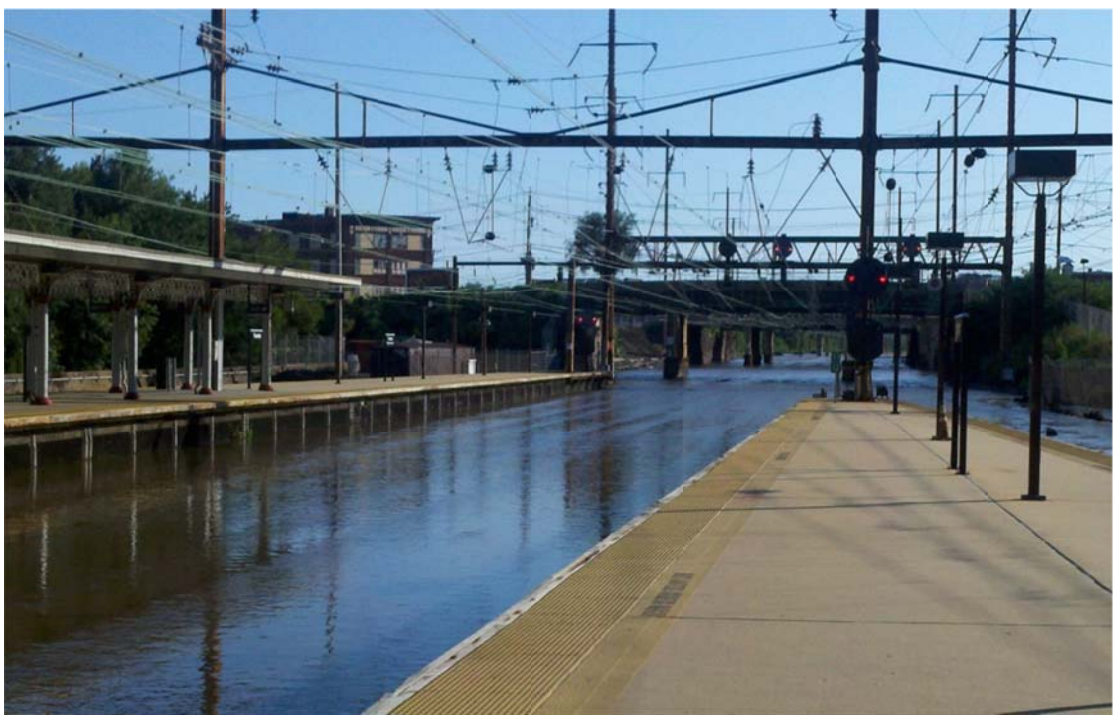
Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure



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The North Jersey Transportation Planning Authority (NJTPA) is the federally authorized Metropolitan Planning Organization (MPO) for the 13-county northern New Jersey region. Each urbanized region of the country is required to establish an MPO in order to qualify for the receipt of federal transportation funding. The NJTPA serves a region of 6.5 million people, one of the largest MPO regions in the country. The NJTPA evaluates and approves proposed transportation improvement projects. It also provides a forum for cooperative transportation planning efforts, sponsors transportation and planning studies, assists county and city planning agencies and monitors the region's compliance with national air quality goals.

The 20-member NJTPA Board of Trustees is composed of local elected officials from each of the region's 13 counties and from the region's two largest cities, Newark and Jersey City. It also includes representatives of state agencies and the Governor's office. NJTPA's host agency is the New Jersey Institute of Technology. More information about the NJTPA is available at www.njtpa.org. This report has been prepared by the NJTPA with financing by the Federal Transit Administration and the Federal Highway Administration of the U.S. Department of Transportation. This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The NJTPA is solely responsible for its contents.

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Front cover photo: Inundated NJ Transit , SEPTA, and Amtrak rail lines at Trenton Transit Center as a result of Tropical Storm Irene, early September 2011 (NJ Transit).

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Executive Summary

In 2010, a partnership of New Jersey state agencies and Metropolitan Planning Organizations (the "New Jersey Partnership") was awarded a grant from the Federal Highway Administration (FHWA) to conduct a Vulnerability and Risk Assessment of transportation infrastructure from the impacts of climate change. The primary objective of this project is to pilot FHWA's Vulnerability and Risk Assessment Conceptual Model using New Jersey as a case study, providing feedback for the advancement of the Conceptual Model as well as develop a greater awareness and understanding of the potential effects of climate change on transportation infrastructure in New Jersey. Based on the feedback received through this and the four other pilot projects funded across the United States, FHWA will revise and finalize the Conceptual Model for application nationwide.

The project was led by the North Jersey Transportation Planning Authority (NJTPA), which was supported by an interagency partnership (NJ Partnership), including:

- New Jersey Department of Transportation (NJDOT)
- New Jersey Transit (NJ TRANSIT)
- New Jersey Department of Environmental Protection (NJDEP)
- Delaware Valley Regional Planning Commission (DVRPC)
- South Jersey Transportation Planning Organization (SJTPO)
- New Jersey State Climatologist

The Conceptual Risk Assessment Model was developed to assist transportation agencies in identifying infrastructure at risk for exposure to climate change stressors and determining which threats carry the most significant consequences. It incorporates the following summary steps:

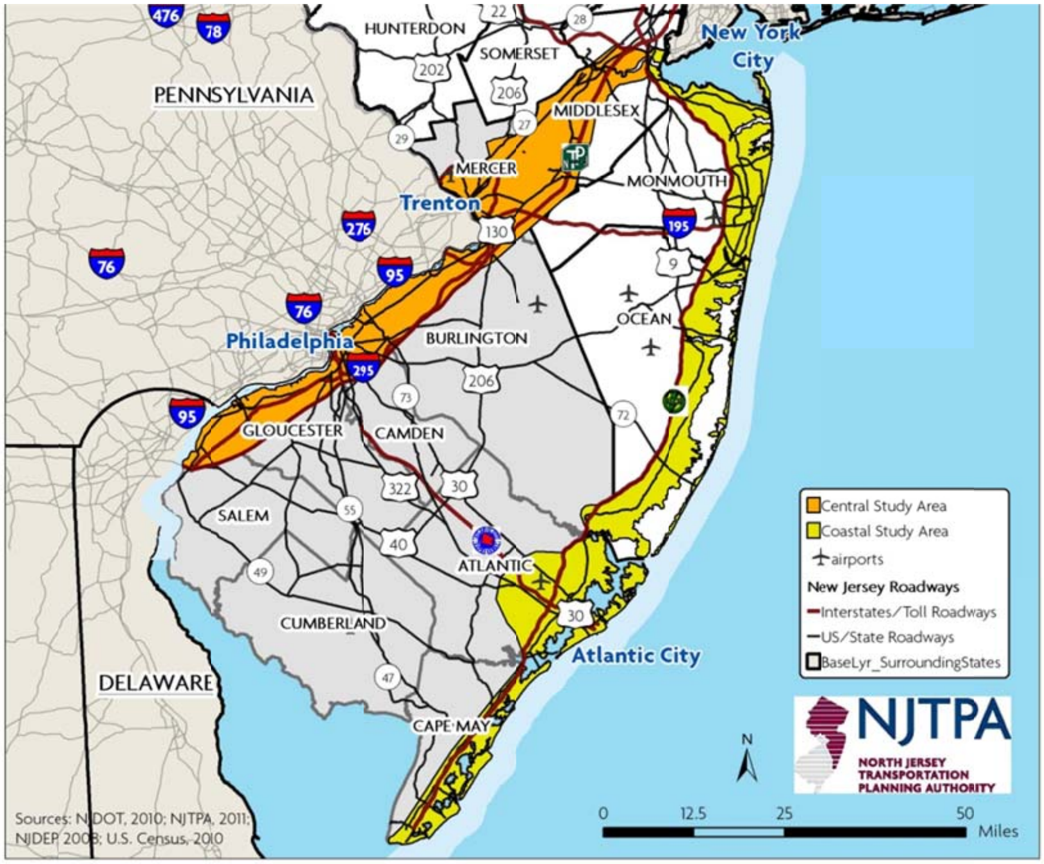
1. Build an inventory of relevant assets and determine which are critical;
2. Gather information on potential future climate scenarios;
3. Assess the potential vulnerability and resilience of critical assets.

These three steps were performed for two study areas in New Jersey, each one of which contains key transportation assets within all three New Jersey MPOs' jurisdictions. One study area focused on coastal NJ, running from the mouth of the Raritan River to the tip of Cape May (Coastal Study Area). The other incorporates much of the Northeast Corridor, and then extends southward along the Delaware River from Trenton to Salem County, as shown in Figure 1.

Step 1: Asset Inventory

The transportation asset inventory first required the identification of applicable asset categories (modes, for example), then the collection of the best available spatial and attribute data in a Geographic Information System (GIS). Information on roadways, passenger and freight rail, airports, and certain maritime assets were collected. The collected assets were organized into tiers of criticality, from "Low" to "Extreme" based on their respective roles in connecting critical destinations—in this case approximated by a combination of population and job density. Therefore, higher volume roadways connecting areas with greater concentrations of people and jobs were generally considered more critical. All major rail lines were considered critical, as were larger airports.

Figure 1. Coastal Study Area (in yellow) and Central Study Area (in orange)



Step 2: Climate Information

This project assessed potential climate impacts for two time periods, 2050 and 2100, from the following climate stressors:

1. Sea level rise,
2. Storm surge,
3. Extreme temperatures and temperature ranges,
4. Extreme precipitation and average precipitation levels,
5. Drought, and
6. Inland flooding (the 100-year flood plain for the Central Study Area only).

To better express the uncertainty inherent in these scenarios, a range of potential outcomes were reported, expressed as low, mid-range, and high scenarios. These scenarios primarily reflected combinations of potential greenhouse gas emissions levels and different climate models.

Based on the scenarios analyzed, sea levels were expected to rise up to 1.5 meters, or 59 inches, globally, exacerbating coastal storm surges due to hurricanes and nor'easters.

Extremely hot temperatures are likely to occur more frequently (and with greater severity), and extremely intense rainfall events may occur more frequently and with greater intensity—increasing inland flood plains. Frost days and very cold temperatures were expected to decline.

Step 3: Vulnerability and Risk Assessment

The vulnerability analysis was performed by merging and superimposing the transportation and climate datasets to enable a spatial analysis of roadways, rail assets, and airports potentially vulnerable to the effects of sea level rise, storm surge, and inland flooding. A digital elevation surface was used to determine the segments in which inundation may occur (in other words, where flood depths eclipse the elevation of the roadway surface, for example). Analysis at this scale did not involve specific site considerations, such as drainage, which could either worsen or lessen the impacts of inundation.

The mid-range sea level rise scenario in 2100 (with just over 1 meter of relative rise) could potentially impact almost 14 miles of roadways in the Central Study Area (about 1 mile of which is comprised of major roadways), approximately 1.4 miles of NJ Transit lines, and over 14 miles of major freight rail lines (50 total rail miles). The Coastal Study Area, under the same sea level rise scenario, may see over 48 miles of roadways impacted, nearly 43 of which are of major functional classifications. 2.9 miles of NJ Transit tracks could be inundated, with about 31 total rail miles impacted (passenger and freight). Among airports, only the Ocean City Municipal Airport would be flooded under the mid-range scenario.

The mid-range inland flooding scenario in 2100 could have devastating effects on transportation infrastructure. Almost 81 miles of roadways could be affected, nearly 59 of which are major. Over 138 rail miles could be impacted, over 25 of which are NJ Transit owned—almost 21 miles are comprised of major freight lines, and 11.7 of which are on Amtrak's system.

Other climate variables, such as extremely hot temperatures and intense rainfall events, currently cause damage or deterioration to transportation infrastructure, and could be expected to do so to a greater extent in the future as these types of events are expected to increase in frequency and/or severity by 2100.

Adaptation

Although external to the FHWA model, this study looked at adaptation strategies to help mitigate potential climate impacts to transportation infrastructure. A review of current and recent research and planning efforts at the national, state, regional, local, and international levels was performed. Based on the findings of the review, the project team developed a series of matrices that identify possible climate change impacts generally applicable to New Jersey and lists potential adaptation strategies that could be taken at various stages of the transportation decision making process, including planning, design, and operations. This effort is a potential precursor to a state or regional climate change adaptation plan.

Recommendations and Conclusions

By embarking on this project, the New Jersey Partnership signals its recognition that the effects of global climate change will likely, as the century progresses, pose a growing threat to transportation infrastructure and operations. However, the significant uncertainties inherent in projecting long-term changes to climate—coupled with the long service life of most infrastructure and assets—present a complex challenge for state, regional, and local transportation decision-makers. Approaching these choices using the climate vulnerability and risk framework developed by FHWA will enable the NJ Partnership to enhance the long-term resiliency of transportation infrastructure and assets, as well as the crucial activities they support.

This project was intended as a pilot, both for FHWA's Conceptual Model and for New Jersey, and as such a primary objective is to make recommendations leading to improved future efforts. High-level recommendations for FHWA and New Jersey include:

FHWA

- **Risk:** Because an understanding of climate risk is not yet mature, the prescribed risk assessment step of the Conceptual Model imparts an expectation that may frustrate agencies. This study recommends developing policy responses that provide the planning and engineering communities with thresholds that reflect a public consensus, an approach which unites public risk tolerance with concrete planning and engineering solutions.
- **Vulnerability Thresholds:** As a longer term goal, a (preferably multimodal) guidebook of vulnerability thresholds—corresponding to the types of climate outputs derived from downscaling—could be developed as a Transportation Research Board project, by AASHTO, or by the American Society of Civil Engineers, for example.
- **Modules:** It may be useful to recreate the primary Conceptual Model tasks (E.g., Asset Inventory) as modules, especially for the assessment phase. Each module could contain guidance on matching approaches with needs, suggest key variables and sources (particularly if a Federal agency can provide relevant information), and links to existing public tools. The creation of modules could also lead to better customization of the process for different analytical scales.
- **Adaptation:** A full-fledged adaptation module could be added to the Conceptual Model. By concluding with vulnerability (and risk), the current Model arms agencies with a rich store of information, but does not complete the final link in the process—adaptation.
- **Opportunities:** The Model could more explicitly highlight opportunities, as its current primary emphasis is limited to the identification of risks. A process, perhaps a separate module, should facilitate the determination of areas of potential intersection with other transportation and non-transportation plans.
- **Uses beyond Transportation**: Both the process and data generated and collected for a climate change vulnerability and risk assessment of transportation infrastructure could have much broader applications; for land use, economic development, natural and cultural resources, utility infrastructure, public health, safety and security, and more. This finding applies in the New Jersey context as well.

New Jersey

- **Data Availability and Sufficiency:** In some cases, initial or ideal approaches were modified due to insufficient data, particularly in the areas of bridges, culverts, weather-related traffic incidents, as well as certain modes, such as ferries and alternative transportation. For future vulnerability and risk assessments, it would help to have richer public data sets, especially pertaining to the above-mentioned areas.
- **Expand or Narrow Assessment Geographies:** New Jersey should consider leveraging relevant data and findings from this study to perform a high-level vulnerability assessment for the entire state. The results of this project could also serve as a foundation for regional or subregional vulnerability assessments (whether focused on transportation or broader in nature), reflecting the policies and priorities unique to each jurisdiction.

- **Continue New Jersey Partnership and Cultivate Supporting Resources:** The communication and collective learning engendered by this work over a 7-month span should continue regularly and indefinitely—and the follow-on initiatives necessary to capitalize on this project should be formulated by the NJ Partnership. The perspectives of other public and private partners will also be needed.
- **Statewide and/or Regional Adaptation Plans:** The adaptation chapter incorporated into this report provides a starting place for considering which adaptation strategies may be appropriate to pursue, given the potential vulnerabilities identified. However, it does not substitute for a comprehensive, stakeholder-driven adaptation plan. An adaptation plan is the appropriate next step after the completion of a vulnerability and risk assessment.

Introduction

Climate is an important factor in the design, construction, safety, operations, and maintenance of transportation infrastructure and systems in New Jersey and around the world. As global temperatures increase, sea levels rise, and weather patterns change, transportation agencies will be challenged to determine how these changes might impact existing roads, airports, rail, transit systems, and ports. In acknowledgment of this challenge, the Federal Highway Administration (FHWA) created a Risk Assessment Conceptual Model (referred to hereafter as the Conceptual Model) for state DOTs and MPOs to use in assessing the vulnerability and risk of their transportation infrastructure to the potential impacts of climate change.

In 2010, a partnership of New Jersey state agencies and MPOs (the "New Jersey Partnership") was awarded funds to pilot the Conceptual Model and assist in advancing existing climate vulnerability assessment activities. Based on the feedback received through this and other pilot projects, FHWA will revise and finalize the Conceptual Model for application nationwide. By embarking on this project, the New Jersey Partnership signals its recognition that the effects of global climate change will likely, as the century progresses, pose a growing threat to transportation infrastructure and operations. However, the significant uncertainties inherent in projecting long-term changes to climate—coupled with the long service life of most infrastructure and assets—present a complex challenge for state, regional, and local transportation decision-makers. Approaching these choices using the climate vulnerability and risk framework developed by FHWA will enable the NJ Partnership to enhance the long-term resiliency of transportation infrastructure and assets, as well as the crucial activities they support.

General Approach

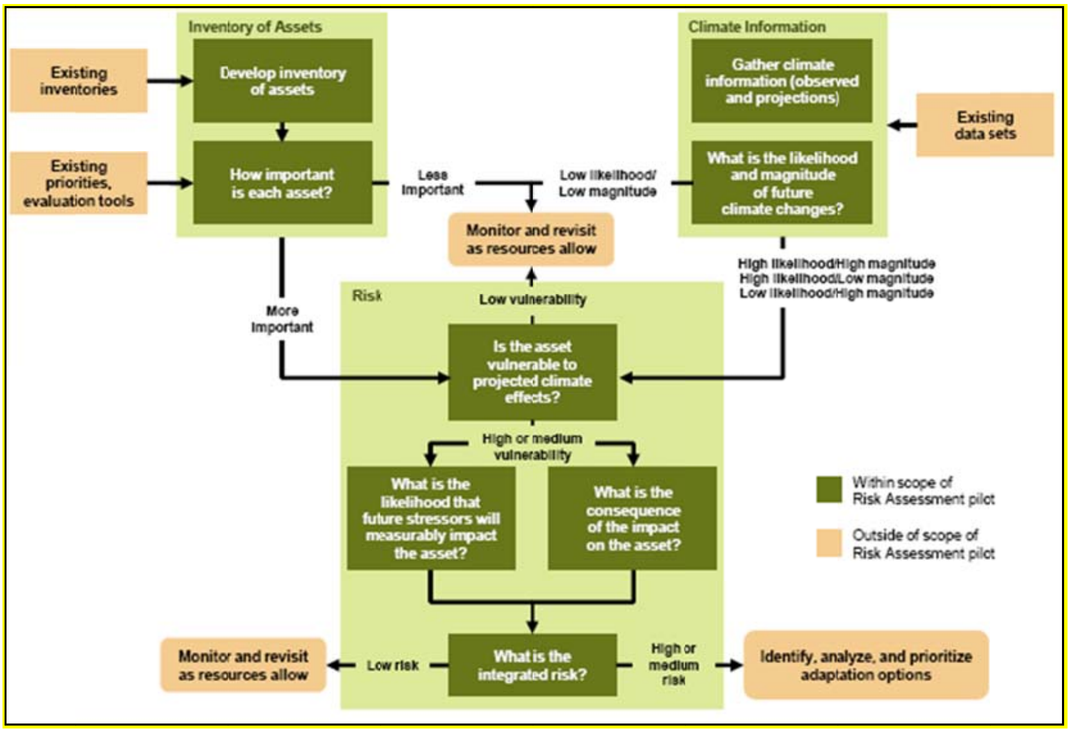
FHWA's Sustainable Transport and Climate Change Team developed a conceptual Risk Assessment Model to assist transportation planners, asset managers, and system operators identify infrastructure at the greatest risk for exposure to climate change stressors and determine which threats carry the most significant consequences. The model, shown as Figure 2, includes three primary steps, the first two of which were executed concurrently and then integrated for the performance of the third step.

1. Build an inventory of relevant assets and determine which are critical to system performance;
2. Gather information on potential future climate scenarios, including the possible magnitude and likelihood of the changes;
3. Starting with the most critical assets and most severe climate stressors, assess the potential vulnerability and resilience of transportation assets.

The New Jersey project assessed potential climate impacts from sea level rise, storm surge, extreme temperatures and temperature ranges, extreme precipitation and average precipitation levels, drought, and inland flooding in 2050 and 2100. The project team was led by NJTPA, and included New Jersey DOT, the state's other two MPOs, (DVRPC and SJTPO) NJ Transit, the NJ State Climatologist, and the NJ Department of Environmental Protection. Multi-modal assets, including roadways, bridges, rail and bus transit, maritime assets, airports, and wetlands, were evaluated for two large study corridors (one primarily inland, one primarily coastal).

The study employed a quantitative and qualitative criticality assessment technique based on the origin and destination of vehicular travel to determine which assets are evaluated for exposure, potential resiliency to climate stressors, and consequences of asset failure to system performance. This effort also includes an adaptation strategies component.

Figure 2. FHWA Conceptual Model



Project Partnership

A Climate Change Adaptation Research Partnership (NJ Partnership) was formed to guide the project team, providing a multidisciplinary and multi-jurisdictional perspective. NJDOT was the lead applicant and the North Jersey Transportation Planning Authority (NJTPA) managed the project. The NJ Partnership also incorporates an oversight committee made up of the following agencies:

- South Jersey Transportation Planning Organization (SJTPO)
- Delaware Valley Regional Planning Commission (DVRPC)
- New Jersey Transit (NJ TRANSIT)
- New Jersey Department of Environmental Protection (NJDEP)

Other agencies and organizations, including a number of county and municipal government agencies, were consulted by the Partnership to obtain input and gain access to additional data.

The consultant team was led by Cambridge Systematics, supported by Dewberry (elevation model and flooding assessment), Stratus Consulting (climate modeling and information), and Paragon Engineers (GIS support and engineering advice).

Description of the Project Area

New Jersey's diverse geography of coastal and riverine environments, as well as its dense, heavily used transportation network, makes it an ideal pilot project for FHWA's Conceptual Risk Assessment Model. A significant portion of New Jersey's infrastructure is concentrated in potentially vulnerable areas near major rivers and the coast and much of the transportation network is aging and requires significant investment for maintenance. A vulnerability assessment was needed to ensure that transportation capital funds can be put to the best and most efficient use. This study focused on transportation assets of state and regional importance, some of which, if damaged or otherwise rendered unusable, could have large ripple effects throughout the state.

Two geographic areas were studied. Both areas contain transportation networks of regional significance and could potentially be heavily impacted by climate change stressors. The study areas are:

- The New Jersey Coastal Study Area
- The Central New Jersey Study Area

See Figure 3 for a map of the Study Areas.

New Jersey Coastal Study Area

The New Jersey Coastal Study Area was chosen primarily because it is susceptible to rising sea levels and increased storm events. This Study Area's northern boundary is State Route 440, and extends south along the coast to Cape May. The western boundary of the Study Area is the Garden State Parkway (occasionally alternating with Route 9) and the eastern boundary is the Atlantic Ocean. The Study Area encompasses six New Jersey counties and portions of all three Metropolitan Planning Organizations, and includes the cities of Toms River and Atlantic City. The area encompasses a significant portion of the State's economic activity and a growing portion of the State's population. The 548 square mile area contains major portions of the state's tourism and gaming industry. This industry generates approximately $38.8 billion per year in New Jersey. Excluding expenditures for goods and services produced outside of New Jersey, the net economic value of tourism for the state of New Jersey is currently estimated at approximately $27.9 billion, including $20.2 billion in core tourism activities (e.g., the industries that provide goods and services directly to visitors), and $7.7 billion in non-core activities (e.g., industries that sell goods and services to the core industries).[1] The tourism and leisure sector,

[1] Tourism expenditures in New Jersey were approximately $38.8 billion in 2008. The $27.9 billion estimate of the economic impact of tourism excludes the value of import leakage (e.g., goods and services from outside the state such as clothing made in China). *NJ Tourism: Holding Its Own During Difficult Times*. Retrieved from NJ.Org, 12/4/2011.

including arts, entertainment, accommodation and food service, is New Jersey's third largest private sector employer, accounting completely or partially for approximately 418,000 jobs in the state, or more than eight percent of the state's total workforce.[2] The tourism sector is estimated to generate approximately $7.7 billion in tax revenue, including $4.5 billion in local and state taxes.

This economic activity is highly dependent upon the area's transportation network, which includes limited access highways such as The Garden State Parkway and Atlantic City Expressway, bridges, State and county roadways, New Jersey Transit rail lines, and freight rail assets. The region also includes barrier islands and low-lying areas where the transportation infrastructure is currently subject to coastal flooding and erosion.

Central New Jersey Study Area

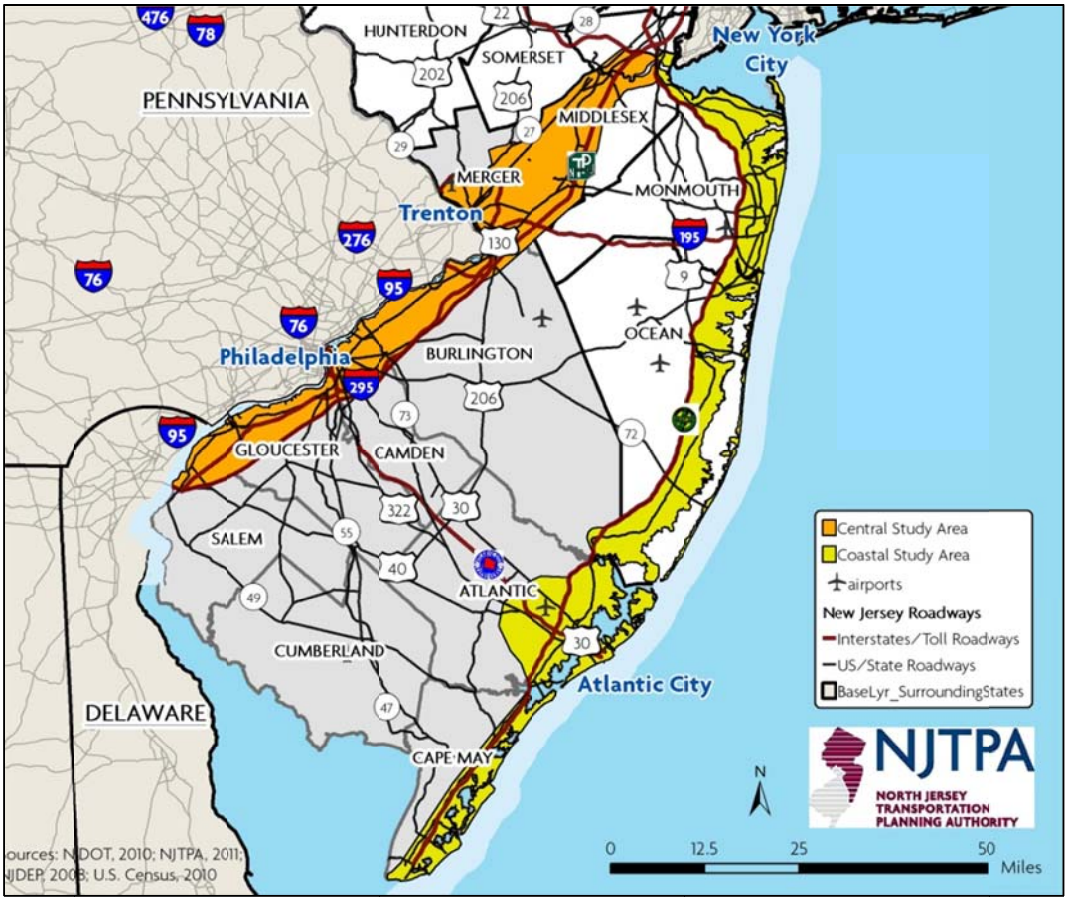
The Central New Jersey Study Area was chosen because it is a critical transportation corridor connecting some of New Jersey's largest metropolitan areas: Camden, Trenton and New Brunswick. Moving from south to north, the western boundary of the Study Area is comprised of the tidal Delaware River, Interstate 95, State Route 27, Interstate 287, and State Route 440. County Route 535 and the New Jersey Turnpike/I-95 form the Study Area's eastern boundary. The Central New Jersey Study Area meets the Coastal Study Area at the Garden State Parkway. This Study Area encompasses six New Jersey counties and includes portions of the State's three Metropolitan Planning Organizations. The 520 square mile area connects many of the State's primary centers of economic activity, industry, government, employment and population and is a significant corridor for both highway and rail freight. The corridor encompasses major interstates, the Northeast rail corridor, and the Delaware Memorial, Commodore Barry, Walt Whitman, and Ben Franklin bridges. As with the Coastal Study area, activities in this corridor rely heavily on a dense and integrated transportation network of limited access highways, bridges, State and county roadways and rail lines. Infrastructure within the Central Study Area is subject to sea level rise, storm surge and riverine flooding and erosion.

Table 1. Counties by Study Area

Coastal		Central
Middlesex		Middlesex
Monmouth		Mercer
Burlington		Burlington
Atlantic		Camden
Ocean		Gloucester
Cape May		Salem

[2] Bureau of Economic Analysis. U.S. Economic Accounts [Data file]. Available at http://www.bea.gov/.

Figure 3. Coastal Study Area (in yellow) and Central Study Area (in orange)



Asset Inventory and Criticality Assessment

Assessing the potential vulnerability of multimodal transportation assets to projected climate stressors is the core mission of this study. Obtaining relevant, accurate transportation and terrain data sets was of paramount importance to the success of the project. The transportation asset inventory first required the identification of applicable asset categories (modes, for example), then the collection of the best available spatial and attribute data in a Geographic Information System (GIS), the identification of critical assets, and finally the superposition of spatial climate data onto spatial transportation data to enable the subsequent vulnerability analysis.

Defining Asset Categories

At the initial NJ Partnership meeting, held in April 2011, a list of potential transportation assets for collection and assessment was reviewed with the Partnership. Based on relevancy, data sufficiency, Partnership preferences, and the availability of resources, a selection of assets was finalized over the course of the following month. The full list, shown in Table 2, placed emphasis on core transportation assets with rich, readily available data sets, although partial data sets are represented as well.

Table 2. Transportation asset data collected

COLLECTED	PARTIAL DATA	OMITTED/ INSUFFICIENT
• ROADWAYS (no local) • BRIDGES (roadway and rail carrying) • PASSENGER RAIL (Amtrak and NJ Transit)[3] • FREIGHT RAIL • AIRPORTS • WETLANDS[4] • TUNNELS	• MARINE (Container, Bulk/Break-Bulk, Roll on/Roll off) • ALTERNATIVE TRANSPORTATION • FERRY TERMINALS [5]	• TUNNELS (rail) • MARINAS • HELIPORTS • SEAPLANE LAUNCHES • PIPELINES • PASSENGER RAIL (SEPTA, West Trenton) • INTRACOASTAL WATERWAY • FUEL DEPOTS

[3] Attempts were made to contact PATCO for GIS layers, without success. The project team built a PATCO layer for the geospatial database, but it does not contain any attribute data (just location of the line).

[4] Data regarding location and extent were collected and integrated into the GIS.

[5] Ferry Terminal shapefiles were created by NJTPA.

Data Collection and Sufficiency

The data collection effort required obtaining spatial layers and attribute tables from regional, state, and national web portals, State transportation agencies, and MPOs, as well as the construction of spatial layers that could not be otherwise obtained. A summary table of data collected is included in Table 3, below.

As they were collected, these layers were added in batches to a geodatabase created for the purpose of storing and organizing asset data. The geodatabase (which is available from NJTPA) serves as a repository and management tool for spatial data and provides the ability to apply rules and relationships to data, to integrate spatial data with other databases (e.g., climate data), and to maintain data integrity. The spatial transportation data is organized by source (e.g., NJ Transit). Feature classes (e.g., points, lines, polygons) collected from a single source are organized under a feature dataset bearing the name of that source. Feature classes created as a result of spatial analysis during the course of the project are organized under the name of the process (e.g., Criticality).

The roadway features dataset, collected primarily from NJDOT, is the most complex, consisting of a highway centerline network feature class and a multitude of attribute tables including bridges, tunnels, and characteristics including functional classification, lanes, and speed. Point and line information from a number of NJDOT management systems were joined to the roadway network using linear referencing (based on the Standard Route Identifier (SRI) and milepost information). Selected data from the Bridge, Pavement, Traffic, and Drainage management systems, as well as the Straight Line Diagram attributes, were joined to the Congestion Management System network. The result is an attribute-rich roadway dataset suitable for complex queries and analysis.

Table 3. Data collection matrix (major assets only)

Asset	GIS Data	Characteristics
Roadways	NJDOT Congestion Management System (CMS)Network[6]	NJDOT CMS data used for study area coverage and volume data. Primarily higher Functional Class highways, a few county roads and collectors included.
	NJTPA Model Network	Does not cover the entire study area. Network is simplified highway stick network. Network density is higher than CMS Network and includes lower level functional classes compared to CMS.
Bridges	NJDOT Bridge Management Data Tables	2009 BMS data used to create linear bridge location GIS layers. NJDOT's bridge locations are point features and do not include length attribute data.
	BTS NTAD	National Bridge Inventory from BTS is an additional source of bridge locations.
Tunnels	NJDOT Data Tables	Tunnels feature class created from NJDOT's data tables by linear referencing from the NJDOT highway centerline feature class.
Passenger Rail	NJ Transit	GIS database layers used directly as received from NJ Transit.
	Amtrak, BTS Data	BTS 2011 has Amtrak's network as a separate GIS layer for download.
Freight Rail	BTS Data	Active Freight Rail data from Oak Ridge National Laboratory Network.
	DVRPC	Data made available from DVRPC, regional in extent.
Traffic Analysis Zones	NJTPA, SJTPO, and DVRPC	A Unified TAZ structure was created by merging NJTPA, SJTPO, and DVRPC's TAZ GIS layers. NJTPA's 2010 socio-economic data was used from the three data sources.
Airports	NJDOT Data Tables, BTS	Runway lengths, airport polygons
Wetlands	NJDEP	Wetlands files provided by NJDEP.
Evacuation Routes	NJGIN	NJDOTs Highway Safety Improvement Program Evacuation Route GIS layers
Ports	BTS Data	
	DVRPC	Port and goods movement data provided by DVPRC.
NJ Transit Bus Routes	NJ Transit	Centerline bus routes GIS layer from NJ Transit.
NJ Transit Signals		NJ Transit GIS layers
NJ Transit Switches		
NJ Transit Track		

[6] Traffic volume data, which is one of the determinants for highway criticality is not available for all features on NJDOT's centerline network. The CMS network data has link level traffic volume information for higher level functional class highways (primarily interstates/freeways, major and minor arterials, and some urban collectors).

Figure 4. New Jersey Roadway Network

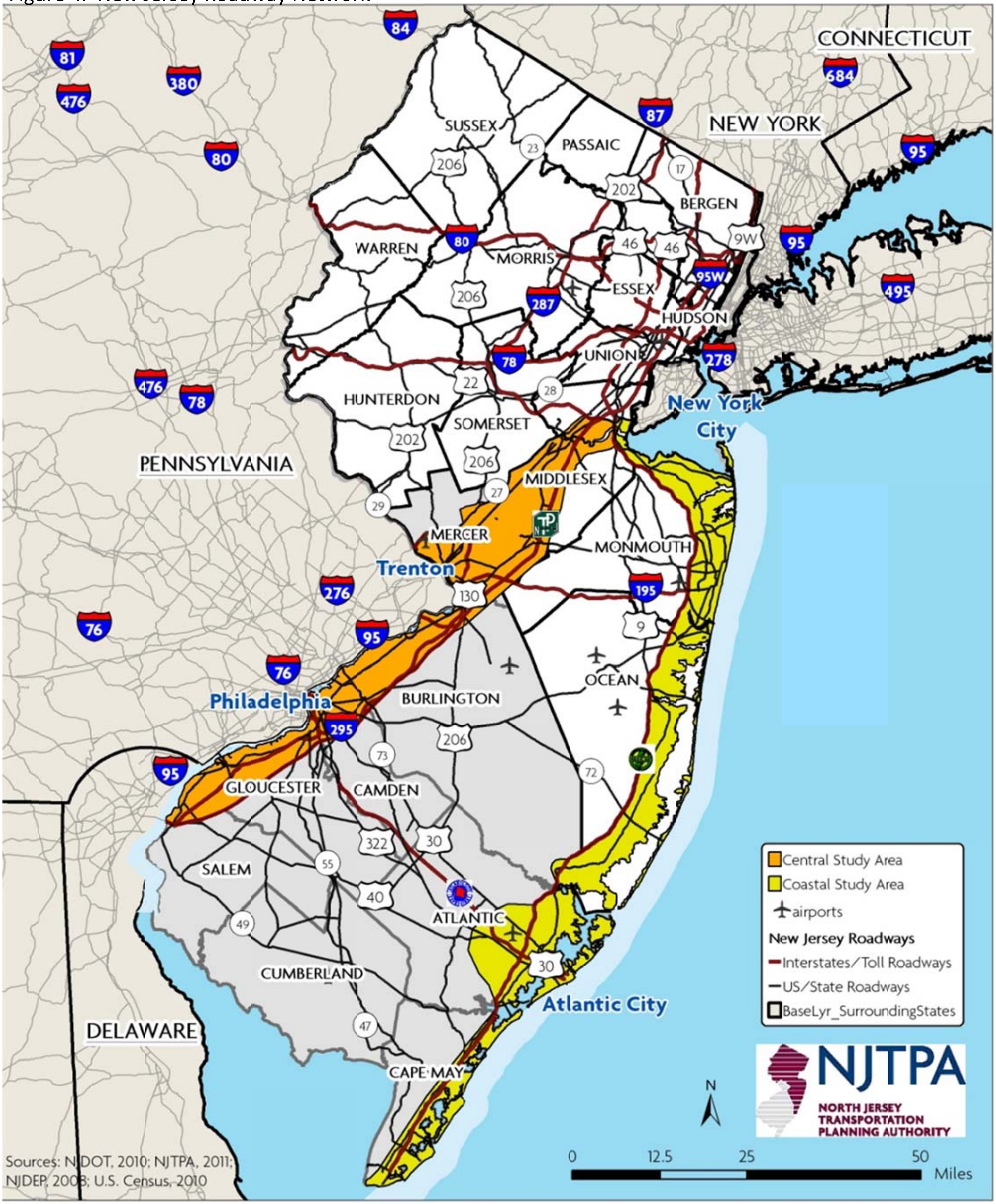
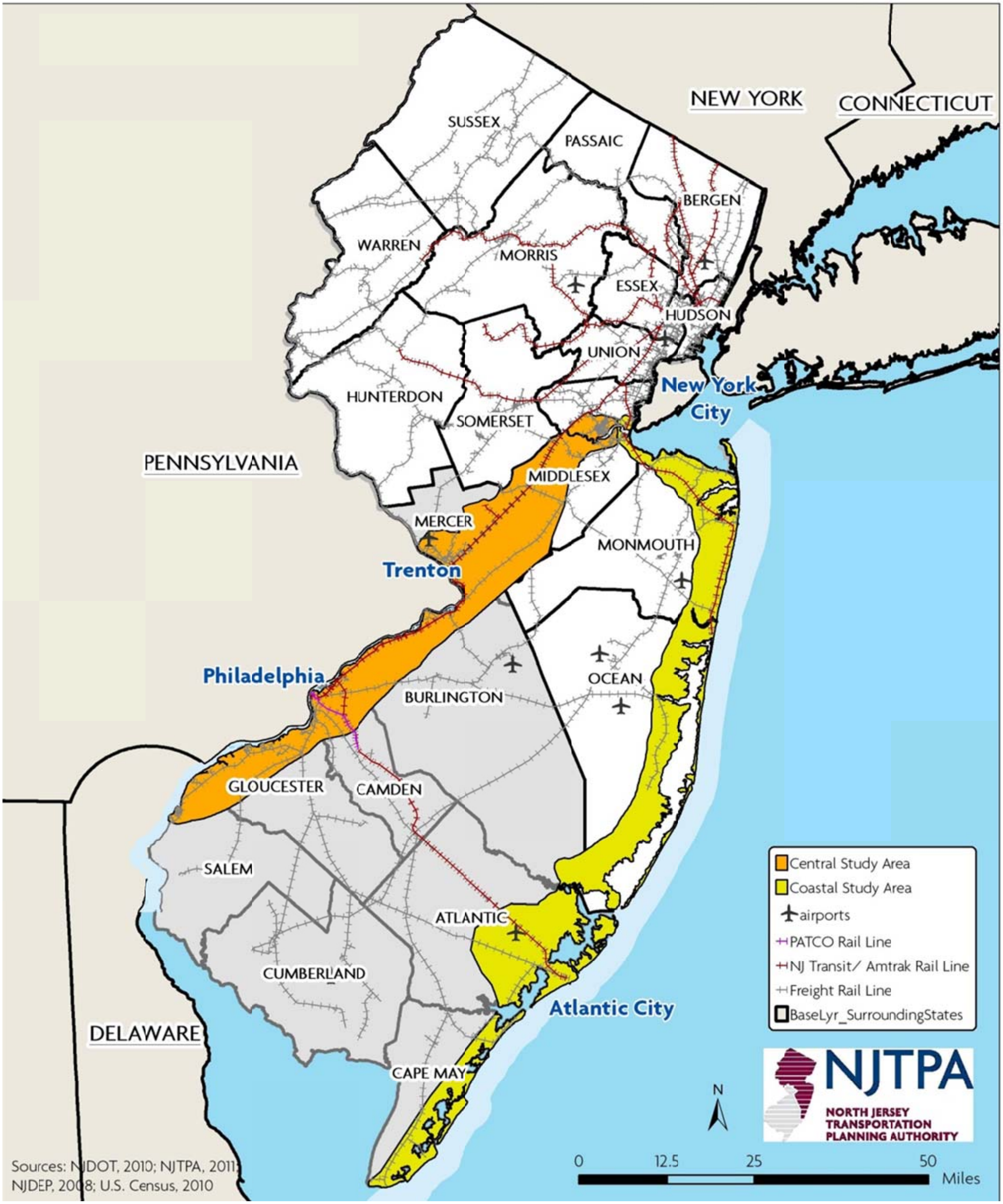


Figure 5. New Jersey Rail Network



Determining Criticality

A criticality assessment asks whether, and to what degree, a given asset is critical to fulfilling the mission and goals of the project sponsor (in this case, a multi-agency coalition). By determining criticality first, analytical resources can be directed to the assets and operations of greatest importance.

