance crews are available to respond quickly and implement diversion plans as necessary. All coordination is handled through the NJDOT incident command center.

In general, response to flooding begins at the local level and progresses to the county and state level as resources are exhausted and emergency events are declared. NJDOT is responsible for and responds immediately to reported flooding on state routes and interstates, unless there is a pre-agreement with a local agency or municipality for specific state routes. In some urban areas responsibility for state routes belongs to the local agencies. In those locations, the local agency will be first to respond to flood events.

All agencies indicated that flood events rarely cause roadway congestion, because residents often do not leave their homes and wait out the floods. TRANSCOM reported that approximately 400 flood events occurred in New Jersey in 2018. Most of the events were isolated standing water and did not necessitate full roadway closures. Weather-related incidents with winds have been the primary concern. The wind events tend to result in debris and potential bridge closures.

City of Newark and Transportation Operations Coordinating Committee

The Newark OEM, police department, and fire department have comprehensive and coordinated plans for each event, including weather-related events. Newark OEM maintains the traffic control points at flood-prone locations, sends out emergency notifications to stakeholders, and makes the response apparatus ready and available. Newark OEM works closely with the Department of Public Works, Department of Water & Sewer Utilities, and Department of Engineering to handle flooding events.

The City of Newark has a traffic signal system that is used in manual control during flood events, and while the system is managed through the city's Traffic Management Center, no automated flood response signal plans exist. The signals are controlled in real-time by staff at the center or by personnel in the field at the signal cabinets and are being upgraded. The city and Newark Police Department have individual ITS camera networks, and the city is integrating cameras into its GIS web system (Live Earth).

The city gets a weather feed from TRANSCOM. The city has a notification system for communications with residents. While social media is used, the city is exploring the use of a public-address system for use in more commonly crowded areas like parks, venues, stations, and airports.

During the interview with TRANSCOM and the City of Newark, a discussion focused on TRANSCOM's capabilities and services and on policies for sharing data and video images.

OEM identified the key challenges as coordination, communication, and planning and expressed willingness to improve on the relationship with TRANSCOM and regional agencies for greater sharing of ITS resources, including data, situational awareness information during events, video images, and real-time informational resources.

Study Area's Incident and Emergency Management Capabilities

Emergency management plans describe procedures to follow in case of emergency events, including evacuation procedures, and procedures for timely communication with other agencies and the public. The emergency plans identify key personnel, define the required level of training, provide instruction to workers and stakeholders on implementing the emergency procedures, and describe emergency equipment and how to use it, as well as other pertinent information.

Because of the information's sensitivity, emergency management agencies generally do not share their emergency management plans with external parties. For this reason, the assessment of I&EM capabilities within the study area presented herein is largely based on the interviews conducted as described in the previous section. Overall, the agencies have defined adequate protocols for responding to flood events and appropriate procedures to ensure good interagency communication. Recommendations for improvement consist of actions to further refine and optimize interagency communications, as no major issues were identified.

On the state highway system, areas most prone to flooding are along the coast. In preparation for these events, NJDOT has identified pre-established diversion routes. However, no flood-specific emergency plan exists. Nuisance floods are treated using established standard response plans. Maintenance crews and safety patrols usually know which routes must be closed and which diversion routes must be activated. In general, crews use truck-mounted changeable message signs and portable changeable message signs to divert traffic. Diversion routes must consider weight limits on bridges and other restrictions. Diversion routes are communicated via the NJDOT website and via 511NJ, a phone and web service that provides up-to-the-minute traffic and transportation information. (See "Intelligent Transportation System Assets.")

Flood events primarily affect local roadways and, less frequently, major roadways. Events usually begin locally—block-by-block or neighborhood level—and as such, initial flood responses are typically managed at the local level. Therefore, ITS resources are handled directly by local agencies, the state- and county-level agencies tend to be less involved.

