South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project

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South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project

Final Report

Broward Metropolitan Planning Organization
Miami-Dade Metropolitan Planning Organization
Monroe County Planning and Environmental Resources Department
Palm Beach Metropolitan Planning Organization

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This report was developed by the Broward MPO as lead agency for the Broward, Miami-Dade, Monroe and Palm Beach Counties and in partnership with other agencies in Southeast Florida in accordance with a grant from the Federal Highway Administration (FHWA). The statements, findings, conclusions and recommendations are those of the author(s) and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation

Table of Contents

List of Figures

List of Tables

Executive Summary

In 2013, the Federal Highway Administration (FHWA) sponsored climate resilience pilot studies in selected states and metropolitan areas in the U.S. The intent of these pilot studies was to examine approaches to "conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency." The Broward Metropolitan Planning Organization (MPO), as lead agency on behalf of the region's three MPOs, and in partnership with other agencies, received one of the pilot projects. The project studied the southeast Florida four-county region. This report presents the results of this study.

Five study objectives were adopted to guide the analysis: 1) provide adaptation analysis capability, 2) identify adaptation projects and strategies, 3) apply a vulnerability framework and provide feedback to the planning process, 4) enhance decision support and 5) strengthen institutional capacity. The study examined three climate change-related stresses: sea level rise (SLR) inundation, storm surge flooding, and heavy precipitation induced flooding. Only roadway and passenger rail facilities on the designated regional transportation network were considered as part of this analysis.

The overall approach to the vulnerability assessment was based on the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework. A scoring system was used to rate each road and rail link in the region with respect to their vulnerability to permanent sea level rise inundation and periodic inundation from storm surge and heavy rainfall. The level of vulnerability for any particular asset was defined as a product of three factors, following the guidance in the FHWA Vulnerability Framework:

- Exposure: The degree to which a transportation facility is subject to adverse climate changes
- Sensitivity: The capacity of an asset to deal with changes in a climate stressor
- Adaptive capacity: The ability of the transportation network to deal with the loss of an impacted asset

Based on the vulnerability assessment, the road and passenger rail segments considered most vulnerable were identified. Regional facilities in Monroe County were most vulnerable due to low elevations and lack of redundancies/alternative routes. Causeways and regional facilities on barrier islands were highly vulnerable due to long detour lengths and low elevations. Regional roadways through the Everglades were highly vulnerable due to high flood exposure, low elevations and long detour lengths.

In addition to the identification of vulnerable assets, the study recommends actions in five areas of decision-making: transportation policy, planning and prioritization; rehabilitation or reconstruction of existing facilities in high risk areas; new facilities in new rights-of-way in high risk areas; system operations; and system maintenance. These recommendations are:

Transportation Policy, Planning and Project Prioritization

- Develop a goal statement relating to climate change that can be used as part of the transportation planning process
- Identify climate change-related prioritization criteria that can be used as part of the project priority/programming process
- Identify and apply performance measures to promote transportation system resiliency
- Apply tools that can be used to identify and assess continuing climate change-related impacts

Rehabilitation or Reconstruction of Existing Facilities in High Risk Areas

- Consider new road and transit design approaches and standards to minimize potential disruption due to extreme weather events (e.g., profile elevation)
- Near coastal areas and over longer term, consider sea level rise as a "given" in design of coastal facilities.
- Redesign drainage systems to handle larger flows
- Harden or armor key infrastructure components (e.g., embankments or bridge piers) against additional extreme weather-related stresses.
- Incorporate "early warning indicators" for potential extreme weather-related risks into asset and maintenance management systems.

New Facility on New ROW in High Risk Areas

- Apply design criteria - but in addition if possible, consider realignments or relocation away from high risk areas.

Operations

- Identify pre-planned detour routes around critical facilities whose disruption or failure would cause major network degradation.

- Although Florida already has well-tested emergency response action plans, in light of the results of this study, coordinate with FDOT and emergency responders to identify potential strategies for dealing with the identified risks.

Maintenance

- Avoid significant disruptions and maintenance demands by “hardening” such items as sign structures and traffic signal wires.
- Keep culverts and drainage structures debris free and maintained to handle flows.

The report discusses lessons learned over the course of conducting the vulnerability assessment. Some of the more important lessons include the following.

- Climate adaptation studies need to consider what types of data will be needed, its availability, and what surrogates can be used if it is found to be inadequate or unavailable. In addition, future climate adaptation studies would benefit greatly if certain types of data were collected periodically by transportation or planning agencies, in some cases, as part of normal data collection activities (e.g., asset management systems).
- A significant challenge with conducting a vulnerability assessment of this type in a region of this size is the processing time required to complete some of the spatial analysis identified. Some of the processes created and run to determine scores across the network for given vulnerability variables took multiple days or weeks of computer processing time to run.
- Marshalling the resources of the many different agencies (even just participating in the planning process) that should be interested in a study such as this can be challenging. A key lesson for the process is that agreements and understandings among the major participants should be put in place as early as possible in the study.
- Given the long time frame and uncertainty of climate change stresses, and the corresponding longevity of many transportation assets, the climate adaptation process cannot be simply a one-time effort, but rather something that needs to part of the normal planning and decision-making process.

Introduction

Southeast Florida, consisting of Broward, Miami-Dade, Monroe, and Palm Beach Counties, is one of the most vulnerable areas of the country to extreme weather conditions and climate change. The entire region is low lying and highly susceptible to hurricanes, storm surge, frequent flooding from heavy rain events and, in the future, permanent inundation from sea level rise. The stakes are high as the region is also one of the densest population centers in the country with more valuable assets (real estate, transportation infrastructure etc.) in harm's way than almost any other city in the United States.

Given the threats, it is not surprising that many agencies and organizations in the region are concerned about future climate changes and their impact on the region's economy and transportation system. In January, 2010, for example, the four counties formed the Southeast Florida Regional Climate Change Compact to "coordinate mitigation and adaptation activities across county lines." Specifically, the Compact was to 1) develop annual legislative programs and jointly advocate for state and federal policies and funding, 2) dedicate staff time and resources to create a Southeast Florida Regional Climate Action Plan to include mitigation and adaptation strategies, and 3) meet annually in Regional Climate Summits to mark progress and identify emerging issues. [1] The Compact is widely recognized as one of the few examples in the U.S. of a region-wide climate change action program, one that provides information and input to local decision-makers on appropriate actions to prepare for future weather-related threats.

In 2013, the Federal Highway Administration (FHWA) sponsored climate resilience pilot studies in selected states and metropolitan areas in the U.S. The intent of these pilot studies was to examine approaches to "conduct climate change and extreme weather vulnerability assessments of transportation infrastructure and to analyze options for adapting and improving resiliency." [2] The Broward Metropolitan Planning Organization (MPO), as lead agency on behalf of the region's three MPOs, and in partnership with other agencies, received one of the pilot projects. The project studied the southeast Florida four-county region. This report presents the results of this study.

The next section of the report presents the study objectives, followed by a description of the study area. The report then describes the climate change forecasts and stressors that the study area will likely face in future years. The following section describes the methodology used in the study, including data sources, technical approach and the scoring method used as part of the

[1] http://www.southeastfloridaclimatecompact.org/who-we-are/

[2] http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/index.cfm

vulnerability assessment. The report then discusses the important linkage between the adaptation strategies identified as part of this study and regional and local decision-making. The report concludes by identifying the lessons learned with respect to adaptation planning as well as observations on the application of the FHWA Vulnerability Assessment Framework.

Study Purpose and Objectives

As part of the FHWA pilot program, this study focused on the application of the FHWA Vulnerability Assessment Framework as well as additional planning tasks related to conducting an assessment study. For example, the FHWA Framework does not provide specific guidance on many of the geospatial quality control activities that were a necessary part of this study. The Broward MPO adopted five study objectives to guide the analysis:

1. Provide adaptation analysis capability
2. Identify adaptation projects and strategies
3. Apply a vulnerability framework and provide feedback to the planning process
4. Enhance decision support
5. Strengthen institutional capacity

The fourth objective was an important point of departure for the study. MPO officials wanted to make sure that the study results provided a good foundation for incorporating climate change risks into the transportation decision-making process. By so doing, the study would promote such consideration long after study completion.

Study Area Description

The study area consisted of four counties in southeast Florida—Broward, Miami-Beach, Monroe and Palm Beach Counties (see Figure 1). With just over 5.8 million residents, the Miami urbanized area, defined primarily by Broward, Miami-Dade and Palm Beach Counties, is the eighth most populous metropolitan area in the U.S. Monroe County, part of the study area, had a 2010 population of just over 73,000. A unique aspect of the metropolitan area is that with the Atlantic Ocean on the east and the Everglades on the west, the Miami urbanized area is approximately 110 miles long and at most 20 miles wide, making it one of the most densely populated urbanized areas in the U.S. This geography also results in a transportation system that is very concentrated in north-south corridors. The City of Miami is the largest incorporated city in the region, with the cities of Hialeah, Fort Lauderdale, and Pembroke Pines each having over 150,000 in population.

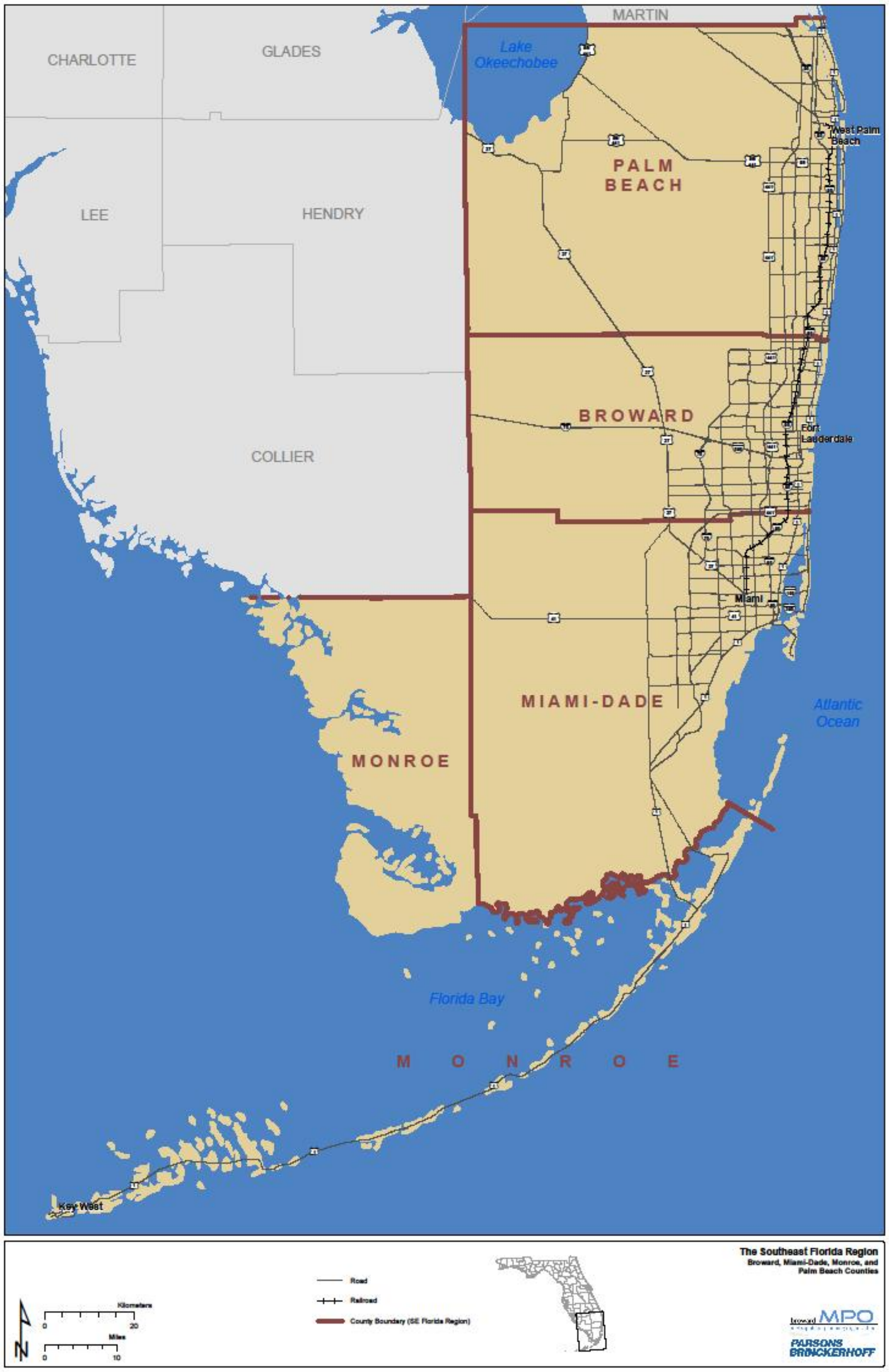


Figure 1: Study Area Consisting of Broward, Miami-Dade, Monroe and Palm Beach Counties and Regionally Significant Road and Rail Network

Economic and Population Characteristics

The population of the Miami urbanized area is projected to increase to 6,246,056 by the year 2020 (between 2000 and 2010, the population in the urbanized area grew by 12 percent). The population of the urbanized area is highly diverse, with the largest group (42%) of the population being Hispanic (in 2005, 37% of the population was foreign born). The White population represents 35% and the African American population represents 21% of the regional population, respectively. The population ages 65 years and over is projected to change from 910,396 (2010) to 1,221,546 (2020), a change of 311,150 (34.2%). Two of the top five municipalities with over 100,000 population in the U.S. having the highest median age are found in the study area (Fort Lauderdale and Hialeah).