A destination-based criticality approach was developed by the project team, acknowledging that the purpose of transportation infrastructure is to connect travelers with destinations. The relative criticality of destinations is a matter of policy—for the purposes of this study, jobs and population density were considered, but any data attributable to a geospatial unit could be used. To account for the magnitude of the connections made by a given asset, volume or ridership data is also factored in—in this specific application, Annual Average Daily Traffic (AADT) is used as an adjustment factor (all rail is considered either highly or extremely critical, a policy decision by the NJ Partnership). Originally, redundancy (or the lack thereof) was to be applied, but no systematic data suitable for GIS analysis was identified[7].

This criticality approach was translated into a GIS-based methodology, using attribute data collected during the asset inventory to quantitatively allocate all Congestion Management System (CMS) network roads into tiers of criticality. Although this application of the GIS tool uses only the jobs and population attributes common to each MPO's Traffic Analysis Zone (TAZ) files, future uses could incorporate a host of other data types (such as industrial jobs, tourists, or cultural resources), use freight volumes to supplement or replace traffic volumes, or add weights to one or more of these factors. It is important to note that this tool provides agencies with a robust platform to support smart decision-making, but it is not intended to substitute for the judgment and discretion of agency officials.

The GIS criticality tool follows a multi-step process to allocate highway assets into four tiers of criticality. The bottom two tiers were collapsed for the vulnerability analysis, leaving three tiers.

1. **Network Selection:** The State of New Jersey has multiple highway network GIS files (as shown in Table 3), but only networks covering the entire State and containing sufficient criticality determinant data (E.g., volumes) for each link were suitable[8]. Accordingly, the NJDOT congestion management system (CMS) was chosen as the highway network, as it has a full complement of actual and estimated traffic volume data.
2. **TAZ Criticality:** Attribute data essential to determining the relative criticality of a given area is usually embedded in TAZ structures. This effort utilized attributes common to each MPO's TAZ structure—population and jobs density—for the analysis. Because NJTPA, SJTPO and DVRPC have different TAZ structures, a unified statewide zonal structure was created. A criticality score was computed for each TAZ based on a composite jobs/population density calculation (shown in
3. Figure 6. TAZ Criticality Map, darker TAZs indicate higher relative criticality).

[7] A filter, which would have provided an upward adjustment for areas with high concentrations of disadvantaged populations or job creation zones, was originally proposed, but dropped because of the complexity of the core analysis. This filter could be used in future analyses.

[8] A MPO model network and TAZ structure would have been ideal for this exercise, but no recent unified statewide network was available.

4. **O-D Criticality:** With a unified TAZ structure established and a criticality score established for over 3100 TAZs, almost nine million origin-destination (O-D) pairs were determined. Using TransCAD transportation planning software, the CMS network was transformed from a centerline GIS layer to a highway network with intersections and centroid connectors for travel modeling purposes. Each centroid represents the activity center for each TAZ, which is connected to a nearby road to represent traffic movements in and out of that zone. Multiple centroid connectors, with a maximum radius of seven miles[9], were created for each TAZ in order to ensure flexible traffic movement from that zone.

   Speed, capacity and free flow times for each link in the network were added, and TransCAD was used to determine the shortest path time between each O-D pair (a highway "skimming" procedure)[10]. By multiplying the criticality score of the origin TAZ with that of destination TAZ and dividing by Travel Time (in seconds), O-D criticality scores (called "Alphas") were created for each pair. This process is identical to a free-flow traffic assignment procedure, with each network link considered to have unlimited capacity to ensure unconstrained assignment. The results were stored in a trip table.
5. **Network Assignments:** In order to translate Alpha scores to the network, each CMS link was assigned the criticality score of *each* O-D pair utilizing it, with a running total of cumulative criticality kept for each network segment. At the end of the assignment process, network links used to connect O-D pairs of high criticality most frequently obtained the highest relative criticality scores. The link scores were multiplied by volumes to better account for the magnitude of usage—future runs could consider weighting volumes and/or including trucks to further refine the link scores. This operation tended to yield marginal refinements, and did not significantly alter the prior results.
6. **Mapping:** The link scores were brought into a GIS as an attribute table associated with the CMS network. The link scores were split into three tiers (top quartile, second quartile, bottom 50%), and then mapped accordingly, as demonstrated in Figure 4. As previously noted, four tiers were initially generated, and the bottom two tiers were collapsed for legibility during impact mapping, leaving three tiers. The tiers were entitled "Extreme," denoting assets which absolutely cannot fail, "High," for assets that, while still critical may be less vital to system functionality, and "Low and Medium," which serve important roles in local and regional transportation, but may not be top priorities from a statewide perspective. Examples facilities within these tiers include:
   a. Extreme: the Garden State Parkway, the NJ Turnpike, and large sections of major arterials, such as Route 40 and 206;
   b. High: Route 70 (connecting Route 206 and the Garden State Parkway) and Route 49, providing important connectivity to rural areas in southern New Jersey;

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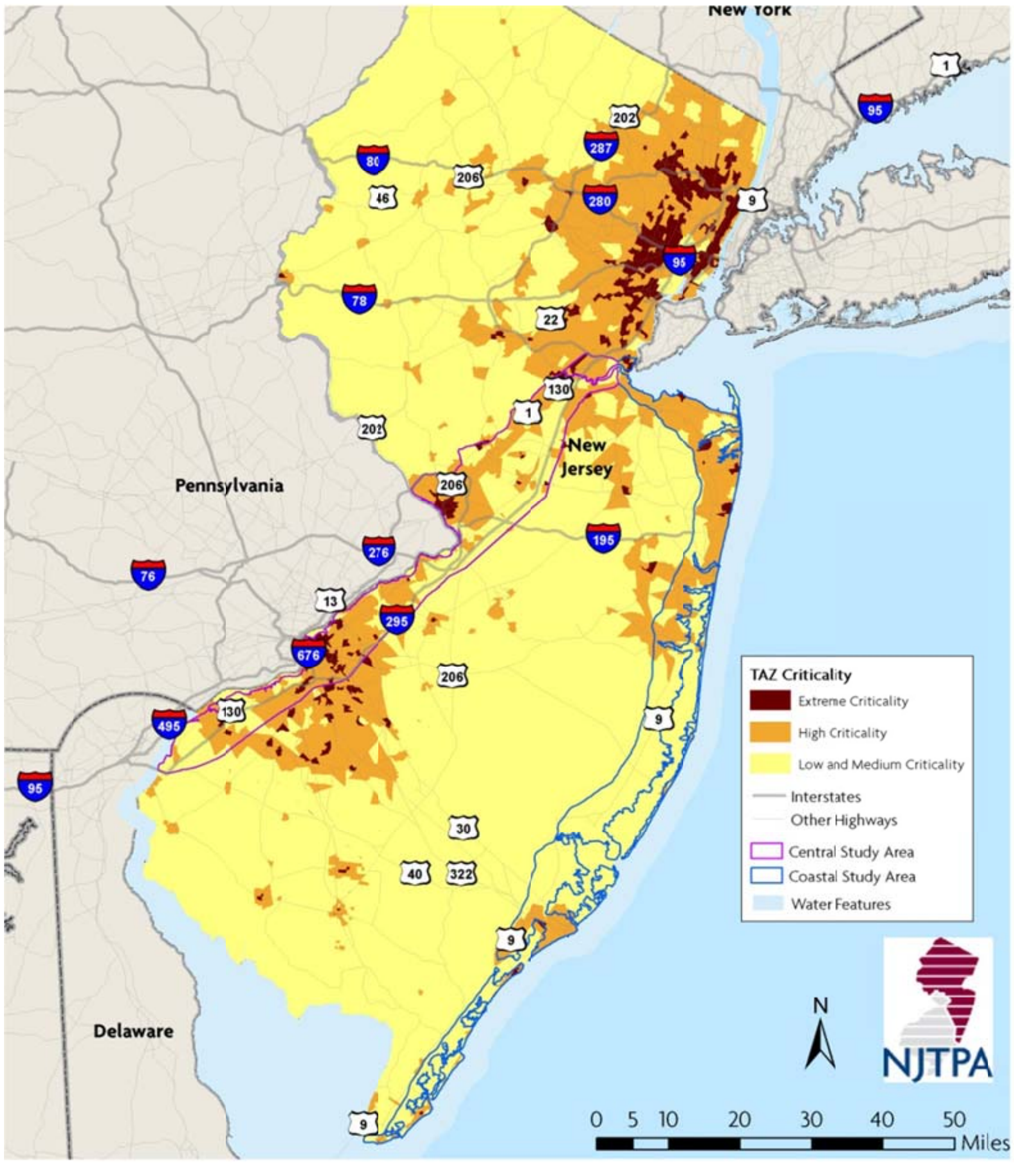
[9] This assumption was used to ensure that each TAZ has multiple connectors to nearby roads, thereby facilitating many points of loading on to the highway network—a necessary step given the limited network density of the CMS.

[10] External TAZs were not included due to the need to construct the unified TAZ structure and run skims in a short time, which means that inter-state connections are under-represented. Running this process on a single MPO network would account for external TAZs.

c. Low and Medium: Limited sections of Route 9, which parallels the Garden State Parkway (many sections are "High") and County Road 539 from Tuckerton to I-195.

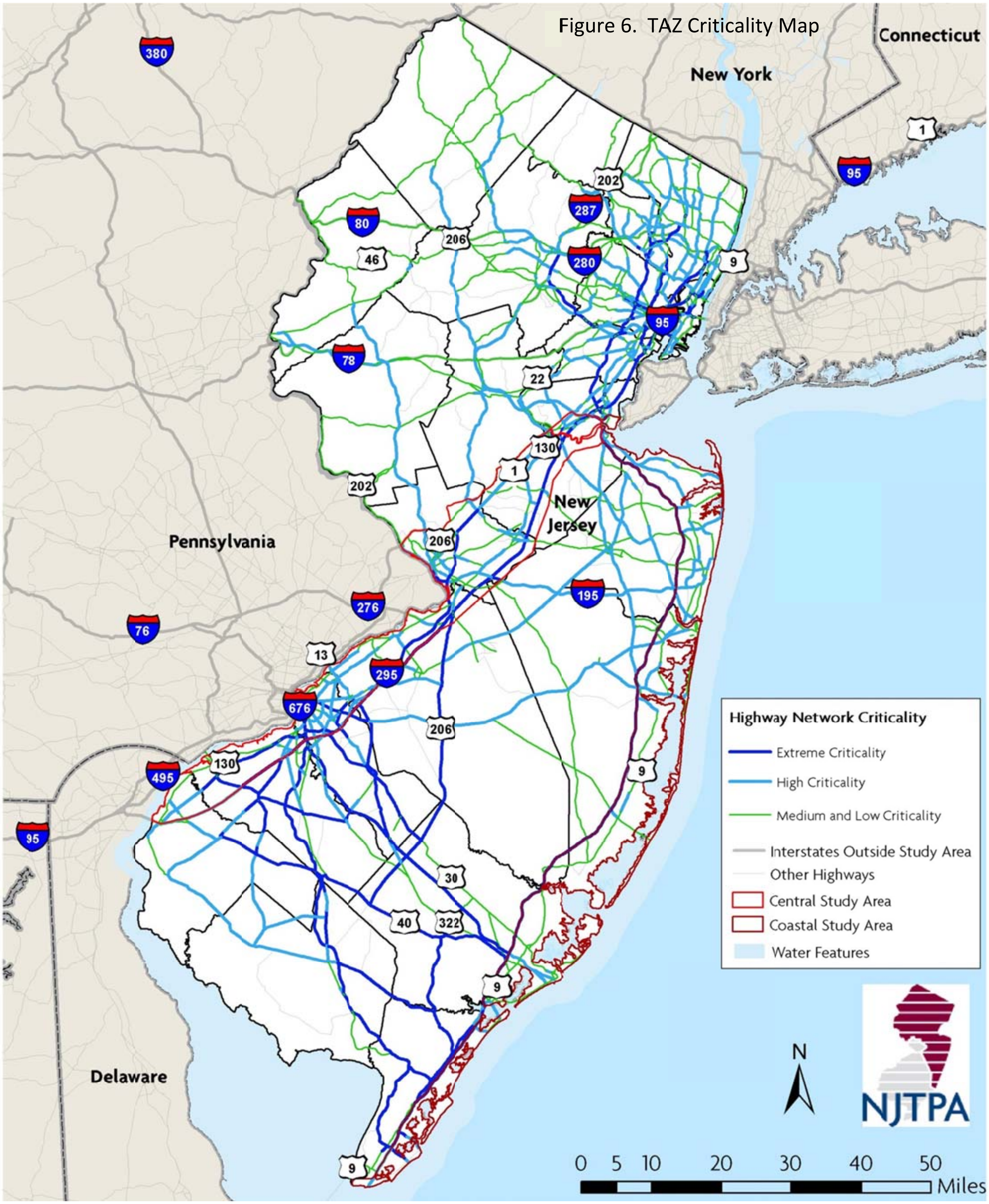
Figure 6. TAZ Criticality Map



Rail assets were classified into two tiers of criticality, with the top tier including all passenger and Class 1 freight rail assets, and the subsequent tier including all active Class 2 and 3 rail lines. The rail system is depicted in **Error! Reference source not found.** All airports with at least one paved runway exceeding 5,000 feet in length were considered critical, although none of these facilities were affected by the flooding scenarios considered subsequently. Maritime facilities were not considered in this analysis, primarily due to data insufficiencies, but this may be a fruitful topic of study for future efforts.

After the criticality maps had been generated, the results were presented to the NJ Partnership, and then subsequently to a number of subregional representatives via webinar. In both instances it was stressed that the criticality tool is intended as an aid to intelligent and comprehensive decision making, and cannot substitute for professional judgment and local knowledge.

Figure 4. New Jersey Link Level Criticality (CMS Network)



Limitations of the Data and Analysis

Although the data collection and criticality assessment tasks were conscientiously performed and delivered robust results, each were constrained by the limits of data, time, and resources. For example, the data collection effort made use of the NJDOT CMS network due to the availability of volume attributes statewide, which provided a core roadway network for analysis but sacrificed the granularity of the NJDOT Roadway Network file (which did not contain volumes). When the NJDOT statewide model has been updated, that roadway file may provide a better platform for assessments (or, for regional- or subregional-scale projects, the MPO model networks could be used).

The absence of a recently updated statewide model network also complicated the criticality assessment approach. For example, it was necessary for the project team to create a unified TAZ structure and perform highway skimming from scratch, which led to the omission of external TAZs (which had overloaded the roadway segments connecting New York City and Philadelphia to New Jersey). Without a single model network to facilitate the analysis, the criticality attributes were limited to those common to all three model networks (population and jobs), whereas a single model network typically contains much richer attribute data. Future applications of this approach will be more successful if confined to a single model network.

Determining Climate Impacts

Although there is widespread scientific consensus that human activities are, even now, changing the dynamics of the global climate, there is uncertainty concerning the timeframes and specific effects associated with the exacerbation of various climate stressors. Therefore, this study adopts a scenario-based approach in which wide ranges of potential climate impacts are simulated by applying the best available climate models and simulation software to historical weather data.

It is vital to note that although many of the stressors are reported as a specific value corresponding to an analysis year and climate scenario, these values often reflect 30-year averages. In reality, there will be significant variation from month-to-month and year-to-year—and climate impacts outside the scenario brackets (which encompass a very broad range of outcomes) may also occur. This study presents plausible climate futures for use in the subsequent vulnerability analysis, but the reader should avoid treating them as predictions.

Developing Climate Scenarios

Low, medium, and high climate change scenarios for 2050 and 2100 were developed for three general categories of climate variable:

- Sea level rise (SLR) and storm surge;
- Average changes in temperature and precipitation; and
- Changes in key extreme events.

Climate change scenarios illustrate plausible changes in future climate as the result of increased greenhouse gas emissions. Scenarios are not predictions and it is difficult to assign credible probabilities to them. Rather, given the significant uncertainties attending climate change, the scenarios bracket a reasonable range of potential outcomes, enabling decision-makers to develop appropriate responses. Climate scenarios are generally[11] comprised of three principal variables (which are applied to observed conditions):

- Emissions: Global greenhouse gas emission scenarios,
- Climate Models: Climate model outputs (or, where models are not used, a publically established planning threshold), and
- Year: Scenario analysis year or years.

Each scenario generated for temperature and precipitation was based on observed data from specific weather stations within or proximate to the Study Areas, and therefore this subsection concludes with a discussion of which stations were used and how they were chosen.

[11] The particulars of climate scenario development for each variable are considered in the explanation of approach and methodology accompanying that variable,

Emissions

The Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios established scenarios of change in greenhouse gas and sulfate aerosol emissions over the 21st Century for use in global climate modeling efforts. These scenarios encompass four basic narratives about potential futures—including demographic, social, economic, technological, and environmental aspects. The Partnership agreed to adopt the three most widely used emissions scenarios—A2, A1B, and B1—as its high, medium, and low scenarios, respectively. The narratives associated with the emissions scenarios are:

- A2 (High): Assumes a high level of population growth, but fragmented economic development and technology transfer. This is the highest emissions scenario considered in this study, but not the most aggressive within the IPCC suite of narratives.
- A1B (Medium): Assumes a high level of economic growth, relatively low population growth, and a mix of high- and low-carbon-emitting energy technologies. This is the medium emissions scenario considered in this study.
- B1 (Low): Assumes that global population growth peaks by mid-century and then declines, the rise of service and information economies, and the introduction of clean and resource-efficient technologies. This is the low emissions scenario considered in this study.

All three emissions scenarios are considered equally probable for the purposes of this analysis, although actual greenhouse gas emissions over the last decade have reflected a higher growth rate than any of these scenarios.

Climate Models

General Circulation Models, or GCMs, are complex numerical models that "make projections of the behavior of the atmosphere, the oceans, and climate, using state-of-the-art supercomputer" resources[12]. The IPCC Fourth Assessment Report (AR4) employed projections from 24 GCMs. Due to the inherent uncertainly of climate responses and methodological variances between models, the use of multiple models generated a broad range of potential climate outcomes at the regional level.

The project team chose 15 GCMs among an initial pool of 20 by assessing the ability of models to accurately simulate current climate—specifically, precipitation, which is generally more difficult to predict than temperature. Although the ability of a GCM to simulate current climate is no guarantee that the model will accurately predict future climate, this step is widely used to select models for use in the analysis of regional climate change. This comparison was performed for precipitation patterns at the global scale, as well as the continental and northeastern United States, with weights of 40%, 35%, and 25% assigned to each, respectively[13]. A natural break resulted in the adoption of the 15 best performing GCMs, and the remaining five were discarded. The remaining GCMs were then arrayed to display which

[12] Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ. http://www.gfdl.noaa.gov/model-development. Accessed 11/20/2011.

[13] See discussion in Appendix B.

ones project the most and least change in precipitation and temperature for New Jersey. A more detailed description of the GCMs and their ranking is provided in appendix B.

The Partnership sought to determine future climate impacts that would take into account the significant variation in both the climate models and emission scenarios, thereby addressing the uncertainty that underlies future climate estimations. The project team accomplished this by combining the low emissions scenario (B1) with the GCM with the least change in the climate variable of interest (lowest sensitivity), the middle emissions scenario (A1B) was paired with an ensemble (average) of all 15 GCMs, and the highest emissions scenario (A2) was coupled with the GCM with the largest change in the climate variable of interest, as shown in Table 4, below.

Table 4. Climate Change Scenario Composition

Emissions Scenario	Year	Emissions	GCM
Low (B1)	2050 and 2100	B1	Least change
Medium (A1B)		A1B	Ensemble of GCMs
High (A2)		A2	Most change

Year

The Partnership designated 2050 and 2100 as the climate analysis years. In actuality, these years represent the midpoint of a 30-year range, which corresponds to the historical period for which observed weather is considered (1971-2000). Projections reflect potential *average* climate over that span, not weather predictions for an individual year. Therefore, a scenario associated with 2050 represents the average of a given climate variable from 2035-2065—the lower end of which intersects with the current Long Range Transportation Plans of the New Jersey MPOs. 2100 is shorthand for 2085-2115, which, while well beyond the current transportation planning out year, is useful for considering potential impacts to long-term assets, such as bridges.

Climate Stations

Eight National Climatic Data Center stations were used in the analysis—four per Study Area. Climate stations were selected based on proximity to the relevant Study Area (either within or immediately adjacent to region), spatial location within the region (to provide good representative coverage), availability of data within the 1971–2000 baseline period, availability of climate variables needed for this analysis (e.g., precipitation, minimum and maximum temperature), and whether the period of record was represented with minimal missing (null value) days. The subsequent analysis often highlights projections associated with particular stations, one within each Study Area. Most frequently, the Atlantic City International Airport station (sometimes referred to as "Atlantic City") and New Brunswick 3 SE station ("New Brunswick") are used.

Coastal Region Climatic Data Center Stations (SW to NE):

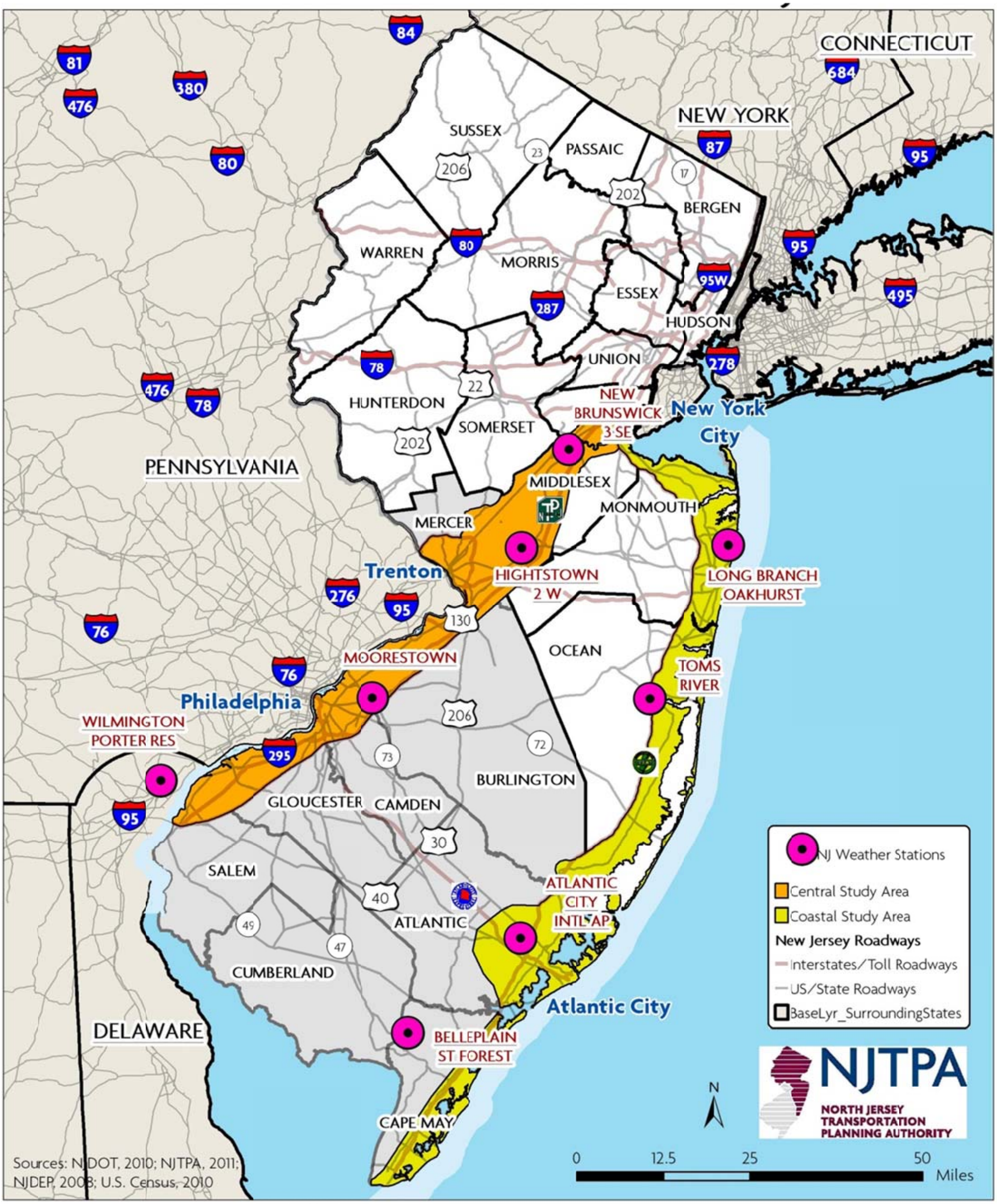
- Belleplain St Forest
- Atlantic City Intl Airport

- Toms River
- Long Branch Oakhurst.

Central Region Climatic Data Center Stations (SW to NE):

- Wilmington Porter Res
- Moorestown
- Hightstown 2 W
- New Brunswick 3 SE

Figure 8. Study areas and Climate stations used for analysis



Sea Level Rise and Storm Surge

The project team generated three sea level rise (SLR) scenarios for both 2050 and 2100. Locally-specific estimation of lands potentially inundated by SLR and storm surge in the future requires a complex analysis. The methodology employed for this project accounts for both the eustatic (global) and regional SLR from climate change models as well as local factors such as crustal movement, subsidence, and other characteristics that vary greatly along the coast. In addition, SLR projections were added to hurricane model output to estimate the added effects of storm surge. A geospatial analysis of potential inundation requires several datasets, including:

- Projections of SLR
- Historical SLR trend data from tide gauges
- Estimates of storm surge
- Digital Elevation Model

Estimates of Sea Level Rise

Three thresholds of total average global SLR by 2100 were modeled: 19.7 inches (50cm), 39.4 inches (100 cm), and 59.1 inches (150 cm)—thresholds selected in consultation with New Jersey DEP. These thresholds accord well with recent scientific literature (e.g., Rahmstorf, 2007; Pfeffer et al., 2008, Vermeer and Rahmstorf, 2009) which posits that late-21st century sea levels could be between 31.5 and 59.1 inches (0.8 and 1.5 m) above late-20th century observations, depending on the emissions scenario assumed. Projections of global average SLR by 2050 were approximated by using a tool developed by the National Center for Atmospheric Research (NCAR) to "calculate" SLR in 2100 corresponding to the NJ thresholds, and then taking the 2050 estimates for the same parameters (Wigley, 2008). Global SLR for both analysis years are represented in Table 5.

Table 5. Global Sea Level Rise Scenarios, in inches

Scenario	2050	2100
Low	6.1	19.7
Medium	10.5	39.4
High	14.6	59.1

To account for regional variability, GCM output was applied to the thermal expansion component of SLR. The GCMs serve as regional scalars to global mean thermal expansion, meaning, for example, that a scalar of 0.9, or 90%, results in the subtraction of 10% from the thermal component of SLR for the region in question (e.g. 9.8 inches global x 0.9 = 8.9 inches regional). To create a sufficiently broad bracket of SLR estimates, the lowest scalar of GCMs was applied to the low SLR scenario, the average scalar of models to the middle scenario, and the highest scalar of GCMs for the high SLR scenario, as follows:

- 19.7 inches by 2100: 10th percentile of GCMs
- 39.4 inches by 2100: ensemble of GCMs
- 59.1 inches by 2100: 90th percentile of GCMs.

The scalar average[14] was then multiplied by an estimate of global average SLR associated with thermal expansion under the middle emissions scenario, corresponding to 4.3 inches (0.36 ft) by 2050 and 9.8 inches (0.82 ft) by 2100. The remaining (non thermal) SLR was then added without application of the regional scalar.

To account for local land movement, a subsidence rate was calculated for several tide stations along the coast. Subsidence values were calculated by removing the historical average global SLR rate of 1.8 mm/yr (to which regional scalars were applied) from the long-term mean sea level trend at each station, as provided by NOAA. Subsidence rates are shown in Table 6.

Table 6. SLR trends and calculated subsidence rates for select tidal stations

Station name	SLR rate at gauge (mm/yr)	GCM regional scalar	Adjusted subsidence rate (mm/yr)
The Battery	2.77	1.06	0.86
Atlantic City	3.99	1.07	2.06
Cape May	4.06	1.06	2.15
Philadelphia	2.79	1.06	0.88
Reedy Point	3.46	1.06	1.55
Sandy Hook	3.9	1.06	1.99

Total subsidence was calculated for 2050 and 2100 at each station and interpolated into a surface of local subsidence. The surface was applied to the regional SLR estimates to obtain total relative sea level rise (RSLR) across the study regions. An example, depicted in Table 7, shows the subsidence, regional SLR, and estimated total relative SLR at the Atlantic City tidal station.

Table 7. Estimated relative sea level rise at Atlantic City tidal station, inches

Year	Scenario (2100)	Subsidence	Regional SLR	Tot Relative SLR[15]
2050	19.7	3.2	5.5	8.8
2050	39.4	3.2	11.1	14.4
2050	59.1	3.2	19.8	23.1
2100	19.7	7.3	18.3	25.6
2100	39.4	7.3	40.0	47.3
2100	59.1	7.3	64.4	71.6

Estimates of Storm Surge

Similar to SLR, storm surge estimates are highly site specific and vary because of differences in the coastal topography/bathymetry and local climatic patterns. To account for the potential effects of storm surge in the analysis years, this study utilized output from NOAA's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model for the Delaware Bay basin[16]. As agreed

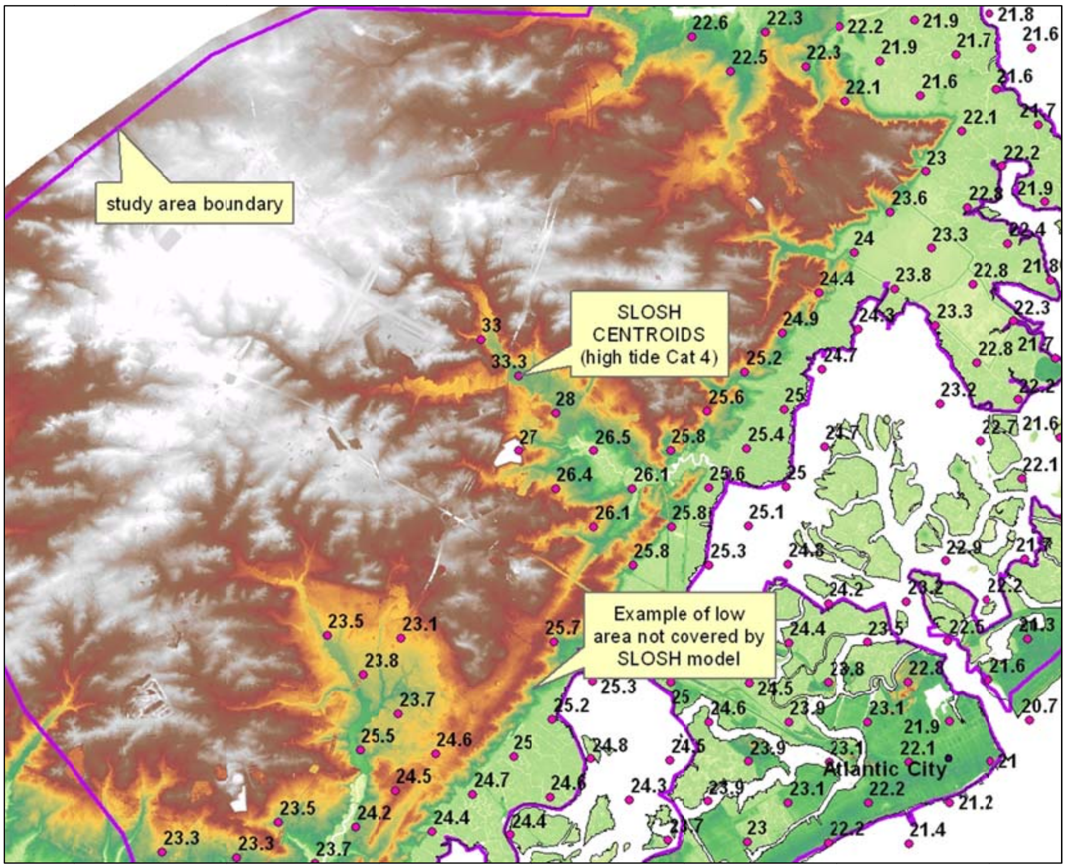
[14] Scalars for the coastal GCM spatial cells ranged from 0.83-0.91 for the low SLR scenario, 1.05-1.07 for the middle scenario, and 1.49-1.61 for the high scenario.

[15] All figures are converted from centimeters and may not sum due to rounding.

[16] The Delaware Basin provides coverage for both Study Areas.

by the NJ Partnership, the Category 1 high tide hurricane event was used[17]. The SLOSH model output was available as cells of variable size, the center points (centroids) of which were interpolated into a surface for geospatial analysis, as shown in Figure 9, below, projected on to an elevation surface. The maximum of the Maximum Envelope of Water, or MOM, was used for each cell, which means that each cell represents the most intense hurricane event simulated for that specific cell (the next cell over may display results from a separate event). Sea level rise was added to the resulting storm surge layer for each climate scenario and analysis year.

Figure 9. SLOSH Centroids[18]



Inland Flooding Assessment

The inland flooding assessment approach involved generating extreme climate variables as inputs into a statistical model, which was used to project future 1-in-100 year floodplains. This operation was performed for low, medium, and high scenarios (to represent a wide range of plausible outcomes) for both analysis years, for a total of six scenarios. Although the flooding

[17] By way of illustration, hurricane Donna (1960), one of the major storm events of the second half of the 20th century, passed off the southern coast of New Jersey as a Category 2 hurricane (but did not make landfall).

[18] This example shows a Category 4 event at high tide, a scenario that was not analyzed.

assessment was performed only for the Central Study Area, climate variables were derived for both Study Areas.

Climate Variables

Climate variables relevant to the production of the floodplains were generated for each Area and scenario. Projections were based on baseline daily climate station data, collected each for region for the baseline (1971–2000) and generated for years 2050 and 2100 under low-, mid-, and high-emissions scenarios. Each emissions scenario was applied to a select GCM or ensemble of GCMs, with the low emissions scenario paired with the GCM with the least change ("low"), the middle scenario with an average of all GCMs ("Mid"), and the high scenario with the GCMs with the most change for precipitation (daily GCM) and temperature (monthly GCM) ("high"), respectively (see

Table 8).[19]

Table 8. Climate change scenarios used in extreme event climate change analysis

Emission Scenario	Sensitivity (2X CO_2)	GCM
Low (B1)	2.7°F (1.5°C)	MIROCMED
Mid (A1B)	5.4°F (3.0°C)	GCM ensemble
High (A2)	8.1°F (4.5°C)	MRI-232A (precipitation)[20] or GISS-ER (temperature)

The climate extremes analysis employed climate modeling software (SimCLIM) to adjust daily climate station data for the analysis years, using either the applicable daily (for precipitation variables) or monthly (for temperature variables) GCM output The climate variables generated were:

- Total number of frost days annually (days below freezing),
- Maximum number of consecutive dry days annually (days),
- Maximum five-day rainfall during a given year (mm).

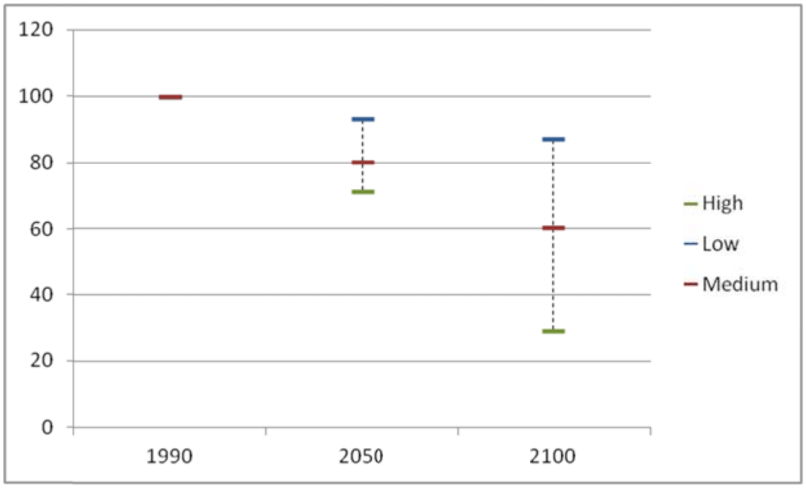
Frost days

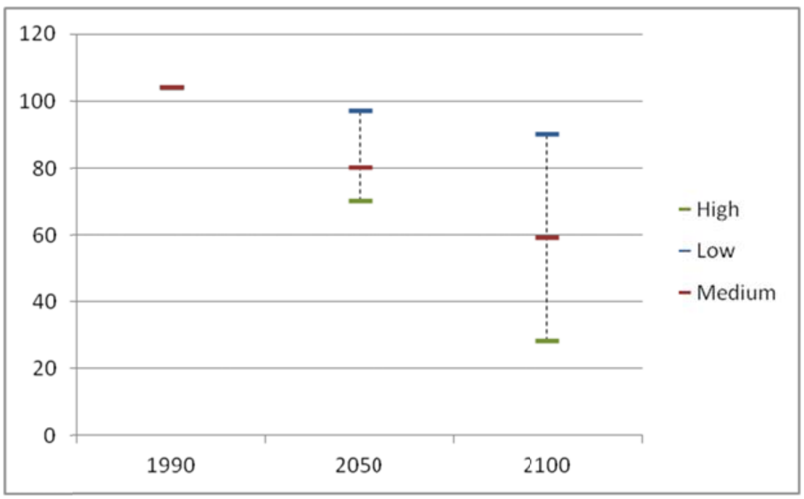
The number of potential future frost days was calculated using baseline (1971-2000) climate station data modified by changes in temperature predicted by climate change scenario and analysis year. The output is an estimated 30-year span of daily future climate projections (using the average change in climate for 2050 and 2100 applied to 30 years of observations from 1971-2000), from which the average number of frost days per year is then calculated.

[19] Of the 15 GCMs used for the *monthly* average analysis, only 11 *daily* GCMs were available for extreme precipitation analysis (monthly GCMs were used for temperature.

[20] GISS-ER is not a daily GCM, therefore the second most aggressive, MRI-232A is used.

Figure 5. Average annual frost days, 1990-2100 (T: Atlantic City; B: New Brunswick)[21]





Maximum number of consecutive dry days

The maximum number of consecutive dry days annually is calculated for each analysis year by applying estimated monthly changes in precipitation for each scenario to baseline climate station data (daily). An analog year from the baseline dataset was selected based on its similarity to the GCM estimated change in precipitation. Once the analog year is determined for each scenario, the number of consecutive dry days over the future analysis year is calculated by applying the appropriate delta (by climate scenario and year) to the analogue year For example, for analysis year2050, if the baseline analog year is 1984, the 1984 data is perturbed by the 2050 delta[22].

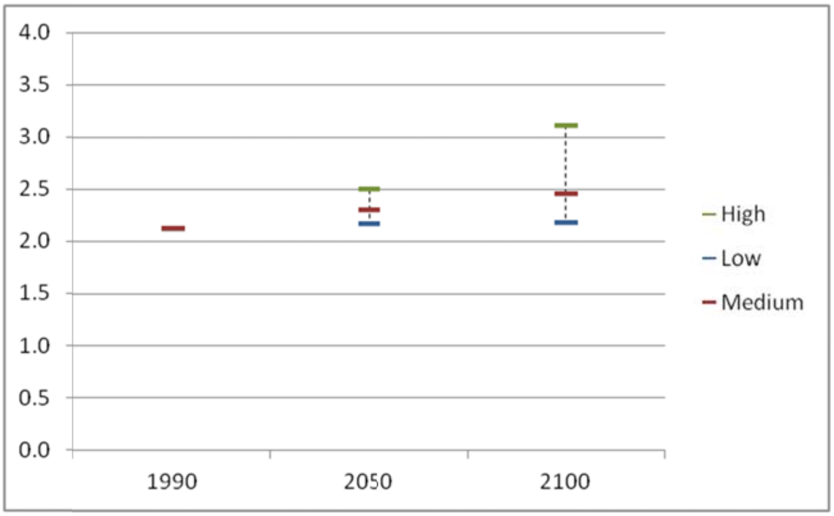
[21] In this and subsequent charts, the value associated with 1990 is shown using the Medium symbol (a red hash mark). This is because, as the baseline, there is only a single (observed) value, not an estimated value range.