Depending on the scale of the event, the public is informed through mobile notifications, social media, or dynamic messaging signs. It is critical that the counties and NJDOT provide accurate and timely emergency notifications, particularly to aid the agencies' efforts to build public trust and increase compliance with alerts. NJDOT uses all available weather data and information to anticipate events. In addition to its own flood gages and readers, NJDOT uses a private meteorological service to predict and issue warnings. However, all agencies recognize that more accurate and granular flooding prediction would be helpful to more directly and effectively alert the public. Specifically, if agencies knew what areas were next to flood—potentially down to the block or building—the agencies could more efficiently focus their resources.

Recommendations for Potential Enhancements

Successful emergency management operations depend on effective planning and the timely deployment of emergency strategies or measures. Emergency planners and coordinators deal with complex transfers of information and manage human or material resources. ITS technologies are tools that can assist with planning for events, management within events, and provide data for analysis after the events have occurred.

Based on the stakeholder interviews and a review of existing ITS assets and procedures in place, it appears that the use of ITS in incident and emergency response within the study area generally follows established best practices. Most events are at least partially anticipated, and agencies have adequate time to mobilize forces. Most events are first addressed at the local level, but there is sufficient coordination between local, county and state agencies to allow for quickly elevating the emergency status of an event if it becomes necessary. However, it is recognized that specific areas or ITS applications could be enhanced to better support emergency and incident management, and recommendations for those enhancements are in the following table.

Recommendations

- **Strengthen operations coordination.**

NJTPA, as the regional MPO, should work with its partner agencies to facilitate implementing recommendations and engage local agencies and counties. This should include communicating with TRANSCOM to manage efforts so they are not duplicative and promote more active roles by all agencies. Meetings of responsible agencies should be held periodically to assess issues and review progress. Formation of an ongoing regional operations coordination committee (ROCC) should be considered.

- **Consider a future study to evaluate the communication network and procedures of all identified agencies above, including county, state and federal, to assess gaps and prioritize any needed improvements.**

For technical communication coordination, the best approach is to conduct a technical study of the region and the participants. This may include detailed radio coverage assessment across the basin and detailed study of the various existing and planned radio systems.

- **Conduct a flood event tabletop exercise with all state and county stakeholders in the NJTPA region to identify gaps and coordination issues. Repeat the exercise on a recurring basis if deemed beneficial by the stakeholders.**

- **Reach out to traffic incident management (TIM) community (e.g., tow companies, local police) to expand the program to include all municipalities and counties in the PRB area and to expand the focus to specifically address flooding events.**

NJDOT has a statewide traffic incident management program (www.NJTIM.org), known as NJ TIM. TIM stakeholders include federal, state, and local agencies such as emergency medical services, fire and rescue, law enforcement, medical examiners, and coroners and private participants, including volunteer and contractors. TIM includes established working groups with these entities. TIM's focus is primarily on roadway incident management. A tabletop exercise or coordination with the potential ROCC could accomplish this recommendation.

- **Address interoperability issues with radio systems.**

Emergency management relies on hierarchical organization that extends from local to regional levels. Overall, the agencies have good interagency communication and have not had any recurrent operating problems. Some exceptions exist: municipalities in Bergen County have indicated interoperability issues with the radio system and the City of Newark expressed communication as an area of improvement. The city would like better integration with the Port Authority of New York and New Jersey and NJ TRANSIT in handling issues related to Newark Liberty International Airport and Newark Penn Station, respectively.

- **Increase further and longer-term coordination between state, regional, and local agencies on flood and climate event planning.**

While many climate events are sporadic, it is expected they will increase in frequency and impact. Several agencies stated additional planning efforts may be required to enhance or improve emergency management, including security operations, response to major crashes, and environmental issues (such as accidental release of fuels and chemicals). An ongoing ROCC to accomplish this should be considered.

- **Develop an emergency plan specific to flood events.**

NJDOT does not have flood specific emergency response plans, but frequently uses their standard protocol for winter operations when responding to flood events. Additionally, it was noted that most minor flooding events are a result of wind events and are therefore already addressed as part of defined wind events response. The emergency plan primarily serves as a guide defining the protocols, procedures, and division of responsibilities in emergency response. Developing an emergency plan for flood events has other benefits. For instance, it may help identify equipment gaps (closed-circuit television cameras, DMS, or other ITS assets), deficiencies in communication, lack of adequate training among personnel, needed supplies, or other items that should be addressed before an emergency occurs. It is recommended to treat an emergency plan as a living document by periodically updating it with new data and information on area demographics, travel patterns, recent flooding and heat events, sea level rise and climate projects.