Much of the high density development is spread out along the coast and in selected activity centers in the region (the urbanized area has one of the lowest percentages of office space located in central business districts in the U.S.). Figure 2, for example, shows the location of the population and employment in Miami-Dade County in 2040. As can be seen, much of the population and employment is located on the coast. Other major locations of employment and population occur include major highway corridors.

Given the importance of the metropolitan area as a major port of entry, it is not surprising that the highest percentage of the region's employment is in the trade, transportation and utility sector (22% of the metropolitan area's 2.4 million employees (2014 estimate)), the second most important being the professional and business services sector.

Transportation System Characteristics

The study area represents a major transportation hub in the U.S. Five interstate highways and eight major expressways handle major traffic flows in the region. According to the 2012 *Urban Mobility Report*, the Miami

The Southeast Florida Regional Climate Change Compact was executed by Broward, Miami-Dade, Monroe, and Palm Beach Counties in January 2010 to coordinate mitigation and adaptation activities across county lines. The Compact represents a new form of regional climate governance designed to allow local governments to set the agenda for adaptation while providing an efficient means for state and federal agencies to engage with technical assistance and support.

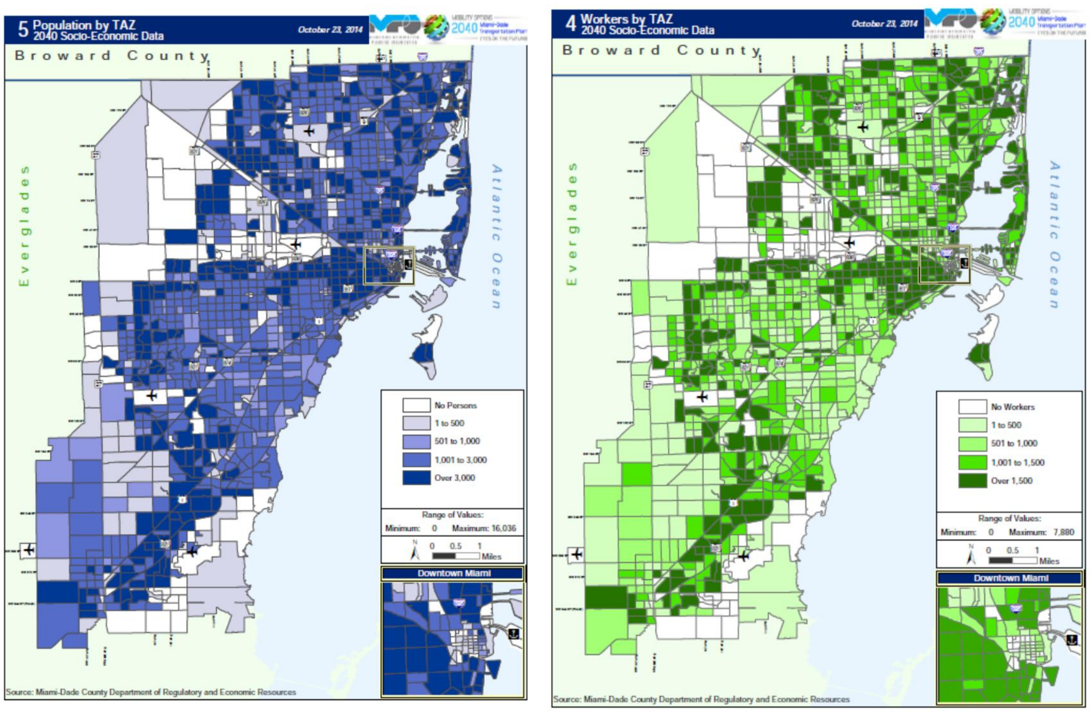
The Compact calls for the Counties to work cooperatively to:

- Develop annual Legislative Programs and jointly advocate for state and federal policies and funding
- Dedicate staff time and resources to create a Southeast Florida Regional Climate Action Plan to include mitigation and adaptation strategies
- Meet annually in Regional Climate Summits to mark progress and identify emerging issues

http://www.southeastfloridaclimatecompact.org/who-we-are/

urbanized area ranks 11th in terms of congestion on the region's highways.[3] The local road network has been designed largely on a grid network, although sizable portions of the tri-county area have typical culs-de-sac and other non-grid networks. Several important roads are causeways with bridges spanning canals and navigation channels. Given the low elevation of the study area, many roads experience flooding during high precipitation weather events.

The study area's public transportation system ranges from a heavy rail system operated by Miami-Dade Transit (MDT) to bus systems operated by Broward County Transit and Palm Tran to trolley service in various municipalities throughout the region. Miami-Dade Transit also contracts to provide two express routes to Monroe County. Key West Transit also provides fixed route transit services in Monroe County just north of Marathon. Metromover, operated by MDT, is a 4.4 mile, 21 station elevated automated people mover system that circulates in downtown Miami. Tri-Rail, the 72-mile, 18 station tri-county commuter rail system, is operated by the South Florida Regional Transportation Authority (SFRTA). Tri-Rail serves just over 4 million trips per year.



Source: http://www.miamidade2040lrtp.com/wp-content/uploads/LRTP2040_data_maps_2040.pdf

Figure 2: Location of Population and Employment, Miami-Dade County, 2040

Three major commercial airports combined make the region the fourth largest domestic origin and destination market in the U.S. Four seaports provide important ports of entry for trade

[3] http://mobility.tamu.edu/ums/

oriented primarily to Latin and South America. Port Miami is the busiest cruise port in the world. In addition, the study area has many miles of bikeways and many communities have emphasized pedestrian walkways to better connect higher density locations.

Given the extent of the study area's transportation system and a limited study budget, the study focused on a subset of the 2035 "regionally significant" transportation system defined by the Southeast Florida Transportation Council (SEFTC) (see Figure 1). The Council was formed in 2005 by the Broward, Miami-Dade and Palm Beach MPOs to provide enhanced coordination of regional transportation planning activities.[4] An important component of this collaboration is SEFTC's Regional Transportation Technical Advisory Committee Modeling Subcommittee, which serves as the forum for collaboration on use of, updates to, data for and management of the regional transportation model. The study examined the regional freeways and arterials, and the regional passenger rail line (Tri-Rail) as shown. Although there are several rail lines in the study area, only the line that currently carries passenger service was examined. Due to budget limitations, airports, seaports, Metromover, Metrorail and freight/passenger hubs were not included in the vulnerability analysis.

Participants in the Study Process

As noted earlier, the Broward MPO served as the lead agency for the study. The Miami-Dade and Palm Beach MPOs also participated in the study, as did the Monroe County Planning and Environmental Resources Department. The four counties had initiated the Southeast Florida Compact in 2010 to "coordinate mitigation and adaptation activities across county lines."[5] A Southeast Florida Regional Climate Action Plan (RCAP) was adopted by all of the counties in spring 2014 with 110 action items aimed at reducing greenhouse gas emissions and adapting to the effects of climate change. The Compact has also sponsored numerous technical documents and workshops on the process of climate adaptation planning.[6]

A study technical advisory committee was established to provide guidance on the overall technical approach and on study recommendations. Many of the participants on this advisory committee represented agencies and organizations that had been involved in climate change planning in southeast Florida for many years. The members of the advisory committee included:

Cities and Counties: Broward County Government

[4] http://seftc.org/system/uploads/documents/SEFTC%20brochure_web%20version.pdf

[5] http://www.southeastfloridaclimatecompact.org/who-we-are/

[6] http://www.southeastfloridaclimatecompact.org/compact-documents/

	City of Coconut Creek City of Fort Lauderdale City of Hialeah City of Margate City of Miami Beach Town of Lauderdale-By-The Sea Miami-Dade County Government Monroe County Government City of North Miami Palm Beach County Government City of Parkland Village of Pinecrest City of Pompano Beach City of Sunrise
MPOs/Regional:	Broward MPO (Lead Agency) Miami-Dade Expressway Authority Miami-Dade MPO Palm Beach MPO South Florida Regional Planning Council South Florida Regional Transportation Authority
Florida DOT:	FDOT District 4 FDOT District 6 FDOT Central Office, Tallahassee
Other:	Chen Moore (consultant) E Sciences Inc. (consultant) Florida Atlantic University HDR Inc. (consultant) Miami Herald University of Florida Whitehouse Group (consultant)

Climate Stressors and their Projections

Three climate change-related stresses were the focus of this study: (1) sea level rise (SLR) inundation, (2) storm surge flooding, and (3) heavy precipitation induced flooding. Each of these climate stressors are described below.

Sea Level Rise

As revealed by the research of the Southeast Florida Regional Climate Change Compact and its federal, state, local, and academic regional partners, sea level rise is the most chronic climate threat facing southeast Florida. The Compact's report, "Analysis of the Vulnerability of Southeast Florida to Sea Level Rise," revealed that nearly 900 miles of roadway, 6 ports, and 28 airports are at risk of permanent inundation to 3 ft. of SLR; a mid-range estimate for sea level change by 2100.[7] Impacts, however, will be felt even more widely than this due to the possibility that roads and other infrastructure, despite not being inundated, could have their sub-bases saturated causing maintenance challenges. SLR inundation could also affect the land uses that transportation serves rendering some areas permanently uninhabitable and altering long term travel patterns and the functioning of the transportation system. These changes will tend to be gradual, but profound, with the rates of change likely increasing over time.

> **University of Florida GeoPlan Center**
>
> The UF GeoPlan Center supports land use, transportation, and environmental planning in the State of Florida by providing geospatial and planning expertise, data, training, and education to those involved in the planning process. The Center houses the Florida Geographic Data Library (FGDL), containing over 400 geospatial layers from 35 different local, state, federal and private agencies. In addition, the Center has developed an interactive Geographic Information System (GIS) planning tool to facilitate the identification of transportation infrastructure potentially at risk from projected sea level changes.
>
> http://geoplan.ufl.edu/projects.shtml

The sea level rise analysis conducted for this study was based on recent work conducted by the GeoPlan Center at the University of Florida (UF) for the Florida Department of Transportation (FDOT).[8] The UF GeoPlan Center developed the Sea Level Scenario Sketch Planning Tool based on a methodology created by the U.S. Army Corps of Engineers for determining projections of local relative sea level for different climate emission scenarios and estimates of glacial melt rates (see Figure 3).[9] This study used this information to investigate the implications of 1-, 2- and 3-foot increments of SLR inundation; a condition that may be reached by the middle to end of this century.

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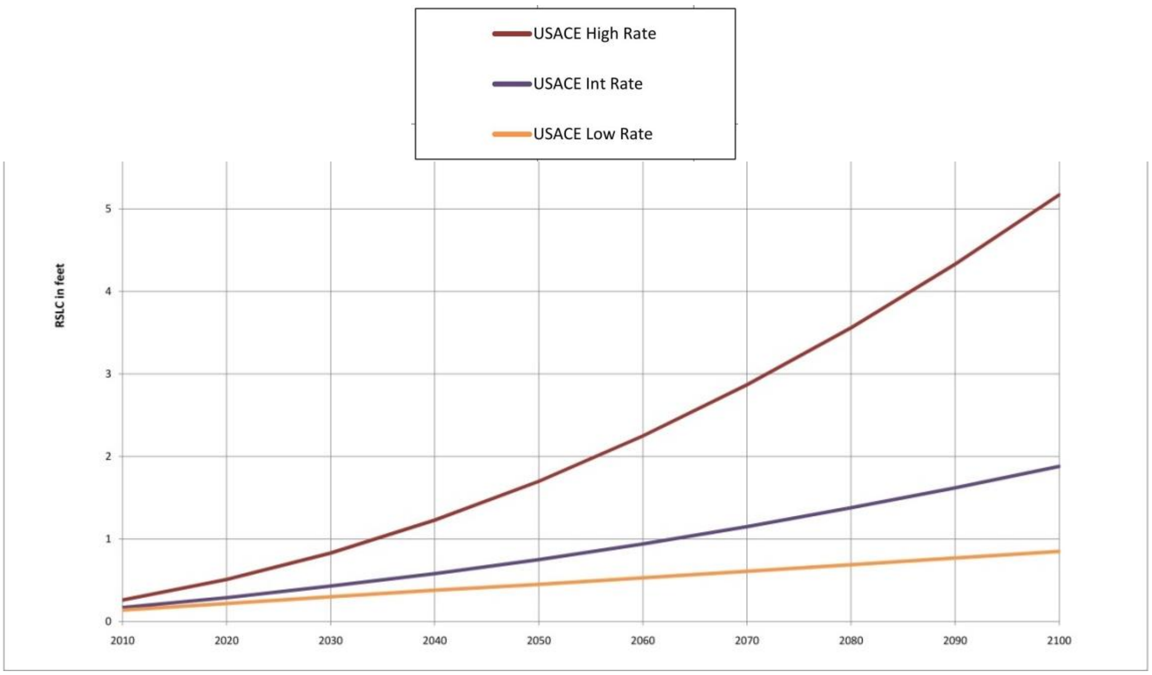
[7] http://pbcgov.com/climate/pdf/vulnerability-assessment.pdf

[8] Thomas, A., Watkins, R. "Development of a Geographic Information System (GIS) Tool for the Preliminary Assessment of the Effects of Predicted Sea Level and Tidal Change on Transportation Infrastructure." September 2013. Accessed from http://sls.geoplan.ufl.edu.