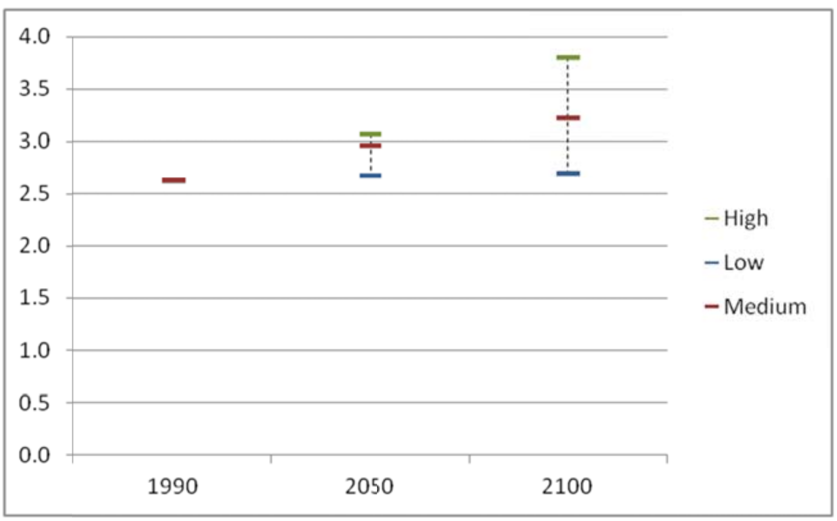
[22] Null values (not reported) represented an interruption in the calculation of "consecutive" days (i.e., consecutive days did not span null values).

Maximum five-day rainfall

The maximum five-day cumulative rainfall is derived by using daily GCM output to adjust the baseline climate data. Maximum five-day cumulative rainfall is expressed as the total precipitation (mm) over a five-day period expected to occur once per year over the 30-year average climate period.

Figure 11. Max annual 5-day rainfall (in), 1990-2100 (T: Atlantic City; B: New Brunswick)





Flooding Assessment

This portion of the assessment quantified the potential impact of climate change on the existing 1-in-100 year (1% chance) floodplain in the Central Study Area. This analysis used regression equations (National Regression Equations) currently being examined for a Federal Emergency Management Agency (FEMA) project.[23] This process created statistically generated potential floodplains corresponding to each emissions scenario for both 2050 and 2100.

Regression Analysis

One percent-annual-chance flood discharge was computed using the National Regression Equations. The equations required the climate variables generated previously, including:

- Total number of frost days annually (days below freezing),
- Maximum number of consecutive dry days annually (days),
- Maximum five-day rainfall during a given year (mm).

These parameter inputs were provided in grids, from which they were extracted and matched with FEMA Flood Insurance Study analysis points. Additionally, the equations required extreme discharge prediction variables, including:

- The drainage area of the watershed, (square miles),
- Channel slope (ft/mile),
- Storage in the watershed as represented by the area of lakes and ponds, as a percentage of the drainage area, and
- Impervious area, in percent of the drainage area (a function of population density, the growth of which is shown in Table 9).

For the current condition, these variables were estimated using the New Jersey StreamStats application, developed by United States Geological Survey (USGS) for extreme flood discharge and parameter calculation. For the analysis years of 2050 and 2100, the estimated population density[24] and climate parameters for those respective years were used. Extreme discharge prediction variables were obtained from StreamStats, and did not change from the base year. Although the northeastern portion of Salem County is within the Central Study Area, no riverine floodplain is located within this portion of the County.

[23] Thomas, Jr., Wilbert O., Kollat, Joshua B., Kasprzyk, Joseph R. (2010, March). *Effects of Climate Change on the National Flood Insurance Program in the United States – Riverine Flooding*.

[24] Population density was calculated using population projections for the study area counties provided by the three NJ MPOs.

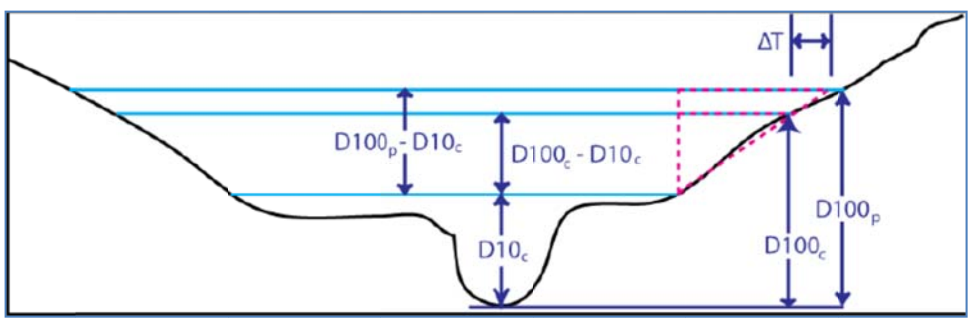
Table 9. Computing Population Density for the Central Study Area

County	2000 Pop	Area (sq. mi.)	2050 Population	%2050 Pop Density Change	2100 Population	%2100 Pop Density Change
Burlington	423,394	819	588,372	39%	745,600	76%
Camden	508,932	229	529,513	4%	545,608	7%
Gloucester	254,673	337	416,947	64%	575,522	126%
Mercer	350,761	229	423,416	21%	488,214	39%
Middlesex	750,162	323	1,072,449	43%	1,367,749	82%

A regression equation for estimating flood depths from flood discharges was also used in this analysis[25]. The equation was developed using data from over 11,000 cross sections across the United States taken from FEMA Flood Insurance Studies.

With current and predicted flows (for years 2050 and 2100) established, the changes in floodplain width at Digital Flood Insurance Rate Map (DFIRM) cross sections were estimated using similar triangle assumptions. Similar triangle is a mathematical formulation that relates sides to two triangles (demonstrated using red dot triangles in Figure 6). In this instance, the top width change and flood depth can be related using the similar triangle formulation.

Figure 6. Relation of Floodplain Top Width to Flood Depth (D= Depth, T= Top width)



The DFIRM cross-sections closest to stream discharge locations (identified using StreamStats) were attributed with the percent change in the floodplain top widths for all three scenarios in each analysis year. The percentage changes varied based on the flow predictions at a given stream discharge location.

[25] See Appendix C.

Average Climate Variables

For each Study Area, potential average temperature and precipitation were projected for 2050 and 2100 under three climate scenarios (low, medium, and high). As with all climate variables generated by this study, the lowest emissions scenario was applied to the least aggressive GCM (with the lowest projected change in precipitation), the Medium emission scenario to an average of 15 GCMs, and the highest emission scenario to most aggressive GCM (see Table 10).

Table 10. Climate change scenarios used in average climate change analysis

Emission scenario	Sensitivity (2X CO2)	GCM
Low (B1)	2.7°F (1.5°C)	MIROCMED
Mid (A1B)	5.4°F (3.0°C)	Ensemble
High (A2)	8.1°F (4.5°C)	GISS-ER

SimCLIM[26] climate modeling software was used to estimate average climate conditions (monthly, seasonally, and annually) for the following climate variables, for each weather station:[27]

- Minimum average temperature (°F),
- Maximum average temperature (°F),
- Mean average temperature (°F), and
- Average total precipitation (in).

Generally, the picture that emerges is that of a hotter, wetter New Jersey, with notable increases in annual rainfall coupled with increases in average temperatures. A summary of results, for the New Brunswick and Atlantic City weather stations under the Medium Scenario, is presented in Table 11.

Table 11. Annual Average Climate for Select Stations

	Precipitation (in)		Max. Temp (°F)		Min Temp (°F)	
Station Name	Base	Mid 2100	Base	Mid 2100	Base	Mid 2100
NEW BRUNS	48.7	52.8	62.8	69.4	42.8	49.3
ATLANT CITY	41.7	45.3	63.1	69.6	44.4	50.5

[26] Please see the Climate Information appendix for an explanation of SimCLIM's methods and parameters.
[27] Interpolated gridded cells at 800-m resolution were also generated, and are available as a data layer.

Extreme Event Climate Variables

Consistent with the technique established for inland flooding variables, extreme climate variables were generated for each Study Area and climate scenario based on climate station data for the historical baseline for years 2050 and 2100. As with the average climate change variable analysis, each emissions scenario was applied to a select GCM or ensemble of GCMs, as shown in Table 12, below, although for precipitation variables only the 11 GCMs projecting daily data were used (the remaining four make monthly projections only). The SimCLIM climate modeling software used GCM output (again, daily for precipitation and monthly for temperature[28]) to adjust daily climate station data for each analysis year and scenario combination (yielding six projections and one baseline).

Table 12. Climate change scenarios used in extreme event climate change analysis

Emission scenario	Sensitivity (2X CO2)	GCM
Low (B1)	2.7°F (1.5°C)	MIROCMED
Mid (A1B)	5.4°F (3.0°C)	Ensemble
High (A2)	8.1°F (4.5°C)	MRI-232A (precipitation) or GISS-ER (temperature)

The climate variables addressed include:

- Average annual number of days equal to or exceeding 95°F,
- Average annual number of days in which the temperature falls to or below 20°F, 10°F, and 0°F (frost days were calculated as flooding assessment inputs, presented previously),
- Average annual return period (years between events) of rainfall exceeding 1 in./day, 2 in./day, and 4 in./day,
- Maximum annual precipitation of 1-in-100-year rainfall event, and
- Average annual return period of historical 10-, 50-, and 100-year precipitation events.

<u>Hot Days</u>

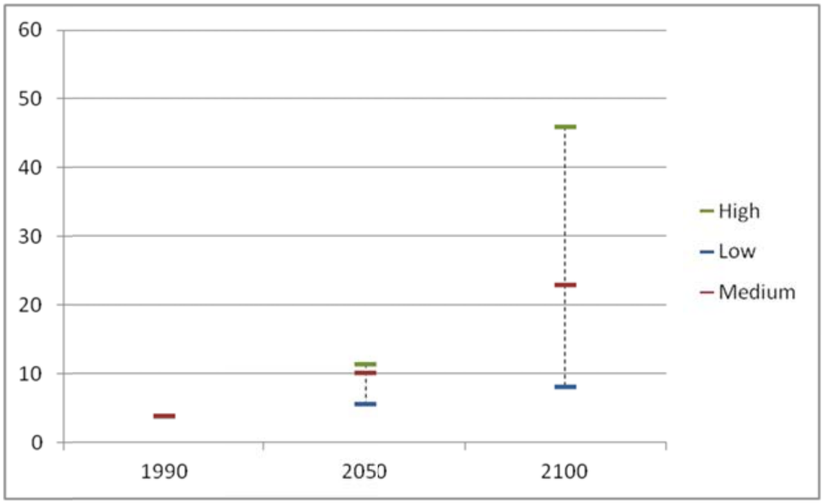
Generally, New Jersey can expect to experience more extremely hot days (reaching or exceeding 95°F) annually as the century progresses, although there will likely be significant variability from year to year. Under the Low scenario, growth will likely be gradual, and the change moderate. Under the Medium and High scenarios, extreme heat days are likely to become a much more common occurrence. Although neither extreme temperature thresholds of greater than 95°F nor the duration of extreme heat events were projected, a recent study focusing on New York City[29] projects 100°F days to increase from 0.4 days (or 1 day about every 2.5 years) to between two to nine days by the 2080s, and heat waves (three or more

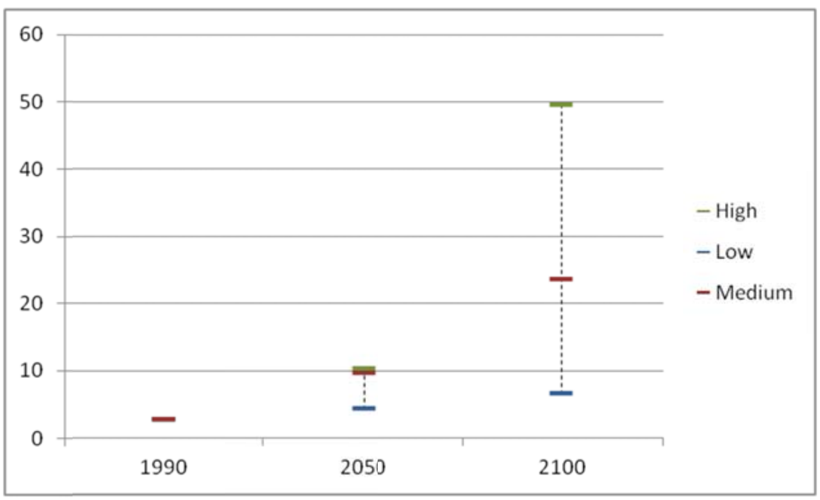
[28] As noted previously, daily GCM data is only available for precipitation variables, therefore, thermal variables are based on monthly GCM data (11 GCMs for precipitation variables and 15 GCMs for thermal variables)

[29] City of New York. *Climate Change Adaptation in New York City* (2010).

days with maximum temperatures exceeding 90°F) to increase from 2 per year (average duration 4 days) to 5 to 8 days per year (average duration of 5 to 7), also by the 2080s.

Figure 7. Average annual number of days equal to or exceeding 95°F, 1990-2100 (T: Atlantic City; B: New Brunswick)





Baseline average hot days (reaching or exceeding 95°F) were 3.8 days/year for Atlantic City and 2.8 days/year for New Brunswick. The Low scenario predicts modest growth throughout the century, with about 8 days predicted for Atlantic City in 2100, and almost 7 for New Brunswick. The Medium scenario predicts significant growth through mid-century (to about 10 days each location), and more rapid growth in the latter half of the century, ending at around 23 days each by 2100. The High scenario roughly tracks the Medium scenario for the first quarter century, then estimates slightly more rapid relative growth through the second quarter (to between 10 and 11 days by mid century), and exponential growth through the remainder of the century—finishing at between 45 and 50 days annually.

Cold Days

Consistent with projected increases in average minimum temperatures (by about 6°F for the Middle scenario in 2100), New Jersey may experience fewer annual frost days and extremely cold days—the State rarely sees 0°F currently (about once a year or slightly less in some locations), an event which becomes very rare under the High scenario for 2100. Average annual frost days, reported and graphed as part of the inland flooding section of this chapter, currently number 100 for Atlantic City and 104 for New Brunswick. Under the Medium scenario, both decrease to about 80 days in 2050, and 60 days in 2100. The High scenario projects slightly fewer than 30 days for both weather stations.

Rainfall

For the average annual rainfall return periods (1", 2", and 4") and 1-in-100 year rainfall event values, a Generalized Extreme Value (GEV) curve was fitted to the data derived by SimCLIM for the baseline and future scenarios. The corresponding annual return periods or absolute amounts were then taken from the curve. Adjusted return periods for current 10%, 2%, and 1% precipitation events were derived by first finding the absolute current values of those events from baseline data and then comparing them to future projections.

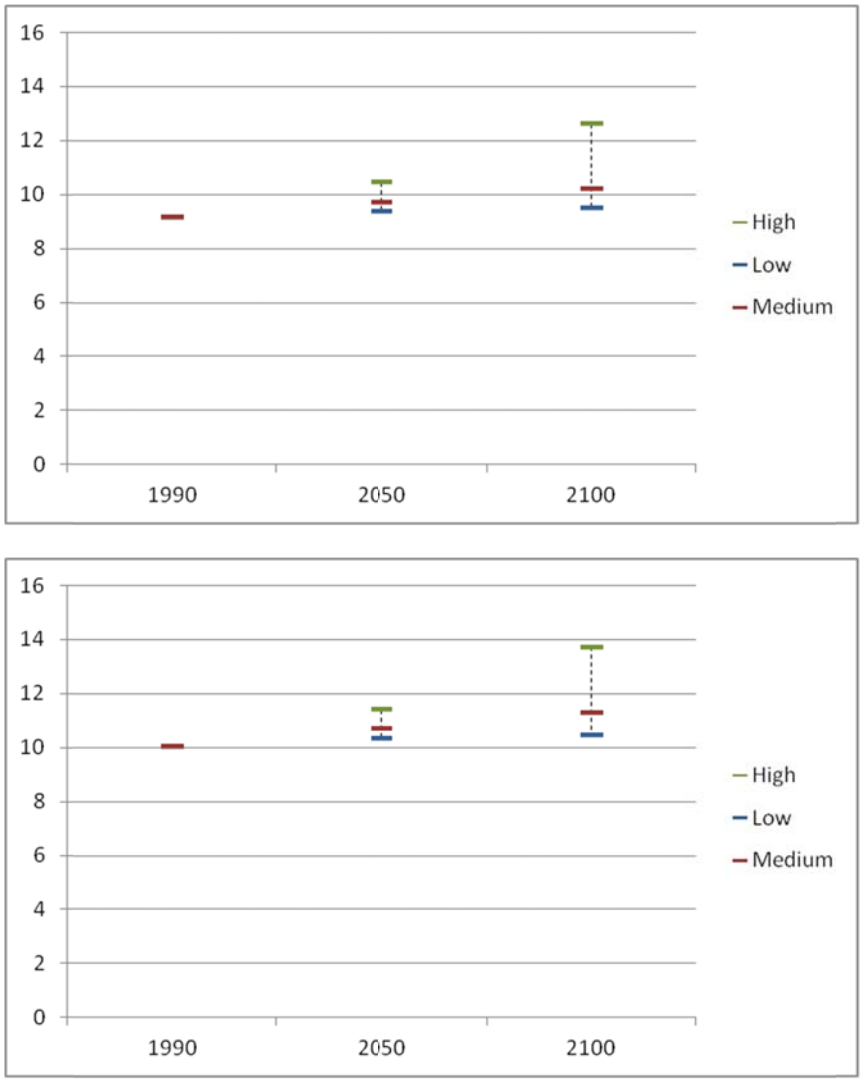
In the analysis years, the intensity of the heaviest rainfalls is projected to increase. The 1-in-100 year event (more properly considered the 1% annual chance event), for example, is projected to yield more absolute rainfall as the century progresses.

The current 1-in-100 year (1%) rainfall event delivers over 9 inches of rain at the Atlantic City weather station, and over 10 inches in New Brunswick. The Low and Medium scenarios track closely to one another over the course of the century, gaining approximately ½ inch and 1½ inches by 2100, respectively, for both weather stations. The High scenario shows significant departure from Low and Medium by 2050, and is significantly higher by 2100: about 12 inches for Atlantic City and 14 inches for New Brunswick. By comparison, the New Brunswick weather station rainfall totals coincident with the arrival of Tropical Storm Irene in late August 2011 yielded 8.02 inches of rainfall over 3 days from August 27-29).[30]

Extreme events are also expected to increase in frequency. A storm event delivering at least 4" of rain in a 24-hour span (greater than any single day associated with Irene), for example, could have decreasing return periods as the century advances. This is to say that the interval between such events could shrink substantially.

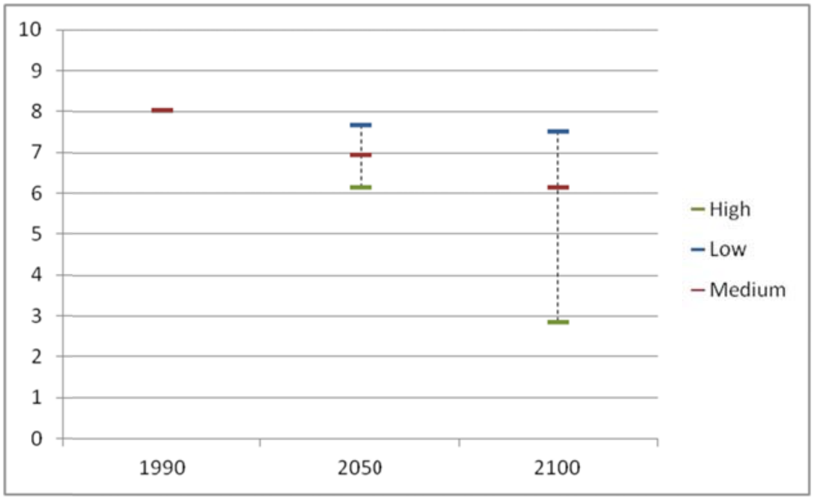
[30] Email communication, NJ State Climatologist (11/26/2011).

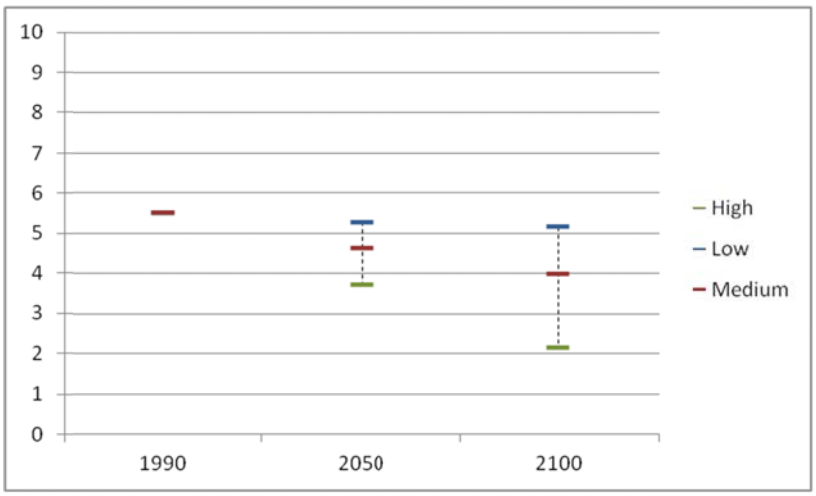
Figure 8. Maximum annual precipitation (in) of 1-in-100-year rainfall event, 1990-2100 (T: Atlantic City; B: New Brunswick)



24 hour rainfalls exceeding 4 inches have historically occurred once or twice per decade on average (currently an 8 year return period for Atlantic City and a 5.5 year return period for New Brunswick). Each scenario showed shrinking return periods throughout the century, with the Low scenario showing less than a year drop for each station in 2100, and Medium showing about a year drop by 2050 for each, widening to a two year drop for Atlantic City (to about 6 years) and a 1.5 year drop for New Brunswick (to about 4 years) in 2100. The High scenario projects that these significant rainfall events could occur with much greater frequency by 2100—an average of every 3 years for Atlantic City and 2 years for New Brunswick.

Figure 9. Average annual return period (years) of rainfall exceeding 4 inches, 1990-2100 (T: Atlantic City; B: New Brunswick)





Limitations of the Data and Analysis

The overarching limitation of all climate change information is uncertainty, particularly as the analysis year extends into the future—the relatively narrow ranges for 2050 estimates, as compared to 2100 estimates, reflect greater consensus as to what kind of climate 2050 will bring. The project team considers uncertainty to be a significant, but inevitable, condition of this type of analysis. Further, the IPCC AR 4 emissions scenarios, which date from 2007, were used and, although they represent the best science available at the time, are due to be replaced by the next generation of emissions scenarios (AR 5) by 2014.

All climate variables relating to temperature and rainfall use historical weather station data as a base input, and therefore all future variables are specific to these stations. The project team chose the stations that provided the best combination of continuity (in terms of records) and coverage for each Study Area. However, historical weather data inescapably contains mistakes or null values (unrecorded days). Nor can eight weather stations provide a comprehensive picture of potential climate (and microclimates) over the two Study Areas, which cover in excess of 1,000 square miles, cumulatively.

Due to the scale of the inland flooding assessment, flood plain top-widths were adjusted statistically, not hydrologically (which would be based on actual elevation data). The impervious surface variable used in the flooding regression equation calculated population density based on projected growth, but did not consider potential changes in land use patterns or building materials.

Finally, SimCLIM, the climate modeling software used, cannot provide rainfall totals for periods of less than 24 hours, nor can it generate events with recurrence periods of less than a year. Climate impacts that stem from multiple variables, like freeze-thaw cycles or snow, also cannot be derived from climate software, although sometime inferences as to the directionality of these effects can be made (significantly fewer frost days likely indicate reduced snow days).

Vulnerability and Risk Assessment

The objective of this task was to provide the NJ Partnership with a realistic, robust assessment of critical assets and infrastructure that may be vulnerable to climate stressors (some of which may increase in frequency and/or severity in the future). As this study was performed on a large scale (over vast and varied spatial extents and considering an array of modes and asset types), the assessment process relied on a GIS based analysis in which climate data and impacts were spatially overlaid on transportation assets—and to which information on observed vulnerabilities was applied.

Methodology

The FHWA Conceptual Model provided a valuable framework for addressing vulnerability and risk. Effectively, the Model's recommended decision points were translated into a sequence of fundamental questions that, when answered through GIS analysis and/or professional knowledge, provided a depiction of potential vulnerability:

Is it critical?

This step, accomplished in tandem with the Asset Inventory task, permitted the application of greater emphasis on critical assets during the presentation of potential impacts.

Is it vulnerable?

This study treated vulnerability as a composite of two primary factors: the potential for a given climate stressor to impact a particular asset and the resiliency (or adaptive capacity) of the asset to that stressor.

Potential impacts

For stressors like sea level rise, storm surge, and inland flooding, potential impact is a two-layered determination, considering 1) the possible exposure of assets to inundation under each climate scenario and 2) the potential effects of inundation on the asset. For stressors without a spatial expression conducive to mapping, like extreme temperature or rainfall, exposure may be considered temporally (frequency or return periods, as provided previously).

Potential *exposure* was determined based on spatial overlay analysis of inundation extents (representing sea level rise, storm surge or inland flooding scenarios) with transportation assets in a GIS environment. Inundation extents were originally created in raster format—which convey both extent and depth (these layers are available from NJTPA). They were converted to polygons (vector format) to facilitate the spatial impact analysis, which involved an "intersect" analysis of inundation polygons and transportation lines or points. This technique extracts assets that geometrically intersect with the inundation polygons, generating new feature classes representing assets potentially impacted by inundation. The extents of impacted transportation assets are entirely coincident with intersecting areas of inundation. Those sections may then be mapped and exported as tabular outputs, cross-referencing tiers of criticality and fundamental attributes, such as functional classification (FC).

Potential *effects* are more difficult to quantify, as it is difficult to draw direct linkages between stressors (whether spatial stressors like inundation or temporal stressors like extreme temperatures) and potential damage or disruptions. Although specifications and operating ratings offer significant insight into potential vulnerabilities, failure can occur well before or well beyond these thresholds, and is highly dependent on other circumstances, including regular maintenance and upkeep of the asset. The kinking of railroad track, for example, may occur at temperatures exceeding 95°F—but does not always and will not affect every type or segment of track equally. The project team approached this aspect of vulnerability assessment by leveraging the knowledge of various divisions at NJDOT and NJ Transit, the principal asset owners and operating agencies represented on the NJ Partnership.

Resiliency/Adaptive Capacity

An asset is not necessarily highly vulnerable just because it is potentially impacted or exposed, however. If an impacted asset is relatively unaffected (physically or temporally) or can be quickly restored, the impact itself may be of minor importance. The operating agency interviewees were asked about potential immediate and short-term adaptive responses to plausible climate stressors—ranging from maintenance and monitoring to emergency construction. This integrated consideration of impacts and resiliency/adaptive capacity allowed the project team to better understand the potential vulnerability of assets and operations to specific stressor scenarios.

What is the risk?

Risk assessments typically integrate considerations of the magnitude of impacts with the probability of occurrence—which in this case is a function of both potential climate hazards and the likelihood of asset vulnerability. Climate change scenarios are not associated with specific probabilities, so a climate change risk assessment requires both scientific guidance and policy input.

Although this study does not delve deeply into issues of risk, per se—instead identifying a broad range of *potential* vulnerabilities—the information generated for this project will permit NJ agencies, regions, and counties to better define risks for their assets within the study areas, if they so choose. In the absence of true failure probabilities, the project team recommends coupling criticality tiers with climate scenarios—pairing the most critical assets with the most aggressive scenarios, and the least critical with the least aggressive scenarios. This way, assets that absolutely must not fail are assessed in relation to the most severe plausible climate impacts[31]. Although, due to resource constraints, the project team performed the analysis of all assets—at all three tiers of criticality—in relation to a single (Medium) scenario, future assessment efforts could generate multiple maps and tables (with varied criticality-scenario combinations) to better understand the range of potential implications of climate change on multiple tiers of critical assets. The accompanying geodatabase contains all layers necessary for this assessment, and specific GIS analysis methodologies are included in the technical documentation (Appendix A).

[31] Another common practice is to assign a qualitative risk metric (e.g. 1-5, with 1 being not likely at all, and 5 being very likely) for both climate stressors and asset impacts, which allows the agency to assess risk numerically without assigning precise probabilities. This process can also be performed using a risk matrix, with tiers of "likelihood of impact" on one axis and "magnitude of consequence" on the other. This technique was recently employed by the New York City Panel on Climate Change.

Digital Elevation Model

In order to facilitate inundation analyses from sea level rise (SLR), storm surge, and inland (riverine) flooding, an elevation surface, called a Digital Elevation Model (DEM), was established for the entire extent of each Study Area. The DEMs were assembled from various LiDAR[32] (Light Detection and Ranging) data sets created for USGS or FEMA. Horizontal resolution was three meters or better (often two meters, or 6.56 ft.), and vertical accuracy meets FEMA standards. The DEMs were processed on a county-by-county basis using ESRI ArcGIS software, with edges matched to minimize sharp elevation changes at county boundaries. A complete explanation of the DEM preparation methodology is included in Appendix C.

Table 13. LiDAR summary information, by Study Area and county

County	LiDAR Source (Year)	Leaf on/off [33]	Vertical Accuracy	Horizontal Accuracy
Study Area: Central				
Burlington	FEMA (2004)	On	36.58 cm	<48.8 cm
Camden	FEMA (2004)	On	36.58 cm	<48.8 cm
Gloucester	N/A[34]	N/A	N/A	N/A
Mercer	FEMA (2000)	N/A	Est. 23.23 cm	N/A
Middlesex	USGS (2007)	Off	18.5 cm	1 m
Salem	USGS (2009)	Off	29.4 cm	1 m
Study Area: Coastal				
Atlantic	FEMA (2010)	On	<18 cm	60 cm
Cape May	USGS (2008)	Off	13-16 cm	1 m
Lower Monmouth	FEMA (2010)	On	<18 cm	60 cm
Upper Monmouth	USGS (2007)	Off	18.5 cm	1 m
Ocean	FEMA (2010)	On	<18 cm	60 cm

Analysis of Potential Exposure

The subsequent vulnerability maps for sea level rise, storm surge, and inland flooding identify potentially impacted assets across all three criticality tiers for the Medium scenario (A1B, ensemble of GCMs), and are accompanied by tabular outputs, which present the potential extent of impacts across criticality tiers and roadway types, as well as rail categories. To enhance legibility, each stressor-analysis year scenario (e.g., SLR 2050) is depicted with a series

[32] LiDAR involves the generation of multiple optical pulses from an aircraft, which, when reflected from an object back to the receiver, are translated from return time to distance (location is measured using corrected GPS). An elevation surface is composed of a multitude of processed pulses.

[33] LiDAR collected during late spring, summer, and early autumn—periods during which deciduous trees have leaves—is "leaf on," whereas late fall, winter, and early spring collections are "leaf off."

[34] N/A indicates that this metadata does not exist; however the source data meets FEMA guidelines and specifications.

of four maps: separate roadway and rail maps for each Study Area. Although the maps are designed to convey various types of information, explained in the accompanying legend, the most important feature is "rail/roadways potentially impacted." This is represented using thick lines on a green color scale, overlaid on relevant segments of the transportation network. The darkest green lines symbolize extremely critical infrastructure (such as NJ Transit lines, Class 1 freight rail, and major roadways), while lighter shades express lower tiers of criticality[35].

A few important caveats apply to each category of inundation analysis, and should be taken into account when considering the impact analysis results:

- **Bridges:** NJDOT bridges were incorporated in the transportation asset geodatabase, but, in their native format, register as points, rather than lines or polygons. Although the project team constructed a NJ roadway bridges line file by joining Straight Line Diagram beginning bridge mileposts with National Bridge Inventory/NJ DOT BMS data on deck lengths, this file only includes a small selection of minimum bridge underclearance data (for navigable waterways). Without consistent elevation data, this bridge file was not applied when conducting the intersections analysis. Even if a roadway segment crossing a flooding polygon can be identified as a bridge, without known elevations it is still considered *potentially* impacted—either due to scour, deck corrosion, overtopping, or flooded approaches. The assessment of specific assets is partially supported in the accompanying geodatabase by turning on the bridge layer file (point or line) or orthographic photos and zooming in on the bridge approaches, which, if they display as potentially inundated, would impact bridge functionality regardless of deck elevations.
- **Rail:** Both Study Areas show a high degree of overlap between freight and passenger rail lines, a product of shared rail rights of way. The inundation maps often represent a nested impact profile for tracks/right of way supporting a highly critical service (all passenger and Class 1 freight rail) and a less critical service (Class 2 & 3 rail). Because line weights for more critical rail service are slightly thinner and on a higher layer, both dark green and lighter green impact lines are shown in this case.
- **PATCO:** The PATCO high speed service from Philadelphia, PA to central New Jersey is included on rail maps, but the associated GIS line file was created by the project team, and includes no attribute data. Therefore, PATCO was not included in the impact analysis.
- **NJ Transit Bus:** NJ Transit bus routes overlap as polyline features. Therefore, reported lane miles for impacted bus miles are route miles and not physical highway centerline miles. An impact on a highly traveled segments can register large route mileage increases.
- **Evacuation Routes:** Originally, all evacuation routes were to be allocated to the top criticality tier. However, given the multitude of designated routes, especially in the Coastal Study Area, a separate intersection analysis was performed for the evacuation route line file. Although many evacuation routes were coincident with CMS routes (regardless of their criticality designation), a number minor roadways excluded from

[35] Only one airport was potentially impacted, which is represented using a yellow circle containing the silhouette of a plane. Airports that are not expected to be impacted, or which lie outside the Study Areas, are represented as black silhouettes if they possess at least one runway of 5,000 feet or more.

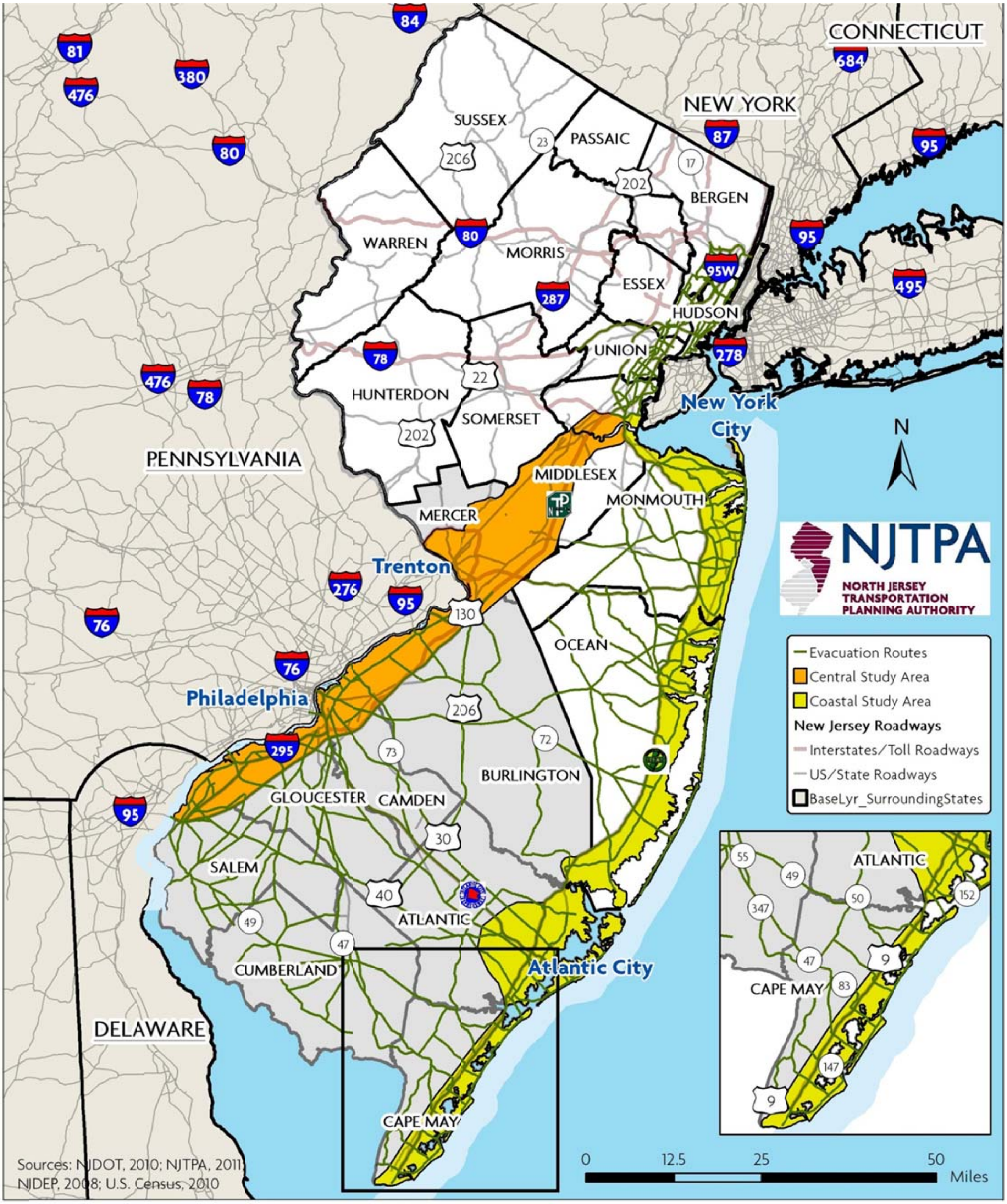
the CMS were designated evacuation routes. These are depicted as thin, dark green lines in the impact maps. A full map of the evacuation routes is included in Figure 10.

To provide context for the associated tabular outputs, the extent of major transportation systems for each Study Area is shown in Table 14.

Table 14. Extent of major transportation infrastructure, by Study Area (in miles)

Study Area	Rail Lines	Highways
Coastal Study Area	88.8	1,849.7
Central Study Area	420.8	2,950.3

Figure 10. Evacuation Routes in or intersecting the Study Areas



Sea Level Rise

In the middle and later portions of this century, transportation infrastructure in proximity to the New Jersey coast may be impacted by sea level rise, or SLR. SLR, unlike the storm surge and inland flooding scenarios also considered in this section, is a gradual phenomenon. SLR is expected to become steadily more evident as the decades pass, first by exacerbating storm events, then by causing impacts during king tides[36], and finally, in certain areas, by causing frequent or permanent inundation. Potential impacts would vary significantly due to differences in topography, land cover, and the built environment. For example, in low lying areas with minimal existing shoreline protection (e.g., sea walls, dikes) or wetlands, areas inundated by SLR may be quite large. In areas with steep coastline profiles or existing shoreline protection, exposure is likely to be limited.

Along with storm surge, the SLR estimates presented in the following maps for 2050 and 2100 were overlaid onto the Digital Elevation Model in order to delineate uplands likely to be submerged and to determine the potential depth and extent of inundation[37]. The DEM, which was originally referenced to the North American Vertical Datum of 1988 (NAVD88), was converted to mean higher high water (MHHW)[38] based on tide gauge data. Because the MHHW value was relative to the 1983–2001 tidal epoch, the mean SLR trend at each station was used to correct the MHHW value to the year 2010. The final DEM used for SLR and surge inundation analysis is therefore relative to MHHW.

In identifying uplands at risk of being submerged, only areas with a direct connection to the sea were considered in the inundation analysis. Inland areas below sea level but not connected directly to the sea were not included. Because the DEM did not always extend into rivers and ocean areas outside the study areas—which were often important to determining the hydrological connectivity of lands within the study areas—the U.S. Geological Survey (USGS) National Hydrography Dataset was used to supplement the DEM. Upland areas connected to the Delaware River or Atlantic Ocean (for the Central and Coastal Study Areas, respectively) were used to create a layer delineating areas of potential inundation. These layers, which cover SLR and surge for all three scenarios (low, medium, high) for both 2050 and 2100, were utilized subsequently in the transportation infrastructure vulnerability intersection analysis depicted in the following maps.

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[36] Particularly high tides coinciding with the arrival of new and full moons.

[37] Again, only the extent of potential inundation is shown in the maps presented in this report, although inundation depth data layers are available.

[38] "The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch" NOAA. http://tidesandcurrents.noaa.gov/mhhw.html. Accessed 11/20/2011.