- **Increase number of surveillance cameras on state highways and major roads.**

While directly mentioned for Morris County, Bergen County, and the City of Newark, establishing and sharing more video was universally requested by the TAC. Cameras would be useful for evaluating the extent and severity of flood events and developing a more timely and effective response. It is recommended to identify gaps in the existing coverage, focusing on areas prone to flooding and building a list of short- and medium-term capital improvements. Identification should include any upgrades required for interagency video sharing. Video sharing of feeds from existing cameras is important and beneficial, and sharing could be accomplished through TRANSCOM instead of accessing several independent platforms. This is preferable, as transportation agencies such NJDOT, New Jersey Turnpike Authority, and the Port Authority of New York and New Jersey are successfully sharing data. Video sharing also can be accomplished through third-party web services or with direct access between systems. Coordination of other ITS assets was not identified as a need by any of the stakeholders interviewed. It is assumed that dynamic message signs, automated gate system, and traffic signal systems will evolve with technology improvements.

Recommendations

- **Invest in redundancy and protection of power and communications infrastructure.**
While many signals are manually controlled during events and portable changeable message signs have their own power, it is generally recognized that because cameras and signal systems are important elements of flood response, there is a need to provide increased survivability of power and communications including redundancy. The recommendation is to identify susceptible systems, specifically focusing on areas that are prone to flooding, and implementing a regional approach to protect these utilities. This may include building a list of short- and medium-term capital improvements especially those that focus on redundancy of ITS and traffic signal systems.

- **Acquire more accurate weather data.**
Agencies recognized that in the past, inaccurate flood warnings and false alarms have resulted in low compliance from the community to evacuate in advance of flood events. Flood forecasting models rely on accurate rain gauge data and radar estimates of current precipitation. The solution is to identify priority areas where flood notification systems are unsatisfactory due to the lack of stream gages and weather stations and work to improve forecasting models. This is primarily the responsibility of the National Weather Service. The immediate recommendation is to reach out to NWS and identify how the agencies can work together to accomplish this. Additional stream rain gages could be installed by local agencies in the most flood prone regions within the basin. Local agencies should keep ownership of these devices and control their O&M. Currently, these flood notification systems are integrated under NJDOT and TRANSCOM but are not available to county OEMs. It is recommended to make these systems available to OEMs to assist in their own emergency response.

- **Improve modeling and visualization of water levels for flood warning.**
With improved forecasting techniques and detailed mapping, it may be possible to visualize floods by city block, by hour, or by amount of rain. Such a tool would be effective in allocating resources in real time, serving as a means to educate and inform the community and to increase compliance during evacuation efforts.

- **Encourage emergency managers to leverage social media.**
In recent years, according to the U.S. Department of Homeland Security, "Social media and collaborative technologies have become critical components of emergency preparedness, response, and recovery." Through the use of social media such as Twitter or Facebook, community members can provide timely, geographic-based information to emergency managers during an event. This information can be used by decision-makers in planning response strategies, deploying resources in the field, and, in turn, providing updated and accurate information to the public. It is important that emergency planners incorporate social media into their communications strategies.

ITS & I&EM Conclusion

Appropriate and timely response to flooding is a challenge within the basin and expected to become more challenging in the coming decades as the frequency and intensity of floods increase. Specific to ITS, the region appears to be well prepared. More and more operational agencies and private sector organizations are relying on video and communications to monitor and manage incidents. Increased sharing of video and increased interagency coordination were identified as areas of improvement. In addition, improved data collection and flood modeling were identified as important elements to help prepare and manage flood events.

While no large-scale ITS deployment projects were identified, increased coordination is seen as a key action item for the region. Specific projects may be identified as coordination increases. This is likely to occur in response to the NWS providing additional data and modeling and TRANSCOM providing increased video sharing. A regional communications study may be beneficial in identifying gaps. The end result of this study could be several smaller scale radio system upgrades or deployments.