[9] http://www.corpsclimate.us/ccaceslcurves.cfm

Storm Surge Flooding

Storm surge refers to abnormally high ocean water levels that, in South Florida, most typically accompany hurricanes. High onshore winds and low atmospheric pressure can combine to create a dome of high water that is brought onshore when a hurricane makes landfall. In southeast Florida, during a storm with a 1% annual chance of occurrence (a 100-year storm), the higher than normal water levels can, under current climate, reach heights of 4 to 12 feet above normal (not counting wave action), depending on one's location in the region. Given the area's flat topography, the surge can often penetrate inland a great distance before topography or friction eventually stop its progress. Furthermore, the region's extensive canal system can act as a conduit for the surge allowing it to penetrate much farther inland than it would had the canals not been present.



Source: http://www.corpsclimate.us/ccaceslcurves.cfm

Figure 3: Florida Coast Sea Level Rise Curves, Three Emission Scenarios, U.S. Army Corps of Engineers

Climate change will exacerbate the already substantial threat surge poses to the region's transportation infrastructure. Higher sea levels will give any surge a higher base from which to start from and will result in the surge penetrating even farther inland. In addition, although the science is not yet settled on this, there is the potential that climate change could result in more frequent and/or more severe hurricane occurrences affecting the region, either of which would exacerbate the surge threat. Details on how storm surge flooding was analyzed in this study are presented in the following section, Vulnerability Methodology.

Precipitation Induced Flooding

Flooding from heavy precipitation events is perhaps the most pervasive threat throughout the region as it affects both coastal and inland locations. Because of the region's flat topography, heavy rain, a frequent occurrence in southeast Florida, has a limited ability to drain and flow to the sea. Adding to the challenges, a generally high groundwater table, limits the capacity of the ground to absorb rainwater. The result is frequent ponding and flooding of roads throughout the region.

Climate change will exacerbate precipitation induced flooding by causing more frequent intense rainfall events due to the fact that a warmer atmosphere can hold more water vapor. Higher sea levels will also reduce the ability of the rain that does fall to drain to the sea. Sea level rise will also contribute by elevating the groundwater table thereby reducing the capacity of the ground to absorb water. Details on how precipitation induced flooding was analyzed in this study are presented in the next section, Vulnerability Methodology.

Vulnerability Assessment Approach

The overall approach to the vulnerability assessment was based on the Federal Highway Administration's (FHWA) Climate Change and Extreme Weather Vulnerability Assessment Framework.[10] A scoring system was used to rate each road and rail link in the region with respect to their vulnerability to the climate stressors discussed above; permanent sea level rise inundation and periodic inundation from storm surge and heavy rainfall. Figure 4 outlines the work flow for the technical analysis of this study and will be discussed throughout the remainder of this section.

[10] http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/vulnerability_assessment_framework/page01.cfm

Figure 4: Technical Flow Diagram for Vulnerability Assessment

Key Considerations

Developing a true understanding of the vulnerabilities of the transportation system to both periodic and permanent flooding, now and in the future, required the use of accurate geospatial data and analysis techniques. Some key considerations included:

- *Use of accurate topographic information*—An elevation difference of a foot or two can determine whether a transportation asset will be inundated by a flood. Because transportation assets are often built on an embankment above the general ground surface, it was important to use topographic information with sufficient resolution to depict road and rail embankment elevations accurately. LiDAR (Light Detection And Ranging) datasets provide the necessary resolution and were used throughout the study area to assess flood exposure.
- *Development of a baseline transportation network*—Understanding the relative vulnerability of transportation assets in the region required an accurate representation of the transportation network itself. This required efforts to ensure the positional accuracy of the network, both horizontally and vertically. Horizontally, the road and rail centerlines needed to fall on top of the embankments. Vertically, special attention needed to be paid to whether the facility was on the ground surface or elevated on a bridge structure (discussed later).
- *Use of rectified baseline flood information*—It was recognized that available sea level rise and 100-year flood data had not been developed using the most accurate topographic data. This resulted in inundation being shown for land above the stated flood elevations. This was especially a problem on roadway embankments. In order to present a more accurate depiction of flood exposure, efforts were undertaken to rectify these datasets with higher resolution elevation data.
- *Defining future flood exposure*—The relatively flat topography of the study area means that slight changes in flood elevations due to future sea level rise and heavier precipitation events can lead to large changes in the horizontal coverage of flooding. However, mitigating factors (e.g. friction with storm surge) can limit the horizontal extent of these changes. A method that was sensitive to elevation and distance from the current flood zone was used to calculate possible future flood exposure.
- *Consistent region-wide* approach—An additional criterion in developing the methods to define relative vulnerability was that the data and methodology had to be consistent across the entire study area to enable comparable analysis among the various transportation links.

Data Sources

Successful transportation planning relies on comprehensive and credible data. This is certainly the case with adaptation planning. Table 1 shows the primary sources of data for the study. As can be seen, data was obtained from national, state, regional and local sources. The elevation data, in particular, were critical to that assessment in that elevation of the terrain and the height of transportation facilities above the ground became an important benchmark in determining facility inundation.

Units of Analysis

The unit of analysis to which vulnerability scores were assigned are individual segments of the regional road and rail network. Roads were generally segmented at the intersections with other regional network roads. The one exception is US 1 in the Florida Keys which entailed a very long segment between intersections and, to make the scoring more geographically specific, was broken up into shorter segments at the locations of major towns. The Tri-Rail passenger rail line was segmented based on stations with a separate segment created for the primary yard and shop facility.

Measures

The level of vulnerability for any particular asset was defined as a product of the following three factors, following the guidance in the FHWA Vulnerability Framework:

- *Exposure:* The degree to which a transportation facility is subject to adverse climate changes
- *Sensitivity:* The capacity of an asset to deal with changes in a climate stressor
- *Adaptive capacity:* The ability of the transportation network to deal with the loss of an impacted asset

Figure 5 shows the specific measures or indicators that were used in each category to assign a vulnerability score for the asset. Each of these measures is discussed below, by category.

Exposure

Three measures were used to capture the exposure of assets to the climate stressors discussed above: 1) the percent of each segment inundated by 1, 2, and 3 ft. levels of sea level rise, 2) a current flood exposure index, and (3) a future potential flood exposure index. Item 1) refers to a permanent inundation condition whereas items 2) and 3) are meant to capture exposure to periodic flooding.

Table 1: Sources of Study Data

Name/Type	Data Collected	Accuracy	Source
LiDAR Derived Elevation Contours and Digital Elevation Map (DEM)	DEM—LiDAR Mosiac	18-ft mosaic for the entire state of Florida	Florida Geographic Data Library (FGDL)
	DEM—South Florida Water Management District LiDAR Mosaics	5-ft DEMs available for western, eastern, and parts of central Palm Beach County; eastern Broward and Miami-Dade Counties; and all of the Keys	South Florida Water Management District
	DEM—South Florida Water Management District LiDAR Mosaics	10-ft DEM available for eastern and central Palm Beach County	South Florida Water Management District
Federal Emergency Management Agency (FEMA)	Flood Insurance Rate Maps for Miami Dade (3/31/14 version), Broward (8/19/14 version) and Monroe Counties (10/13/14 version)		FEMA-National Flood Hazard Layer
	Preliminary Flood Insurance Rate Map for Palm Beach County (8/18/14 version)		Palm Beach County & FEMA
Florida DOT (FDOT)-University of Florida (UFL)-GeoPlan Tool	Sea Level Rise Inundation Areas—1, 2, and 3-ft		UFL-GeoPlan Website
Transportation Network	Road and rail centerlines		FDOT-GIS

Periodic flood risk was considered using the traditional approach found in the transportation profession; that is, incorporating return-period information for weather-related events into the analysis. Return period flood events (in the case of this study, a flood event having a 1% annual chance of occurrence, a 100-year flood) are typically used to guide design decisions on transportation projects and are based on statistically derived values for precipitation or storm surge determined from observed conditions (precipitation) or a combination of observed historic values and synthetic storms (storm surge). Maps of the areas expected to be inundated by a 100-year flood event are generated by the Federal Emergency Management Agency (FEMA) and used in identifying areas where flood insurance is required. These maps are, in this study, applied to foster an understanding of flood exposure to transportation facilities through the use of geographic overlays. This approach was used to identify areas of inundation along the regional transportation network during a 100-year flood event under current climate and to highlight hotspots for possible inundation with climate change.

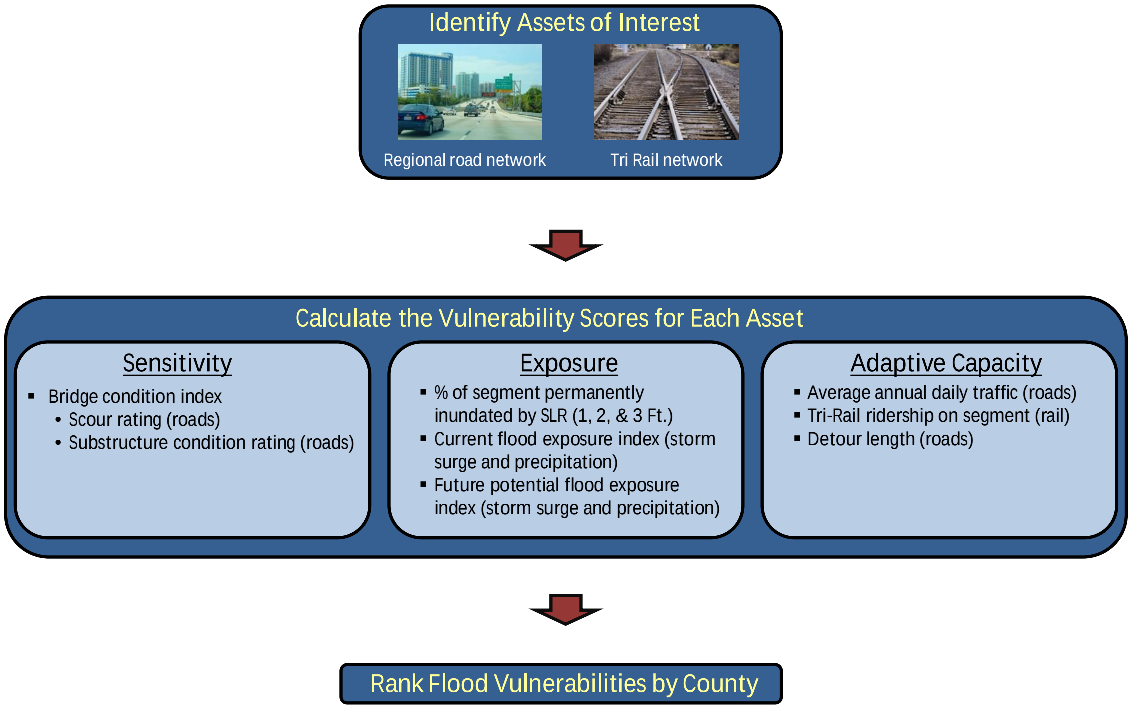


Figure 5: Approach to Climate Vulnerability Analysis

Sea level rise was considered differently since it will be a permanent inundation condition. Permanent inundation was considered to occur in the area reached by mean higher high water (MHHW) levels. Three increments of sea level rise were considered based on input from the project advisory committee: one, two, and three feet. An incremental perspective was chosen so that an understanding could be developed of the sequence in which assets would be affected. Note that this sequence will remain the same regardless of the sea level rise scenario that ultimately occurs (see Figure 4); the scenarios affect the timing and rate of impacts.

For both periodic and permanent inundation, one of the key challenges in the technical analysis was reconciling the differing datasets to be used; each of which was developed at different scales, at different points in time, by different agencies, for different purposes. Both the sea level rise and 100-year flood inundation mapping were developed using different topographic datasets at differing resolutions. To reconcile the various datasets, a mosaic of the highest resolution LIDAR datasets for the region was created. The rectification occurred through the application of geospatial processes that eliminated those portions of the inundated area where the land elevation was higher than the indicated flood zone elevation. For example, say there was a 100-year flood zone with a stated flood elevation of 7 feet that extended over the top of a roadway embankment whose actual elevation is 8 feet. In this example, the rectification process would "erase" inundation from being shown on the 8 foot high roadway embankment. These operations were performed throughout the region to eliminate false positive impacts on the transportation network.

It is important to note that the rectification process did not take into account the changes in flow, forces or depth of water that may be associated with using higher resolution land topography; only hydraulic modeling efforts using the new elevation data, beyond the scope of this study, could accomplish this accurately. For this reason, flood zones were never expanded horizontally if the lands neighboring the current inundation areas were found to be at or below the elevation of the contiguous flood zone on the higher resolution LiDAR mosaic. Again, the rectification process only "erased" those areas where the ground elevation was clearly above the stated flood elevation.

A similar rectification process was used for bridge decks whereby the elevation of the bridge deck was obtained and used to ensure that flooding underneath the bridge (either from sea level rise, surge, or heavy rains) did not register as affecting the road itself. This consisted of several steps. Two sources of information were used to determine the correct bridge deck elevations. In populated areas of the region, the University of Florida GeoPlan Center obtained the bridge deck elevations from the LiDAR source data. For the Everglades region, where LiDAR source data was not available, manual coding of bridge decks occurred based on the elevations of the bridge abutments. The road and rail line segments were next segmented into those sections on and off the bridge deck and overlain on a bridge deck layer. The segments were then checked to make sure the road or rail line was indeed located on the bridge deck and not passing underneath that bridge deck. For those segments on the bridge deck, the rectification was run again now using the corrected bridge deck and embankment elevations.