Figure 11. SLR 1 Meter Scenario, 2050, Central Study Area (Roadways)

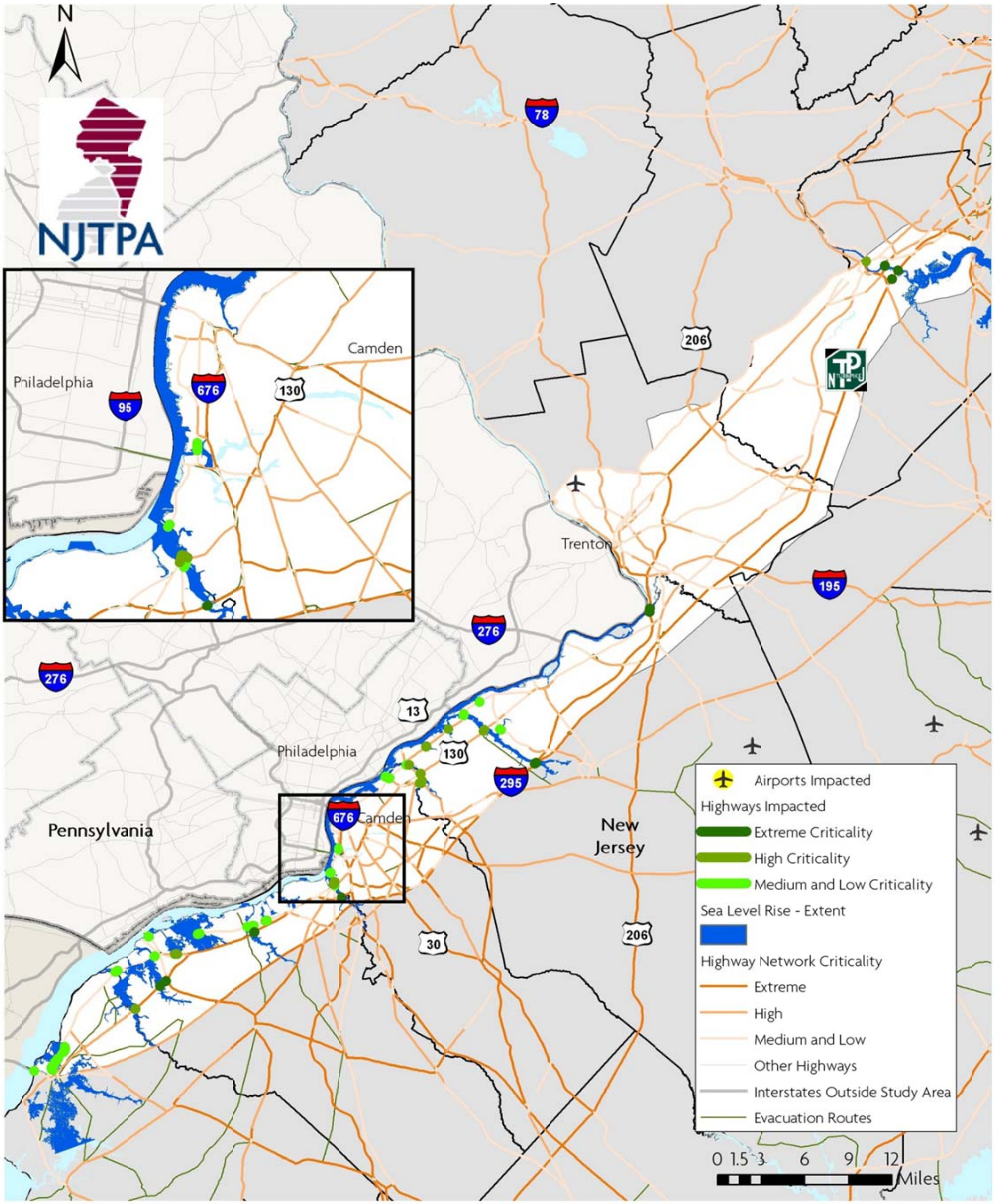


Figure 18. SLR 1 Meter Scenario, 2100, Central Study Area (Roadways)

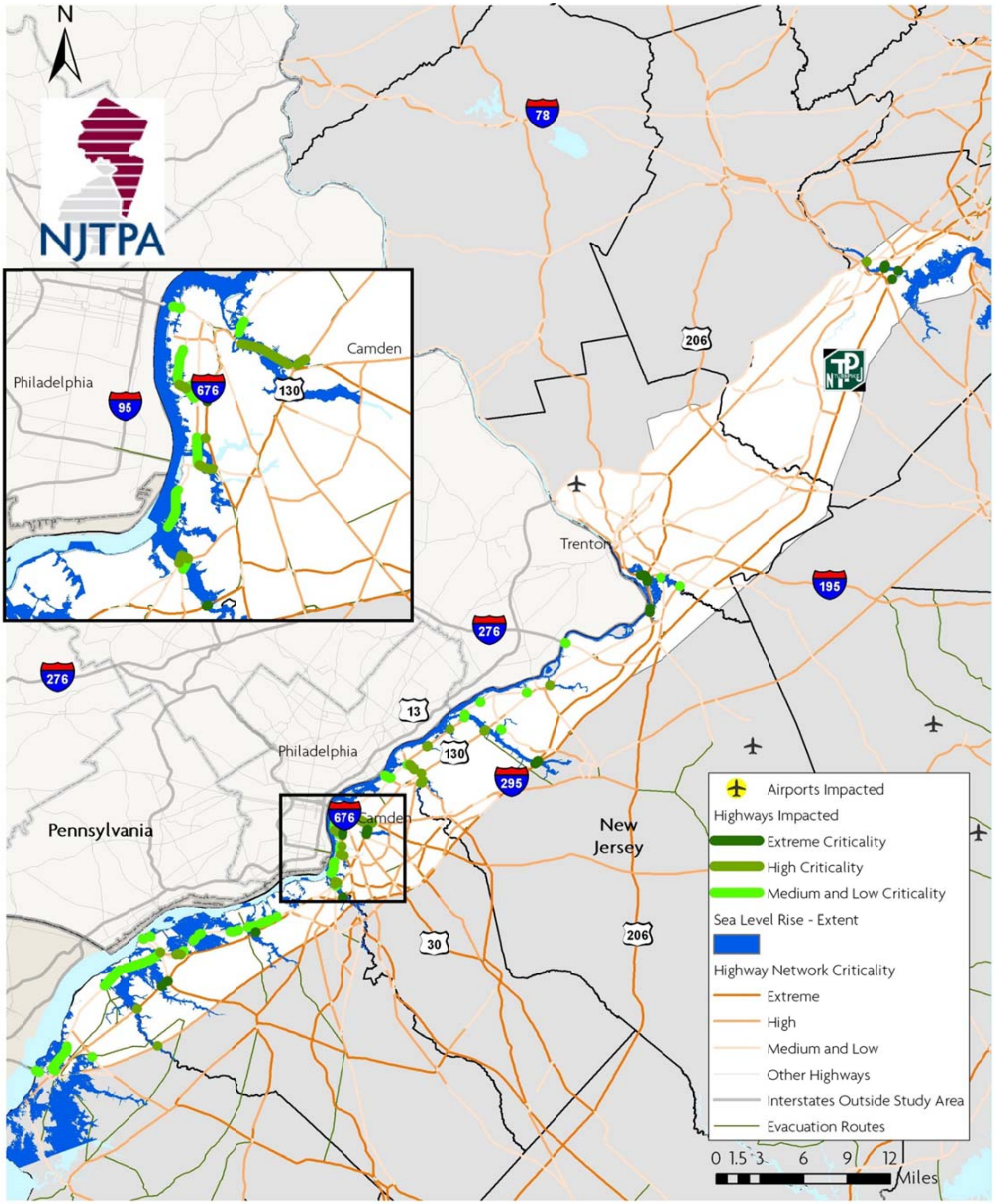


Figure 19. SLR 1 Meter Scenario, 2050, Central Study Area (Rail)

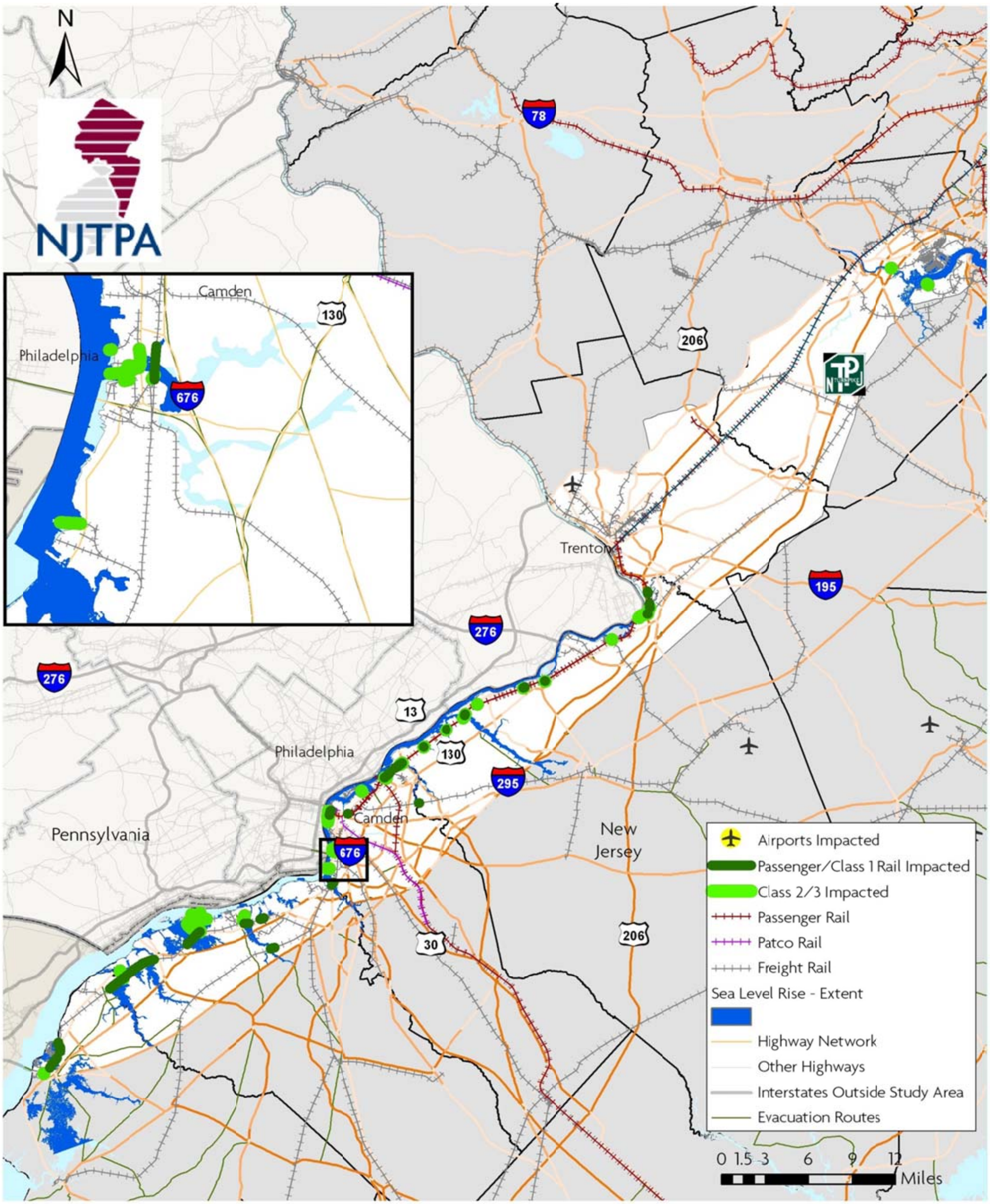
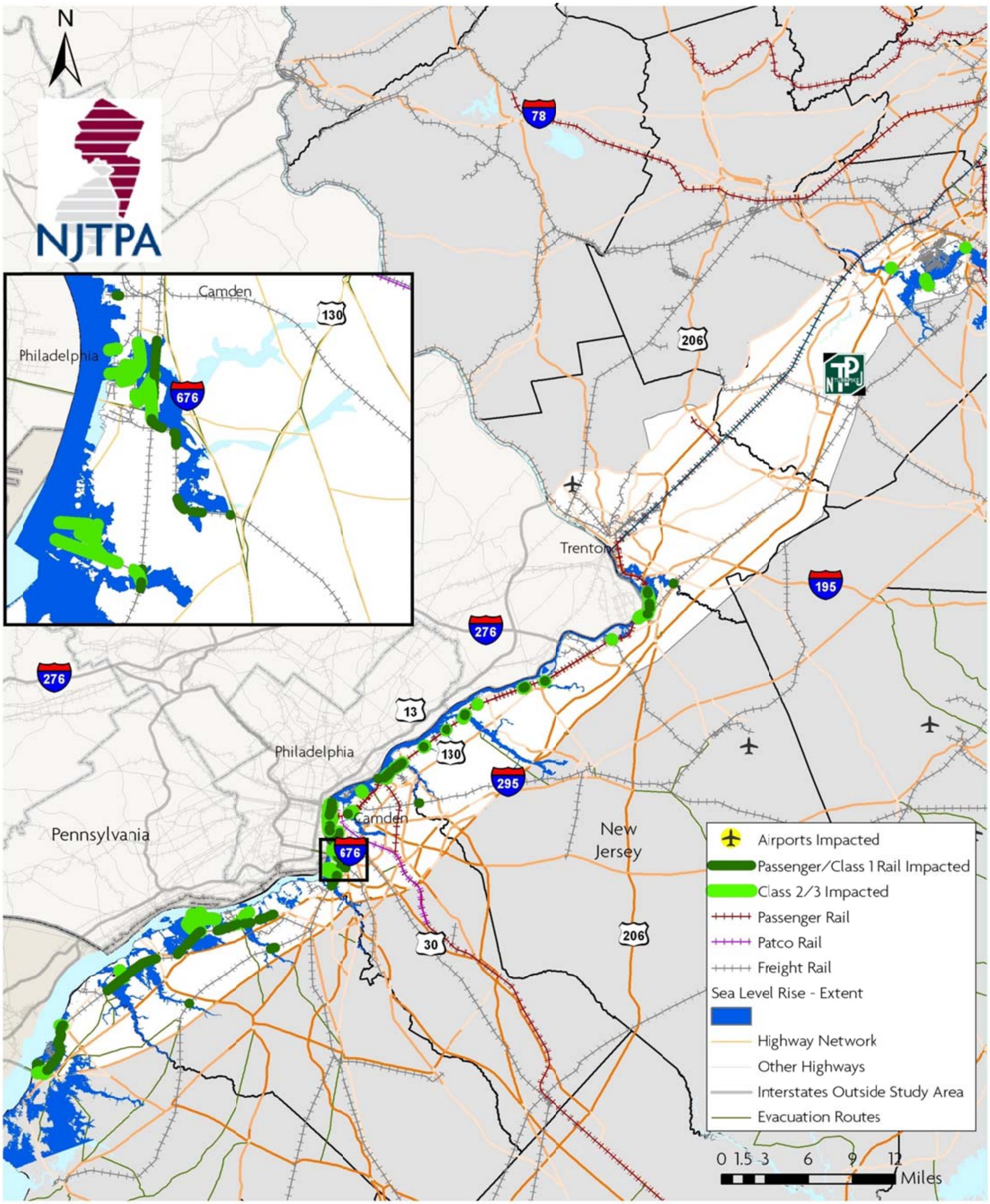


Figure 12. SLR 1 Meter Scenario, 2100, Central Study Area (Rail)



Sea Level Rise: Central Study Area Potential Impacts (Medium Scenario)

Under the Medium scenario (39.4 inches or 1 meter of global SLR, adjusted to local relative SLR using thermal data from the A1B model and observed subsidence data), few extremely critical assets are potentially impacted in the Central Study Area (just over one mile, cumulatively, of major urban highways). However, nearly 9 miles of evacuation routes are potentially vulnerable, along with almost 260 NJ Transit bus route miles—a potentially significant burden on public transit users[39].

Table 15. SLR 1 Meter, 2100, Central Study Area (Roadways).

Roadway Type	Criticality Tier			Total	Increase from 2050
	Extreme	High	Med/Low		
Major Urban	1.36	2.38	1.02	**4.76**	3.35
Minor Urban	0.00	0.17	6.43	**6.60**	5.05
Major Rural	0.00	0.03	0.04	**0.07**	0.03
Minor Rural	0.00	0.17	2.35	**2.52**	2.39
Total	**1.36**	**2.75**	**9.84**	**13.95**	**10.82**
Evacuation Routes				**8.66**	6.36
NJ Transit Bus Routes				**259.59**	220.15

Many rail lines are situated on low-lying lands proximate to the Delaware River. Several small segments of the River Line (some of which may correspond to bridges) would be potentially vulnerable in 2100, along with significant portions of freight track, both Class 1 and below. With the exception of Amtrak (for which no impact is shown), there is a significant increase in vulnerable track miles for all rail types between 2050 and 2100.

Table 16. SLR 1 Meter, 2100, Central Study Area (Rail).

Rail Type	Miles	Increase from 2050
NJ Transit	1.4	1.1
Amtrak	0.0	0.0
Class 1 Freight Rail	14.3	7.9
Class 2& 3 Freight Rail	34.7	18.6
Total	**50.4**	**27.7**

[39] Because multiple bus routes may travel over the same roadway segment, bus “route miles” impacted are often significantly greater than “centerline miles” impacted.

Figure 13. SLR 1 Meter Scenario, 2050, Coastal Study Area (Roadways)

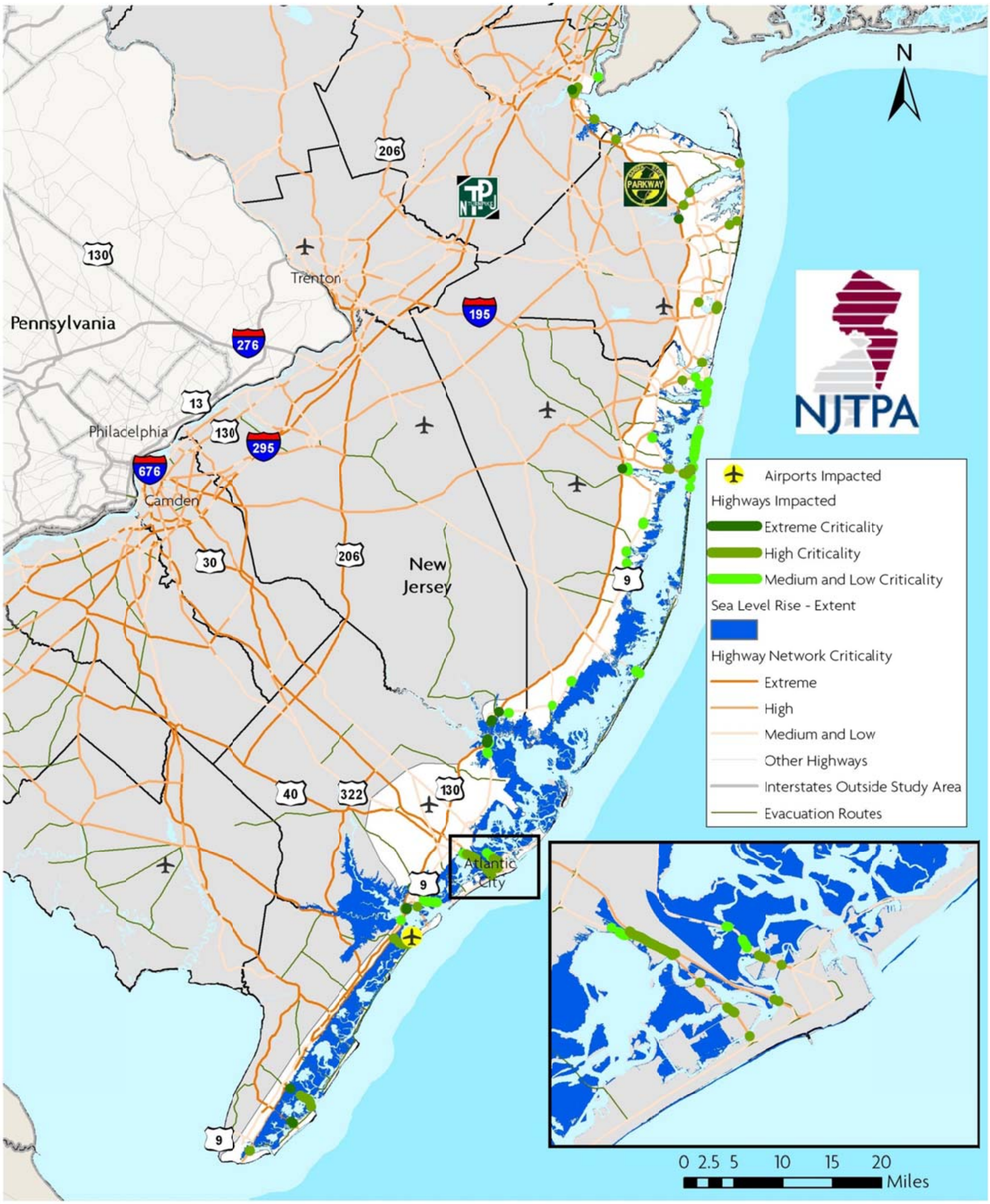


Figure 14. SLR 1 Meter Scenario, 2100, Coastal Study Area (Roadways)

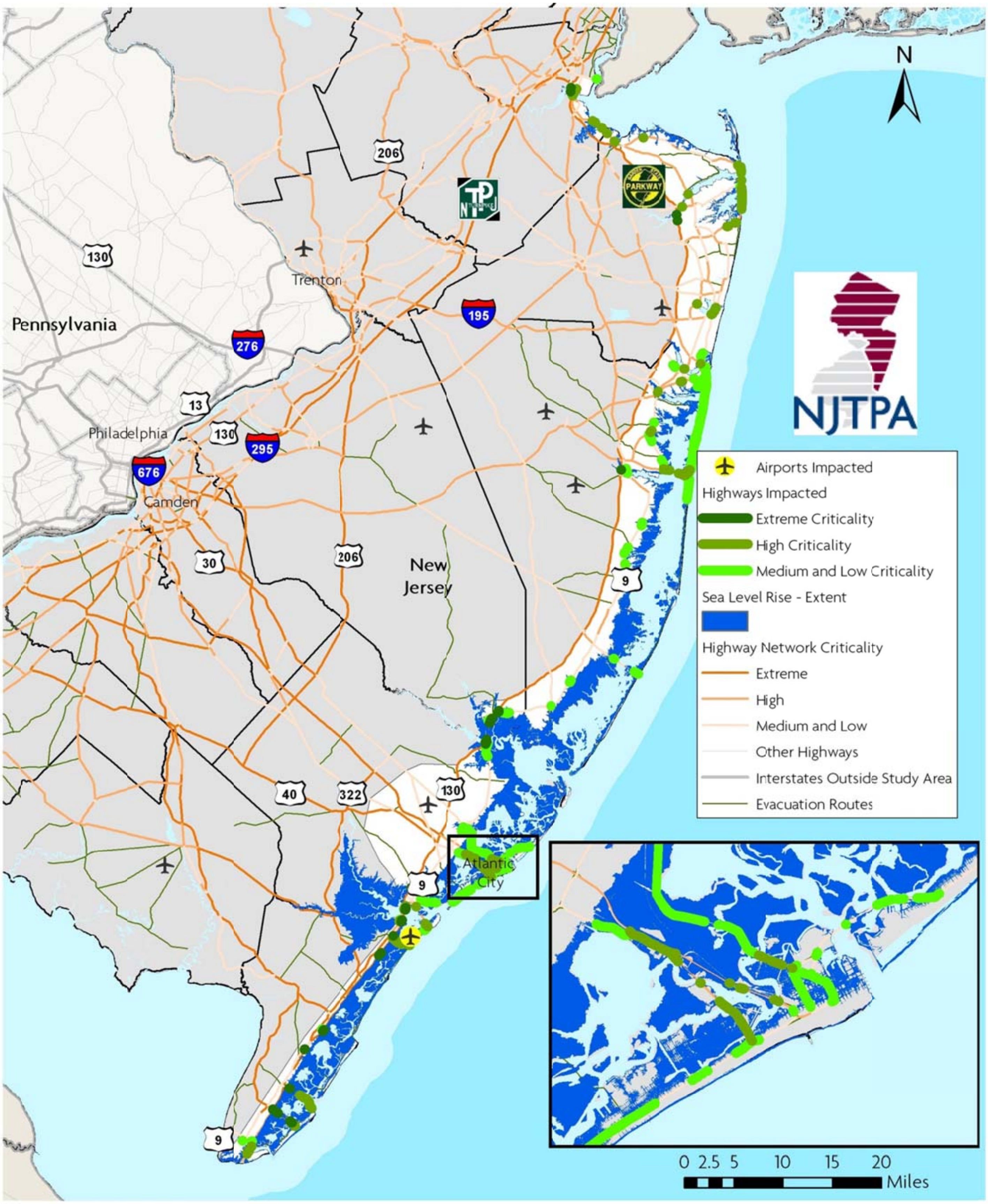


Figure 15. SLR 1 Meter Scenario, 2050, Coastal Study Area (Rail)

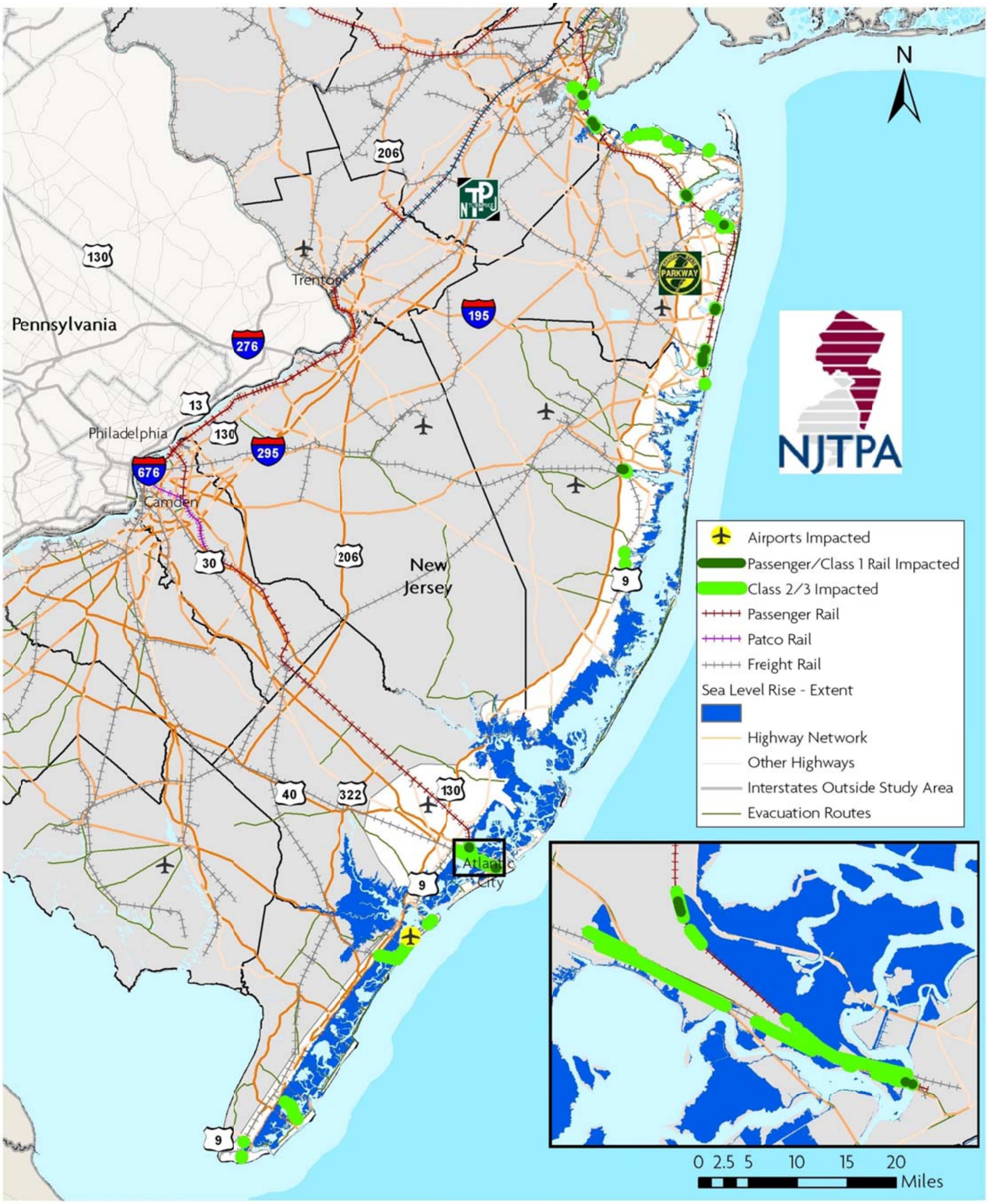
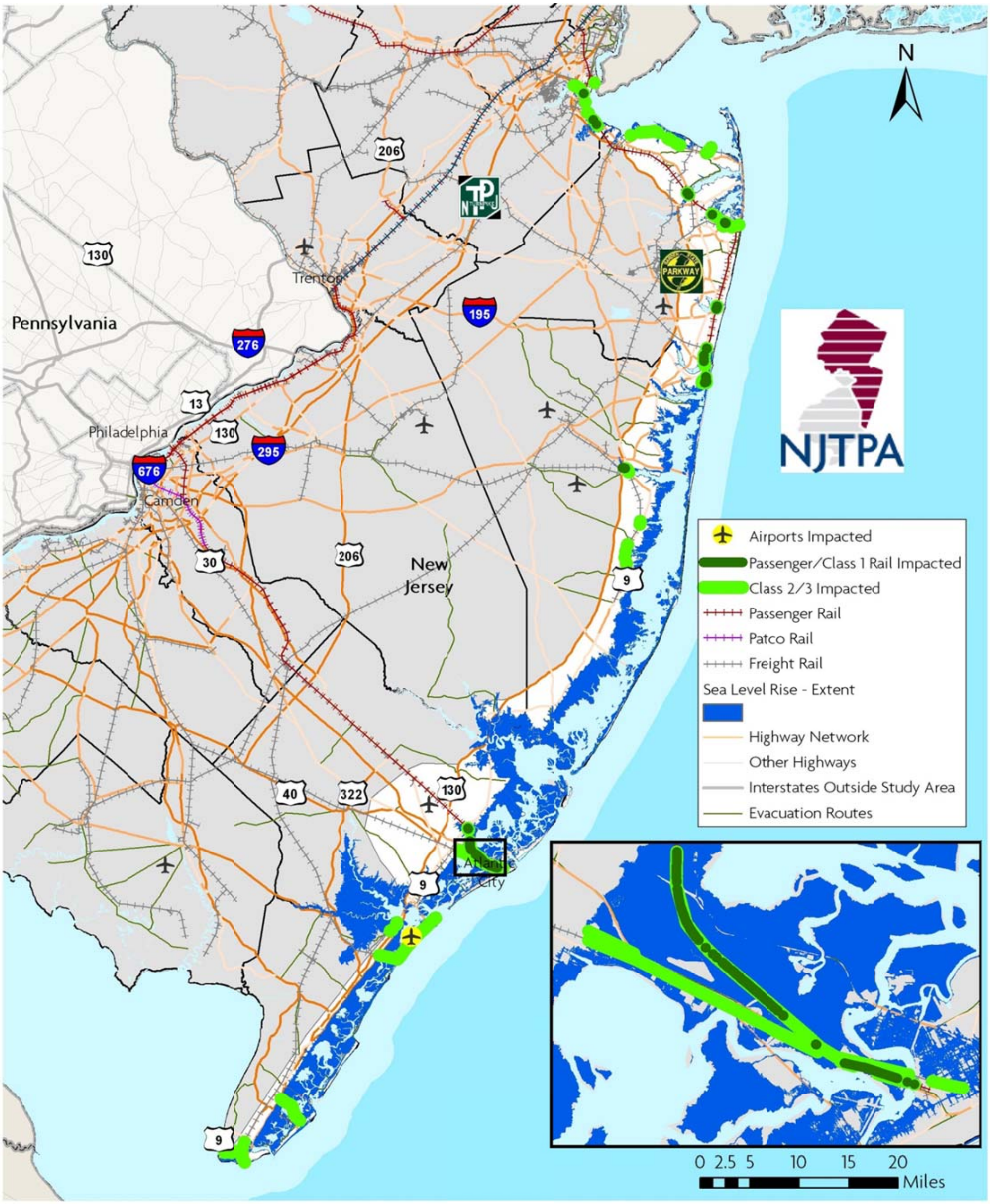


Figure 16. SLR 1 Meter Scenario, 2100, Coastal Study Area (Rail)



Sea Level Rise: Coastal Study Area Potential Impacts (Medium Scenario)

The Coastal Study Area SLR scenario shows limited vulnerability of extremely critical roadway assets in 2100, although the Garden State Parkway and its principal redundant route (9W) may be subject to inundation in a few key locations (particularly northeast of Atlantic City). If both of these assets were to fail simultaneously, there would likely be major network impacts. In addition, significant centerline mileage in less critical tiers could be vulnerable, especially key entry points to Atlantic City and the northern Jersey Shore.   In addition, a large quantity of evacuation routes and NJ Transit bus routes could be affected.

Table 17. SLR 1 Meter, 2100, Coastal Study Area (Roadways).

Roadway Type	**Criticality Tier**			**Total**	**Increase from 2050**
	Extreme	High	Med/Low		
Major Urban	0.75	11.69	28.50	**40.93**	29.62
Minor Urban	0.02	0.30	3.93	**4.26**	3.57
Major Rural	1.26	0.00	0.14	**1.40**	0.89
Minor Rural	0.00	0.00	1.83	**1.83**	1.19
Total	**2.03**	**11.99**	**34.40**	**48.42**	**35.27**
Evacuation Routes				**86.90**	71.50
NJ Transit Bus Routes				**657.88**	623.18

NJ Transit's North Jersey Coast line shows points of potential vulnerability to SLR as far north as the Raritan River, as does the Atlantic City Line as it enters Atlantic City.

Table 18. SLR 1 Meter, 2100, Coastal Study Area (Rail).

Rail Type	**Miles**	**Increase from 2050**
NJ Transit	2.9	2.8
Amtrak	0.0	0.0
Class 1 Freight Rail	0.2	0.1
Class 2& 3 Freight Rail	28.1	18.9
Total	**31.1**	**21.8**

Storm Surge

As noted previously, storm surge was estimated by adding potential sea level rise to SLOSH model outputs. The Maximum of the Maximum Envelope of Water, or MOM, was used, which shows the most intense hypothetical storm (among potentially thousands) simulated for each SLOSH inundation cell. Therefore, the overall SLOSH polygon, crafted from a collection of cells, shows a collection of intense storms—not a single storm event.

In many scenarios, little apparent difference registers between the spatial extent of inundation from SLR and that of potential storm surge polygons with the addition of SLR, especially when viewed at the Study Area scale. The reason for this is that the SLOSH output generated by NOAA is based on current sea levels rather than predicted SLR. Therefore, only those cells that are currently impacted by the SLOSH model will have any impact on SLR projections—resulting in significantly increased depths, but only nominal polygon expansion. Accordingly, the tabular impact analysis is not replicated for SLOSH, as the outputs closely resemble those of the corresponding SLR scenario.

It is recommended that subsequent study efforts consider using Highest Observed Water Level (HOWL) at each tide station to adjust SLR polygons by a static amount. Although HOWL encompasses only recorded events, and not simulated maximums at multiple storm angles like SLOSH, a multiple could be used to adjust HOWL to reflect the potential for more intense storms and more damaging storm angles (e.g., HOWL x 1.5). Finally, SLOSH could be run based on future SLR scenarios, but generating new MOMs requires simulating thousands of storms—a task best undertaken by NOAA.

Figure 17. SLR (Blue) Overlaid on Storm Surge (Purple), Atlantic City (2050)

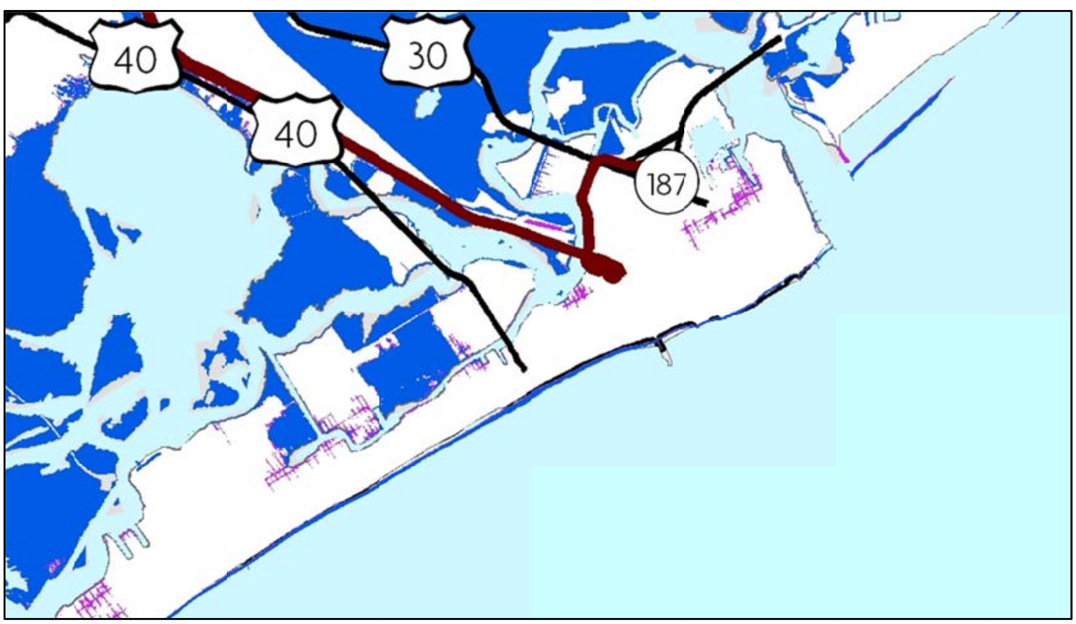


Figure 18. Storm Surge, SLR 1 Meter Scenario, 2050, Central Study Area (Roadways)

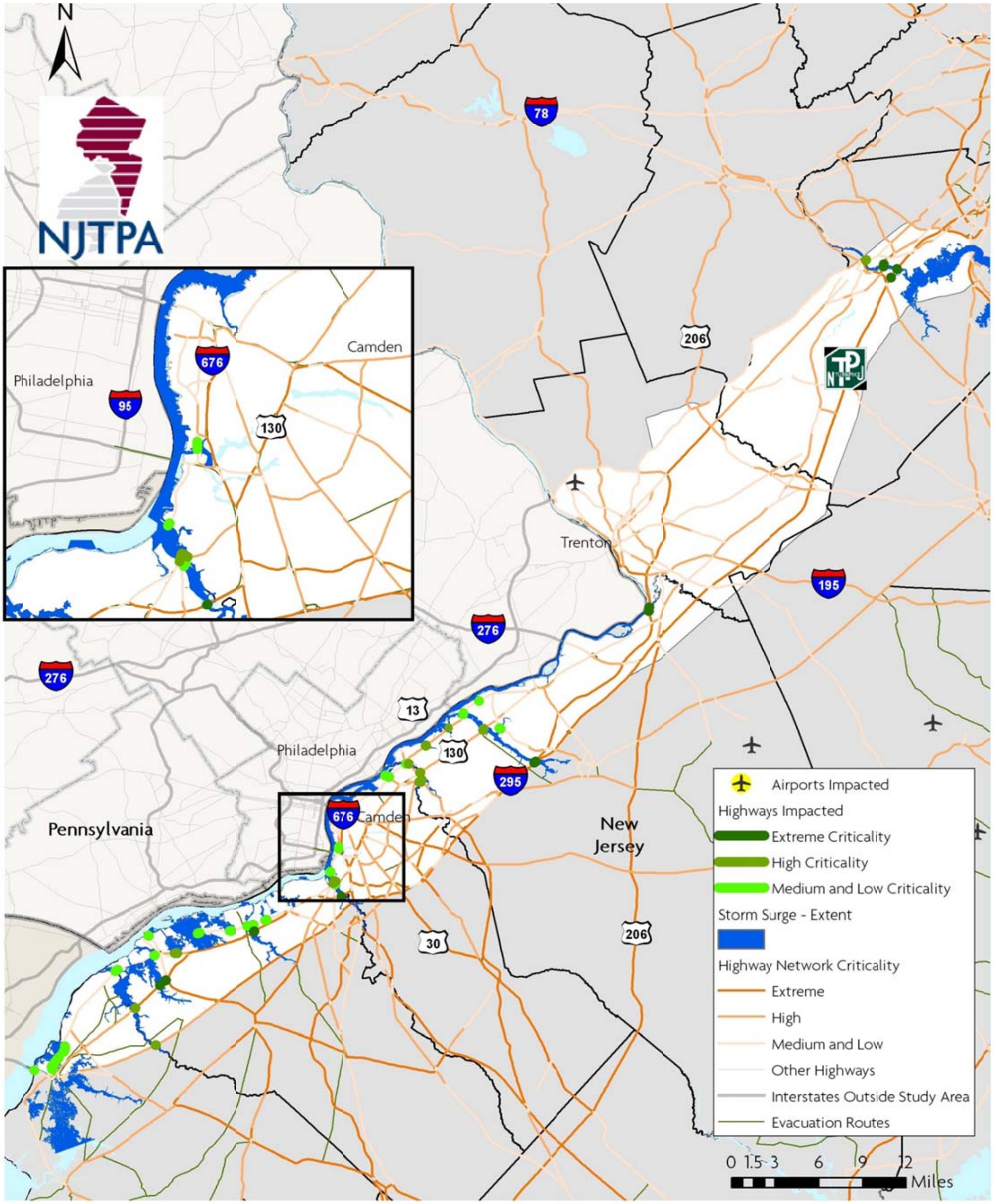


Figure 19. Storm Surge, SLR 1 Meter Scenario, 2100, Central Study Area (Roadways)