Section 6
Conclusions

The PRB climate resilience planning study highlights the importance and challenges of fostering the development of a resilient transportation network not only in the PRB but also throughout northern New Jersey and neighboring areas. The PRB has a documented history of flooding, which is projected to increase in frequency and severity within the study planning horizons of 2045 and 2080. Furthermore, the occurrence of extreme heat events is projected to increase three- to five-fold by year 2080. At least 10 percent of the 3,245 transportation assets evaluated in the PRB study were determined to be highly vulnerable to existing and future heat and/or floods events. Seventy-one adaptations strategies were developed to aid integration of transportation resiliency measures into planning, construction and rehabilitation, O&M, and policy-making. Adaptation strategy fact sheets present planning-level technical and financial considerations for each strategy. Further detailed study will be required in interpreting the results to more accurately evaluate assets, especially those in the high vulnerability category.

In consultation with the TAC, recommendations were developed to advance integration of resiliency into the PRB transportation network. The TAC identified the following approaches to aid in prioritization and implementation of resiliency measures:

- Create a stakeholder collaborative for a local corridor or subarea to coordinate a strategy to plan, fund, and implement adaptation strategies. Examples of regional collaboratives are the New York - New Jersey Harbor & Estuary Program (HEP) created by the EPA and the Paterson Smart collaborative headed by the Great Swamp Watershed Association. The TAC

Resiliency Funding Opportunities

- FEMA (Funding Agency)
  - **Hazard Mitigation Grant Program** assists in implementing long-term hazard mitigation planning and projects following a Presidential major disaster declaration
  - **Pre-Disaster Mitigation Grant Program** provides funds for hazard mitigation planning and projects on an annual basis
  - **Flood Mitigation Assistance Grant Program** provides funds for planning and projects to reduce or eliminate risk of flood damage to buildings that are insured under the NFIP on an annual basis
- FHWA (Funding Agency)
  - **Infrastructure for Rebuilding America Grant** provides funds to nationally and regionally significant freight and highway projects that align with the program goals, including resiliency enhancement
  - **Emergency Relief Program** provides funds from the Highway Trust Fund for the repair or reconstruction of Federal-aid highways and roads on Federal lands which have suffered serious damage as a result of (1) natural disasters or (2) catastrophic failures from an external cause.

recommended a non-profit lead to bring together this collaborative, such as the Lower Raritan Watershed Partnership or Montclair State University Passaic River Institute. The collaborative should include transportation operators/owners, municipalities, and community representatives.

- Identify emergency routes and sole access points for incorporation into Hazard Mitigation Plans. Subsequently, prioritize assets that serve an emergency management function or response in the adoption and implementation of adaptation strategies. Also, prioritize major local roadways that have a sole access point not included this in study. Counties or municipalities performing this action could collaborate with FEMA Community Rating System user groups, such as Morris County.
- Facilitate implementing recommendations and engage local agencies and counties on I&EM. This should include pursuing redundancy projects for ITS and traffic signal systems. Refer to **Section 5** of this report for specific recommendations.

The following recommendations should be performed as next steps and as a collaboration among the responsible agencies, operators, and other relevant stakeholders of each asset.

- Transportation agency owners and operators should use the study findings to provide justification and support in requests for funding to construct or rehabilitate an asset(s) to be resilient to existing and future climate scenarios. NJTPA already includes resiliency scoring criteria in evaluating proposed federally funded TIP projects and other relevant project proposals.
- Transportation agency owners and operators should continue to update and refine the vulnerability scoring of PRB assets as information becomes available. Data gaps should be addressed to the extent possible and the vulnerability scoring should be reevaluated. A current data limitation is the identification of evacuation routes within the PRB, not including NJ OEM coastal evacuation routes. Other data gaps are the elevation of the bridge segment suspended above the waterbody surface and the depth of the superstructures or entranceways below the bridges.
- The NJTPA and stakeholders should use study findings and data compilation to perform adaptation strategy analysis on other PRB subareas or at a finer geographic scale, as necessary. Study findings can also be applied to other basins, such as the Raritan River Basin and the Hackensack River Basin. The type of additional modeling and assessment required is project-specific.
- Transportation agency owners and operators should integrate vulnerability into asset management systems to track asset-specific vulnerability scores, rehabilitation need(s), and repair/reconstruction schedules. Current asset management systems include but are not limited to the NJDOT Bridge Management System and Morris County in-house roadway asset system.
- Transportation agency operators should develop and maintain an O&M plan that encompasses implementation, tracking, and roles of responsible parties for performing O&M adaptation strategies.
- Use the vulnerability assessment findings in current and future planning and design studies to inform the siting of new infrastructure and updates and improvements to existing infrastructure. Resiliency measures can be considered in an improvement project when repairing and upgrading infrastructure, such as retrofitting an asset to be compliant with the Americans with Disabilities Act and Passaic County's Green Infrastructure Plan.