Figure 6 to Figure 8 shows the steps in the surface and bridge rectification process. Figure 6 shows the LIDAR elevation data along with a road (black and red lines) and FEMA 100-year flood zones (in blue). As can be seen, the elevated embankment of the roadway, which would be above water, and the bridge deck, which also would be above water, were indicated as being inundated with the first application of the flooding assessment (red portion of the road line). Figure 7 shows the corrections for the land elevations that were incorrectly indicated as being inundated due to the lower resolution elevation data. After the correction, the road embankment is now shown above water, which it would be with flooding to the elevation stated by FEMA. This rectification greatly reduces the proportion of the road shown as inundated (in red), however, the bridge deck is still shown as being impacted. After applying the bridge deck rectification process, Figure 8 shows that the bridge deck is now indicated as being above water and the entire facility is correctly shown to have no inundation. This example illustrates the degree to which impacts can be overstated if proper care is not taken when conducting climate vulnerability assessments.

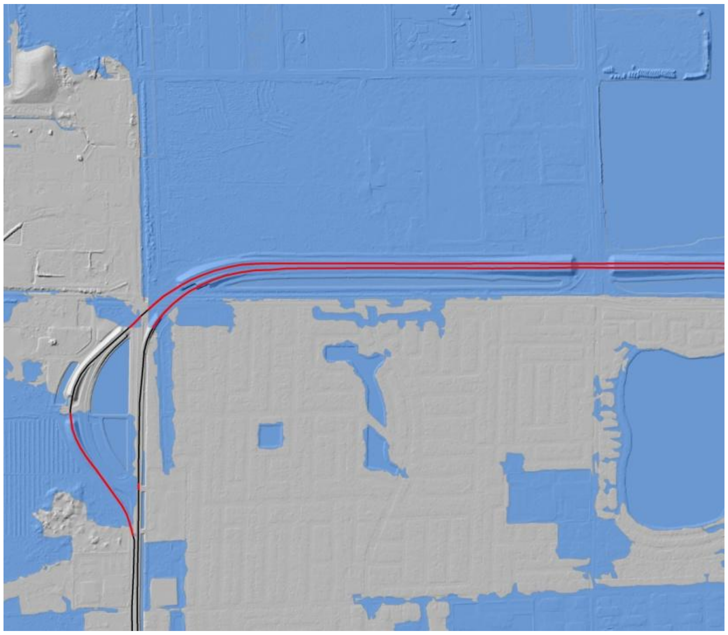


Figure 6: Application of LIDAR Elevation Database and Flooding Scenario

Figure 7: Corrections Made to Incorrectly Identified Land Elevations

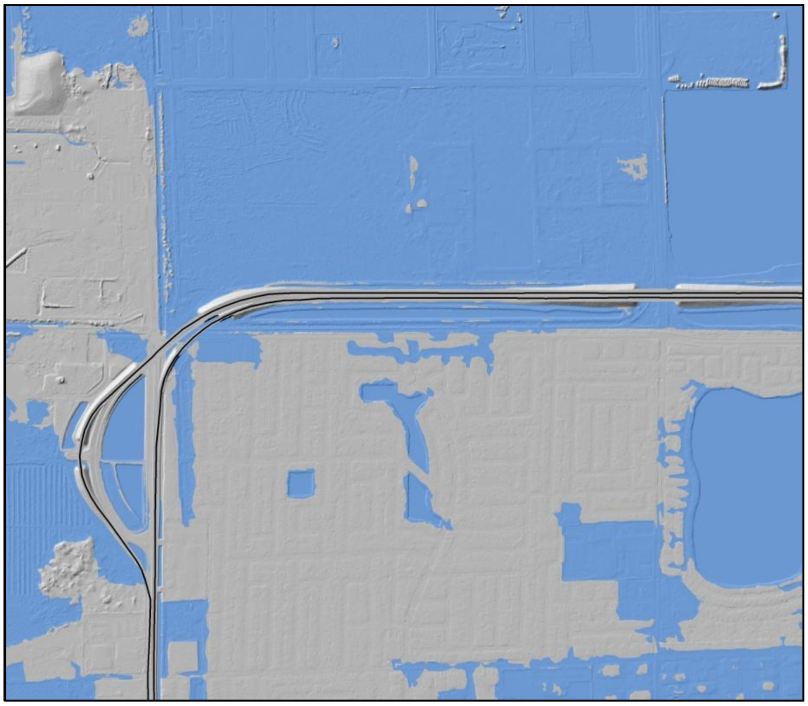


Figure 8: Corrections Made to Incorrectly Identified Bridge Deck Inundation

Once the sea level rise and 100-year flood zone inundation areas had been rectified, these layers could then be used to develop the exposure metrics used in the vulnerability scoring. The percent of segment inundated by sea level rise was a relatively straightforward measure to generate once the rectification had been completed; essentially just an overlay of the regional network on the sea level rise inundation layers. Appendix A shows those portions of each road segment inundated by the current 100-year flood. Appendix B shows the areas where permanent sea level rise inundation is projected to occur on the regional network.

For capturing present-day periodic flood exposure, a current flood Inundation exposure index was developed by overlaying the rectified current 100-year flood zones (which, again, capture both storm surge and precipitation caused flooding) on the regional network and calculating the following:

- The percent of the segment inundated by the 100-year flood zone
- If inundated, the average depth of inundation (this was included as a proxy for the severity of flooding and the amount of time it might take floodwaters to drain).

The current flood exposure index was calculated by multiplying each of these two factors.

With climate change, it is understood that the current 100-year flooding areas are likely to expand due to higher storm surges and more frequent and severe precipitation events. To capture the portions of each roadway that would have the greatest exposure to future increases in the size of these flood zones, a future potential flood exposure index was developed for those portions of the regional network that were not currently inundated by the 100-year storm. The index was generated after dialogue with coastal engineers and hydrologists and encompasses the following two components which were calculated at points every five feet along the regional network:

- The distance from the roadway/railroad to the closest FEMA 100-year flood zone
- The difference in elevation between the roadway/railroad and the flood level in the nearest FEMA zone

Weights were assigned to each of the above factors and the products were summed to calculate the index. All else being equal, roads or railroads that are very close to a flood zone and not very high above it are considered more exposed. Figure 9 to Figure 12 show future flooding hotspots where the index indicates a high exposure to future expansion of the flood zones.

Prior to settling on the distance and elevation approach to future flood potential, some other analysis techniques were considered to attempt to show the actual extent of the 100-year flood zone at various points in the future rather than relying on an index. With respect to precipitation driven flooding, in Broward County, the United States Geological Survey (USGS) is currently working on a project to define the impact of sea level rise and heavier precipitation on inland flood zones. However, this data was not complete at the time of this study nor would it have been available for the other counties in the study area creating consistency issues. Given this, it was decided that accurately trying to specify the change in the boundaries of inland flood zones was not possible at this time given the complex modeling required and that an index driven approach would need to suffice.