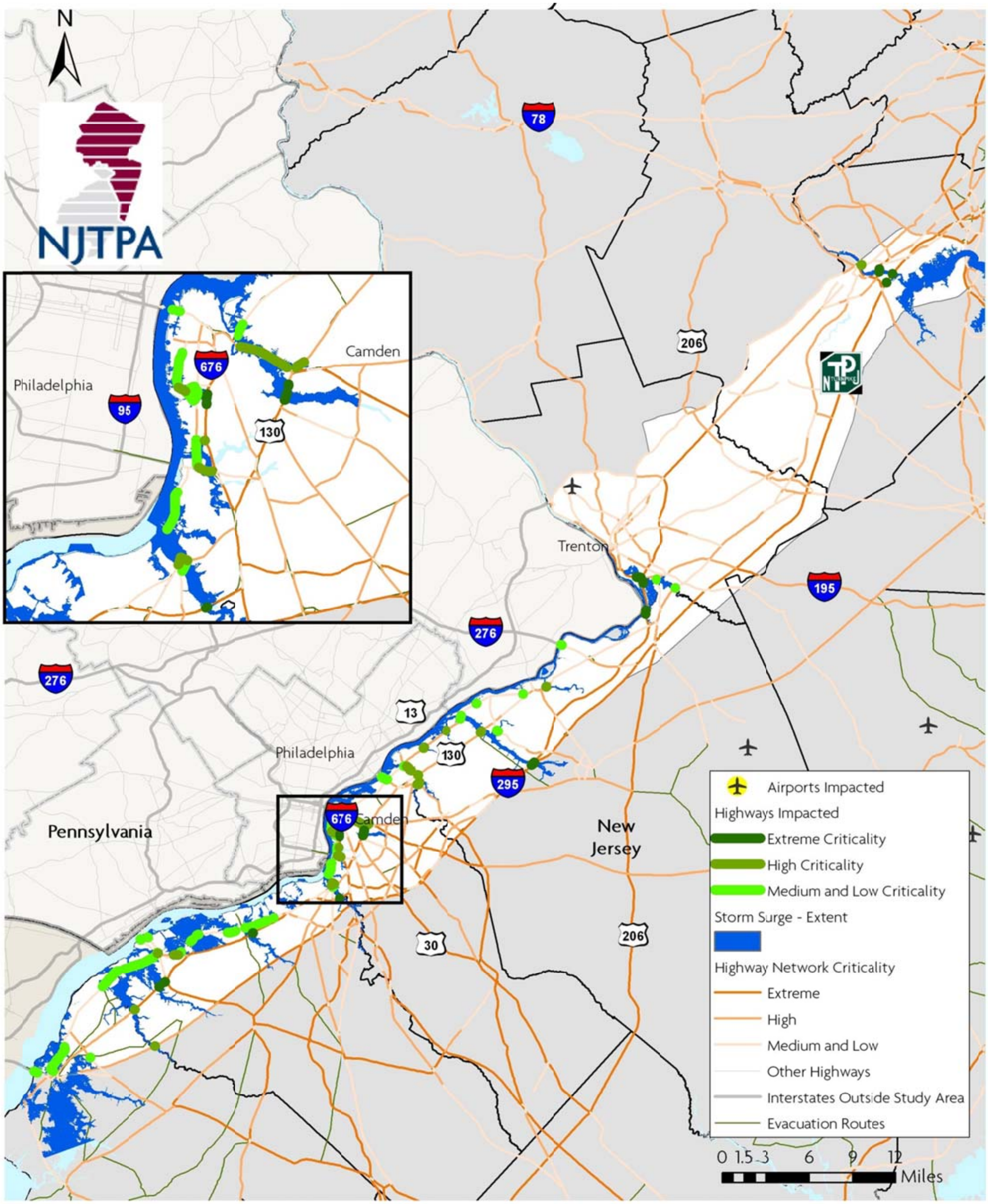


Figure 28. Storm Surge, SLR 1 Meter Scenario, 2050, Central Study Area (Rail)

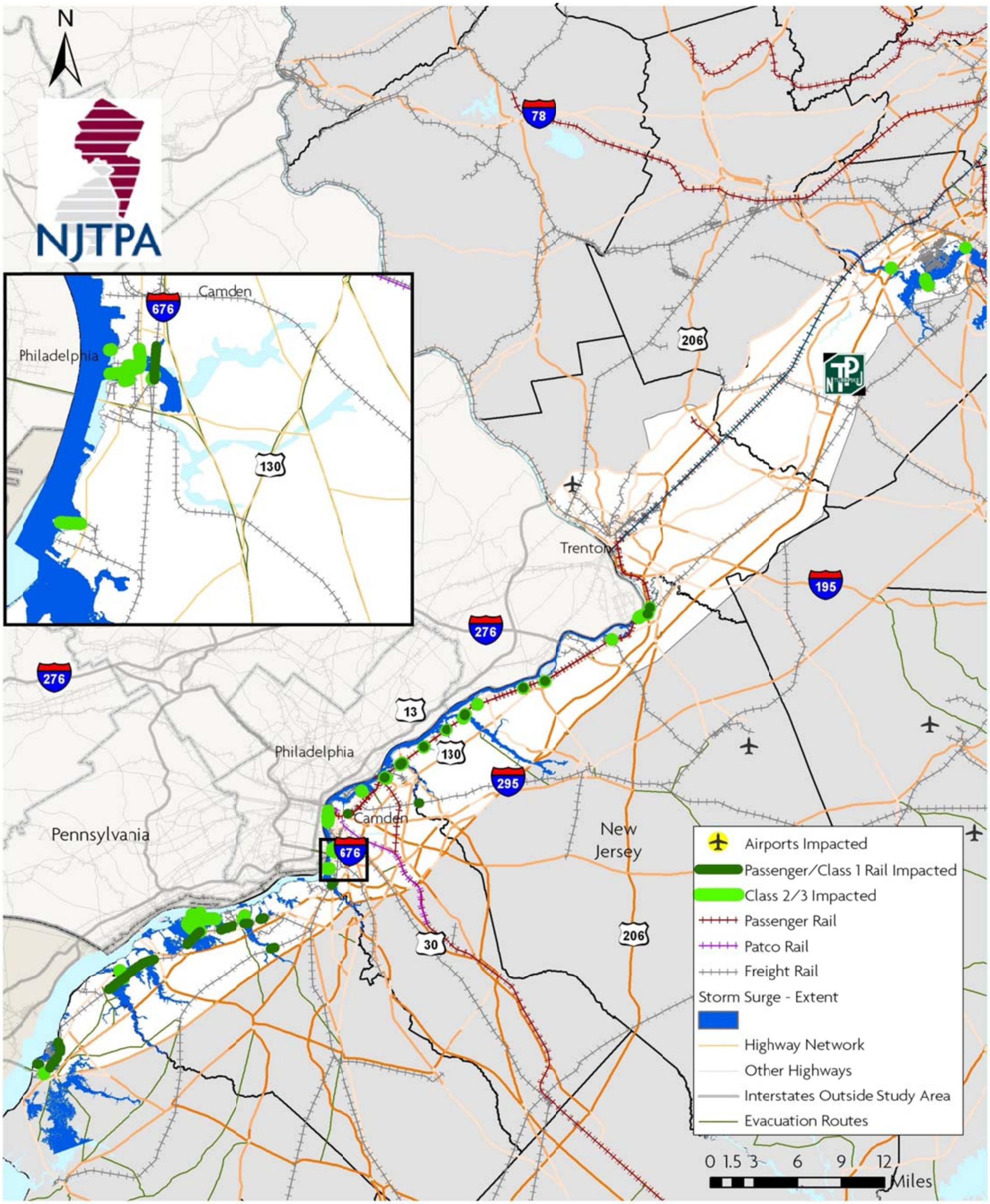


Figure 29. Storm Surge, SLR 1 Meter Scenario, 2100, Central Study Area (Rail)

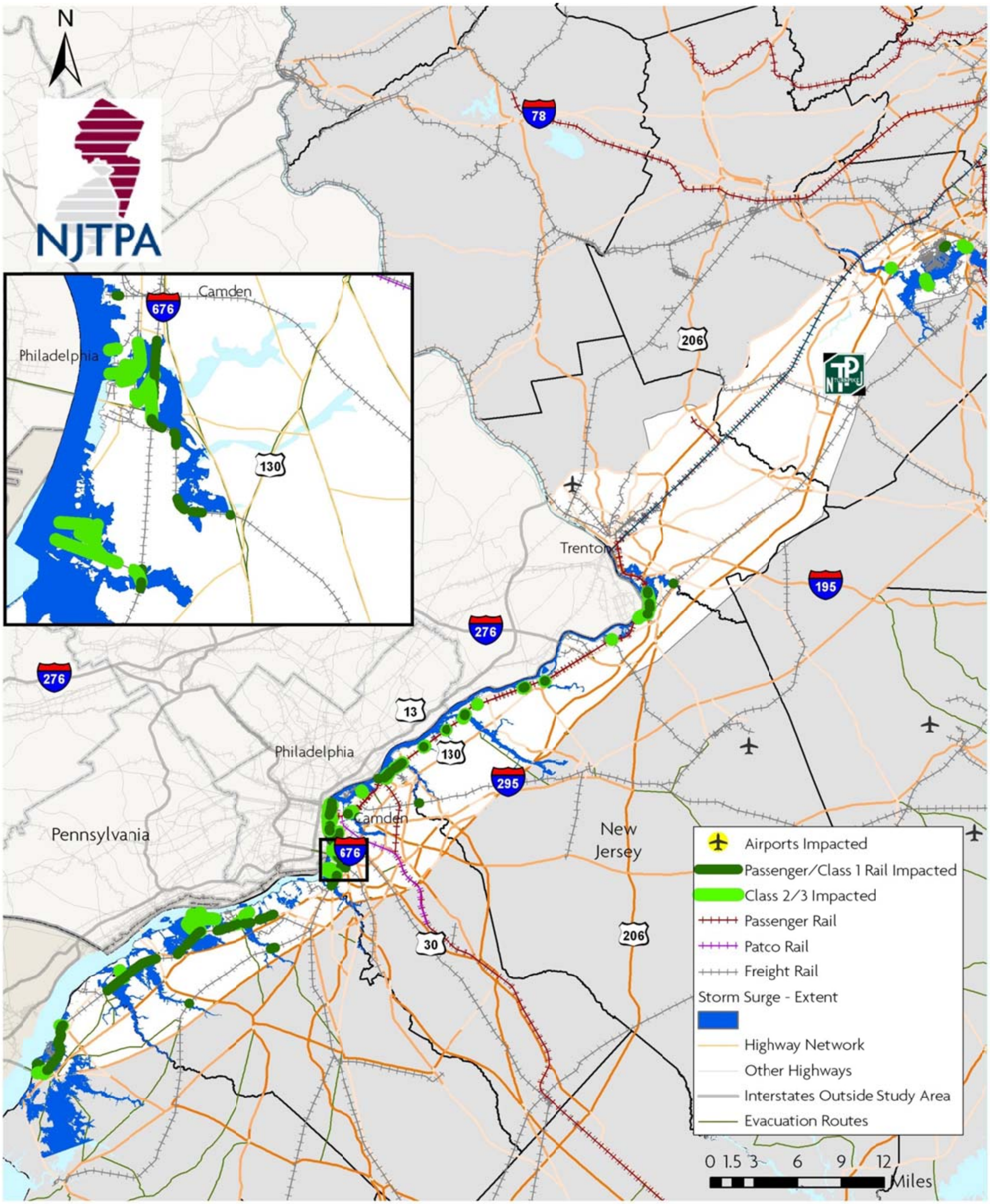


Figure 20. Storm Surge, SLR 1 Meter Scenario, 2050, Coastal Study Area (Roadways)

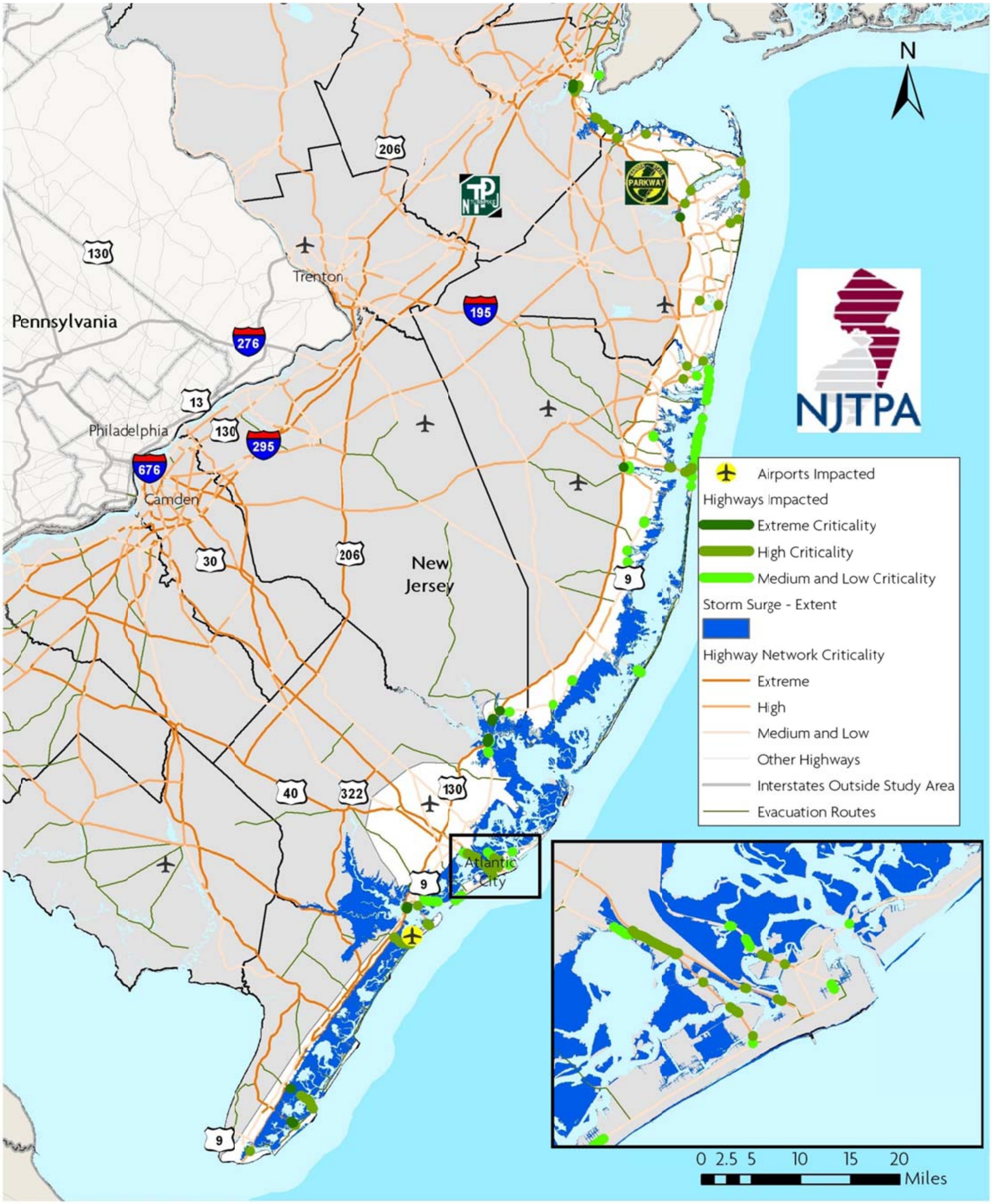


Figure 21. Storm Surge, SLR 1 Meter Scenario, 2100, Coastal Study Area (Roadways)

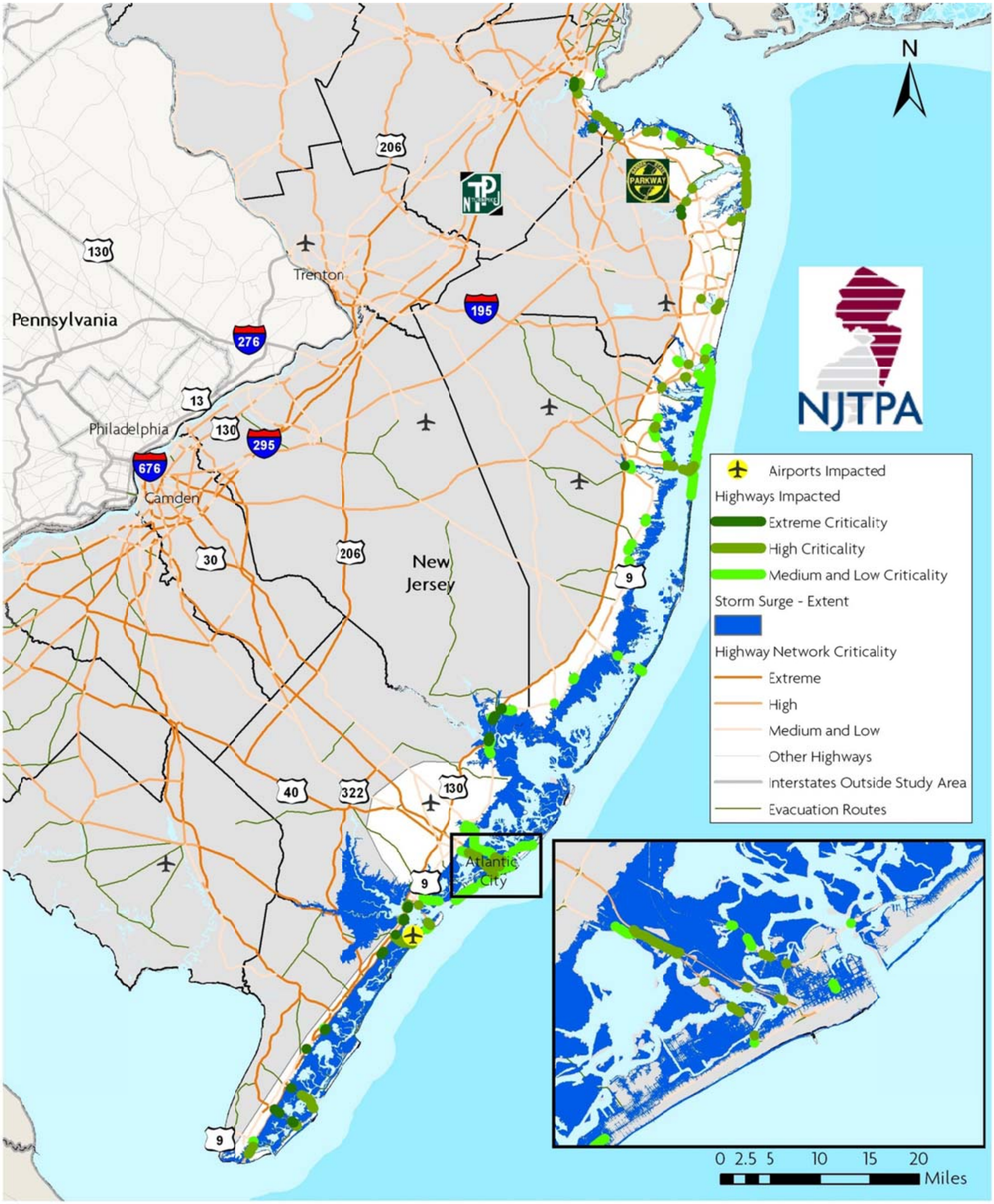


Figure 22. Storm Surge, SLR 1 Meter Scenario, 2050, Coastal Study Area (Rail)

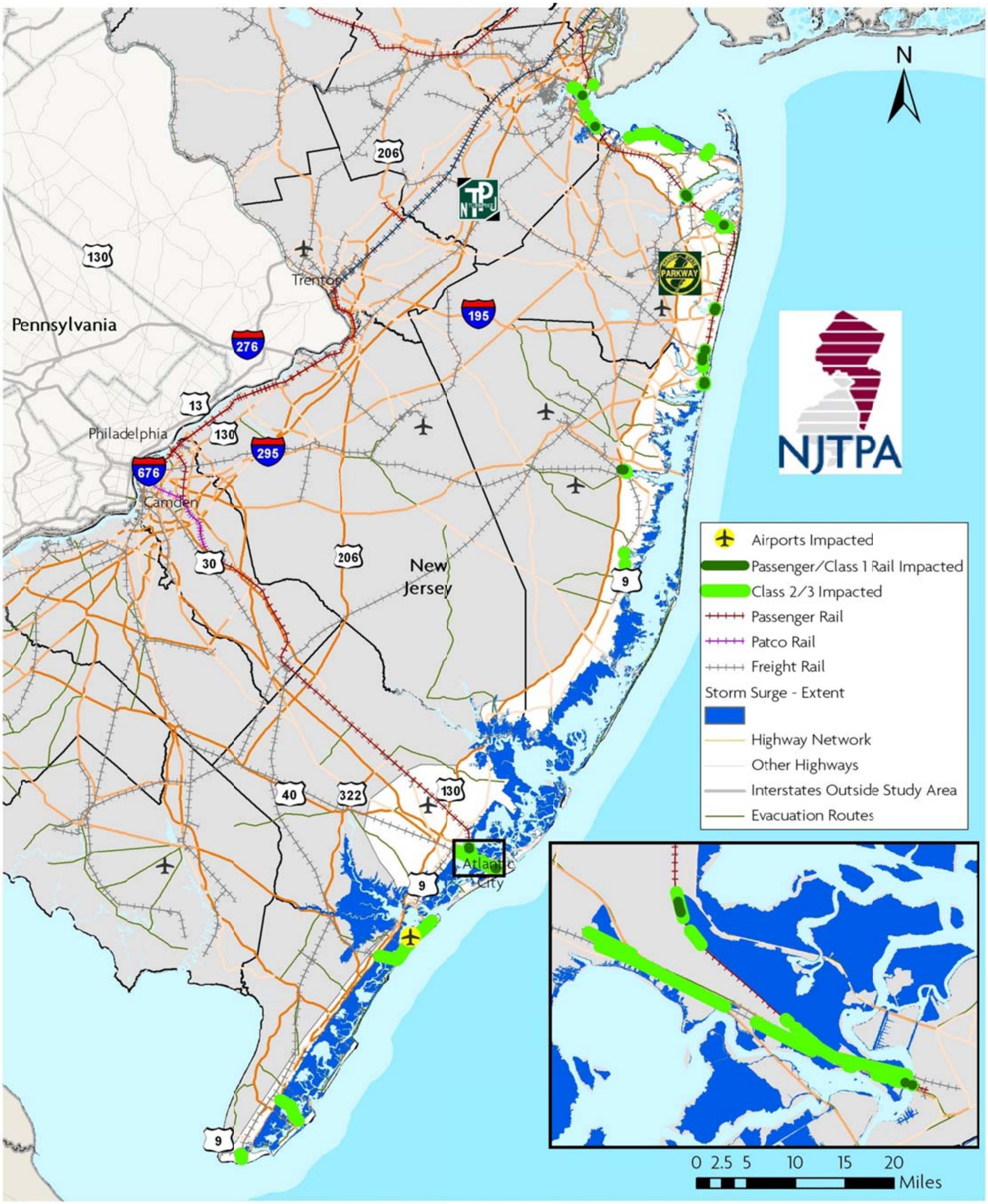
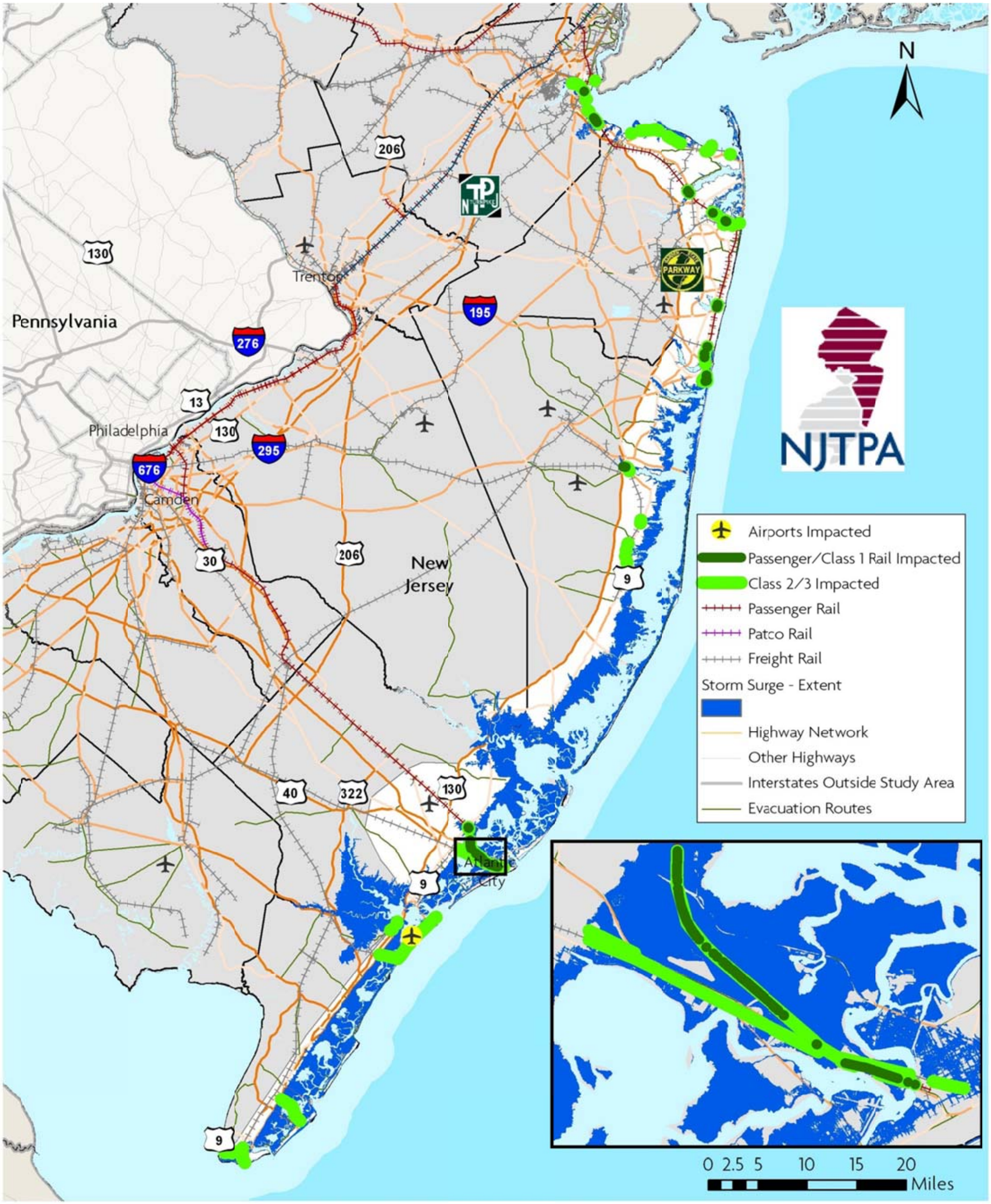


Figure 23. Storm Surge, SLR 1 Meter Scenario, 2100, Coastal Study Area (Rail)

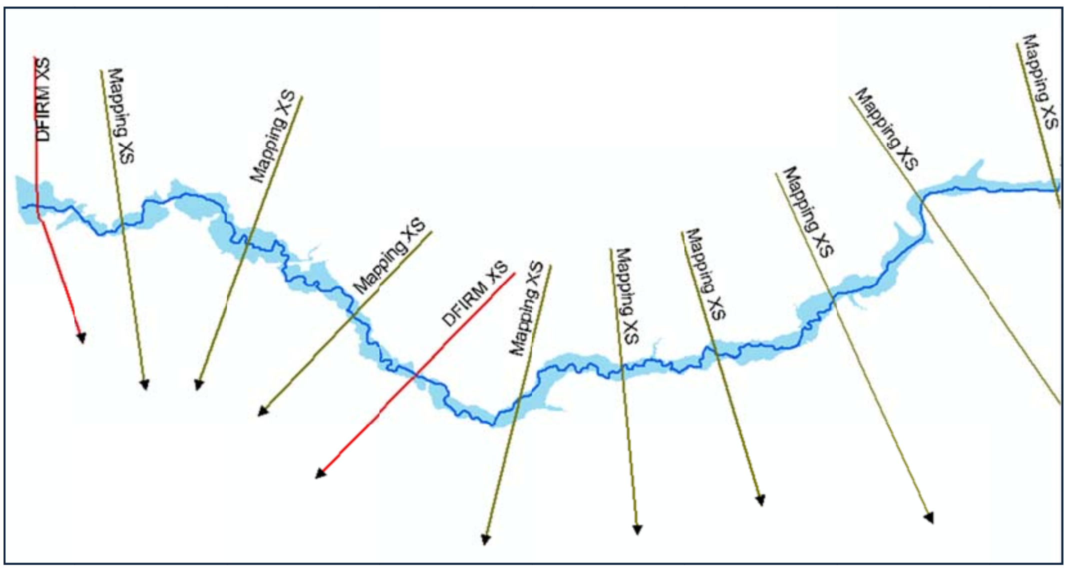


Inland Flooding

Increasingly severe rainfall events, coupled with decreasing pervious surfaces due to other climate factors (such as frost and drought) and the potential for increased urban development, could lead to more intense inland flooding events—represented in the expansion of the 1-in-100 year (1% chance) floodplain.

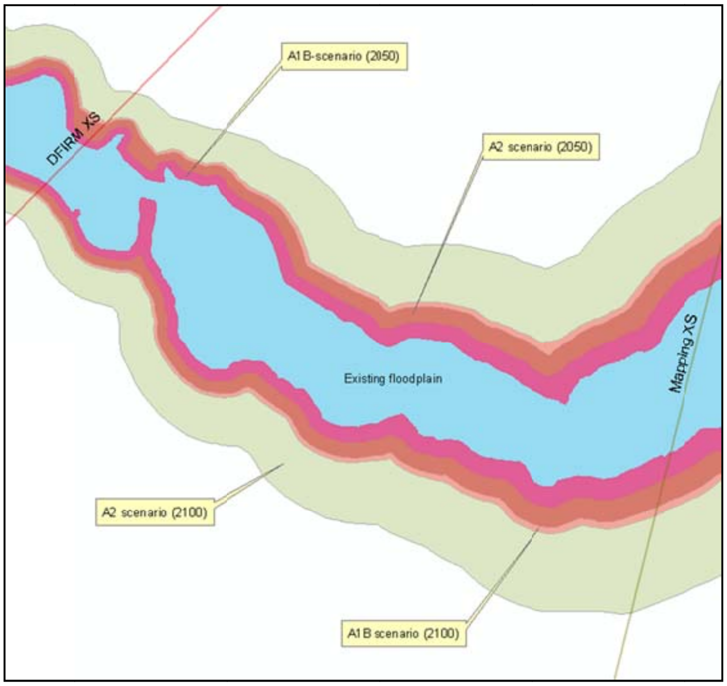
To facilitate the transportation vulnerability assessment, the inland flooding regression analysis described previously was converted into a surface representing the projected spatial extent of the 1% chance floodplain (also referred to as the Special Flood Hazard Area, or SFHA). This was accomplished by translating flood plain widths at strategic locations into a flooding polygon. Updated The Digital Flood Insurance Rate Maps First, additional cross sections (mapping cross sections) were placed strategically amid the DFIRM cross sections in order to account for the sinuosity of a given stream or river. Figure 24 shows a typical DFIRM Special Flood Hazard Area (SFHA) with DFIRM (red lines) and mapping (green lines) cross-sections.

Figure 24. River and SFHA showing the DFIRM and mapping cross-sections



Initially, the mapping cross-sections are not assigned a top width percent change, which must be interpolated based on the distance between the mapping cross-sections and the DFIRM cross-sections along the river centerline. With a top width percent change assigned to each cross section (DFIRM and mapping), a GIS shapefile is created for each scenario. Subsequently, a polygon (showing area) is generated for each pair of cross sections (A to B, B to C, etc.), with the polygon boundary representing an interpolation between the cross sections bracketing the polygon. The cross section polygons are then merged, creating the estimated floodplain. For each river or stream, this operation is performed six times, once for every scenario and analysis year combination (see Figure 25, below, which shows estimated floodplains for A2 and A1B scenarios in 2050 and 2100 along a single riverine section). All floodplains for a given scenario were merged with the original SFHA, creating a floodplain map for the entire Central Study Area.

Figure 25. Estimated floodplain boundaries for the various scenarios (illustrative)



The average percent change (from the base condition) in floodplain top widths for the riverine floodplain generally increase for the three emission scenarios (from low emissions to high emissions). As expected, the top width percent change increases from 2050 to 2100. Table 19 summarizes the minimum, maximum and average percent floodplain top width changes.

Table 19. Percent Top Width Floodplain Changes in Riverine Floodplain

Year	Scenarios	Top Width Change [%]		
		MIN	MAX	Average
2050	B1	-11.4[40]	18.9	7.8
	A1B	19.2	65.1	40.0
	A2	48.6	76.9	59.4
2100	B1	-5.3	36.0	16.6
	A1B	50.6	119.0	79.7
	A2	154.6	202.0	177.5

[40] Within emission scenario B1 (low emissions scenario), a shrinking in floodplain top width for some individual streams and rivers was observed in both projection years. This is due to the change in climate parameters from the base year resulting in reduced runoff rates in some instances.

Figure 26. Inland Flooding, Mid-range Emissions Scenario, 2050, Central Study Area (Roadways)

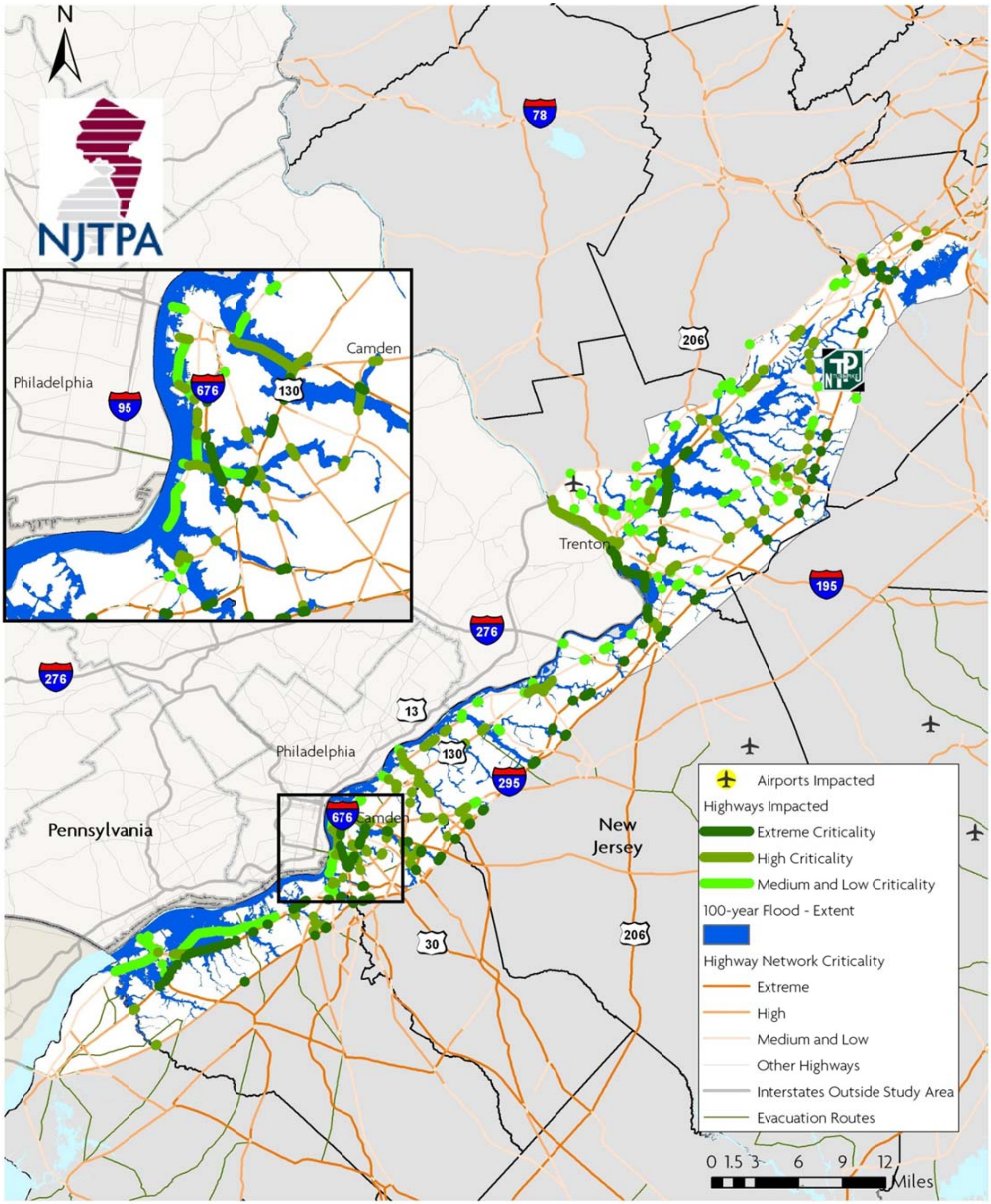


Figure 27. Inland Flooding, Mid-range Emissions Scenario, 2100, Central Study Area (Roadways)

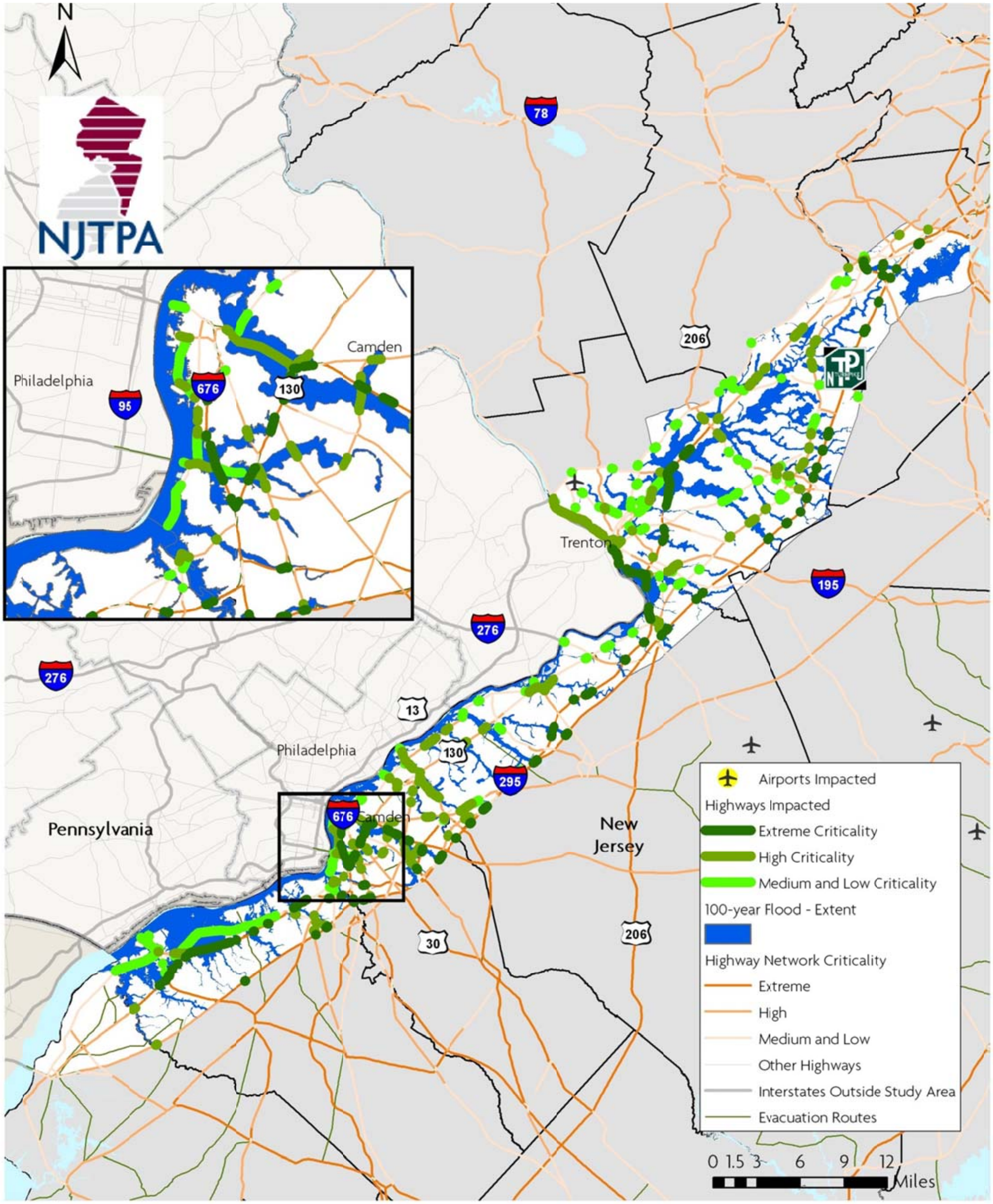


Figure 38. Inland Flooding, Mid-range Emissions Scenario, 2050, Central Study Area (Rail)