The following recommendations should be performed as next steps and as a collaboration among the responsible agencies, operators, and other relevant stakeholders of each asset.

- Prepare public outreach materials to communicate present and future risks of extreme heat and flood events to the transportation network and surrounding community. Provide stakeholder engagement materials to facilitate dialogue and inform decision-making for property buyouts due to flooding and implementation of green and gray infrastructure adaption strategies.
- Develop workshops for Department of Public Works (DPW) and other user/operators to provide educational opportunities to learn about resiliency and adaptation measures. Create a checklist or fact sheet to aid integration of vulnerability assessments and resilient adaptation measures. These next steps can be modeled after Complete Streets initiatives and supporting materials.

The following recommendations are to assist NJTPA and its partner agencies expand and build upon the data and modeling provided in this planning study.

- Evaluate the role of a supersaturated subsurface, due to excessive snowmelt and frequent precipitation events, in contributing to nuisance and severe flooding. Results of such a study could advise in location and design of green infrastructure strategies.
- Evaluate future land use changes under the NJDEP Blue Acres Program, county and municipal master plans, and similar studies, to refine the H&H model findings and inform the location and design of green infrastructure and flood protection infrastructure strategies. Update existing policy to consider incorporation of climate change projections in stormwater control plans.
- Refine H&H models of the state's watersheds that do not meet Tier 1 modeling approach requirements. Updated models can then be used to map the flood inundation footprint of current and future climate scenarios across a greater extent of the basin, region and state.
- Additional climate scenarios could be modeled to better represent an asset's lifespan and state of good repair. Also, the 500-year storm event is becoming a more common flood scenario to model, including EPA recommendations of flood resilience for water and wastewater utilities. Performance of additional modeling should supplement this study and not hinder taking action on the planning study's findings.

The TAC identified the following as opportunities for the stakeholders to enhance resiliency planning in northern New Jersey.

- Identify other critical watersheds (e.g., Raritan River Basin and Hackensack River Basin) and transportation hubs (e.g., Newark Airport and Port of Newark) and perform a complementary climate resilience planning study.
- Continuously update hazard mitigation plans, long-term combined sewer outflow control plans, green infrastructure plans, and other related planning documents to incorporate the most recent resilience planning studies.
- Evaluate stormwater retainage potential of local green infrastructure projects to advise in location and design of green infrastructure strategies.
- Map stormwater infrastructure and identify capacity potential to further optimize stormwater volume retainage capacity, with a specific focus on the segments of the PRB that are prone to excessive flooding and serve as a stormwater sink.
- Conduct a study to evaluate innovative, cutting edge adaptation strategy measures and BMPs not currently vetted on a planning scale. These would include research and development and academic evaluations. For example, innovative adaptation strategies to mitigate the heat island effect include painting parking lots white, creating "cooling walls" with water in terracotta pots, and creating a green canopy over major streets to provide shade. These strategies can be implemented as pilot studies to test the practicality of innovative climate solutions and enable owners/operators to be a leader in implementing innovative solutions.

This study concluded that the total number of assets highly vulnerable to heat and/or flood events are relatively similar in the 2045 and 2080 planning horizons, and identified potential adaptation strategies to protect the assets. With the evolving science regarding climate change, the assumptions, such as feet of sea level rise or precipitation projections, should be reevaluated and updated on a periodic basis.