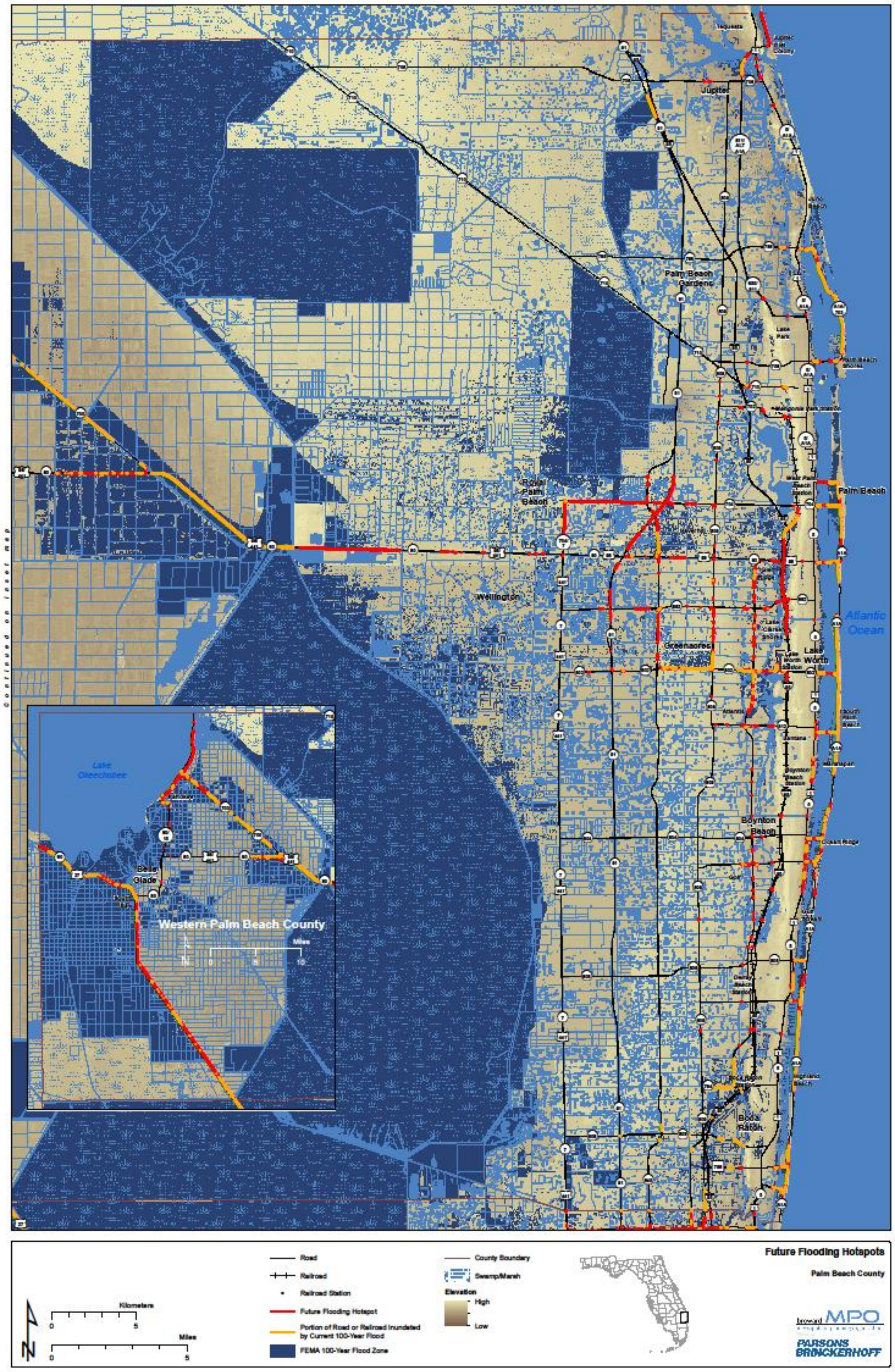


Figure 9: Future Flooding Hotspots, Palm Beach County

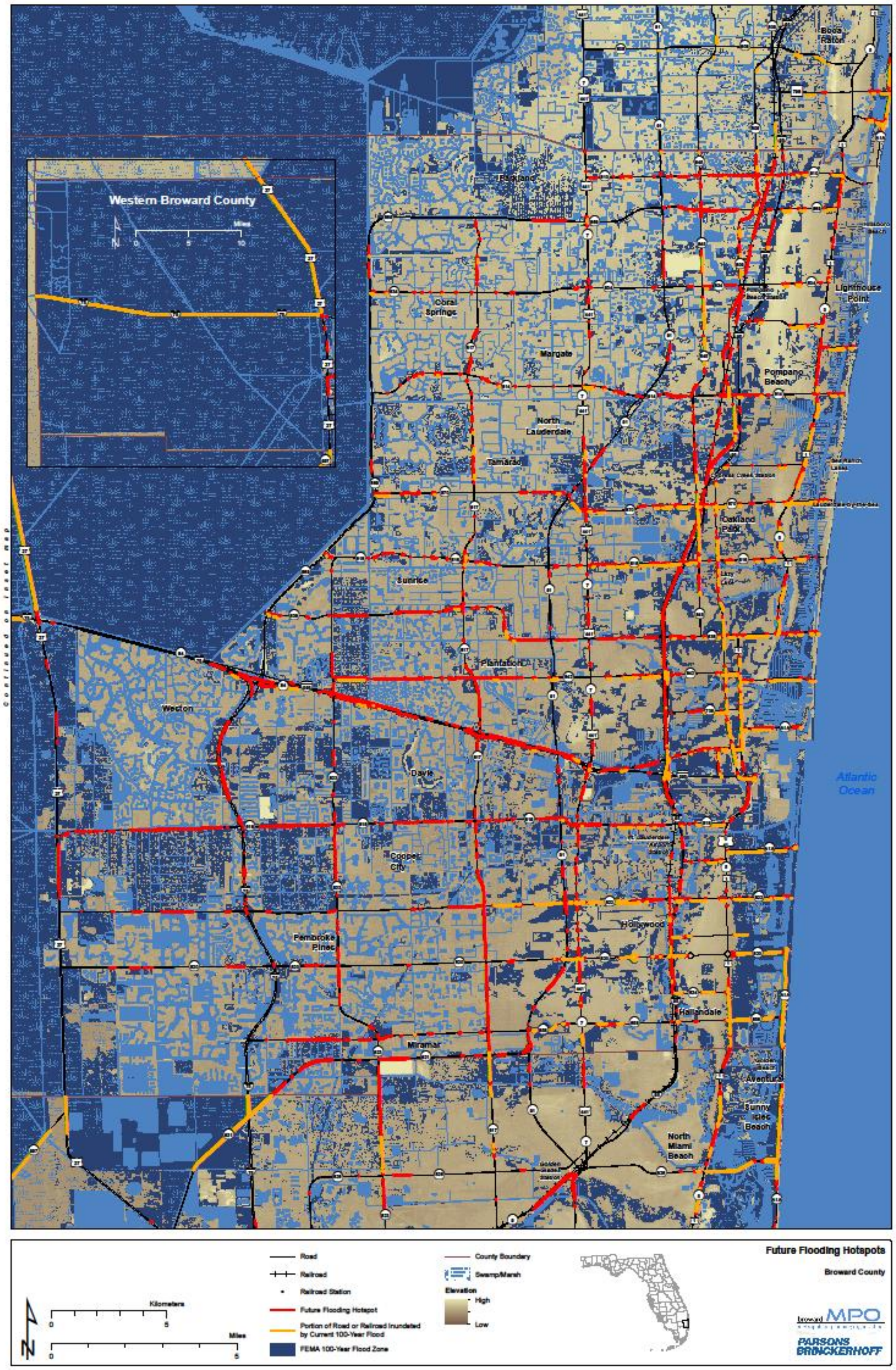


Figure 10: Future Flooding Hotspots, Broward County

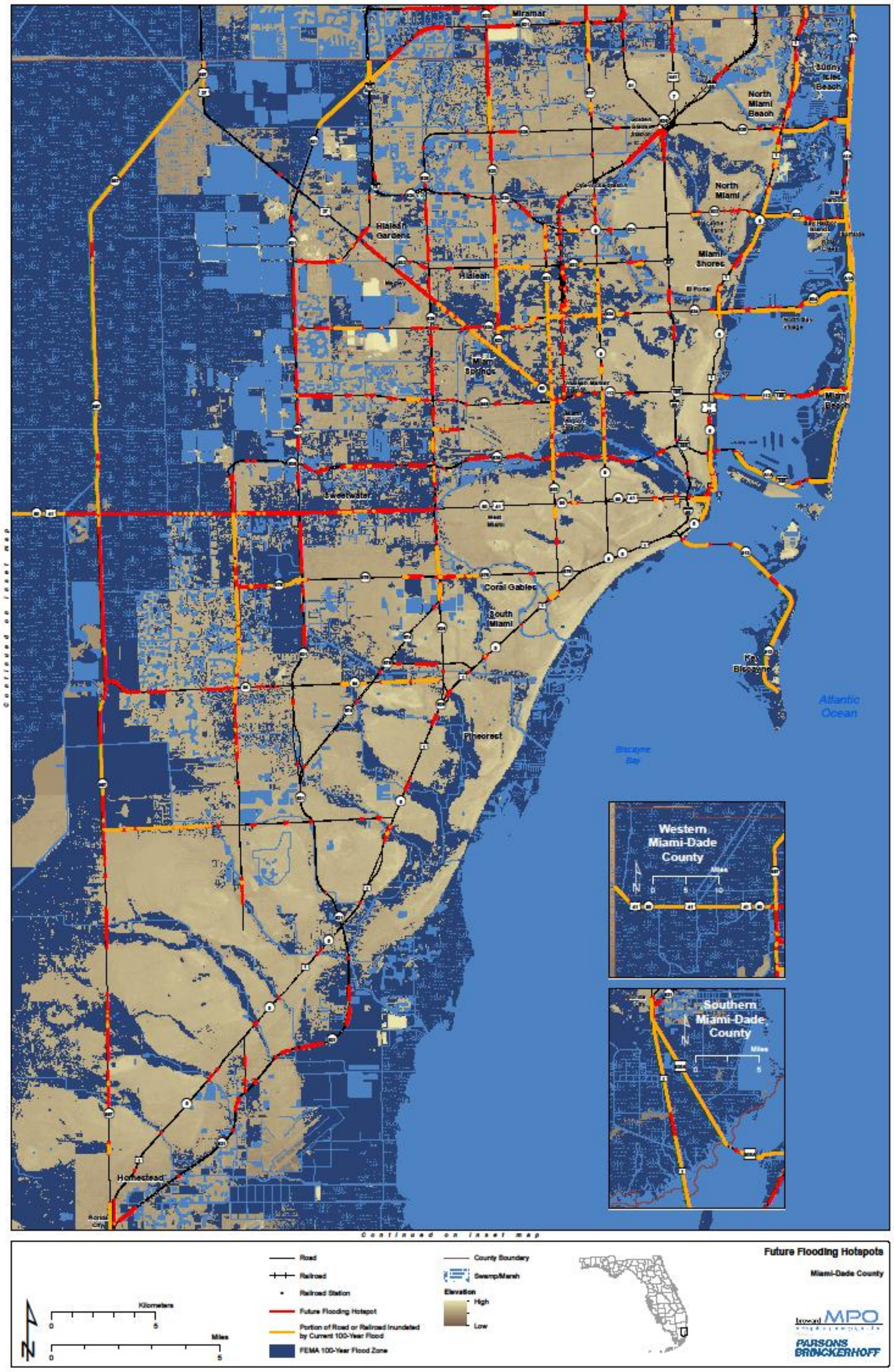


Figure 11: Future Flooding Hotspots, Miami Dade County

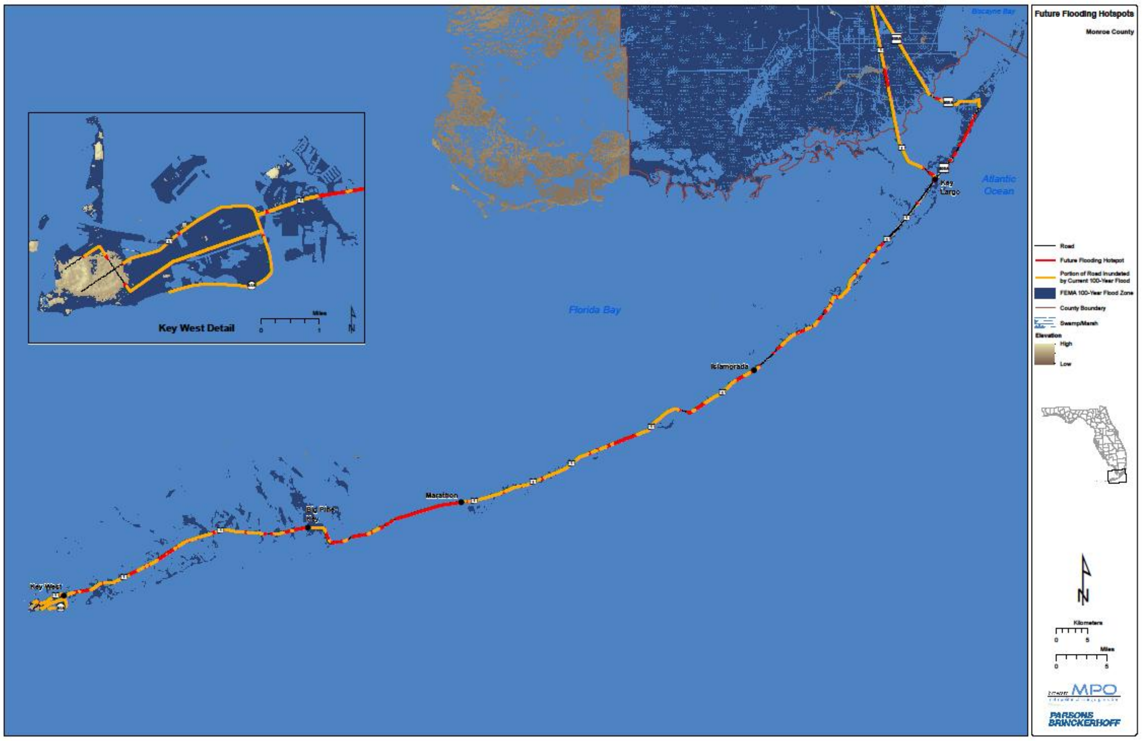


Figure 12: Future Flooding Hotspots, Monroe County

For showing the extent of future 100-year storm surge with sea level rise, the HAZUS-US model developed by FEMA was evaluated. Through coordination with other HAZUS users, the team identified a method to reflect changing sea levels to develop future 100-year storm inundation levels and coverage. This model, however, uses an algorithm that does not reflect surge attenuation (loss of wave height over distance) and instead follows land features inland until the surge level no longer exceeds identified land elevations. This program has been applied in other areas of the country with more pronounced topography at the shoreline to estimate potential future conditions, however, given south Florida's exceedingly flat topography, use of this program was not considered advisable, as it overstated the extent of future storm surge inundation. Thus, as with precipitation induced flooding, it was decided that the future potential flood exposure index would provide a better metric for capturing relative differences in storm surge exposure under climate change.

Sensitivity

The sole sensitivity measure used in this analysis focused on the number and condition of bridges along each segment. A bridge condition index was developed that took into account the scour condition rating and sub-structure condition rating from the National Bridge Inventory. The index was calculated so that the greater the number of bridges on a segment and the worse their condition, the more sensitive that segment was considered to flood hazards. Note that the bridge condition index was only done for the road network as similar information was not available for rail bridges.

Adaptive Capacity

Two measures were used to capture the adaptive capacity of the regional transportation network to flooding: volume measures that provide an indication of the number of travelers affected and, for roads, detour lengths around each segment. For roads, the volume measure was the average annual daily traffic (AADT) on the segment.[11] For Tri-Rail, volume was measured by the 2013 ridership on each segment. Detour lengths were calculated by finding the shortest path around the segment of interest under the assumption that detours had to follow other regional network (i.e. major) roads. Figure 13 to Figure 16 show the overall adaptive capacity ratings of each segment in the regional network.

Scoring and Weighting

In order to prioritize road and track segments that were most vulnerable to future climate change threats, vulnerability scores for each segment were calculated by combining the measures described above. Each vulnerability score was scaled from 0 to 100, with 0 being the lowest possible vulnerability and a score of 100 indicating the highest possible vulnerability.

One of the first steps in calculating the vulnerability scores was to translate each of the metrics onto a common 0 to 100 scale. Scaling was necessary because the specific scores for each metric are different in terms of their measures. For example, a highway link could be found to exhibit the following:

- A bridge condition index value of 5
- 10% of its length being inundated by a 3 ft SLR
- A current flood exposure index of 2
- A future flood exposure index of 58
- AADT of 57,000
- A detour length of 3.5 miles

The entire range of scores for each variable was used to determine the scaling range, and each variable was assigned a score based on where it fell within the overall category range for the variables.

[11] If a segment had multiple AADT values, the value used was the weighted average of each value based upon its length (i.e. the AADT that made up a greater proportion of the overall segment length was factored in more heavily to the overall AADT for that segment).