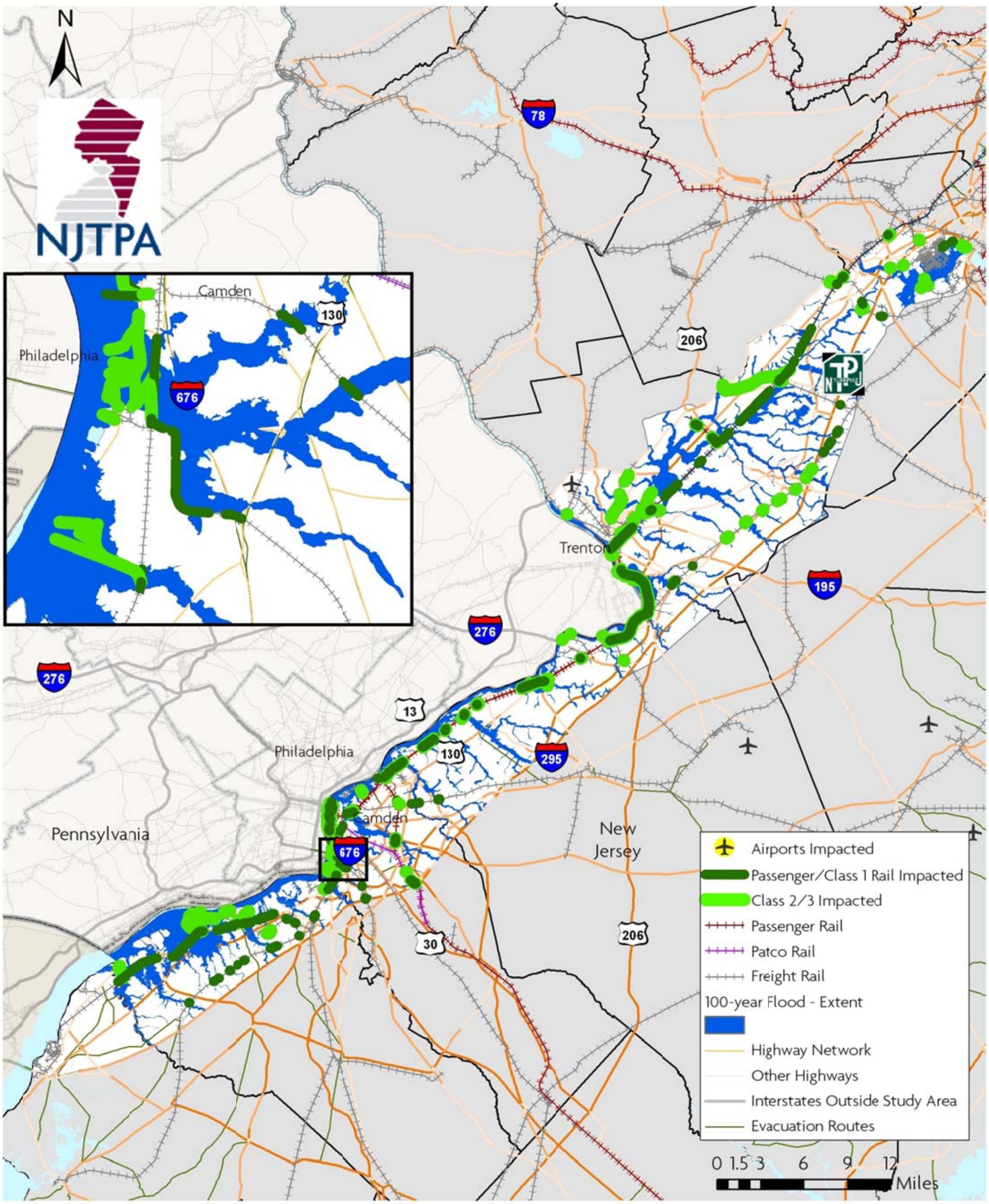
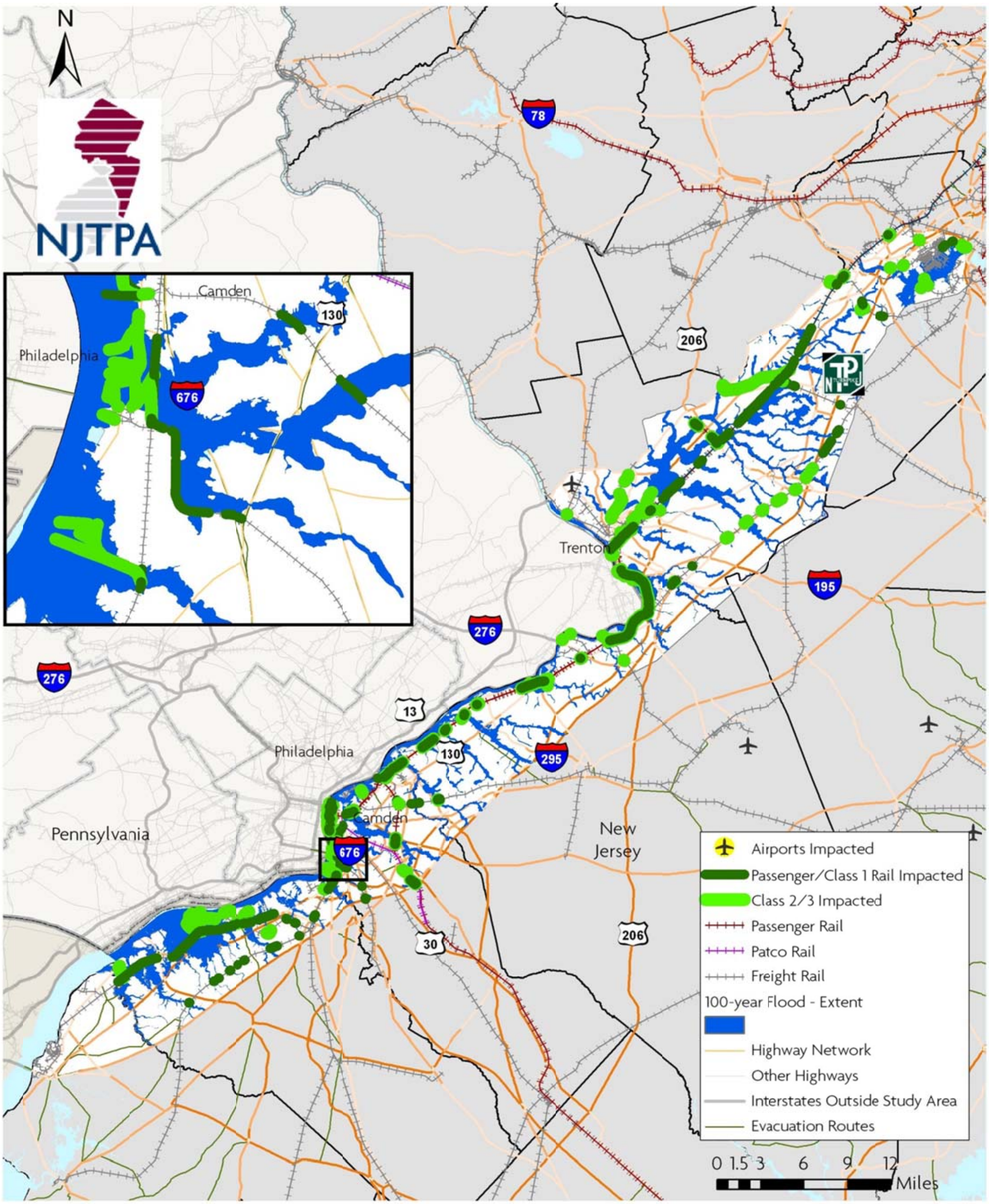


Figure 39. Inland Flooding, Mid-range Emissions Scenario, 2100, Central Study Area (Rail)



Inland Flooding: Central Study Area Potential Impacts (Medium Scenario)

As shown in the accompanying tables, flooding impacts in the Central Study Area could be tremendous by 2100—and even 2050—with over 19 miles of extremely critical roadways potentially impacted. Almost 81 total miles of roadways register as vulnerable, even excluding the lower functional classification roadways not represented in the CMS network. Over 1,100 NJ Transit Bus route miles are potentially subject to flooding impacts.

Table 20. Inland Flooding, A1B, 2100, Central Study Area (Roadways)

Roadway Type	**Criticality Tier**				**Increase from 2050**
	Extreme	High	Med/Low	**Total**	
Major Urban	18.52	27.61	12.60	**58.73**	10.60
Minor Urban	0.00	1.12	17.21	**18.33**	1.66
Major Rural	0.49	0.20	0.10	**0.78**	0.18
Minor Rural	0.00	0.00	3.06	**3.06**	0.00
Total	**19.01**	**28.93**	**32.97**	**80.91**	**12.44**
Evacuation Routes				**32.77**	4.05
NJ Transit Bus Routes				**1120.00**	176.52

As demonstrated by Tropical Storm Irene, rail in the region is particularly vulnerable to inland flooding impacts. By 2100, the extent of vulnerable rail assets could number almost 26 miles of NJ Transit track, 12 miles of Amtrak track (coincident with NJ Transit's Northeast Corridor Line), and 21 miles of Class 1 freight rail lines. Additionally, over 80 miles of Class 2 & 3 freight track could be impacted.

Table 21. Inland Flooding, A1B, 2100, Central Study Area (Rail)

Rail Type	**Miles**	Increase from 2050
NJ Transit	25.6	3.0
Amtrak Miles	11.7	3.2
Class 1 Freight Rail	20.6	2.2
Class 2& 3 Freight Rail	80.6	6.6
Total	**138.5**	**15.0**

Extreme Temperature and Precipitation

As previously noted, the project team considered the potential effects of various climate stressors by conducting outreach to NJDOT and NJ Transit. While in-depth engineering assessments were infeasible at this scale of analysis, the team solicited general information on potential vulnerability thresholds, whether official (such as a specification) or anecdotal (experience and observations). This was accomplished through structured interviews or focus groups with a variety of agency representatives with expertise covering design engineering, maintenance, asset management, materials sciences, and emergency management. Although this outreach necessarily focused on current vulnerabilities, qualitative extrapolation could be applied to reflect increasing frequency or severity under future climate scenarios (e.g., drainage problems and resultant flooding can occur during severe rainfall events, which could occur between *x* and *y* times more often in future years unless adaptation measures are undertaken). The team interviewed the following agency representatives[41]:

Table 22. Operating Agency Interviewees

Agency	Interviewee	Division/Office
NJ Transit	Ian Finn	Construction Management
	Jerry D'Andrea	Technical Services
	Bill Larkin	Facilities Construction and Contracts (Bus)
	Tim Purcell	Division Engineer
NJDOT	Bill Kingsland	Maintenance Operations, South Region
	Lisa Webber	Emergency Management
	Eileen Sheehy	Materials
	Susan Gresavage	Pavement Management
	Kiong Chan	Drainage Management
	Gregory Renman	Bridge Inspection
	Jack Evans	
	Ayodele Oshilaja	
Rutgers	Nicholas Vitillo	Center for Advanced Infrastructure and Transportation (CAIT)

Summaries of these conversations are included below, organized by climate stressor.

Extreme Heat

This study considered temperatures reaching or exceeding 95°F to constitute extreme heat events. Historically, these events have occurred fewer than 5 times per year on average (with significant variability from year to year, and by weather station). Although modest increases are expected even under the Low scenario, both the Medium and High scenarios show significant potential increases, culminating with averages approaching 50 days annually by 2100 for the High scenario (closer to 60 for the Camden area, probably due to urban heat island

[41] Although all efforts were made to faithfully document the proceedings of these interviews, all errors and omissions are the responsibility of the project team.

effect). Although even greater temperatures were not estimated as part of this study, the *Climate Change Adaptation in New York City* report (2010) estimates an increase in 100°F days from 0.4 historically to between 2 and 9 days, on average, in the 2080s.[42]

Potential effects of extreme heat events may pose the following risks to transportation infrastructure.

Rail

- **Track[43]:** NJ Transit rail is set at 95°F, which means that temperatures greater than 95°F may cause tracks to kink. Because the track is warped, rather than broken, events of this nature cannot be detected by the control center (breaks can be detected due to the interruption of a low-voltage current channeled through the tracks). Heat kink often requires a slow speed order for affected segments of track, followed by a maintenance response.
- **Catenary:** In New Jersey, electrified rail corridors draw power from overhead wires, called catenary, which is neutral at 60°F (as opposed to 3rd-rail electrification seen on some other systems). In extreme heat, fixed tension catenary may experience sagging, and constant tension lines may experience pulley failures (only Coast Line from Hazlet to Long Branch). The common response to sagging catenary, which may be snagged by fast-moving trains, is a slow speed order.
- **Load Centers/Sub Stations:** Rolling brownouts can cause brief delays (1-2 minutes) in service due to dips and momentary losses, which in turn can cause temporary signal failures. On NJ Transit lines, power supplies are generally redundant—electrified rail lines through catenary wires, non-electrified rail lines through utilities and back-up generators.
- **Switches and Signals:** Due to potential issues with interconnection switches, slow speed orders may be instituted. Although signals may fail due to power interruptions, signals themselves are designed to tolerate temperatures from -40 to 140/165F.
- **Vehicles:** In hotter weather, air conditioning needs increase in order to maintain passenger comfort. This may lead to some auxiliary system failures (and an increased potential for engine cooling system failures for buses). This is a particular problem at enclosed stations (such as New York Penn), where hot air exhaust is trapped, further increasing air conditioning loads.
- **Bridges:** Temperatures at both extremes (high and low) cause expansion and contraction of bridge structures. Bridges are designed with dynamic ranges of movement to compensate for temperature fluctuations. Although over time frequent or severe expansion-contraction cycles may cause wear and tear, generally there is little risk of operational disruption to stationary bridges. Moveable bridges (draw, lift, or swivel) become more susceptible to binding or locking in extreme heat, and interlocking track at rail bridges may fail to connect properly. The most common response to this threat is to monitor locations prone to failure, and to pump water onto tracks to mitigate problematic expansions.

[42] This shows only the central range (middle 67% of values) across GCMs and GHG emissions scenarios.

[43] All Amtrak and NJ Transit tracks are continuous weld.

Roadways

- **Asphalt Pavement:** Extremely hot days may lead to pavement rutting over time, especially for routes with heavy truck traffic. This effect is especially pronounced on sunny days, when pavement temperatures can greatly exceed ambient temperatures (E.g., a 100°F sunny day may result in pavement temperatures of 140°F). Higher grade binders and newer pavement mixes are already being used in New Jersey to partially mitigate the effects of heat on asphalt.
- **Concrete:** Although the extent of concrete paving in New Jersey is diminishing (and no new segments have been added for at least a decade), maintenance personnel have observed that "blow ups," the violent displacement of adjacent concrete pads, occasionally occur during very hot weather.
- **Bridges:** Like rail bridges, roadway bridges are designed for a certain range of expansion and contraction due to temperature variation. Moveable bridges may lock up during high heat events, and may need to be hosed down to prevent failure.

Although not an infrastructure impact, high temperatures may necessitate counter measures to ensure that road/track and yard workers are not overwhelmed. This may include more frequent water and/or cooling breaks, the installation of swamp coolers for yard workers, and performing non-emergency maintenance and construction during night hours.

Frost Days and Extreme Cold

The average number of frost days (days in which the minimum temperature is 32°F or less), currently about 100 per year at the Study Area weather stations, could decline significantly by 2100—to about 60 days under the Medium scenario, and to fewer than 40 days under the High scenario. Extremely cold days are also expected to decline—with most Study Area locations expected to experience less than one day annually below 0°F, on average.

Together with winter precipitation events, temperatures that fluctuate between non-freezing and freezing (often, but not necessarily, a day-night cycle) can lead to heaving and roadway deterioration. Although this study considers both precipitation and temperature variables separately—future winters may become wetter and warmer—the potential convergence of conditions leading to freeze-thaw events cannot be established.

Potential effects of frost days and extreme cold may pose the following risks to transportation infrastructure:

Rail

- **Track:** Because rail is neutral at 95°F, temperatures below 32°F may cause broken rails due to contraction. Broken rails usually break the signal circuit, sending out an alert to the control center. (This stressor is likely to occur less often, on average, in the future).

Roadways

- **Asphalt Pavement:** Colder temperatures may cause fatigue cracking, which then increases asphalt's susceptibility to moisture infiltration, which could lead to heaving and deteriorating during freeze-thaw cycles. Proactive crack sealing can help prevent water infiltration.

Extreme Precipitation

Extreme precipitation may increase in the future, with 1% chance precipitation events becoming more intense (potentially approaching 14" of rainfall in some areas) and intense 24-hour rainfalls (4") potentially occurring much more frequently.

Heavy precipitation events do not directly impact infrastructure, although they may disrupt operations by creating slippery conditions or poor visibility. Instead, potential wet weather impacts to infrastructure are as much a function of local and/or regional hydrology (e.g., stream flows, drainage capacity, standing water, etc.) as the intensity of rain or snow events. Although extreme precipitation events may lead to more flooding and washouts, for example, impacts will be locally specific and would require an engineering evaluation to better understand potential risk thresholds.

Potential effects of extreme precipitation events may pose the following risks to transportation infrastructure:

Rail

- **Track:** Intense rainfalls can lead to track flooding from adjacent rivers and streams, consistent with the inundation observed during Tropical Storm Irene. Although effects on NJ Transit and Amtrak were resolved in days, large segments of trackage on Metro North Railroad's Port Jervis line, just north of New Jersey, were destroyed, putting the line out of commission for several weeks.
- **Signal Circuits:** Inundation can cause problems with signal track circuits.

Bus

- **Infrastructure:** Flooding at bus garages can cause facility evacuation and necessitate the transfer of work to other NJ Transit garages.
- **Bus Vehicles:** When bus wheels are submerged in water, damage to air braking systems, wheel bearings, and brake linings may occur. Electronic controls located in the baggage bays of some buses may be damaged by high water.

Roadways

- **Roads:** Heavy rains can cause temporary flooding due to stream bodies overflowing their bounds, or washouts due to rapid flows next to roadways (a prominent example is I-287 in Morris County, a lane of which was washed out by the adjacent stream in the wake of Irene).
- **Asphalt Pavement:** Although temporary overtopping constitutes an operational problem more than an infrastructure issue, asphalt that is subjected to standing water for multiple days may deteriorate due to the gradual stripping of pavement binder.

Moreover, roadways that remain in operation despite a small amount of standing water may deteriorate faster under the stresses of heavier vehicles.

- **Culverts:** Culverts are designed to meet recurrence interval standards appropriate to the facilities they serve (see Table 23, below). However, severe events may occur with increasing intensity and frequency in future years. The historic 100-year rainfall event (1% chance) delivers the equivalent of about 10 inches of rain, whereas the 1% chance event in 2100 under the High scenario yields about 14 inches, depending on the weather station. Especially for culverts that are affected by damage or blockage, the events for which they were originally designed might exceed the capacities of certain culverts, leading to temporary flooding or roadway damage.

Table 23. Recurrence Intervals for culvert design (NJDOT Roadway Design Manual)

Recurrence Interval	Facility Description
100-Year	Any drainage facility that requires a NJDEP permit for a non-delineated stream.
50-Year	Any drainage structure that passes water under a freeway or interstate highway embankment, with a headwall or open end at each side of the roadway.
25-Year	Any drainage structure that passes water under a land service highway embankment, with a headwall or open end at each side of the roadway. Also, pipes along the mainline of a freeway or interstate highway that convey runoff from a roadway low point to the disposal point, a waterway, or a stormwater maintenance facility.
15-Year	Longitudinal systems and cross drain pipes of a freeway or interstate highway. Also pipes along mainline of a land service highway that convey runoff from a roadway low point to the disposal point, a waterway, or a stormwater maintenance facility.
10-Year	Longitudinal systems and cross drain pipes of a land service highway.

Sea Level Rise/Storm Surge Inundation

As with inland flooding, storm surge can disrupt operations and potentially damage infrastructure. Like fresh water flooding, the standing water resulting from sea level rise and storm surge may lead to asphalt binder deterioration. Brackish water may additionally lead to corrosion of rebar embedded in concrete paving or structural elements.

Limitations of the Data and Analysis

At this scale of analysis—covering over 1,000 square miles—the primary emphasis of the assessment was in identifying potential vulnerabilities at a sketch planning level. The results are intended to provide decision-makers with information that will help determine needs for more in-depth analysis—not attribute vulnerability to specific transportation assets. Moreover, data limitations and certain analytical approaches may either overstate or understate potential vulnerabilities, including:

- The inland flooding assessment analysis generated flood plain top widths using a national regression equation, rather than a hydrological analysis based on defined runoff coefficients and actual elevations. The latter approach would have been too resource- and time-intensive to incorporate into a project of this scope and scale, but could be considered for future analyses of certain significant and/or high risk stream bodies.
- The storm surge inundation approach, which added sea level rise to SLOSH outputs, led to significant understatement of the potential extent of inundation (as previously explained). Future efforts should consider using Highest Observed Water Level (HOWL) data (or a multiple thereof) to project storm surge extents (although the depths provided by SLOSH are also useful). For future in-depth, site specific analyses, storm surge modeling software, like ADCIRC, could be used, although this a relatively resource intensive approach.
- The absence of consistent bridge elevation and underclearance data caused the potential overstatement of vulnerability (some areas represented as "inundated" may in fact be spanned by bridges, although the approaches may still be vulnerable). The geodatabase developed for this analysis could be used to scrutinize sites of interest by zooming in to a specific "impacted" asset, and then applying the bridge line files created by the project team and/or orthographic photos.

Another notable limitation is the impossibility of precisely and directly correlating non-spatial climate variables, such as extreme temperatures, to specific impacts on infrastructure. Instead, this study reasonably infers that, generally, infrastructure vulnerability will increase indefinably as climate variables exceed critical thresholds more frequently and/or occur with great intensity.

Finally, as an important global caveat, this study uses estimations of future climate to assess the potential vulnerability of today's infrastructure. Planned and programmed infrastructure for MPO regions is included in the project geodatabase (when provided), but transportation planning horizons do not yet extend into the climate analysis years (although 2050, as a 30-year average centered on the year 2050, intersects with 2035—the horizon year for most MPO Long Range Transportation Plans). However, relatively few major infrastructure expansions are expected to occur within the study areas, and for those do, the climate scenarios can and should be included as a major consideration for siting decisions.

Adaptation

Over the last few years, many transportation agencies have begun to consider the possibility of climate change and the significant impacts it may have on their transportation systems. These transportation agencies realize that increases in extreme temperature, increases in intense precipitation, more severe storms and rising sea levels could have considerable impacts on all modes of transportation in future years. Furthermore, these agencies have begun to include potential climate change impacts in their planning, programming and project development processes. These state and regional efforts were underscored by U.S. DOT Secretary LaHood's recent policy statement on climate change adaptation, which mandates the integration of climate change impacts and adaptation into the planning, operations, policies, and programs of DOT. The new policy statement also directs the federal modal administrations to encourage state, regional and local transportation agencies to consider climate change impacts in their decision-making. As a result, transportation agencies are expected to further integrate climate change considerations into their activities. This section of the report presents a summary of current research and practices pertaining to adaptation planning in the transportation field, and concludes with a series of adaptation strategy matrices covering roadways, rail assets, and bridges.

Summary of Current Research and Practices

Various studies have been sponsored at the national level by the Federal Highway Administration (FHWA) and the National Academies of Science to identify potential future changes in climate change stressors such as temperature, precipitation, sea level rise and storm surge. These institutions also have begun to develop decision frameworks that consider potential climate change induced vulnerabilities and risks to the transportation system and identify potential adaptation strategies at a relatively conceptual (planning, policy, or sketch) level. Prominent examples of recent and ongoing work include:

National

Impacts of Climate Change and Variability on Transportation Systems and Infrastructure – Gulf Coast Phases 1 and 2. FHWA initiated the Gulf Coast Study, Phase I to analyze potential climate change impacts on transportation in the Gulf Coast Region as part of the Climate Change Science Program. This study examined likely changes in temperature, precipitation, sea level rise and storm surge along with potential impacts on highway, water, air, rail and transit modes in the Gulf Coast states (Texas, Louisiana, Mississippi, Alabama) and identified adaptation measures. The study outlined four major conceptual factors to support the consideration of climate change in transportation:

- exposure to climate stressors,
- vulnerability,
- resilience, and
- adaptation.

Gulf Coast, Phase II is currently underway. The project team is working with the Mobile, Alabama Metropolitan Planning Organization (MPO) to more closely examine adaptation measures. The goal of this phase is to make this process replicable, so that other MPOs can conduct similar assessments.

NCHRP 20-83 (Task 5) – Climate Change and the Highway System: Impacts and Adaptation Approaches. This ongoing National Cooperative Highway Research Program study on climate change and highway adaptation is in the process of developing a decision framework to identify potential climate change impacts to the highway system, risks and vulnerabilities, and possible adaptation strategies (including a climate risk-adjusted benefit cost methodology). The framework is being tested through a number of case studies, and technical memorandums are being developed to help transportation agencies implement this framework in planning, design, operations, and construction decision making.

As part of the NCHRP 20-83(5) study, an extensive literature review and telephone interviews with various agencies were conducted to determine the "state of the practice" in climate change adaption planning. It was determined that many states are developing Climate Action Plans. However, most of these efforts focus on mitigation strategies and very few address climate change adaptation or implementation of specific adaptation strategies. Most agencies were found to be in the preliminary stages of identifying the major climate drivers, risks and vulnerabilities, and high-level adaptation strategies; but most are not yet at the implementation stage.

Many state adaptation plans are multi-sectoral, and therefore combine transportation with all other infrastructure types. Nonetheless, there are some leaders in adaptation planning who have taken a more focused look at transportation infrastructure. In the U.S., the study has identified the current leaders in transportation adaptation as the States/Commonwealths of Alaska, California, Maryland, Washington and Massachusetts, as well as some local governments such as New York City and King County, WA. These are all coastal governments and their work shows particular concern about the potential for sea level rise. Many of these governments require specific adaptation efforts by all their agencies. In California, all state agencies are required by Executive Order (S-13-08) to adapt to a changing climate. California also requires a biennial science assessment on climate impacts and adaptation. King County, WA and Maryland require updates each year detailing each applicable agency's activities in addressing their respective comprehensive climate plans, including the adaptation component, and plans for the coming year.

State, Regional, and Local

California DOT (Caltrans). Caltrans has developed criteria to help determine when sea level rise poses enough of an overall threat to warrant programming of additional funds in design and project development to avoid or mitigate the identified risks. This includes considering criteria such as the design life of the proposed project and whether it is a large investment, critical commercial route, evacuation route, has anticipated delays, and where there are alternate routes.

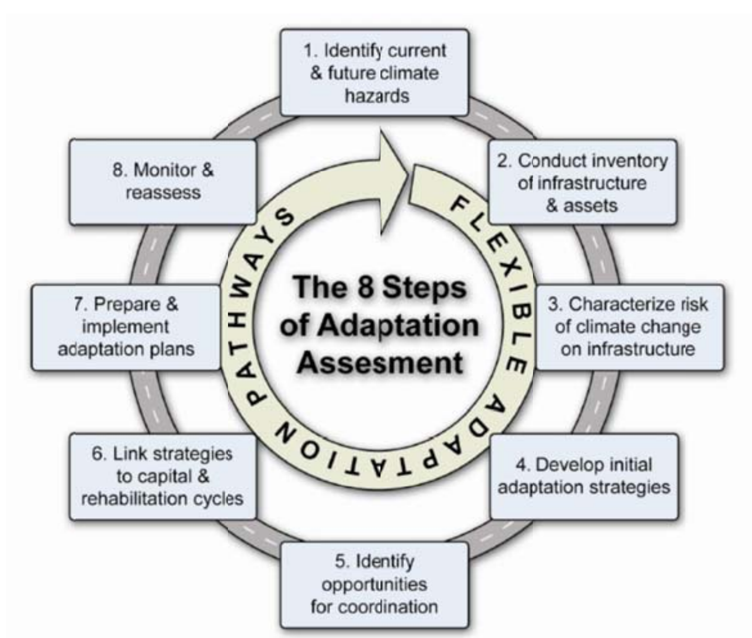
Massachusetts Climate Change Adaptation Report. One of the most recent adaptation efforts is the Massachusetts Climate Change Adaptation Report issued in September, 2011. The report provides a high level sector-by-sector look at how climate change may impact natural resources, infrastructure, health, economy and coastal zones and oceans. In the transportation area, the short- range strategies include adjusting standard maintenance and inspection procedures to account for climate change impacts and developing new design standards to reflect climate considerations. Longer-term strategies include new technologies for aircraft and airports, enhancement of water-based transit options in coastal areas and new ways to fund the anticipated expenses to address climate change impacts.

Climate Change Adaptation in New York City: Building a Risk Management Response. An overall framework for developing and implementing adaptation policy was developed for the New York Panel on Climate Change (NPCC) Adaptation Assessment Guidebook (a document developed prior to the final report). Although created for New York City, it is designed to be a framework that can be used in any urban area, with region-specific adjustments related to climate risk information, critical infrastructure, and protection levels. It is detailed enough to serve as a template for developing and implementing a sector's adaptation efforts.

The New York City Adaptation Assessment Guidebook includes an 8-step process to inventory at-risk infrastructure and develop adaptation strategies to address those risks. These steps are designed to be incorporated into the risk management, maintenance and operations, and capital planning processes of agencies. The steps are shown below and illustrated in Figure .

1. Identify current and future climate hazards.
2. Conduct inventory of infrastructure and assets.
3. Characterize risk of climate change on infrastructure.
4. Develop initial adaptation strategies.
5. Identify opportunities for coordination.
6. Link strategies to capital and rehabilitation cycles.
7. Prepare and implement adaptation plans.
8. Monitor and reassess.

Figure 40. New York City Process for Adaptation Planning



King County, Washington— Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments. In conjunction with the execution of its Climate Plan, the County formed an interdepartmental climate change adaptation team, partnering with the Climate Impacts Group at the University of Washington for scientific expertise. The King County Guidebook includes adaptation strategies such as replacing or rehabilitating bridges, using pervious pavement in low lying areas, modifying existing seawalls, improving roadway surfaces to withstand weather extremes, increasing the use of non-highway modes, and others. Each year, the Executive Action Group is required to produce a report that provides updates on the County's climate planning. These annual reports include transportation-related measures that have been accomplished such as institutional capacity building, analyzing impacts of higher sea levels, and evaluation of construction modifications due to higher water levels. The Road Services Division is currently rebuilding over 57 bridges and 40 culverts to improve stream flows and endure the most significant impacts of climate change.

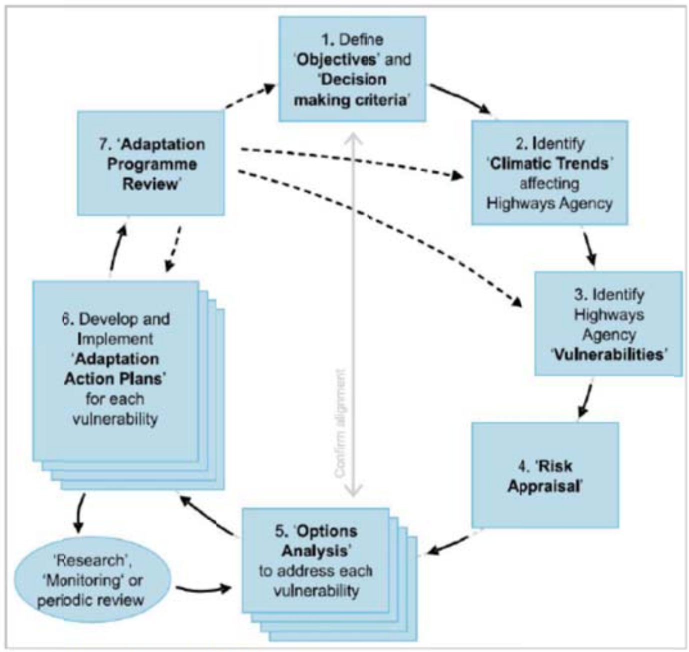
International

The international experience has been very similar to that in the U.S. Other countries are starting to gather information on climate projections and determine the severity of the impacts. A few countries have begun to develop adaptation strategies including the United Kingdom/ Scotland and Australia.

Climate Change Adaptation Strategy, Volume 1 (United Kingdom). Perhaps the most fully-developed adaptation framework is that described in the UK Highway Agency's Climate Change Adaptation Strategy, Volume 1. The Highway Agency Adaptation Strategy Model (HAASM) is a seven step process for developing a climate change program (Figure 28). It provides a method for prioritizing risk and identifies staff members responsible for different climate change adaptation program development efforts. The steps include:

1. Define objectives and decision-making criteria,
2. Identify climate trends affecting the highways agency,
3. Identify highways agency vulnerabilities,
4. Risk appraisal,
5. Options analysis to address each vulnerability,
6. Research monitoring or periodic review,
7. Develop and implement adaptation action plans for each vulnerability, and
8. Adaptation program review.

Figure 28. Highway Agency Adaptation Strategy Model



Source: Highways Agency of the U.K., 2008.

Scottish Road Network Landslide Study: Implementation Report. This report is focused on assessing and ranking the hazards presented by debris flow. Scotland's hazard assessment involves mapping areas of the road network that are vulnerable to flow paths. This desk exercise was supplemented by site-specific inspections with a hazard score for each site of interest. The hazard ranking process also took into consideration the socioeconomic impact of debris flow events. The end result is a listing of high hazard sites in Scotland where the road network is vulnerable to debris flow. Once these hazard sites are identified, they are monitored and at some point warning signs may be installed, the road closed, or traffic diverted. In the long run, adaptation may include measures to protect the road such as installing barriers, engineering to reduce the opportunity for debris flows, or road realignment.

Australia—Climate Change Impacts & Risk Management: A Guide for Businesses and Government. This Guide proposes a process for organizations to follow as they investigate the risks of climate change. The guide asks users to identify activities or assets that are at risk of a changing climate and to determine whether the risk is significant. The guide is general enough that it can be used by various agencies.

Adaptation for New Jersey

Based on the findings of the aforementioned reports, this study has developed a series of matrices that identifies possible climate change impacts generally applicable to New Jersey and lists potential adaptation strategies that could be taken at the various stages of the transportation decision-making process—including planning, design, and operations. Three matrices are included:

- Table 24. Adaptation Strategy Matrix (Roadways and Bridge Approaches, Tunnels);
- Table 25. Adaptation Strategy Matrix (Rail);
- Table 26. Adaptation Strategy Matrix (Roadway and Rail Bridges).

The matrices also consider whether the potential impacts are likely to occur more or less often in the future *if no prior interventions are taken*. An up arrow (↑) indicates that the impact can generally be expected to occur more often (such as extremely high temperature days), or be more severe in nature, whereas a down arrow (↓) indicates less frequent or severe events (such as extremely cold days). Events that rely heavily on exogenous variables (such as vehicle failure or traveler safety), the confluence of two stressor types (such as snow), or which are too fine grained to estimate reliably (such as freeze-thaw cycles) are indicated with a sideways, or neutral, arrow (➲).

Although these matrices cannot substitute for a full-fledged climate adaptation plan specific to New Jersey, they provide agencies with general categories of potential responses to the climate vulnerabilities previously identified, drawing from the research performed by FHWA, as well as other states, regions, cities, and countries.

Table 27. Adaptation Strategy Matrix (Roadways, Bridge Approaches, and Tunnels)

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	Design	Operations	
Climate Stressor: Sea Level Rise				
Flooding	• Site future infrastructure out of or above estimated flood impact zone • Identify or create redundant routes • Abandon/ relocate infrastructure (for chronically flooded segments) • Land use policies discouraging development in at-risk zones	• Enhance shoreline infrastructure (sea walls and shoreline armoring) • Elevate infrastructure • Enhance drainage to minimize road closure time and pavement deterioration (pumping infrastructure for tunnels)	• Road closures as necessary • Traveler notification of flooded roadways and alternative routes/modes (ITS)	↑
Erosion		• Create/ strengthen seawalls and barriers	• More frequent inspections and maintenance • Beach nourishment • Wetland maintenance	↑
Corrosion (from chronic sea water exposure)		• Design infrastructure to resist salt water corrosion	• More frequent inspections and maintenance	↑
Climate Stressor: Storm Surge (Hurricanes and Nor'easters)				
Flooding	• Establish and frequently update emergency detours and evacuation routes • Site future infrastructure out of or above estimated flood impact zone • Abandon/ relocate infrastructure (for chronically flooded segments) • Land use policies discouraging development in at-risk zones	• Enhance shoreline infrastructure (sea walls and shoreline armoring) • Elevate infrastructure • Enhance drainage to minimize road closure time and pavement deterioration (pumping infrastructure for tunnels)	• Emergency sandbagging • Road closures as necessary • Traveler notification of flooded roadways and alternative routes/modes (ITS)	↑
Erosion/ washouts		• Create/ strengthen seawalls and barriers • Harden/ stabilize slopes	• More frequent inspections and maintenance • Beach nourishment • Wetland maintenance	↑

IMPACT	STRATEGY Planning	Design	Operations	Frequency/ Severity of Future Incidence
Closures/ disruptions	• Establish and frequently update emergency detours and evacuation routes • Install ITS infrastructure to inform travelers		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Regularly trim vegetation to minimize debris • Temporarily close vulnerable routes	↑
Driver safety/ accidents	• Establish and frequently update emergency detours and evacuation routes		• Close roadways before extreme weather events • Dispatch more roadway assistance vehicles	→
High Winds		• Design overhead sign structures to withstand high wind events	• Send out emergency maintenance patrols after storm events • Regularly trim vegetation	→
Lightning		• Protect wiring/ use redundant or remote power sources		→
Climate Stressor: Inland Flooding				
Flooding	• Establish and frequently update emergency detours • Site future infrastructure out of or above estimated flood impact zone • Abandon/ relocate infrastructure (for chronically flooded segments) • Land use policies discouraging development in at-risk zones	• Build flood control protection structures for frequently inundated areas (levees, bunds, or weirs) • Elevate infrastructure • Enhance drainage to minimize road closure time	• Emergency sandbagging • Road closures as necessary • Traveler notification of flooded roadways and alternative routes/modes (ITS)	↑
Erosion/ washouts		• Harden/ stabilize slopes • Over-design culverts	• More frequent inspections and maintenance of culverts and drainage systems	↑

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	Design	Operations	
Closures/ disruptions	• Establish and frequently update emergency detours • Install ITS infrastructure to inform travelers		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Regularly trim vegetation to minimize debris • Temporarily close vulnerable routes	↑
Driver safety/ accidents	• Establish and frequently update emergency detours and evacuation routes		• Close roadways before extreme weather events • Dispatch more roadway assistance vehicles	→
Climate Stressor: Temperature				
Pavement rutting	• Institute load restrictions on vulnerable roads	• Use more heat tolerant binders and materials	• More frequent inspections and maintenance • Mill out ruts	↑
Blow outs (concrete paving)		• Replace concrete pavements with asphalt	• More frequent inspections and maintenance	↑
Heaving/Potholes (due to freeze-thaw)		• Enhance drainage to minimize moisture penetration • Replace or stabilize susceptible soils and/or subgrades	• More frequent inspections and maintenance	→
Fatigue cracking (cold temperatures)		• Use more cold tolerant binders and materials	• More frequent inspections and maintenance • Crack sealing	↓

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	**Design**	**Operations**	
Healthy and Safety			• Improve systems to monitor and advise travelers • Establish protocols for road worker safety during heat events • Conduct road work at night	➡
Vehicle failures			• Dispatch more roadway assistance vehicles	➡
Climate Stressor: Precipitation				
Flooding	See Inland Flooding			
Erosion/ washouts	See Inland Flooding			
Erosion (construction sites)	• Strengthen erosion and sedimentation controls for construction			⬆
Culvert failures	• Reconfigure NJDOT *Roadway Design Manual* culvert warrants • Institute statewide culvert management system	• Reconstruct culverts without adequate capacity (whether due to failures or insufficient design capacity)	• More frequent inspections and maintenance	⬆
Snow emergencies		• Investigate skid and/or freeze resistant pavements	• More frequent plowing • Dispatch more roadway assistance vehicles	➡
Embankment failures		• Harden/stabilize slopes	• More frequent inspections and maintenance	⬆
Vegetation failure (due to drought)		• Drought-resistant plantings	• For aesthetic plantings, water more frequently	⬇
Corrosion (from increased surface salts due to less precipitation)			• More frequent inspections and maintenance	⬇

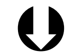
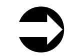
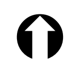
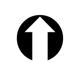
IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	**Design**	**Operations**	
Closures/ disruptions due to fire			• Regularly trim vegetation	
Health and safety		• Reflective striping to increase visibility	• Dispatch more roadway assistance vehicles • Lower speed limits during rain events	

Table 28. Adaptation Strategy Matrix (Rail)

IMPACT	STRATEGY Planning	Design	Operations	Frequency/ Severity of Future Incidence
Climate Stressor: Sea Level Rise				
Flooding	• Site future infrastructure out of or above estimated flood impact zone • Abandon/ relocate infrastructure (for chronically flooded segments)	• Enhance shoreline infrastructure (sea walls and shoreline armoring) • Elevate infrastructure • Enhance drainage	• Track closures as necessary • Rider notification of flooded rail segments and alternatives (passenger information systems)	
Erosion		• Create/ strengthen seawalls and barriers	• More frequent inspections and maintenance • Beach nourishment • Wetland maintenance	
Corrosion (from chronic sea water exposure)		• Design infrastructure to resist salt water corrosion	• More frequent inspections and maintenance	
Climate Stressor: Storm Surge (Hurricanes and Nor'easters)				
Flooding	• Site future infrastructure out of or above estimated flood impact zone • Abandon/ relocate infrastructure (for chronically flooded segments)	• Enhance shoreline infrastructure (sea walls and shoreline armoring) • Elevate infrastructure • Enhance drainage	• Emergency sandbagging • Track closures as necessary • Rider notification of flooded rail segments and alternatives (passenger information systems)	
Erosion/ washouts		• Create/ strengthen seawalls and barriers • Harden/ stabilize slopes	• More frequent inspections and maintenance • Beach nourishment • Wetland maintenance	
Closures/ disruptions	• Establish emergency operating plans • Install passenger information systems to inform travelers		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Regularly trim vegetation to minimize debris	

IMPACT	STRATEGY Planning	Design	Operations	Frequency/ Severity of Future Incidence
Rider safety/ accidents			• Close routes before extreme weather events • Dispatch buses to transport stranded passengers/ vulnerable populations	➡
High Winds		• Design catenary to withstand higher winds	• Send out emergency maintenance patrols after storm events • Regularly trim vegetation along tracks	➡
Lightning		• Use redundant or remote power sources	• Send out emergency maintenance patrols to restore impacted infrastructure	➡
Climate Stressor: Inland Flooding				
Flooding	• Site future infrastructure out of or above estimated flood impact zone • Abandon/ relocate infrastructure (for chronically flooded segments)	• Build flood control protection structures for frequently inundated areas (levees, bunds, or weirs) • Elevate infrastructure • Enhance drainage to minimize track closure time	• Emergency sandbagging • Route closures as necessary • Rider notification of flooded rail segments and alternatives (passenger information systems)	⬆
Erosion/ washouts		• Harden/ stabilize slopes • Over-design culverts	• More frequent inspections and maintenance of culverts and drainage systems	⬆
Closures/ disruptions	• Establish and frequently update emergency detours • Install passenger information infrastructure		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Regularly trim vegetation to minimize debris • Temporarily close vulnerable routes	⬆

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	Design	Operations	
Rider safety/ accidents	• Install passenger information systems to inform travelers		• Close routes before extreme weather events • Dispatch buses to transport stranded passengers/ vulnerable populations	→
Climate Stressor: Temperature				
Track kinking		• Use more robust and heat resistant materials (e.g., concrete cross ties)	• More frequent inspections and maintenance • Rapid response crews for identified kinks • Slow speed orders (or, for severe kinks, route closures) • Water cooling of vulnerable segments	↑
Catenary failure	• Move system to third rail power	• Upgrade catenary to minimize sagging	• More frequent inspections and maintenance • Slow speed orders	↑
Power interruptions (load centers)	• Work with relevant utilities to ensure more resilient power supply	• Enhance redundancy of power sources (most NJ Transit lines already have sufficient redundancy)		↑
Switch and signal failures		• Signals are already tolerant to temperatures of up to 160°F	• Slow speed orders for switches interrupted by temporary power failures	↑
Broken rails (cold temperatures)			• More frequent inspections and maintenance • Slow speed orders	↓
Healthy and Safety			• Improve systems to monitor and advise riders • Establish protocols for track worker safety during heat events • Conduct track work at night	→

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	Design	Operations	
Vehicle failures		• Install additional venting equipment in close-roofed stations (E.g., NY Penn) • Upgrade power systems		➲
Climate Stressor: Precipitation				
Flooding	See Inland Flooding			
Erosion/ washouts	See Inland Flooding			
Health and safety			• Slower speeds (especially in autumn due to effects of slippery rail)	➲

Table 29. Adaptation Strategy Matrix (Roadway and Rail Bridges)

IMPACT	STRATEGY Planning	Design	Operations	Frequency/ Severity of Future Incidence
Climate Stressor: Sea Level Rise				
Flooding	• Generally, impacts on bridge approaches (covered under "Roadways") are the cause of failure			↑
Erosion				↑
Corrosion (from chronic sea water exposure)		• Design infrastructure to resist salt water corrosion	• More frequent inspections and maintenance	↑
Climate Stressor: Storm Surge (Hurricanes and Nor'easters)				
Flooding	• Generally, impacts on bridge approaches (covered under "Roadways") are the cause of failure			↑
Erosion/ washouts				↑
Closures/ disruptions	• Establish and frequently update emergency detours and evacuation routes • Install ITS infrastructure to inform travelers		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Temporarily close vulnerable bridges	↑
Driver safety/ accidents	• See Roadways			→
High Winds		• Bridge structures to withstand high wind events	• Send out emergency maintenance patrols after storm events	→

IMPACT	STRATEGY Planning	Design	Operations	Frequency/ Severity of Future Incidence
Climate Stressor: Inland Flooding				
Flooding	• Generally, impacts on bridge approaches (covered under "Roadways") are the cause of failure			↑
Erosion/ washouts				↑
Scour		• Reconstruct/ reengineer scour critical bridges • Alter water body hydrology to reduce flow rates	• Send out emergency monitoring and maintenance patrols during and after storm events	↑
Closures/ disruptions	• Establish and frequently update emergency detours • Install ITS infrastructure to inform travelers		• Send out closure broadcasts/ messages • Send out emergency maintenance patrols after storm events • Regularly trim vegetation to minimize debris • Temporarily close vulnerable routes	↑
Driver safety/ accidents	• See Roadways			→
Climate Stressor: Temperature				
Bridge expansion (especially moveable bridges)		• Use more heat tolerant materials	• More frequent inspections and maintenance • Water cooling of vulnerable segments	↑

IMPACT	STRATEGY			Frequency/ Severity of Future Incidence
	Planning	Design	Operations	
Climate Stressor: Precipitation				
Flooding	See Inland Flooding			
Erosion/ washouts	See Inland Flooding			
Embankment failures		• Harden/stabilize slopes	• More frequent inspections and maintenance	↑
Corrosion (from increased surface salts due to less precipitation)			• More frequent inspections and maintenance	↓

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Recommendations and Conclusions

The vulnerability and risk assessment performed for this project was enabled by the FHWA Conceptual Model, which provided a framework for analysis, and the strong participation of a host of regional and statewide New Jersey agencies. The process and inputs employed by the project team provide a robust, high-level analysis of potentially vulnerable infrastructure, and as such represent an important contribution to the information available to decision-makers. However, without diminishing the significance of the current effort, this project was intended as a pilot, both for FHWA's Conceptual Model and for New Jersey, and as such a primary objective is to make recommendations leading to improved future efforts. Below, suggestions pertaining to FHWA and New Jersey are offered separately and in no particular order, although there are several points of intersection.

FHWA Conceptual Model

Treatment of Risk

FHWA's Conceptual Model suggests conducting an integrated risk assessment, which implies that agencies should have quantified, with some degree of precision, the likelihood of a given climate impact and the consequence of that impact on the asset in question—an expectation that is not realistic. As noted previously, climate change scenarios are not associated with specific probabilities, and an asset's potential resiliency is also a matter of some conjecture (as one interviewee stated, just because a climate variable exceeds the threshold implied in an asset's design specifications does not mean that asset will fail, and failures occasionally occur within the bounds of specifications).

Because a comprehensive understanding of risk (both isolated and integrated) is not yet mature, the prescribed risk assessment step imparts an expectation that may frustrate agencies. In response, public entities are left to devise quasi-quantitative solutions (such as ranking risk on a simple scale for multiple factors and then summing) that may not adequately reflect uncertainty, ignore the issue of risk entirely, or develop policy responses that provide the planning and engineering communities with thresholds that reflect a public consensus.

This study recommends the latter approach, which unites public risk tolerance with concrete planning and engineering solutions. If an asset serves a relatively insignificant function or has a high degree of redundancy, a lower threshold might be appropriate for planning and design. If an asset is absolutely critical and *must not fail* under any circumstance, a higher threshold (meaning a minimal risk tolerance) may be in order. The Dutch have adopted this approach in the construction of their Delta Works dyke system by designing for the 4,000 year storm surge event in Zeeland, a popular tourist area, and the 10,000 year event in the urban economic center of Rotterdam[44].

[44] http://www.deltawerken.com/Projekt-Zeeweringen/865.html. Accessed 12/1/2011.

Vulnerability Thresholds

For this project, the determination of climate vulnerability thresholds for transportation assets and components was accomplished through a series of interviews with a variety of professionals within the primary operating agencies (NJDOT and NJ Transit). Although this step took place concurrently with the generation of climate scenarios, it should have occurred prior in order to better align the variable produced with vulnerability thresholds. This instruction could easily be integrated into the Conceptual Model.

As a longer term goal, a (preferably multimodal) guidebook of vulnerability thresholds—corresponding to the types of climate outputs derived from downscaling—could be developed as a Transportation Research Board project, by AASHTO, or by the American Society of Civil Engineers, for example.

Work Flow and Hierarchies of the Conceptual Model

Although, for simplicity of expression, it can be useful view the Conceptual Model in flow chart form, the tasks embedded in the model need not be performed sequentially. For example, more granular studies may benefit from determining vulnerability prior to criticality. Although some sequencing must be maintained, it may be more useful to recreate the primary tasks (E.g., Asset Inventory) as modules, especially for the assessment phase. Each module could contain guidance on matching approaches with needs (based initially on the diverse approaches used by the Pilots), suggested key variables and sources (particularly if a Federal agency can provide relevant information), and links to existing public tools (such as NOAA's CanVis, for example).

The creation of modules could also lead to better customization of the process for different analytical scales, from a high-level sketch analysis to an in-depth analysis of a specific asset or group of assets (for example, "consider collecting the following data if your need is ____").

Adaptation Module

In the future, a full-fledged adaptation module could be added to the Conceptual Model. By concluding with vulnerability (and risk), the current Model arms agencies with a potentially very rich store of information, but does not complete the final link in the process—adaptation. The work of ongoing TRB projects, such as NCHRP 20-83(5)—*Climate Change Adaptation and the Highway System*, and existing adaptation plans and frameworks (such as *Climate Change Adaptation in New York City*) could be leveraged to build this critical module.

Opportunities

In the spirit of the ubiquitous SWOT analysis framework (Strengths, Weaknesses, Opportunities, and Threats), the Model could more explicitly highlight Opportunities, as its current primary emphasis is oriented to the identification of risks (Threats). A process, perhaps a separate module, should facilitate the determination of areas of potential intersection and integration with plans (Long Range Transportation Plans, greenhouse gas mitigation plans, state growth plans, emergency management and hazard mitigation efforts, etc.) as well as project programming exercises.

Uses beyond the Transportation Sector

Both the process and data generated and collected for a climate change vulnerability and risk assessment of transportation infrastructure could have much broader applications; for land use, economic development, natural and cultural resources, utility infrastructure, public health, safety and security, and more. FHWA should encourage coordination with other agencies or jurisdictions, which could lead to more efficient resource deployment and more robust results.

State of New Jersey

Correlate Weather Events with Congestion/Service Interruption Data

The NJDOT Traffic Management System contains a series of records of traffic disruptions related to weather events, coded by traffic station. Unfortunately, the data do not capture the length (temporally or spatially) of the disruption, nor the network effects or ability of redundant routes to handle the additional flow. For future efforts, it would be useful to correlate weather events (as reported by the National Weather Service) with third-party traffic data, such as INRIX, to gain a better picture of the potential impacts of weather events based on historical examples. Although this data could not be directly extrapolated to predict impacts based on a given climate scenario, it nonetheless would enrich the information available to analysts and decision-makers.

Bridge and Culvert Information

Currently, bridge data in New Jersey are insufficient for spatial vulnerability assessments. Two data sets (the Straight Line Diagrams and Bridge Management System) must be joined in order to create linear bridge files, and data on elevations above water (minimum underclearance, deck heights, etc.) are not available for many bridge types. In the short term, future efforts of this nature should consider leaving bridge elevation data from LiDAR intact when building Digital Elevation Models.

Culverts, the failure of which is the cause of many serious flooding events, are not included in the Bridge Management System unless they are 1) equal to order greater than five feet in diameter, and 2) run under (rather than parallel to) roadways. There are indications that New Jersey DOT has begun collecting data for a culvert management system, and effort which should be encouraged and accelerated.

Integrated Model Network

This particular criticality approach developed for this project would have benefited greatly from the availability of a statewide model network. Such a model is currently available, but outdated, and was undergoing updating during this project's period of performance. Once the new statewide model is available, its utility will extend well beyond the criticality assessments, providing a tool to analyze any characteristic or project that needs to be measured beyond regional model boundaries.

Integration with other Sectors

Disciplines outside of transportation could benefit from the climate data and projections collected for this project—including land use and comprehensive planning, agriculture, public health and safety, and recreation and tourism, for example. The results could also be utilized by transportation dependent agencies and sectors, such as emergency management, economic development, and goods movement. Coordinating with stakeholders outside of the realm of transportation could bring more resources to the process, and eventually help strengthen the resiliency of the state as a whole.

Expand or Narrow Assessment Geographies

This study covered a great deal of territory, over 1000 square miles, containing some of the State of New Jersey's most important transportation resources. However, vast areas in the north most region of the state, as well as much of the southern interior, were not covered. Areas that were not assessed comprise large populations, critical economic assets, and important natural resources—many of which were especially hard hit by Tropical Storm Irene. New Jersey should consider leveraging relevant data and findings from this study to perform a high-level vulnerability assessment for the entire state.

The results of this project could also serve as a foundation for regional or subregional vulnerability assessments (whether focused on transportation or broader in nature), reflecting the policies and priorities unique to each jurisdiction. A project at the scale of a county or region, for example, would be better equipped to perform a finer-grained analysis, perhaps even at the level of a single asset. An assessment at this level of granularity could incorporate site-specific engineering (civil, structural, electrical and/or hydrological) considerations and benefit-cost analysis, for example.

Continue NJ Partnership Coordination and Cultivate Supporting Resources

This project has succeeding in bringing together an interagency partnership, which has worked together to help craft the first large scale climate change vulnerability assessment in the State of New Jersey. The communication and collective learning engendered by this work over a 7-month span should continue regularly and indefinitely—and the follow-on initiatives necessary to capitalize on this project should be formulated in this forum.

The perspectives of other partners will also be needed, including public agencies and authorities at the Federal, bi-state, state, regional, and subregional levels, as well as New Jersey's numerous private and educational entities.

Statewide and/or Regional Adaptation Plans

The adaptation chapter incorporated into this report provides a starting place for considering which adaptation strategies may be appropriate to pursue, given the potential vulnerabilities identified. However, it does not substitute for a comprehensive, stakeholder-driven adaptation plan, such as those recently authored by the City of New York and the Highway Agency of the UK. An adaptation plan is the appropriate next step after the completion of a vulnerability and risk assessment.

Conclusion

The *Climate Change Vulnerability and Risk Assessment of New Jersey Transportation Infrastructure* project was a FHWA-funded pilot with the overarching goal of providing feedback to support the advancement of the Conceptual Model. In the process of fulfilling this objective, the New Jersey pilot project generated results that will better equip state, regional, and local transportation decision-makers to respond to the potential impacts of climate change. Although, as a first exploratory effort, this work necessarily leaves some questions unanswered and certain avenues of inquiry untraveled, it provides a springboard for future initiatives—as well as a framework for interagency collaboration in New Jersey. As this pilot study concludes, the opportunity to move New Jersey—and the nation— toward a more resilient future is just beginning.

Appendices

Appendix A—Asset Inventory

Criticality Flow Chart

The initial criticality assessment process was to have incorporated three primary factors in order to allocate assets into tiers of criticality: Access & Connectivity, Magnitude & Degree, and Redundancy and Capacity. An additional weighting factor for assets that "serve disadvantaged population s" was also considered. Due to issues of data sufficiency and resource availability, the methodology was altered, and redundancy (for which not even a proxy dataset could be located) was dropped entirely. The revised approach, which is explained subsequently, is shown in Figure 1, below, which can be compared to the original approach, shown on the following page as Figure 2.

Figure 1. Revised Criticality Assessment Flow Chart

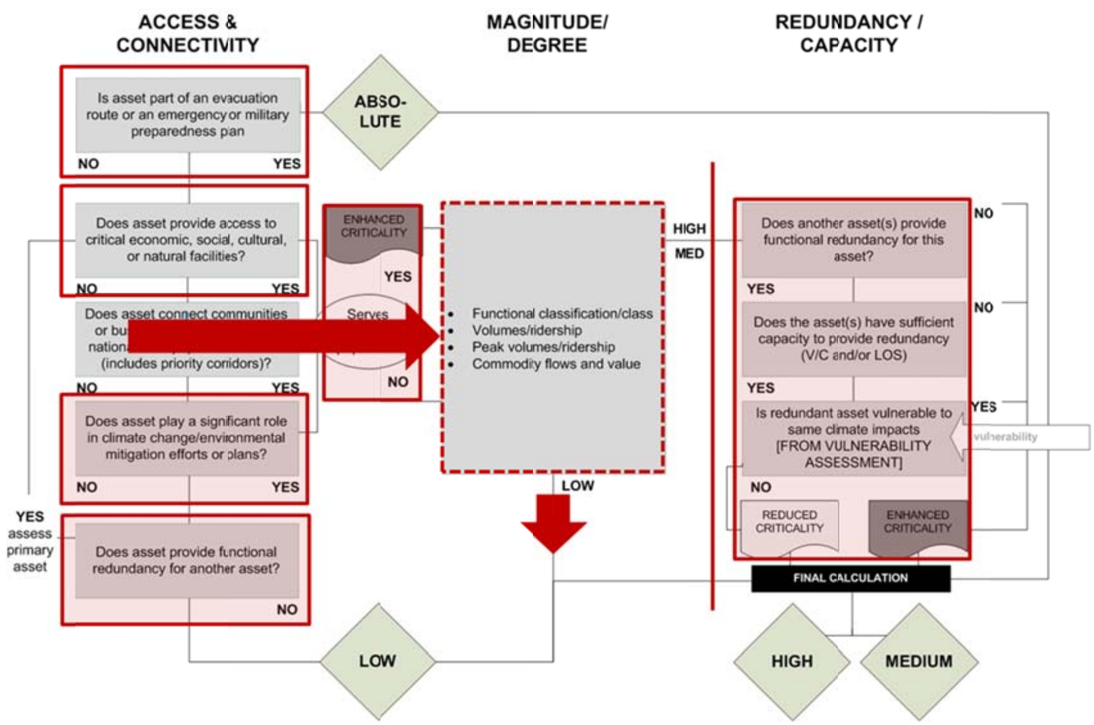
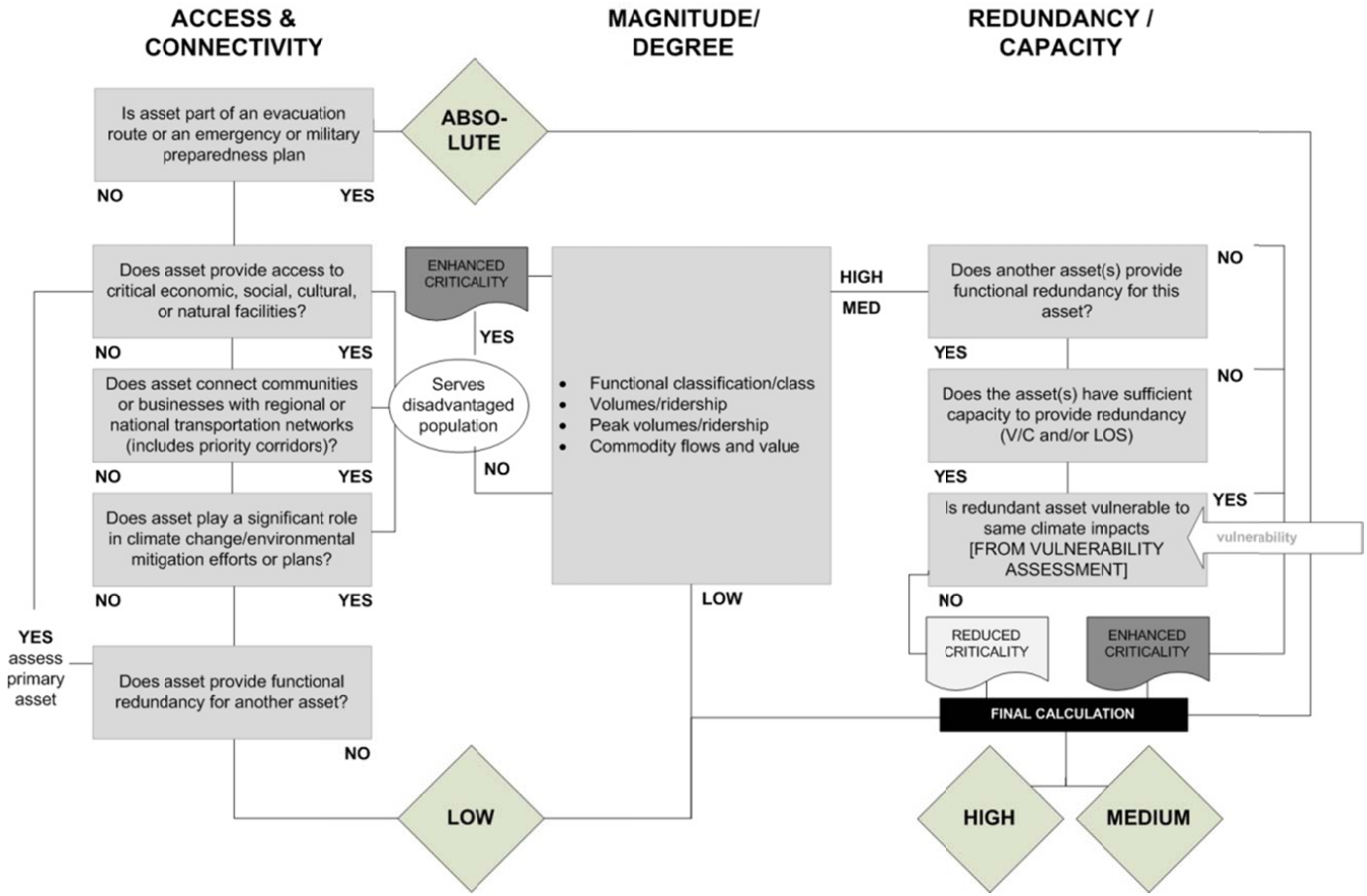


Figure 2. Original Criticality Assessment Flow Chart



Criticality Assessment Methodology

Selection of the highway network database was the foremost step before determining the criticality of highway transportation assets. The highway network selected needed to have criticality determinant data available for all its constituent links. Hence, the congestion management system was chosen as the highway network as it had traffic volume data. NJTPA's travel model network also provided traffic model information, but the extent of its network did not cover a substantial portion of the study areas.

A unified zonal structure was created by combining NJTPA, SJTPO and DVRPC traffic analysis zones (TAZs) to cover the spatial extent of the study areas. These TAZs are used to determine criticality based on the magnitude of a combined measure of employment and population density to determine the criticality of a given zone. This criticality measure is then assigned to the highway network based on a gravity model calculation between each TAZ pair in the study area, as follows:

TAZ Criticality = TAZ Population * TAZ Employment/TAZ Area

However, the CMS network needed to be transformed from a centerline shapefile to a highway network fit for travel model purposes. The topology of the network needed to be refined to create intersections where necessary. The next step in the refinement process was to add centroids and centroid connectors to this road network. Each centroid represents the activity center for each zone that needs to be connected to the nearby local or arterial street in order to represent the traffic movements in and out of that zone. Multiple centroid connectors were created for each zone in order to ensure flexible traffic movement from that zone. A maximum radius of 7 mile s was used to connect the centroid connectors to the highway network in the vicinity of any given zone. This assumption was used to make sure each TAZ is connected to the nearby roads with multiple connectors, thereby facilitating many points of loading on to the highway network, which makes up for the deficient roadway network density for the model network being used in this process. The final step in the refinement process was to add speed, capacity and free flow time for each link in the network. The following speed table was used for this purpose:

Functional Class	High Spd Limit	Low Spd Limit	Avg Spd Limit	Used in the network
1	55	30	47.23404255	65
2	55	30	47.96178344	55
6	55	25	47.44680851	50
7	55	30	44.4	40
8	55	30	44.54545455	35
9	55	50	53.75	40
11	55	30	46.83006536	55
12	55	25	45.96825397	55
14	55	25	47.37546992	40
16	55	25	46.86003683	35
17	55	30	48.18965517	35
19	55	30	49.16666667	30

A uniform speed of 20 mph is used for all the centroid connectors. The free flow travel time is then calculated based on the following formula:

Free Flow Time (minutes) = Length of the Network Link * 60/(speed on the network link)

TAZ criticality is assigned to the highway network by running highway skims using TransCAD's multi path procedure. This created a shortest path time between each zone pair. A criticality measure was given to each origin-destination (O-D) pair in order to facilitate the criticality assignment procedure. This process is identical to a free-flow traffic assignment procedure. Each network link in the network was assigned unlimited capacity to ensure free flow assignment. The criticality measure between any O-D pair is denoted by an alpha as derived from the following formula:

Alpha = Origin TAZ Criticality X Destination TAZ Criticality / Travel Time

Thus each O-D pair (total about 9 million pairs) was assigned a measure of criticality, which was thereby used during the network assignment process, which was stored in a trip table format. Each given link is assigned the score of O-D pair utilizing it, which meant that every time the link was used in the assignment process, the running total of criticality for that network segment is updated with the O-D pair criticality. At the end of the assignment process, the network links which were used to connect O-D pairs of high criticality along with those which were more frequently used in the assignment process together, were the ones which were designated as relatively high criticality highway links. The results were multiplied by (AADT/10,000) and then broken into quartiles, creating the initial criticality tiers.

Spatial Vulnerability Assessment Method

Following is the procedure used to conduct the vulnerability analysis of SLR, storm surge, and inland flooding.

<u>Pre-processing Spatial Data for Identifying Vulnerable Infrastructure</u>

The climate data representing inundation extents is in raster format. It needs to be converted into vector format to perform spatial analysis to extract impacted transportation assets. As the raster data provided was in a floating point format, a two step process was executed to transform the inundation extents into vector format for impact analysis.

1. Floating point raster data needs to be transformed into an integer raster format. First, the Spatial Analyst extension must be enabled in ArcGIS. For converting to an integer raster layer, the raster calculator tool from ArcToolbox is employed. The following steps demonstrate the conversion process using ArcGIS toolbox:
    a. ArcToolbox > Spatial Analyst Tools > Map Algebra > Raster Calculator
    b. IntegerRasterLayer = Int([floatingPointLayer])*10000
2. The integer point raster is then converted into vector format using the conversion tools in ArcToolbox:
    a. ArcToolbox > Conversion Tools > From Raster > Raster to Polygon

<u>Spatial Analysis for Identifying Impacted Features</u>

The resulting inundation extents are represented as polygon features, while the transportation assets can be polylines or points. A geoprocessing technique known as "intersect" extracts transportation assets whose sections geometrically intersect with the inundation polygons and new feature classes representing transportation assets impacted by inundation are created.

ArcToolbox >Analysis > Overlay > Intersect

The result of the geoprocessing approach results in the identification extents of impacted transportation assets that are coincident with the inundation polygons that geometrically intersect them. Given the extents of the inundation vectors and transportation assets, which extend beyond the study area boundaries, the intersect geoprocess results in returning impacted transportation assets beyond the study area boundaries. Therefore, the impacted transportation assets that are within the study area boundaries are extracted for the depiction of potential impacts and the accompanying tabular representation of “miles impacted.”

NJ Transit (Sample)

WORKSHEET INSTRUCTIONS

The purpose of this worksheet is to enhance NJ Transit's understanding of the potential vulnerability of various transportation assets to climate-related stresses, some which are expected to become more frequent and/or severe in the future. By documenting the thresholds at which extreme temperatures, heavy or frequent precipitation, drought, cold/frost, and flooding cause damage or deterioration to infrastructure (or trigger maintenance responses), we are better able to assess the risks to New Jersey rail infrastructure posed by climate change. The following worksheet provides a sample template for synthesizing the quantitative and qualitative knowledge of vulnerabilities from across the agency, whether for a specific asset (the example shown is of a truss-deck rail bridge) or a general type of asset (e.g. commuter rail tracks). The worksheet may be modified to meet the needs of users.

1. **TYPE:** Please input the general asset type (this may be pre-entered), such as bridge, tracks, etc.
2. **SUBTYPE:** Please input the asset subtype (e.g. truss deck), if applicable.
3. **ASSET ELEMENTS:** Please input the various elements comprising the asset, each of which may exhibit different vulnerabilities to climate stresses. For example, bridge elements might be considered in broad terms (deck, superstructure, substructure, etc.) or more specifically (substructure could be divided into abutments, piers, slope protection, etc.), depending on the reviewer's knowledge of specific vulnerabilities. Please use the fewest elements necessary to provide an accurate depiction of known vulnerabilities.
    a. **Complementary assets** are infrastructure elements necessary for proper and/or efficient performance of the primary asset, or which are commonly integrated into the primary asset. For example, catenary is not part of commuter rail trackage, per se, but failure of this system compromises the functionality of the entire asset. Utilities, for instance, are not typically an integral part of a stationary bridge (although they may be for a lift, draw, or swivel bridge), but are often incorporated into bridge projects.
4. **MATERIAL(S):** The potential vulnerability of a given element might change depending on the materials used. If evaluating a specific asset, please input the relevant material(s) for each element, if known. For generic assessments, please create separate entries for common materials exhibiting different levels of vulnerability. For example, the damage or deterioration characteristics of rails are likely to change depending on whether the rails are jointed or continuous welded (CWR).

"DETERIORATION" AND **"DAMAGE"**

Both terms may be considered qualitatively, or a specific definition may be appended (see #6). Generally, **deterioration** refers to the gradual reduction in functionality of an asset (such as accelerated pavement roughness over time, potentially leading to premature failure). **Damage** refers to acute stress that renders the asset suddenly inoperable, whether temporarily (such as flooding) or permanently (such as a washout). Climate stresses that typically trigger a maintenance response intended to prevent either deterioration or damage should also be noted.

5. **POTENTIAL CLIMATE STRESSORS:** Please input, to the best of your knowledge, the thresholds at which damage, deterioration, or an enhanced or emergency maintenance response may be triggered for each element-material combination. Characterization of these potential impacts should, whenever possible, *include the following three components*: 1) quantitative magnitude of the stress (e.g. degrees of temperature, inches of rain), 2) the duration per event (e.g. longer than 3 days, or within a 12 hour period), and 3) the frequency of the event (e.g. 10 times in a given season). Stressors include:
    a. **Extreme heat:** Sustained very high temperature events (e.g. 95 degrees for 3 days or more). Increased nighttime "lows," which may prevent proper heat discharge, may also be relevant.
    b. **Precipitation**: Inches of rain within or over a specific period of time, either for acute events (leading to flooding or washouts, e.g. 1 inch of rain per day) or over time (e.g. 3 days or more of at least one inch of rain).
    c. **Drought:** Extended periods (30 days or more) of dry weather (below 50^{th} percentile).
    d. **Cold/Frost:** 5 consecutive days (or more) of sub 32F temperatures.
    e. **Flooding:** Rise, in inches, of surrounding water bodies or ditches/swales/wetlands adjacent to transportation asset, or, for coastal areas, storm surge.
6. **COMMENTS/DESCRIPTION:** Please succinctly qualify and/or characterize the nature of the deterioration or damage, as well as the typical response, as applicable. For example, if the entry in 5a (extreme heat) reads "95 degrees for 3 days, nighttime temps <80 degrees," then the applicable condition might be "increased susceptibility to track buckling (heat kink), order operators to monitor rails."

Table 1. Sample Thresholds Worksheet

1. ASSET TYPE: RAIL BRIDGE	**2. SUBTYPE:**						
		5. POTENTIAL CLIMATE STRESSORS					
3. ASSET ELEMENTS	**4. MATERIAL(S)**	A. EXTREME HEAT	B. PRECIP.	C. DROUGHT	D. COLD/ FROST	E. FLOODING	**6. COMMENTS/DESCRIPTION**
		3 days x 95F	3 days x 1”/day	30 day < 50th %-ile	5 days < 32F max	3 days x 1”/day	
BRIDGE							
DECK STRUCTURE							
WEARING SURFACE							
SUPERSTRUCTURE							
SUBSTRUCTURE							
CHANNEL/CHANNEL PROTECTION							
CULVERTS							
RAIL							
3a. COMPLEMENTARY ASSETS							
CATENARY							
LOAD CENTERS							
UTILITIES							
LIGHTING							
SIGNALS							

Appendix B—Climate Information

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Contents

Climate change scenarios are used to capture a range of plausible changes in climate and other variables. We needed three types of scenarios for our analysis: scenarios of sea level rise (SLR), scenarios of average changes in temperature and precipitation, and scenarios of changes in key extreme events. There is uncertainty about how much sea level and temperatures will rise as well as how precipitation will change. Consequently, the scenarios are intended to reflect a wide enough range that decision-makers can use them to develop management approaches that will be effective across a range of potential climate futures. Below we discuss the methods used to generate geographic information system (GIS) layers as input into further analysis. Section 1 discusses the methods used to create the SLR inundation datasets that are used for overlay with infrastructure. Section 2 discusses the methods used to generate the non-SLR climate variables needed, including development of average climate change data, extreme event variables needed for inland flooding, and lastly, extreme event variables needed for non-flooding analysis.

Sea Level Rise Projections

Climate change impacts natural and built environments along the coast in several ways: net SLR, more frequent and/or intense storm surges, coastline erosion, and inland flooding, which inundates low-lying coastal areas, or through the combination of inland flooding and high SLR. However, the magnitude of these impacts will vary spatially due to differences in topography, land cover, and the built environment. For example, in areas with low topographic relief and minimal existing shoreline protection (e.g., sea walls, dikes) or wetlands, areas inundated by SLR may be quite large. In areas with steep coastline profiles or existing shoreline protection, the horizontal extent impacted is likely to be much smaller. However, in either case, the magnitude of the impact is dependent upon the type, density, and extent of the built environment that is affected. Thus, in highly populated areas with no existing shoreline protection, the total impact may be large even though the spatial extent may be small. In addition, the timing of inundation under a given SLR scenario can vary substantially from location to location, depending on local factors such as crustal movement and subsidence, which affect the rate of SLR.

Quantify Coastal Impacts

We estimated the impact from SLR and storm surge on the built and natural environments along the coast of New Jersey under alternative emissions scenarios and multiple timeframes. Specifically, we addressed the local variation of historical SLR and combined it with the latest SLR projections from climate models under corresponding emissions scenarios and timeframes to estimate the amount of relative SLR spatially along the coast. In addition, we used hurricane model output added to SLR projections to estimate the added impact from storm surge.

Sea Level Rise Projections

SLR presents a direct and obvious challenge to maintaining coastal infrastructure. Throughout the late Holocene (post-Glacial) period and coincident with the rise of human civilization, sea level remained relatively constant. Since the mid-19th century, however, sea levels have been rising and are currently estimated to increase by roughly 3 mm/yr (Solomon et al., 2007). This rise is projected to accelerate through the 21st century, although the rate and extent are uncertain (e.g., Hansen, 2007). The Intergovernmental Panel on Climate Change (IPCC) presents projections based on two primary mechanisms: thermal expansion of the oceans and melting of glaciers and ice caps. The IPCC concludes that late 21st century sea levels will be between approximately 18 and 61 cm higher compared with those of the late 20th century (1980–1999) depending on the emissions scenario (Solomon et al., 2007).

However, these estimates exclude full consideration of ice sheet dynamics in Greenland and Antarctica. Recent studies examining the long-term historical relationship between global temperature and sea level (e.g., Rahmstorf, 2007; Vermeer and Rahmstorf, 2009) conclude that late 21st century sea levels are more likely to be between 1 and 1.5 m above late 20th century elevations, depending on the emissions scenario assumed. Pfeffer et al. (2008) found that SLR is unlikely to exceed 2 m by 2100 and is most likely to be 0.8 m.

The term “sea level” is often used interchangeably with “mean sea level.” However, when discussing SLR, it is important to differentiate between the eustatic (or global) rate and the local rate, sometimes referred to as “relative sea level rise.” Eustatic SLR is defined as the average rate of SLR over the world’s oceans; relative SLR refers to the rate of change in the sea surface relative to the land at a specific location. The eustatic rate represents an average value and that SLR varies regionally due to a number of factors such as variations in temperature, salinity, winds, and ocean circulation (see Figure 1; Solomon et al., 2007). Relative SLR, on the other hand, takes into account both the global rate as well as local factors that may influence sea level. These include such factors as crustal movement resulting from deweighting since the last ice age (isostatic rebound) and subsidence from groundwater withdrawals and organic decomposition. Therefore, the local rate of SLR can be much greater or much less than the global average.

As discussed above, estimating the lands that are likely to be inundated in the future at any specific location requires a complex analysis. This analysis takes into account both the eustatic and regional SLR from climate change models as well as local factors such as crustal movement, subsidence, and other characteristics that vary greatly along the coast. In conducting this type of analysis within a GIS, several datasets are required. These include:

- Projections of SLR
- Historical SLR trend data from tide gauges
- Estimates of storm surge
- Digital elevation model (DEM) data.

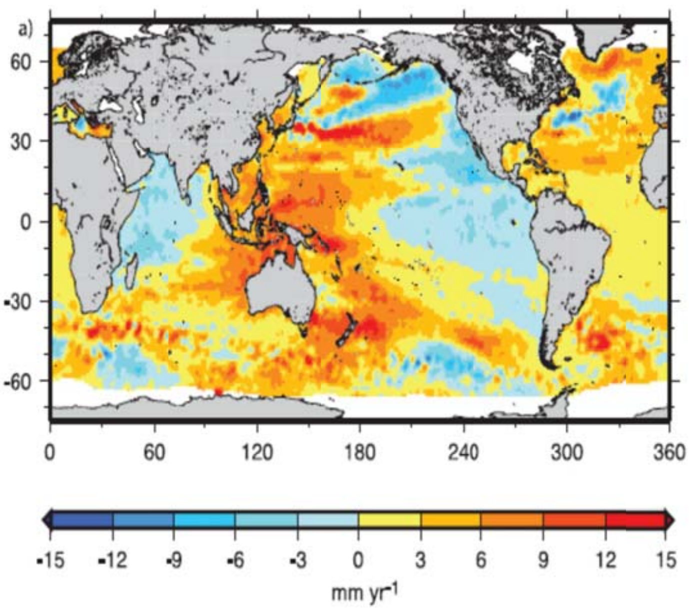

Figure 1. Geographic distribution of mean sea level based on satellite altimetry 1993–2003 (millimeters per year).

Source: Bindoff et al., 2007, Figure 5.159(a), p. 412. GIS data related to SLR and storm surge.

Sea Level Rise Estimates

Three scenarios of total average global SLR by 2100 were modeled – 50 cm, 100 cm, and 150 cm – as selected by the State of New Jersey. These scenarios were chosen to capture the uncertainty associated with ice sheet dynamics. Projections of global average SLR by 2050 were approximated using the MAGICC tool (version 5.3) developed by Tom Wigley at the National Center for Atmospheric Research (Wigley, 2008).[45] To account for regional variability along the coast, we used General Circulation Model (GCM) output obtained from the SimCLIM software package (CLIMsystems, 2010), which uses CMIP3 grids based on estimates from IPCC's Fourth Assessment.[46] The GCMs are expressed as scalars to the global mean (e.g., 0.9) and are applied solely to the thermal component of SLR.[47] To further bracket the SLR estimates, we used the lowest scalar of GCMs for the low SLR scenario, an ensemble mean of models for the middle scenario, and the highest scalar of GCMs for the high SLR scenario as follows:

- 50 cm (1.64 ft) by 2100: 10th percentile of GCMs
- 100 cm (3.28 ft) by 2100: ensemble of GCMs
- 150 cm (4.92 ft) by 2100: 90th percentile of GCMs.

[45]. Estimates by 2050 correspond to 15.6 cm (low), 26.7 cm (mid), and 37 cm (high).

[46]. GCMs available within the SimCLIM software (version 2.5.0.8) include CCCMA31, CSIRO30, GFDLCM21, GISSEH, GISSER, GISSAOM, MIROCHI, MIROCMED, ECHO-G, MPIECH5, MRI232A, CCSM30, and UKHADCM3.

[47]. If thermal expansion raises global sea levels 25 cm, then applying a scalar of 0.9 in a region results in thermal expansion being 90% of 25 cm or 22.5 cm in that region.

The scalar average[48] was then multiplied by a middle estimate of global average SLR associated with thermal expansion under the A1B emissions scenario as provided in the IPCC Fourth Assessment (Meehl et al., 2007). Using MAGICC software, the thermal SLR corresponded to 11 cm (0.36 ft) by 2050 and 25 cm (0.82 ft) by 2100. The remaining SLR was then applied without application of the regional scalar. The specific calculations are shown in Equation 1:

$$SLRreg=(RegScalar*SLRtherm)+(SLRtot-SLRtherm)$$

where:

SLRreg is SLR for the cell, *RegScalar* is the GCM-specific or average scalar, *SLRtherm* is the amount of SLR associated with thermal expansion, and *SLRtot* is the total SLR amount by the respective time period.[49]

Additionally, to account for local land movement, a subsidence rate was calculated for several tide stations along the coast (Figure 2). Subsidence values were calculated by removing the historical average global SLR rate of 1.8 mm/yr (Bindoff et al., 2007) from the long-term mean sea level trend at each station as provided by the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (NOAA, 2011a). Subsidence rates are shown in Table 1. It should be noted that the historical SLR rate was adjusted using an ensemble of GCM scalars as follows in Equation 2:\

$$SubRate=HistRate- (HistRate*RegScalar)$$

where:

SubRate is the regionally adjusted subsidence rate, *HistRate* is the global average SLR rate (1.8), and *RegScalar* is the average of regional scalars from the full set of GCMs.