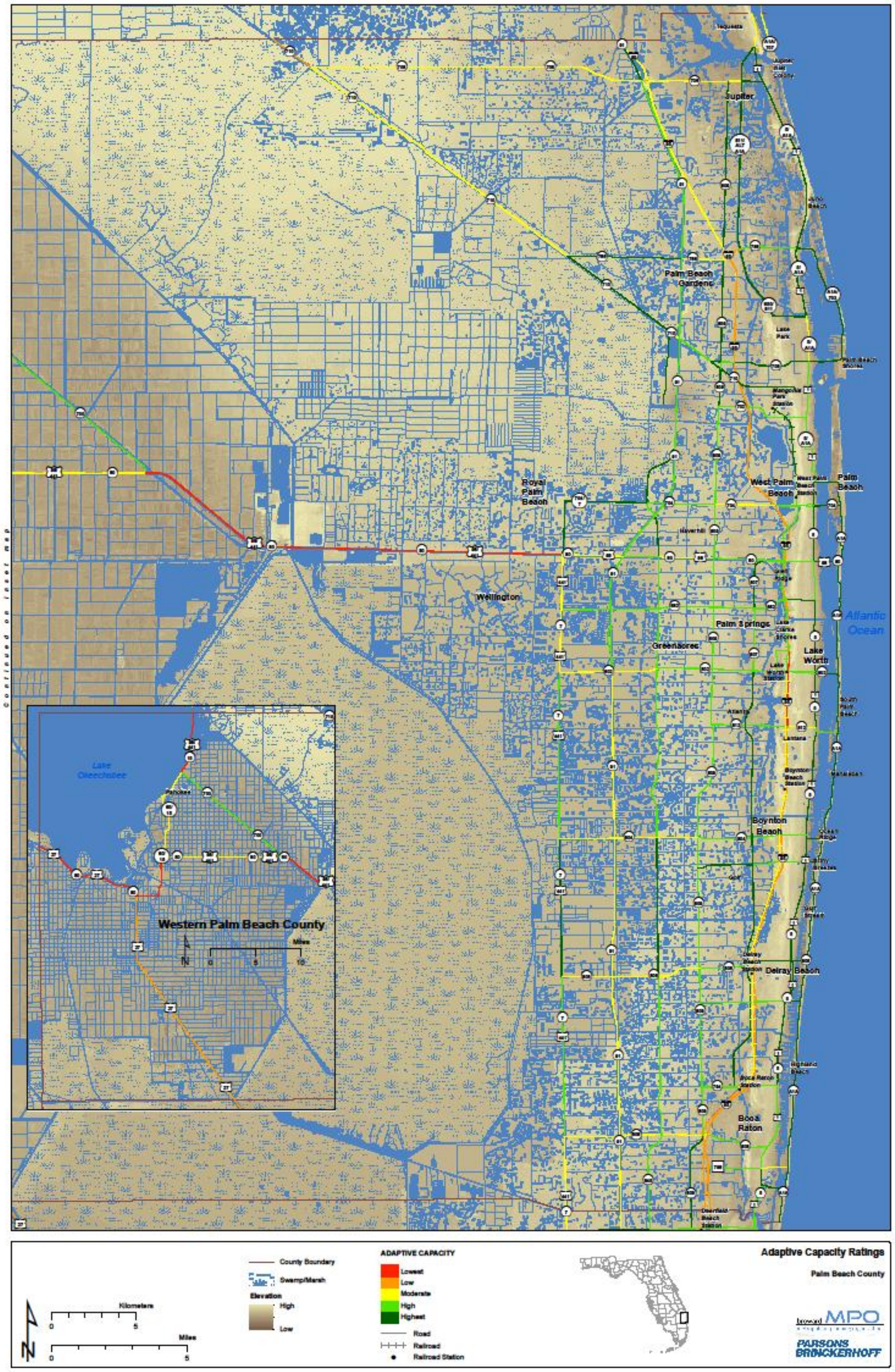


Figure 13: Adaptive Capacity Ratings, Palm Beach County

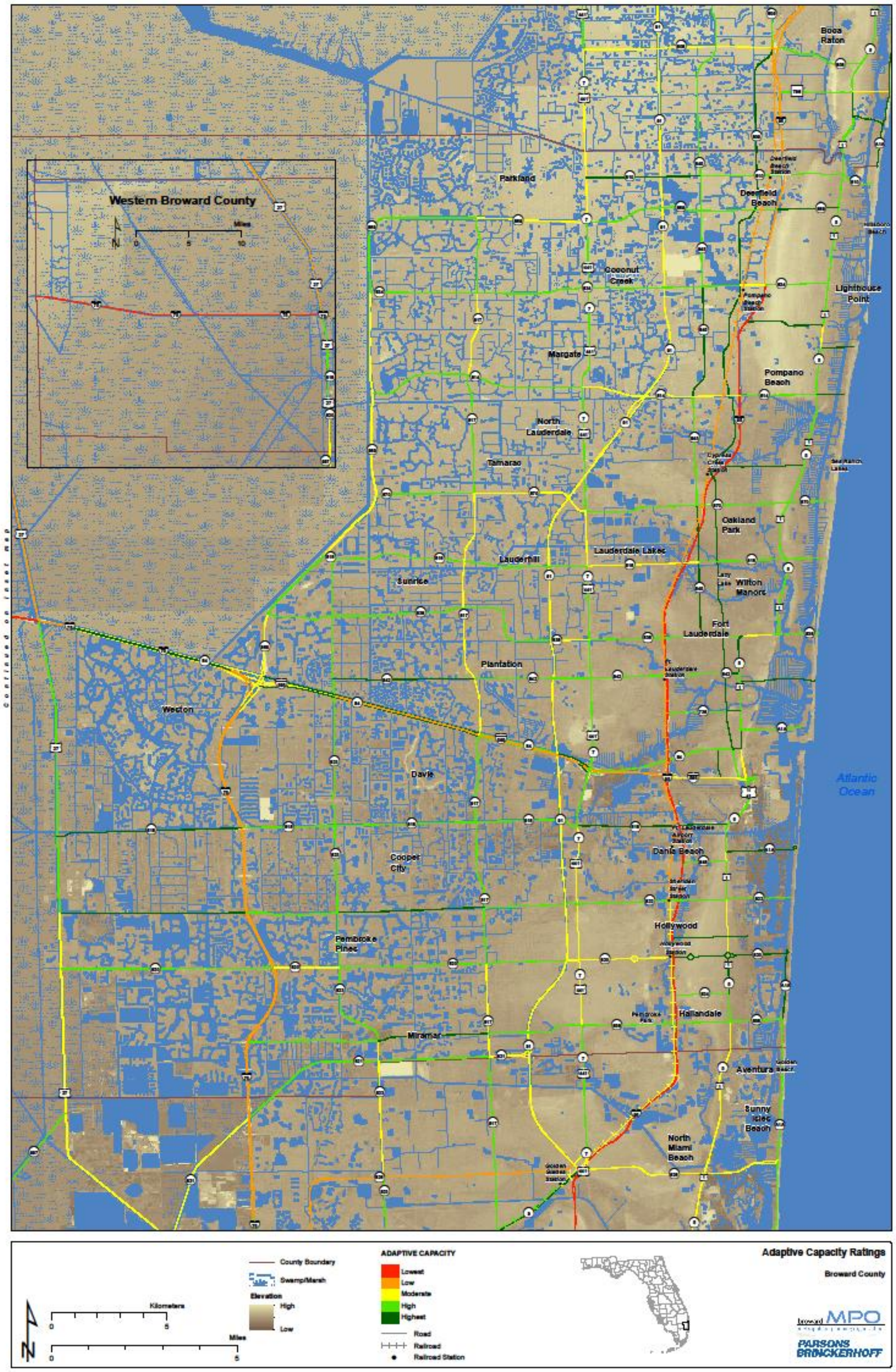


Figure 14: Adaptive Capacity Ratings, Broward County

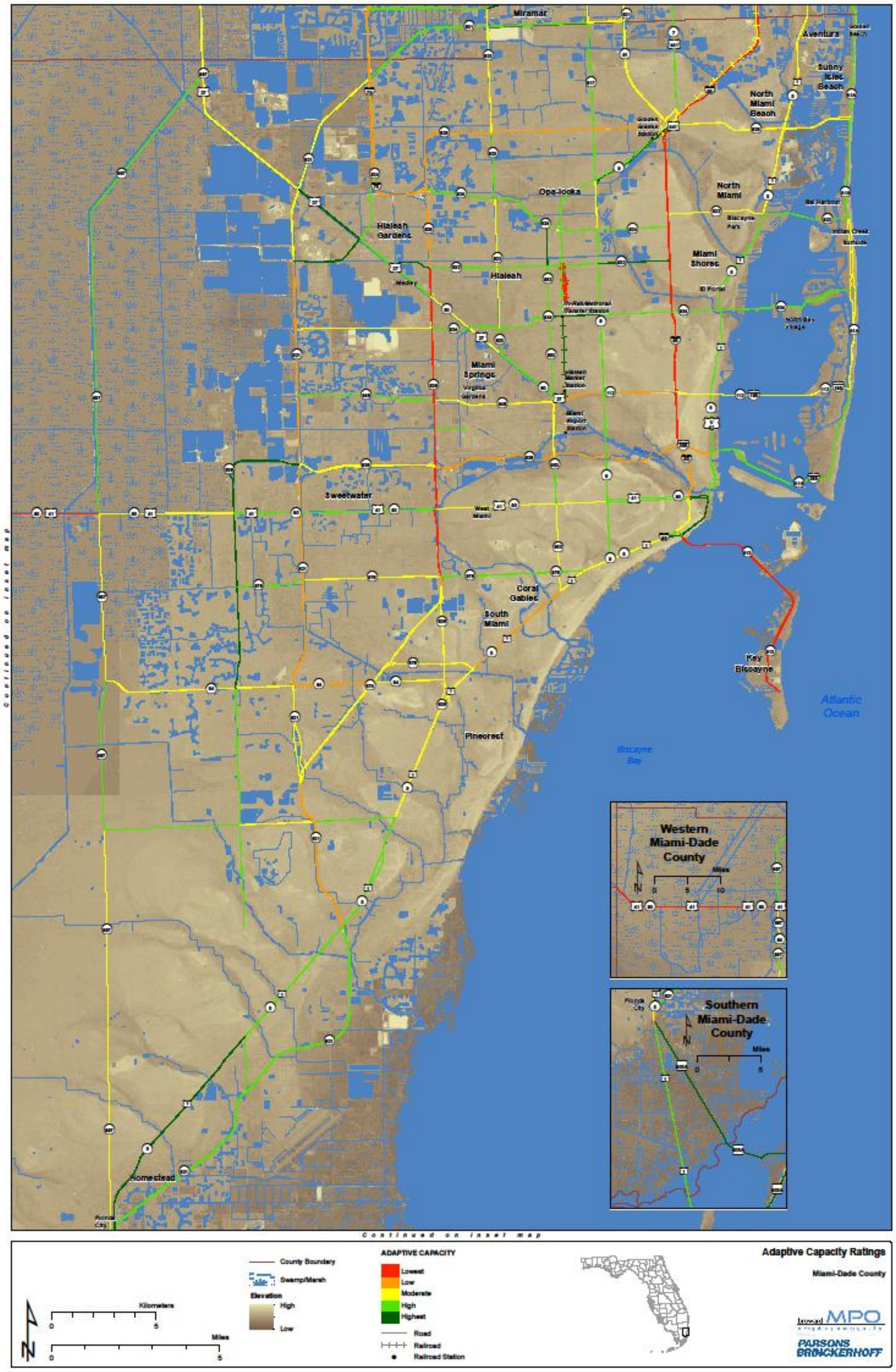


Figure 15: Adaptive Capacity Ratings, Miami-Dade County

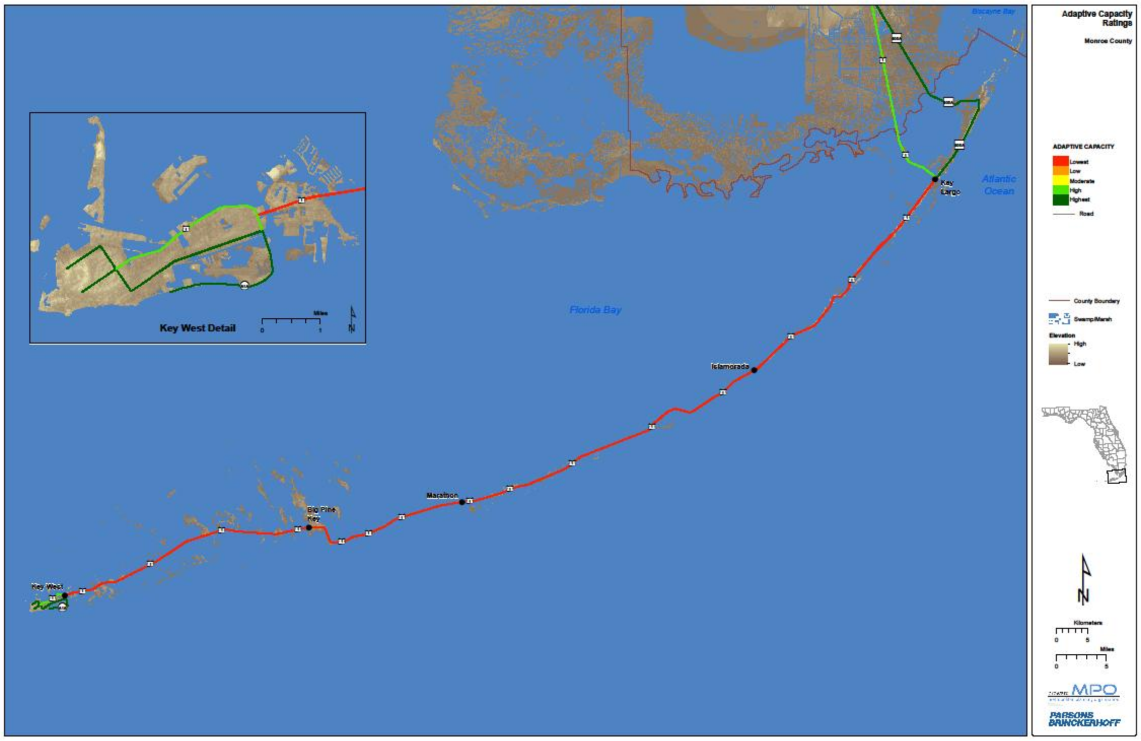


Figure 16: Adaptive Capacity Ratings, Miami-Dade County

In addition to scaling, each variable was assigned a weight to indicate its relative importance within its category (exposure, adaptive capacity, and sensitivity). In addition, each category was assigned a weight indicating its importance to the overall vulnerability score. Table 2 summarizes the various weights applied in the assessment. The best way to read the weights is from right to left—that is, looking at the overall score weighting by category, then looking to see how the scores for each variable are calculated to sum up into the overall score.

There are a few observations to note with this scoring methodology:

- The data on current/future flood potential was split into two separate scoring processes rather than combining them. This seemed a more appropriate method to identify the strong existing and future risk without combining them into one score.

Table 2: Weighting Values for Vulnerability Scores

Variable Weighting Schema - South Florida Climate Vulnerability Assessment			
Roads			
Category	Variable	Variable Weighting	Category Weighting
Sensitivity		*100*	20
	Bridge condition index (scour, substructure condition, # of bridges)	100	
Exposure		*100*	70
	% of segment permanently inundated by 1 ft. of SLR	25	
	% of segment permanently inundated by 2 ft. of SLR	20	
	% of segment permanently inundated by 3 ft. of SLR	15	
	Current flood exposure index (storm surge & precipitation)	30	
	Future potential flood exposure index (storm surge & precipitation)	10	
Adaptive Capacity		*100*	10
	Average annual daily traffic (AADT)	50	
	Detour length	50	
Rail			
Category	Variable	Variable Weighting	Category Weighting
Sensitivity		*0*	0
Exposure		*100*	95
	% of segment permanently inundated by 1 ft. of SLR	25	
	% of segment permanently inundated by 2 ft. of SLR	20	
	% of segment permanently inundated by 3 ft. of SLR	15	
	Current flood exposure index (storm surge & precipitation)	30	
	Future potential flood exposure index (storm surge & precipitation)	10	
Adaptive Capacity		*100*	5
	Ridership	100	

- The weighting is higher for exposure across both modes than it is for other factors in the overall vulnerability framework, sensitivity and adaptive capacity. This is due to the observation that exposure is a threshold factor and adaptive capacity and sensitivity are not important if there is no exposure to begin with.
- There is no sensitivity measure for rail, as the type of information needed for the vulnerability scoring was not available for bridge structures along the passenger rail alignment.