---

[48]. Scalars for the coastal GCM cells ranged from 0.83-0.91 for the low SLR scenario, 1.05–1.07 for the middle scenario, and 1.49–1.61 for the high scenario.

[49] For example, for the 150 cm by 2100 scenario and assuming the 90th percentile GCM regional scalar at a specific location 1.61:

$$SLRreg = (1.61 \times 25\ cm) + (150\ cm - 25\ cm) = 165.25\ cm$$

Figure 2. NOAA tide gauge stations used to derive subsidence values.

Table 1. SLR trends and calculated subsidence rates for select tidal stations

Station name	Station ID	SLR rate at gauge (mm/yr)	GCM ensemble regional scalar	Regionally adjusted subsidence rate (mm/yr)[a]
The Battery	8518750	2.77	1.06	0.86
Atlantic City	8534720	3.99	1.07	2.06
Cape May	8536110	4.06	1.06	2.15
Philadelphia	8545240	2.79	1.06	0.88
Reedy Point	8551910	3.46	1.06	1.55
Sandy Hook	8531680	3.9	1.06	1.99

a. Based on 1.8 mm/yr average global SLR rate.

Total subsidence was calculated for each time period (assuming a base year of 2010) at each station and used as input for interpolation using a triangulated irregular network (TIN) surface of local subsidence. The TIN was converted to ESRI GRID format at a resolution of 500 m (1,642.2 ft) and applied to the regional SLR estimates to obtain total relative sea level rise (RSLR) across the study regions. Table 2 shows the subsidence, regional SLR, and the estimated total relative SLR at the Atlantic City tide station.

Table 2. Estimated RSLR at Atlantic City tidal station

Time period	Scenario	Subsidence (cm)	Regional SLR (cm)	Total relative SLR (cm)
2050	50 cm (by 2100)	8.25	14.01	22.26
2050	100 cm (by 2100)	8.25	28.2	36.45
2050	150 cm (by 2100)	8.25	50.39	58.64
2100	50 cm (by 2100)	18.57	46.44	65.01
2100	100 cm (by 2100)	18.57	101.5	120.07
2100	150 cm (by 2100)	18.57	163.35	181.92

Estimates of Storm Surge

Similar to SLR, storm surge estimates are highly site specific and vary because of differences in the coastal topography/bathymetry and local climatic patterns. To account for the impact of storm surge in the future, we used output from NOAA's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model for the Delaware Bay basin (NOAA, 2011b). As requested by New Jersey TPA, we used values estimated for a category 1 hurricane. The SLOSH model output was available as vector cells of variable size and was limited to the lowest elevations in our study areas (Figure 3). Because a seamless raster dataset addressing the full extent of our spatial domain was needed, we interpolated a raster surface from the centroids of each polygon using inverse distance weighting (IDW; Figure 4).

The resulting surface, at 10 m (32.8 ft) resolution, represented the estimated storm surge for a category 1 hurricane covering the full extent of our study areas. We applied (added) the final storm surge layer to our SLR data for each climate scenario and time period within the GIS to provide an estimate of the area impacted and the depth of inundation.

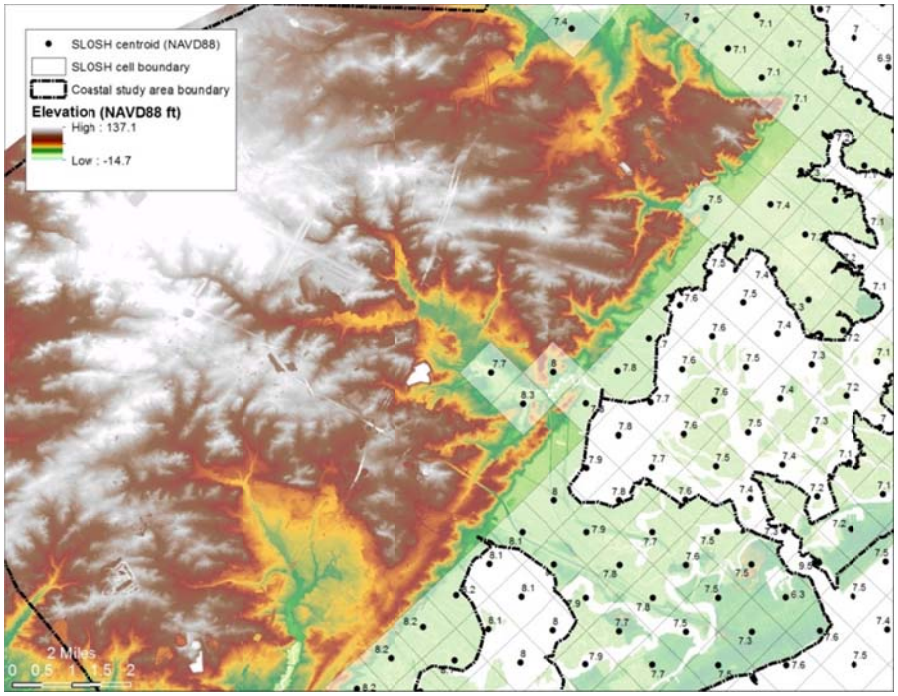

Figure 3. SLOSH cells and centroid points used as input to generate a storm surge layer.

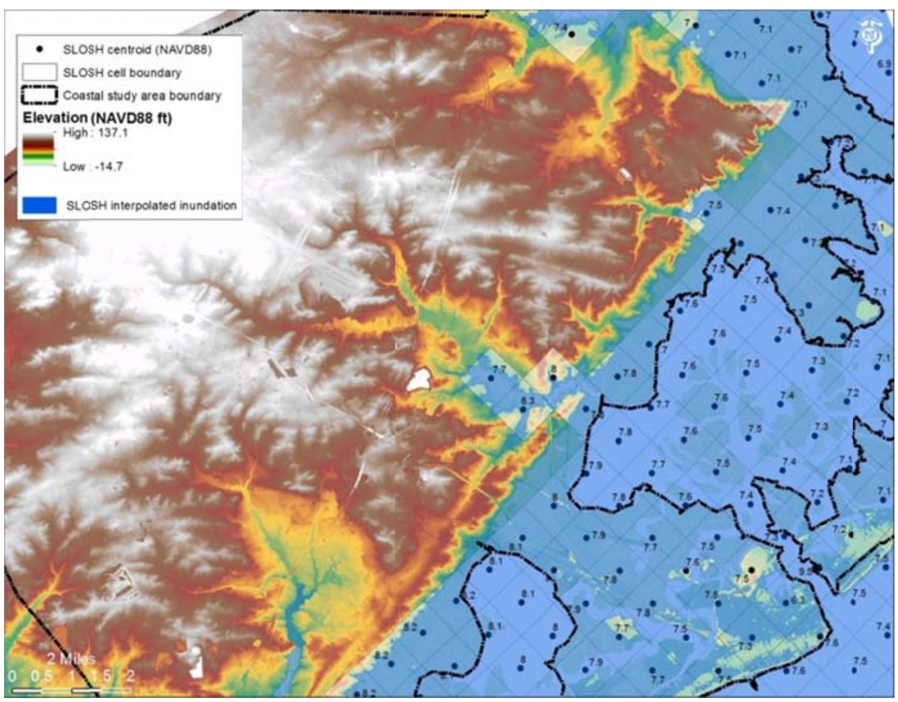

Figure 4. SLOSH cells and final interpolated storm surge raster layer.

Digital Elevation Model Data

We used high-resolution [2 m (6.56 ft)] DEM data provided by Dewberry and Associates developed from LiDAR. The county-level data were merged into two seamless datasets covering each study area. The data, as provided, were referenced to the North American Vertical Datum of 1988 (NAVD88). To conduct our inundation analysis relative to the high tide rather than NAVD88, we used tide gauge data[50] to convert the NAVD88 elevations to mean higher high water (MHHW) based on the translations between NAVD88 and MHHW provided in the benchmark sheets for each station. Because the MHHW value was relative to the 1983–2001 tidal epoch, the mean SLR trend at each station was used to correct the MHHW value to 2010. We then generated a surface representing the height of MHHW above NAVD88 using a TIN interpolation for each study area and then converted to ESRI GRID format at a resolution of 500 m (1,642.2 ft). This layer was then subtracted from the DEM to create the final DEM relative to MHHW.

Inundation Modeling

The SLR and storm surge datasets were then overlaid with the DEM to delineate uplands likely to be submerged and to determine the potential depth and extent of inundation. In identifying the lands likely to be inundated, only those areas with a direct connection to the sea were considered for inundation. Inland areas below modeled sea level not connected directly to the sea were not included. Because the DEMs did not always extend into rivers and ocean areas, we used the U.S. Geological Survey (USGS) National Hydrography Dataset (NHD; USGS, 1999) to create an additional layer that provided connectivity between inundated areas. Inundation areas connected to the Delaware River or Atlantic Ocean were used to create the final layer delineating the area of inundation. Lastly, the inundation layer was used to “mask” areas less than zero in elevation to generate a raster of inundation depths.

Inland Climate Projections

To estimate how changes in climate will impact transportation infrastructure in New Jersey, we examined average change in temperature and precipitation on a monthly, seasonal, and annual basis. We also examined several “extreme event” climate variables, including:

- Inland climate variable grids for flood analysis
    - Average total number of frost days annually (defined as number of days where minimum temperate is below 0°C)
    - Maximum number of consecutive dry days annually
    - Maximum five-day rainfall during a given year (mm; probability of one for any given year)

[50]. Tide stations used in this analysis included Atlantic City, NJ; Cape May, NJ; Philadelphia, PA; Reedy Point, DE; and The Battery, NY.

- Average annual number of days equal to or exceeding 95°F (days)
- Average annual return period (years) of rainfall exceeding 1 in./day, 2 in./day, and 4 in./day (years)
- Average annual number of days equal to or less than 20°F, 10°F, and 0°F (days)
- Maximum annual precipitation (mm) of 100-year event
- Return period of historical 10-, 50-, and 100-year precipitation events.

Average Climate Change Projections

We generated gridded surfaces of average temperature and precipitation under climate change for years 2050 and 2100 under three IPCC emission scenarios: B1 (using 1.5°C sensitivity), A1B (using 3.0°C sensitivity), and A2 (using 4.5°C sensitivity), representing the "low," "mid," and "high" greenhouse gas emissions and climate sensitivity scenarios, respectively. However, because the projected changes in temperature and precipitation vary spatially by GCM, and in order to capture this uncertainty in our analysis, we applied specific GCMs to each emissions scenario. The models were selected from an ensemble of the 15 "best" models[51] based upon their projected change in mean precipitation by 2100 (2086–2115) relative to baseline conditions (1971–2000). As such, we applied the lowest emissions scenario to the GCM with the lowest projected change in precipitation, the mid-emission scenario to an ensemble of the 15 GCMs, and the highest emission scenario to the GCM with the highest projected change in precipitation. Figure 5 shows a plot of mean precipitation change versus the mean of mean temperature change over the State of New Jersey that was used for model selection.

[51]. The following 15 GCMs were selected based on how well they simulate the current climate: BCCRBCM2, CCCMA31, CCSM30, UKHADGEM, CNRMCM3, ECHOG, GFDLCM20, GFDLCM21, GISSEH, GISSER, IPSL_CM4, MIROCMED, MPIECH5, MRI232A, and UKHADCM3. The full details of the analysis can be found in Stratus Consulting (2011).

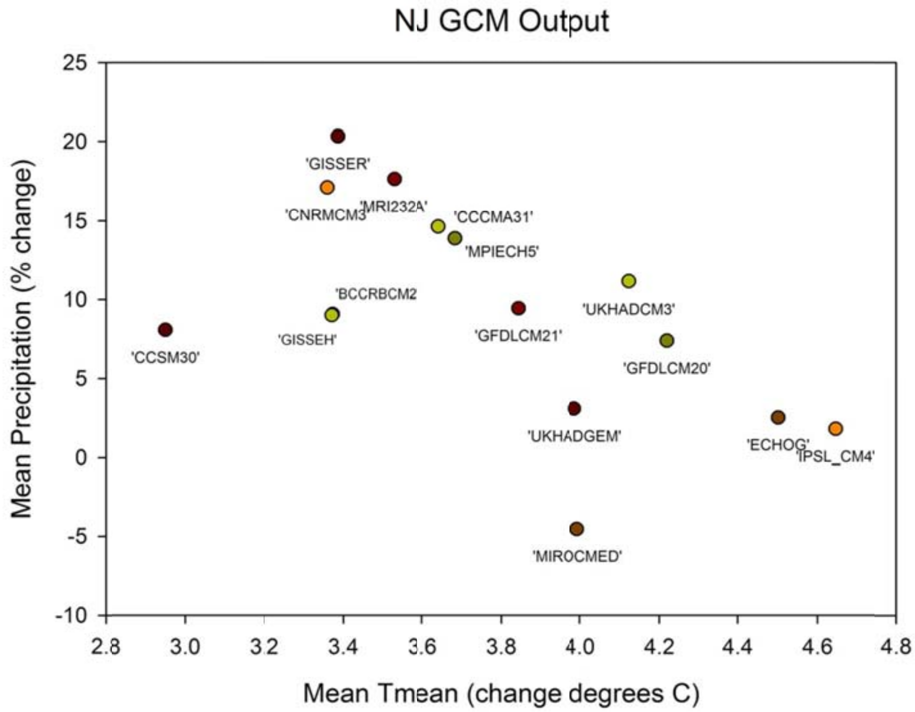

Figure 5. Plot of mean precipitation change and the mean of mean temperature change used for GCM model selection.

We used the SimCLIM software to generate raster surfaces for average climate conditions for the following climate variables: minimum average monthly temperature (°C), maximum average monthly temperature (°C), mean average monthly temperature (°C), and average total monthly precipitation (mm). The SimCLIM software uses the bias corrected spatial downscaled (BCSD)[52] CMIP3 gridded estimates from IPCC's Fourth Assessment applied to baseline climate conditions to generate absolute values (as opposed to deltas) for the climate variables. Baseline average monthly conditions used in SimCLIM are based on the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2011). Monthly mean grids at 800-m resolution were generated for each climate variable by individual month, season[53] (spring, summer, fall, winter), and annually for baseline, 2050, and 2100 time periods.

[52]. The BCSD approach is fully described in http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html#About.

[53]. Spring (March, April, May), summer (June, July, August), fall (September, October, November), and winter (December, January, February).

The three emissions/GCM scenarios area summarized in Table 3.

Table 3. Climate change scenario used in average climate change analysis

Scenario	Emission scenario	Sensitivity (2X CO_2)	GCM
Low	B1	1.5°C	MIROCMED
Mid	A1B	3.0°C	Ensemble
High	A2	4.5°C	GISSER

Extreme Event Climate Variables

Inland climate projection grids were generated for each study region and climate scenario based on daily climate station data provided with the SimCLIM software, which are based on National Climatic Data Center stations (NCDC, 2010). Separate grids were generated for each region for baseline (1971–2000) and years 2050 and 2100 under low-, mid-, and high-emissions scenarios.

Similar to the average climate change grid analysis, each emissions scenario was applied to a select GCM or ensemble of GCMs, as shown in Table 4. Note that the 11 GCMs used in the extreme event analysis are based on daily GCMs that are available for extreme precipitation analysis, which is a subset of those used for the monthly average analysis.[54] Additionally, the MRI-232A GCM was the model with the second highest precipitation change based on monthly GCM data (see Figure 5).

Table 4. Climate change scenario used in extreme event climate change analysis

Scenario	Emission scenario	Sensitivity (2X CO_2)	GCM
Low	B1	1.5°C	MIROCMED
Mid	A1B	3.0°C	Daily GCM ensemble
High	A2	4.5°C	MRI-232A (precipitation) or GISS-ER (temperature)

The SimCLIM software uses either the daily (for precipitation variables) or monthly (for temperature variables) GCM output to adjust daily climate station data for climate extremes analysis. Eight climate stations were used in the analysis – four per study region. Climate stations were selected based on proximity to the region (either within or immediately adjacent to region), spatial location within the region (to represent overall coverage), availability of data within the 1971–2000 baseline period, availability of climate variables needed (precipitation, minimum and maximum temperature), and whether the period of record needed was represented

[54]. Daily GCMs used in the extreme analysis for precipitation: BCCRBCM2, CCCMA31, CCSM30, CNRMCM3, ECHOG, GFDLCM20, GFDLCM21, IPSLCM4, MIROCMED, MPIECH5, and MRI232A.

with minimal missing days. The climate stations used in the analysis are as follows and are also shown in Figure 6.

Figure 6. Climate stations used in analysis.

Coastal Region (SW to NE):

- Belleplain St Forest
- Atlantic City Intl Ap
- Toms River
- Long Branch Oakhurst.

Central Region (SW to NE):

- Wilmington Porter Res
- Moorestown
- Hightstown 2 W
- New Brunswick 3 SE.

Inland Climate Variable Grids for Flood Analysis

A select set of extreme climate variable grids were generated for use in inland flooding analysis by Dewberry and Associates. The climate variable grids generated include:

- Total number of frost days annually (days below freezing)
- Maximum number of consecutive dry days annually (days)
- Maximum five-day rainfall during a given year (mm).

Below we describe the methodology used to generate each variable.

Frost days

The number of frost days represents baseline climate station data modified by monthly changes in temperature provided by climate change scenario and year. Monthly deltas were applied to each day in the historical record. The output is 30 years of daily data, as representative of future climate for the model year [e.g., for January 2050, each day in the historical period in January would be adjusted by the monthly change from the GCM(s) for that emission scenario].[55] The average number of frost days per year is then calculated over the 30-year period of perturbed data.

Maximum number of consecutive dry days annually

The maximum number of consecutive dry days annually is calculated from monthly changes in precipitation by climate change scenario and year applied to baseline climate station data (daily).[56] We used an analog year from the baseline dataset. The analogue year was selected based on the annual change in average precipitation that is closest to the GCM estimated change in precipitation. The procedure for calculating the analog year is as follows:

1. Calculate the average annual precipitation for baseline (1971–2000).

2. Calculate the average annual precipitation for the climate scenario/time period[57] and then determine the percent change by year from steps 1 and 2.

3. Calculate the average of the annual percent changes in step 2.

4. Using baseline data, calculate for each year the percentage change from average baseline precipitation. Find the year that is closest to the average projected change (i.e., #3). This is the “analog year” used for consecutive dry days.

[55]. If the GCM projects a 3°F warming for January 2050, 3°F would be added to each historical observation.

[56]. Note that even though this variable is for precipitation, we used monthly GCM deltas (as opposed to daily GCM deltas that are used for the other extreme precipitation event variables) for this variable as we needed a full 30-year daily dataset in order to calculate this variable which was only available using the monthly GCM data.

[57]. As noted previously, this represents the 30-year baseline data adjusted by the climate change scenario.

For example, if the average annual percent change for the future scenario/time period from baseline was 4.47%, we used the year from our baseline data that deviated from the average baseline precipitation that was closest to 4.47% as our analog year.

Once the representative analog year is determined, the number of consecutive dry days over the year is calculated from the corresponding future year. For example, for 2050, if the baseline analog year is 1984, the 1984 data perturbed by the 2050 delta are used for analysis. It should also be noted that null values represented an interruption in calculation of “consecutive” days (i.e., consecutive days did not span null values).

Maximum five-day rainfall annually

The maximum five-day cumulative rainfall is derived from the daily GCM output (as opposed to the other variables that were derived using monthly deltas) to perturb the baseline climate data. Maximum five-day cumulative rainfall is expressed as the total precipitation (mm) over a five-day period with a probability of 1.0 for any given year over the 30-year average climate period.

Generation of gridded surfaces

Once the climate variables were calculated for each of the eight stations, gridded surfaces at 800 m (2,624.67 ft) resolution were generated over the two study areas using IDW with all eight stations as input.

Additional Extreme Climate Variables

In addition to the climate variables needed for flood analysis, we generated grids of extreme precipitation and temperature grids for both study areas for baseline (1971–2000) and years 2050 and 2100 under low, mid, and high carbon dioxide emissions scenarios (Table 4). The climate variables addressed include:

- Average annual number of days equal to or exceeding 95°F (days; “Hot Days”)
- Average annual number of days equal to or less than 20°F, 10°F, and 0°F (days; “Cold Days”)
- Average annual return period (years) of rainfall exceeding 1 in./day, 2 in./day, and 4 in./day (“Extreme Precipitation”)
- Maximum annual precipitation (mm) of 100-year event
- Average annual return period of historical 10-, 50-, and 100-year precipitation events.

As in the inland flooding analysis, the SimCLIM software was used to perturb the daily climate station using either daily (precipitation extremes) or monthly (temperature extremes) GCM deltas for each climate scenario and time period.[58]

Extreme temperature grids

Four extreme temperature grids were generated for each study area: the average annual number of days equal to or exceeding 95°F and the average annual number of days equal to or less than 20°F, 10°F, and 0°F. All variables were calculated for each climate station from the 30-year baseline record (1971–2000), using the monthly delta values from the GCMs for each climate scenario and time period. The average annual number of days corresponding to each variable was then calculated from the perturbed data for each climate station. The calculated values at each station for each variable, climate scenario, and time period were then used as inputs for interpolation (using IDW) to generate continuous raster surfaces.

Extreme precipitation grids

Several extreme precipitation grids were generated for each study area for each time period and climate change scenario. The variables derived include:

- The average annual return period (years) for the projected extreme precipitation events exceeding 1 in./day, 2 in./day, and 4 in./day
- The total amount of precipitation over a 24-hour period for a 100-year event
- The projected average annual return period (years) of the historical 10-, 50-, and 100-year extreme precipitation events.

The SimCLIM software was used to derive each of the variables above. Similar to the extreme temperature analysis, each variable was calculated by climate station from the 30-year baseline record (1971–2000). The daily data were then adjusted with change values from the GCMs for each climate scenario and time period. However, for these extreme precipitation variables, deltas from *daily* GCMs were used as opposed to the *monthly* deltas that were used for the temperature variables. Once the perturbed dataset was generated, a Generalized Extreme Value (GEV) curve was fit to the data for the baseline and future scenarios. The corresponding annual return periods or absolute amounts were then derived from the curve for the first two variables above. The last variable above was derived by first finding the absolute amounts of the 10-, 50-, and 100-year events from the baseline data. Because GEV curves are generated for both baseline and projected climates, the SimCLIM software can then derive the projected return period from those absolute amounts.

Once the variables specific to each climate station were derived, they were used as input for interpolation (IDW) into raster surfaces for both study areas.

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[58]. As noted in Section 2.2, daily GCM data is only available for precipitation variables, therefore, thermal variables are based on monthly GCM data.

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Memorandum

To: Josh DeFlorio

cc: Russ Jones

From: Joel B. Smith, Stratus Consulting Inc.

Date: 6/14/2011

Subject: Recommended Selection of GCMs

Summary: I analyzed how well 20 general circulation models (GCMs) simulate current climate and based on the analysis, I recommend that 15 models be used to develop climate change scenarios for the New Jersey Transportation Planning Authority (NJTPA) project.

Discussion: To select the GCMs to use in the NJTPA project, I analyzed how well 20 GCMs simulate current precipitation patterns. Table 1 displays the 20 GCMs. A common test of climate models is to examine their ability to simulate current climate. To be sure, and as many scientists will point out, the ability of a climate model to simulate current climate is no guarantee the model will give a more reliable projection of future climate change than a model that does simulate current climate as well. Nonetheless, the best information we have on the quality of the models is their ability to simulate current climate. Furthermore, a model that cannot simulate current climate well has to be questioned.

I used the tool MAGICC/SCENGEN,[59] developed by Dr. Tom M. L. Wigley of the National Center for Atmospheric Research. MAGICC/SCENGEN is a user friendly tool, which enables one to examine GCM simulation of current climate and projections of climate change. Among the capabilities MAGICC/SCENGEN has is comparison of GCMs' simulation of current climate with actual climate.

I analyzed how well the GCMs simulate current precipitation patterns. This is done because the models have much more difficulty simulating precipitation than temperature. The behavior of temperature is much less heterogeneous than precipitation. Analysis of GCMs' ability to simulate current temperature patterns would show far less differences than analysis of precipitation.

Even though we are primarily interested in the GCMs' simulation of climate over New Jersey, the analysis considered model skill in simulating global precipitation, continental United States precipitation, and precipitation in the Northeast U.S. Climate scientists advise not relying on how well models perform in simulating climate in a particular area (particularly an area as small as a state) as an indicator of the models' skill.

I examined two statistics that help in determining model's skill in simulating current climate. The first statistic is pattern correlation. It measures how well the models simulate the wet and dry areas of the Earth (or of a selected region). Essentially, this statistic measures the degree to which models get precipitation to fall in the right places. The second statistic, root mean square error minus bias (RMSE-corr) is a measure of the absolute difference in models' projections of precipitation from actual

[59] Wigley, T. M. L. 2008. "MAGICC/SCENGEN 5.3." Boulder, Colorado: National Center for Atmospheric Research. http://www.cgd.ucar.edu/cas/wigley/magicc/

precipitation. It uses the root of the mean square error (difference) between model simulations of current precipitation and actual precipitation. Dr. Wigley notes in (Wigley, 2008) that difference between average model precipitation and actual is not a good indicator of a model's performance, because it may reflect differences in assumed climate forcing. Subtracting off average bias (difference between model's simulation of precipitation across a selected region and actual) then focuses on whether some areas have a high error in simulating precipitation.

I compared the 20 models' ability to simulate current precipitation, using pattern correlation and RMSE-corr for the entire globe, the continental U.S., and the Northeast US. Wigley (2008) contains pattern correlations and RMSE-corr for the Earth and the US by model. I used his reported results. To get results for the Northeast US, I defined the region as a rectangle going from 37.5oN to 47.5oN and from 70oW to 82.5oW.[60] This is roughly a rectangle going from Boston to Cleveland, and as far south as Richmond, Virginia. I created the region to minimize use of grid boxes over the Atlantic Ocean. So, the center of the grid box is west of New Jersey. This is preferable to using too many ocean grid boxes since they behave differently than land areas. I used MAGICC/SCENGEN to calculate pattern correlation and RMSE-corr coefficients for each model in the defined Northeast region.

How well models do in simulating global precipitation patterns is most important; then how well they do in simulating the U.S., then the northeast. I combined the correlations for each model using weights of 40% for global correlation, 35% for US, and 25% for the Northeast. I then ranked results for pattern correlation and RMSE-corr. Those results are displayed respectively in Tables 2 and 3. There are strong similarities in the rankings across the models, but do better in one metric than the others. Note that the average pattern correlation for all 20 models is just slightly below the top ranked model and is better than all of the others. The model average for RMSE-corr is better than all of the individual models.[61]

I then combined the two rankings. I think pattern correlation is a more important measure of model reliability so I put 2/3 weight on that score and 1/3 weight on RMSE-corr. The combined rankings are displayed in Table 4.

Recommendations. I analyzed Table 4 to see where there are relatively large differences in the score combining rankings (the 2nd column in Table 4). One break happens between models 4 and 5 (GFDL 2.1 and GFDL 2.0). It would be quite constraining to limit the analysis to just four GCMs It is unlikely the range of projections across these four models would reflect a broad range of uncertainty. Indeed, it is quite possible the four models could skew the analysis.

The next break is between the models ranked 11 and 12, MIROC-Medium and CNRM. It would be acceptable to use eleven models in the analysis. The last break is between models 15 and 16, BCCR and FGOALS and CSIRO3.0, which are tied for 16th place.

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[60] MAGICC/SCENGEN divides the globe into grid boxes measuring 2.5o across. So I selected those grid boxes that I thought captured the Northeast US.

[61] The propensity of average of all GCMs to simulate current climate better than any individual climate model has been published in the literature, e.g., Reichler, T. and J. Kim. 2008. "How Well Do Coupled Models Simulate Today's Climate?" *Bulletin of the American Meteorological Society*. (March). 303-311.

The tradeoff of including more or fewer models is between having a larger number of models to work with verses including models that do not score as well. It is preferable to have more models, but adding models which do not perform as well may not necessarily increase performance.

In my view, the advantage of having 15 models from which to select scenarios outweighs the lower scores of the models ranked 12 to 15. So, I recommend using the top 15 models. Note that two of the 15 were not used by the New York City Panel on Climate Change. These two are the GISS-EH (from the Goddard Institute for Space Studies in New York City) and the CCCMA (Canadian Climate Model). The NYCPCC did not use those two because there was insufficient data from them. The other 13 GCMs are the same as those used by New York, so there is significant overlap. All 15 models are in SimCLIM, the tool we will use to provide output for the climate variables.

Table 2. Ranking of GCMs. By Pattern Correlation.					
	Global	USA	Northeast		
Weights	40%	35%	25%	Combined	Rank
MRI232	0.886	0.909	0.899	0.897	1
ECHO-G	0.910	0.840	0.892	0.881	2
HADCM3	0.858	0.916	0.870	0.881	2
GFDL2.1	0.857	0.789	0.939	0.854	4
GISS-ER	0.774	0.795	0.943	0.824	6
GFDL2.0	0.868	0.773	0.799	0.818	7
CCSM3	0.797	0.777	0.893	0.814	8
CNRM3	0.772	0.761	0.939	0.810	9
ECHAM5	0.808	0.807	0.814	0.809	10
MIROC3.2Med	0.833	0.687	0.890	0.796	11
GISS-EH	0.733	0.726	0.953	0.786	12
CCMA3.1	0.888	0.836	0.549	0.785	13
BCCR	0.793	0.684	0.894	0.780	14
IPSL4	0.808	0.752	0.711	0.764	15
MIROC3.2HI	0.800	0.650	0.818	0.752	16
FGOALS 1.0	0.816	0.441	0.909	0.708	17
CSIRO3.0	0.814	0.588	0.619	0.686	18
INMN 3.0	0.700	0.456	0.857	0.654	19
PCM	0.665	0.474	0.882	0.652	20
Model Average	0.910	0.843	0.944	0.895	

Table 3. Ranking of GCMs by RMSE-corr					
	Global	USA	Northeast		
Weights	40%	35%	25%	Combined	Rank
MRI232	0.963	0.437	0.162	0.579	1
ECHO-G	0.854	0.535	0.203	0.580	2
CCMA3.1	0.949	0.541	0.322	0.649	3
HADCM3	1.235	0.397	0.264	0.699	4
GFDL2.1	1.128	0.606	0.189	0.711	5
GFDL2.0	1.095	0.632	0.225	0.715	6
ECHAM5	1.328	0.476	0.255	0.762	7
MIROC3.2Med	1.162	0.752	0.215	0.782	8
CCSM3	1.317	0.622	0.317	0.824	9
GISS-ER	1.399	0.598	0.284	0.840	10
CSIRO3.0	1.198	0.826	0.338	0.853	11
IPSL4	1.266	0.682	0.431	0.853	11
FGOALS 1.0	1.187	0.969	0.247	0.876	13
GISS-EH	1.473	0.688	0.224	0.886	14
BCCR	1.275	0.733	0.534	0.900	15
MIROC3.2HI	1.311	0.827	0.351	0.902	16
CNRM3	1.333	0.654	0.659	0.927	17
INMN 3.0	1.590	0.905	0.242	1.013	18
HADGEM1	1.568	0.605	0.725	1.020	19
PCM	1.680	0.875	0.190	1.026	20
Model Average	0.850	0.539	0.183	0.574	

Table 4. Combined Rankings		
Model	Weighted Avg.	Rank
MRI232	1.0	1
ECHO-G	2.0	2
HADCM3	2.7	3
GFDL2.1	4.3	4
GFDL2.0	6.7	5
GISS-ER	7.3	6
CCSM3	8.3	7
ECHAM5	9.0	8
HADGEM1	9.7	9
CCMA3.1	9.7	9
MIROC3.2Med	10.0	11
CNRM3	11.7	12
GISS-EH	12.7	13
IPSL4	13.7	14
BCCR	14.3	15
FGOALS 1.0	15.7	16
CSIRO3.0	15.7	16
MIROC3.2HI	16.0	18
INMN 3.0	18.7	19
PCM	20.0	20

Appendix C—Inland Flooding and DEMs

Dewberry Deliverables Documentation

NJTPA Climate Change Vulnerability and Risk Assessment of New Jersey Transportation Infrastructure

OBJECTID_1	ObjectID	Shape_Leng	JoinID	pct2050b1	pct2050a1b	pct2050a2	pct2100b1	pct2100a1b	pct2100a2	Shape_Le_1	
2	357	385.368296	255	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661	6578.62156	DFIRM XS
29	780	1262.961766	219	0.371388	30.977662	53.441325	3.366922	65.797874	162.739607	6718.587219	DFIRM XS
54	0	0	0	0	0	0	0	0	0	7334.973407	Mapping XS
55	0	0	0	0	0	0	0	0	0	7140.36669	Mapping XS
56	0	0	0	0	0	0	0	0	0	5811.624017	Mapping XS
57	0	0	0	0	0	0	0	0	0	6583.879983	Mapping XS
58	0	0	0	0	0	0	0	0	0	6555.213393	Mapping XS
59	0	0	0	0	0	0	0	0	0	6516.96561	Mapping XS
60	0	0	0	0	0	0	0	0	0	8760.711947	Mapping XS
61	0	0	0	0	0	0	0	0	0	9709.048826	Mapping XS
62	0	0	0	0	0	0	0	0	0	8648.900378	Mapping XS

Figure 5. Top width percentages on DFIRM cross-sections

3. Create a single cross-section shapefile that includes the DFIRM and mapping cross-sections, attributed with a top width change percentage for all 6 scenarios (Figure 6)

ObjectID *	Shape *	Shape_Length	JoinID	pct2050b1	pct2050a1b	pct2050a2	pct2100b1	pct2100a1b	pct2100a2
2	Polyline	6578.62156	255	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
57	Polyline	6583.879983	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
58	Polyline	6555.213393	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
59	Polyline	6516.96561	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
60	Polyline	8760.711947	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
61	Polyline	9709.048826	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
62	Polyline	8648.900378	<Null>	-3.358217	27.324622	52.831249	1.527323	61.442815	160.872661
56	Polyline	5811.624017	<Null>	-2.642215	28.025925	52.94837	1.880485	62.278889	161.231073
55	Polyline	7140.36669	<Null>	-2.116272	28.541072	53.034402	2.139903	62.893034	161.494347
54	Polyline	7334.973407	<Null>	-1.531412	29.113924	53.130071	2.42838	63.575974	161.787113
29	Polyline	6718.587219	219	0.371388	30.977662	53.441325	3.366922	65.797874	162.739607

Figure 6. Interpolated top width percentages on mapping cross-sections

4. Identify cross-section bounding polygons (one per river) to demarcate the associated floodplain. The existing DFIRM SFHA was clipped to the bounding polygons. Thus, each river has its own SFHA polygon.
5. Each SFHA was processed separately. The processing included:
    a. Compute the floodplain width at each cross-section intersecting with the SFHA.
    b. Use the floodplain width and the percent top width changes to estimate the magnitude of the increase in floodplain top width at each cross-section. The percent top width increase was distributed evenly on either side of the river. The cross-section shapefile was attributed accordingly with the new projected SFHA top widths.
    c. Split the SFHA polygon at each cross-section (Figure 7).
    d. Once the split is complete, the SFHA polygons were attributed according to the following rules:
        i. The split polygons upstream or downstream of the end cross-sections will have the same top width change as attributed in the end cross-sections.
        ii. The split polygons bound by one cross-section on each side will have an interpolated new boundary.

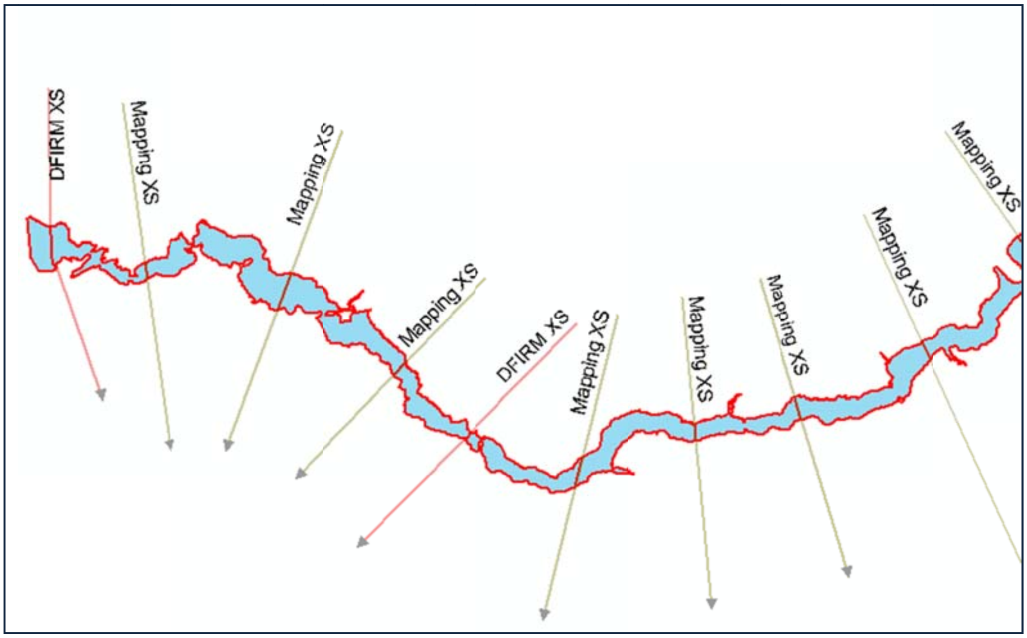

Figure 7. Map showing split SFHA polygon features. The SFHA polygons are split at each cross-section (XS)

6. Identify the tail and head pieces of the SFHA and buffer them. The buffer width for the tail and head pieces were estimated as explained in 5(d) above.
7. Delineate an interpolated floodplain boundary between the mapping cross-sections.
8. Merge all the SFHA together to create the projected riverine floodplain for the years 2050 and 2100 based on climate change parameters (Figure 8).

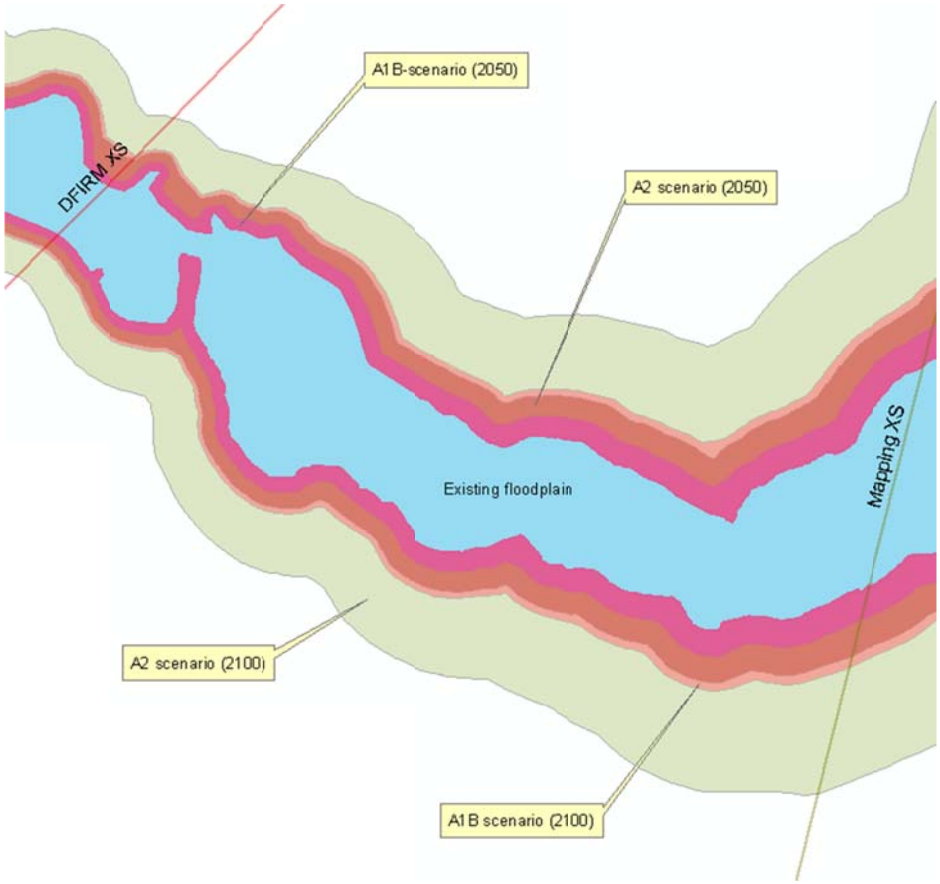

Figure 8. Predicted floodplain boundaries for the various scenarios

9. Once the projected floodplains for 2050 and 2100 were mapped, all floodplains from the same scenario were merged with the original SFHA and subsequently dissolved – or made into one piece. If needed, the floodplains were clipped to their respective county's boundaries. This resulted in six separate floodplains per county, each representing a different scenario. An example of the exported floodplains is shown below:

Name	Type
Middlesex_Scenario_B1_2100.shp	Shapefile
Middlesex_Scenario_B1_2050.shp	Shapefile
Middlesex_Scenario_A2_2100.shp	Shapefile
Middlesex_Scenario_A2_2050.shp	Shapefile
Middlesex_Scenario_A1B_2100.shp	Shapefile
Middlesex_Scenario_A1B_2050.shp	Shapefile
Middlesex_Original_SFHA.shp	Shapefile

Figure 9. Example of Shapefile Exports

draft report

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