Analysis Results

The maps in Figure 18 to Figure 21 display the results of the vulnerability assessment on the regional road and rail network. The vulnerability scores have been organized into five tiers applying the Jenks natural breaks methodology for classifying data. Classifying the scores facilitates differing policy treatments for each tier, if desired, and also addresses error margin between scores. Note that just because a segment is shown as Tier 4 or Tier 5 does not mean it has no vulnerability to the stressors evaluated; it is just an indicator that, *relative* to the other segments, its vulnerability is lower.

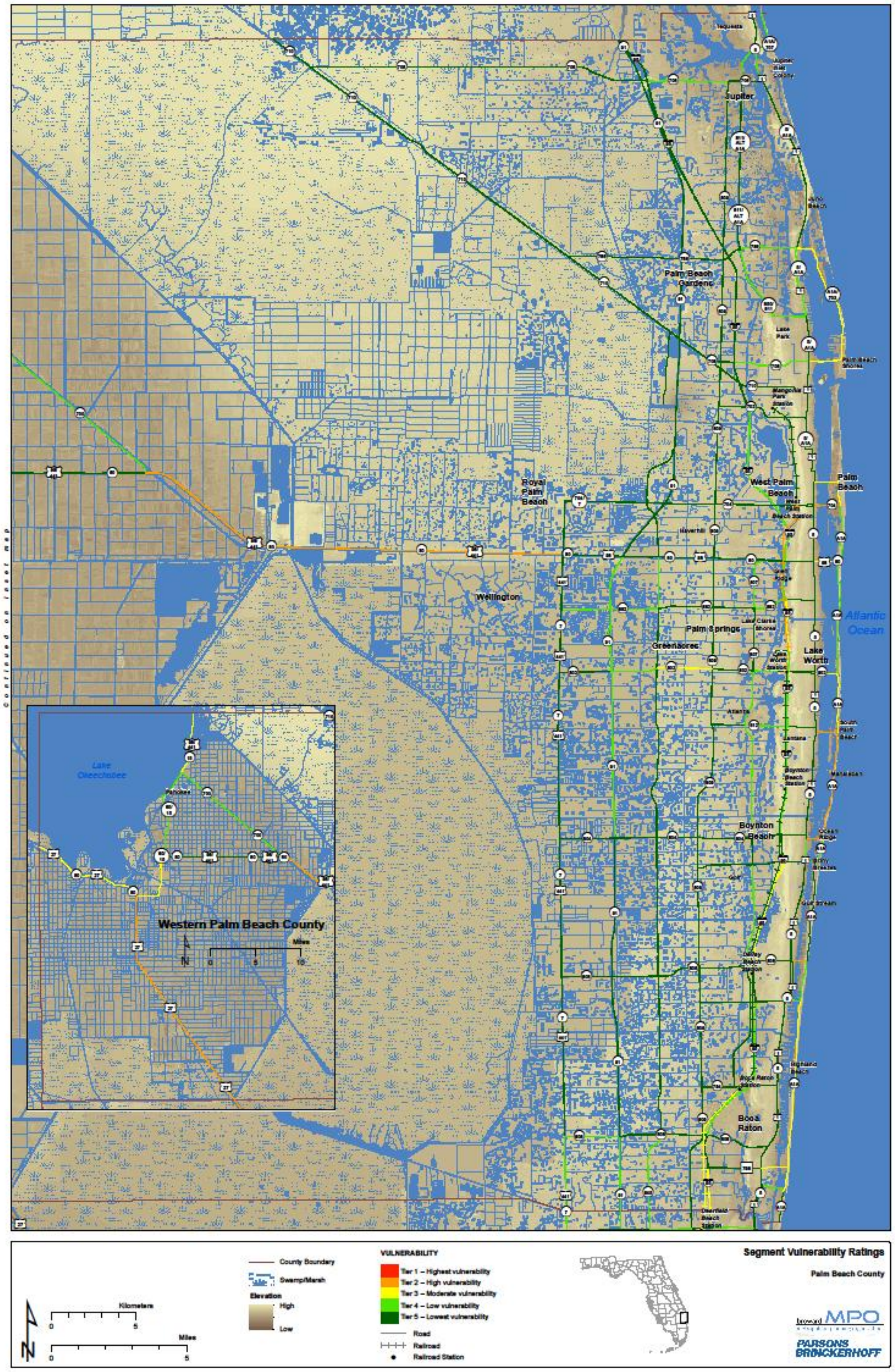


Figure 17: Vulnerability Ratings, Roads and Rail Track in Palm Beach County

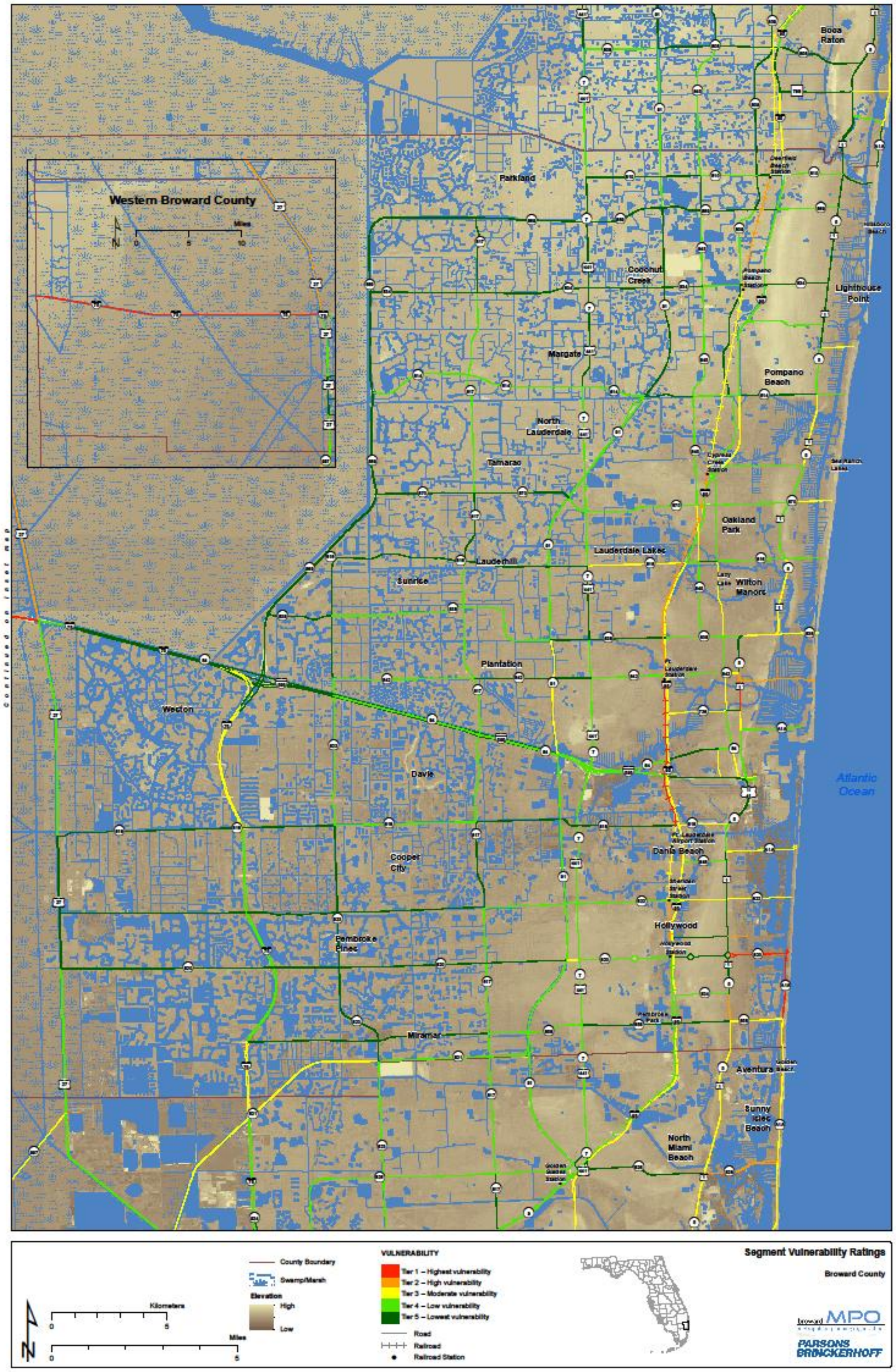


Figure 18: Vulnerability Ratings, Roads and Rail Track in Broward County

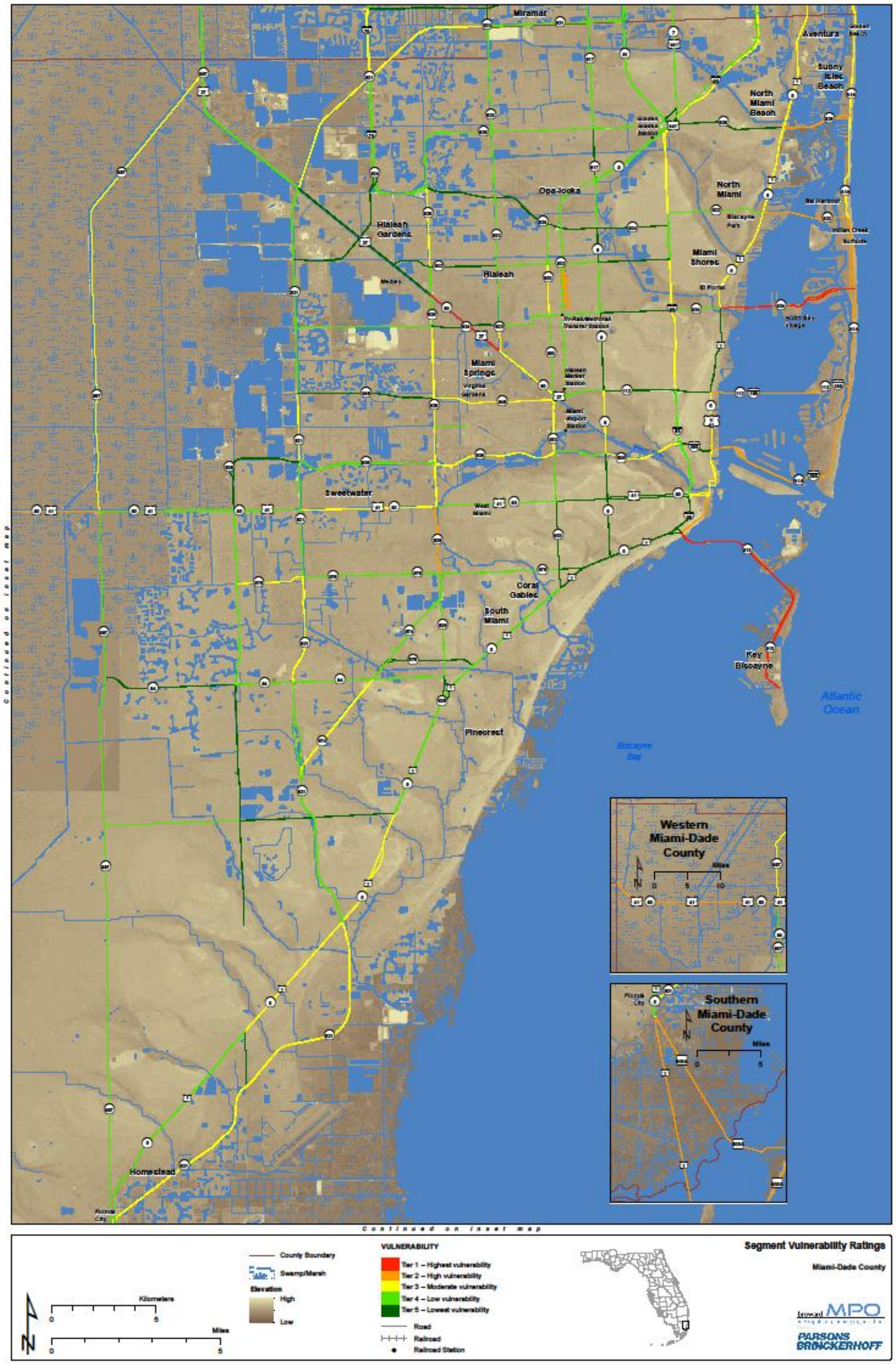


Figure 19: Vulnerability Ratings, Roads and Rail Track in Miami-Dade Beach County

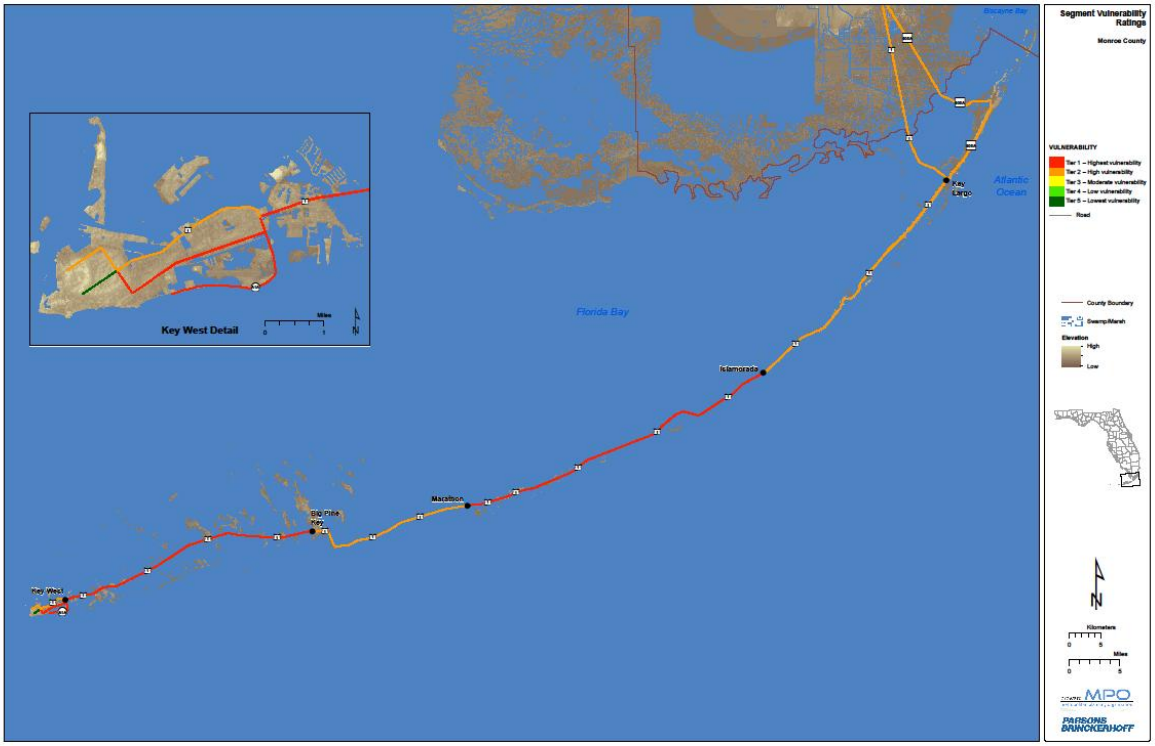


Figure 20: Vulnerability Ratings, Roads in Monroe County

It is important to emphasize several observations concerning the rankings shown in Figure 17 to Figure 21. These observations provide important context for the following discussion on adaptation strategies. These observations include:

- Only roadway and passenger rail facilities on the regional transportation network were considered as part of this analysis.
- Regional facilities in Monroe County were most vulnerable due to low elevations and lack of redundancies/alternative routes.
- Causeways and regional facilities on barrier islands were highly vulnerable due to long detour lengths and low elevations.
- Regional roadways through the Everglades were highly vulnerable due to high flood exposure, low elevations and long detour lengths.

Adaptation Strategies/Linkage to Decision-making

One of the key objectives of this study was linking a concern for climate change and related stresses to different aspects of transportation decision-making. As is typical for a metropolitan area the size of the Miami urbanized area, there are many different agencies actively engaged in a variety of decisions that affect transportation system performance. The study identified five major types of transportation decision-making processes in the region that are directly related to the disruptions that might be caused by changing climate and weather conditions. These five areas of decision-making relate to: transportation policy, planning and prioritization; rehabilitation or reconstruction of existing facilities in high risk areas; new facilities in new rights-of-way in high risk areas; system operations; and system maintenance. Each of these decision-making areas is described below.

Transportation Policy, Planning and Project Prioritization

The transportation policy, planning and project prioritization process precedes project development and often establishes overall policies and strategies to be applied in transportation investment decisions. The study area is unique in that there are three MPOs leading the study, but many other agencies and organizations with relevant decision-making roles are important actors in the regional decision-making structure as it relates to planning and project prioritization. The region's transit agencies are responsible for providing transit service, and for protecting the assets that allow such service to occur. Local communities and counties undertake their own planning and project prioritization that affects the performance of the local road network. Thus, the linkage between climate change factors and planning and project prioritization decisions can occur in many different agencies at different levels of decision-making.

The study has identified four major actions that can provide a stronger linkage between climate change concerns and decision-making.

Develop a goal statement relating to climate change that can be used as part of the transportation planning process

Community planning as well as transportation planning begins with an understanding of what is important to the community and how the planning process and project evaluation criteria should reflect such key concerns. A review of the current long range transportation plans for the three MPOs in the study area shows that climate change is not included explicitly in the goals statements.[12] Statements are made about "promoting sustainable transportation

[12] Broward MPO: http://www.browardmpo.org/userfiles/files/2035%20Broward%20Transformation%20Long%20Range%20Transportation%20Plan%20-%20Amended_reduced.pdf; Miami-Dade County MPO:

systems" or "minimizing environmental impacts," and in some cases climate change is addressed within the body of the document. However, in order to highlight the importance of potential climate change risks, a more directed statement on its importance should be included in transportation plans. The importance of such an action was recognized by the Broward County Climate Change Task Force in 2010 when it recommended that the County:

> "Amend the County Comprehensive Plan To ensure that Broward County is prepared to address climate change adaptation measures, recommended actions include amending the Broward County and local government Comprehensive Plans, including creation of a Climate Change Element, to provide for a sustainable environment and to reflect the best available data and strategies for adapting to future climate change impacts. Similarly developing and implementing adaptive planning and zoning policies, regulations and programs to ensure appropriate land use, construction and redevelopment activities address the potential impacts of climate change, to include mitigating the impacts of sea level rise on Broward County's economy and infrastructure are proposed."[13]

Identify climate change-related prioritization criteria that can be used as part of the project priority/programming process

Similar to the concept of a goals statement, the criteria used to prioritize projects as part of the programming process should reflect the needs associated with climate change-related disruptions. Thus, to the extent that points or weights are used to assign relative importance to different goals, a desire for adaptive design concepts or of investing in projects that are in high risk areas should be part of the prioritization criteria. The following factors could be incorporated into the prioritization approach (with relative weights assigned through the normal planning process).

- Is the project located in an area of high risk to future climatic conditions? If so, to what extent does the project include design or operational strategies to protect against future threats?
- To what extent does the project enhance transportation system resiliency?
- Is the project on an evacuation route?

http://www.miamidade2040lrtp.com/wp-content/uploads/2040Plan_FinalDraft.pdf; and Palm Beach County MPO: http://palmbeachmpo.org/2040LRTP/2040_LRTP_Main_Document_&_Appendices.pdf

[13] http://www.broward.org/NaturalResources/ClimateChange/Documents/FinalCCActionPlan_forBCBCCappdxB.pdf

Identify and apply performance measures to promote transportation system resiliency

The most recent federal transportation legislation, *Moving Ahead for Progress in the 21st Century Act* (MAP-21), requires state DOTs and MPOs to adopt performance measures as part of the planning process. The law specifies a list of performance measures that must be used, but allows states and MPOs to adopt other measures that reflect the issues of most concern to state and local decision-makers. In areas such as the Miami metropolitan area where extreme weather events are likely to affect system performance significantly, it makes sense to identify a performance measure or a set of measures that can be related to potential climate change stresses on the transportation system or system resiliency. The current Miami-Dade MPO long range transportation plan, for example, identifies 89 measures that can be used to monitor the overall effects of transportation system performance, with two relating to climate change-related transportation system resiliency (highway lane and centerline miles within the 100-year flood plain and percent of funding allocated to maintenance and rehabilitation of evacuation corridors). Possible measures include:

- Number of weather-related transportation system disruptions (normalized to account for varying frequencies of extreme weather events)
- Number of weather-related disruptions reoccurring at the same locations
- Percent of the population having access with road and transit services protected against extreme weather stresses (increasing the probability of maintaining access after extreme weather events)
- Number of projects including adaptive engineering design approaches (this would be more of a program progress report than a system performance metric)
- Percent of funding to improve evacuation routes (this would be more of a program progress report than a system performance metric)

Apply tools to identify and assess continuing climate change-related impacts

Southeast Florida is fortunate to have several government agencies, university research centers and other groups that are developing new databases and analysis tools relating to climate change. The Compact is an example of a regional approach to providing information and analysis capability to local decision-makers, and the GeoPlan Center at the University of Florida is a good example of a source of updated tools that will be very useful to local planners and decision-makers. It seems likely that new tools and data will be developed as scientists better understand the phenomena underlying climate change and the resulting impacts. Decision-makers in the study area will thus be able to use state-of-the-practice models and analysis tools to gain a better sense of the implications of climate change to the region's transportation system, and to provide inputs into the performance measures and prioritization criteria described above.

Inherent in these recommended actions is the need for funding. Funding should continue to become available not just for planning studies such as this, but for implementation as well. This would be true not just for MPOs, which will have to collect additional data, calculate scores and apply them as criteria for project prioritization, but even more so for other, often smaller jurisdictions that will also have responsibility for taking into account climate change in their planning and project implementation. Federal funding should provide flexibility to allow use of planning funds for this purpose.

Rehabilitation or Reconstruction of Existing Facilities in High Risk Areas

Many agencies are responsible for some part of southeast Florida's transportation system. Thus, for example, the Florida DOT (Districts 4 and 6) has a key role in managing the state highway network in the study area. Several transit agencies are responsible for both infrastructure and rolling stock. As is the case in similar metropolitan areas, system preservation, in many cases through rehabilitation and reconstruction of existing facilities, is one of the most important goals of transportation decision-makers. Given that much of the transportation infrastructure in areas like Miami has been in place for decades and will be in need of rehabilitation in coming years, an opportunity exists to use the rehabilitation and reconstruction process to upgrade designs to meet potential climate change threats.

Consider new road and transit design approaches and standards to minimize potential disruption due to extreme weather events (e.g., profile elevation)

In areas that are considered highly vulnerable to current or future weather-related stresses, any project that is to be reconstructed or rehabilitated should consider new design approaches and standards that allow for greater protection against future stresses. In most cases, this would be done on a project-by-project basis given the project-specific context that determines design characteristics (e.g., drainage requirements). In some cases, government agencies have provided such a flexible design approach in context sensitive design projects; or in other cases, agencies have used design exceptions for standard approaches when circumstances have suggested an approach that is more appropriate compared to the norm. From a planning perspective, the long-range plan can be part of this overall design approach by identifying those areas that are considered highly vulnerable and the planning agency can interact with implementing agencies to assure that a flexible design approach will be applied.

Near coastal areas and over longer term, consider sea level rise as a "given" in design of coastal facilities.

The U.S. Army Corps of Engineers and a new executive order from the Obama Administration have adopted a policy whereby SLR must be considered in the design of federally-supported projects in coastal and riverine areas. Other states, such as California and Washington State, have adopted a similar policy. The Compact effort at defining a consistent SLR projection scenario for southeast Florida is another example of providing technical guidance on infrastructure planning and decision-making. Study area communities and the related transportation agencies should consider SLR as a given design input for facilities adjacent to the coast or in riverine environments. Many already do, but a consistent regional policy that influences the project review process to make sure SLR is considered should be adopted by member governments.

Redesign drainage systems to handle larger flows.

In many ways, this is subset of the above recommendation concerning project reconstruction and rehabilitation. However, given the importance of drainage systems to projects in southeast Florida, it is called out as a separate recommendation. The handling of water, either in areas subject to SLR or experiencing high levels of flooding due to intense precipitation, has been a design challenge for decades in the study area. It is likely that this will continue to be a serious challenge in future years as environmental conditions change due to a changing climate. As before, drainage redesign would most likely occur when projects are being reconstructed or going through an upgrade process.

Harden or armor key infrastructure components (e.g., embankments or bridge piers) against additional extreme weather-related stresses.

Similar in concept to the previous recommendation, either in response to repeated failures or system disruptions due to extreme weather events, or as part of a scheduled project upgrade, engineers should examine carefully where "hardening" techniques could be used to protect key infrastructure assets.

Incorporate "early warning indicators" for potential extreme weather-related risks into asset and maintenance management systems.

Many of the transportation agencies in the study area have fairly sophisticated asset and maintenance management systems as part of their investment programming process. MAP-21 also requires each state to develop a risk-based asset management plan for the National Highway System (NHS). In an area like the study area where extreme weather events could significantly affect both the condition and performance of transportation assets, transportation agencies should link their asset and maintenance management systems to potential environmental threats. This could be done by:

- Identifying locations on the network where assets might be highly vulnerable to climate change-related risks due to topography, hydraulic or hydrological characteristics and/or soil conditions in the asset management system.
- Examining the potential impacts of climate change and extreme weather on certain types of assets, and using the asset management system to identify which assets need to be monitored more closely over time. For example, some types of assets (e.g., traffic signal control boxes) might be highly susceptible to prolonged high temperatures. Culverts, which experience has shown to be some of the more vulnerable assets to extreme precipitation events, might be targeted for additional monitoring in areas where such events are expected to happen more often.
- Providing an important means of monitoring asset performance over time, as it relates to increasing problems caused by certain types of environmental threats. Thus, for example, the asset management system could use performance standards associated with critical assets that reflect trends in agency corrective action (e.g., number of times water flows in culverts back up).
- Providing criteria for defining critical facilities (which, in many cases, is already provided), and for identifying the types of risks involved if such facilities are disrupted…..although this effort could be done in system planning or some other functional area of a typical state DOT.
- Discussing lifecycle strategies and management methods that will be applied in the study area for the assets considered to be the most vulnerable and a description of the environmental drivers that lead to such vulnerability.

New Facility on New ROW in High Risk Areas

Apply design criteria - but in addition if possible, consider realignments or relocation away from high risk areas.

Many of the above recommendations would apply to instances where new facilities on new rights-of-way are being constructed in high risk areas. As for rehabilitation or reconstruction projects, if it was determined that a project was being built in an area that was susceptible to potential climate-related stresses, the design process would consider different ways of designing the facility. For new facilities in particular, the design (and environmental review process) could also consider new alignments that either reduce the level of risk or avoid the risk altogether.

Operations

The level of impact of weather-related stresses on transportation system performance is directly related to the impact on system operations. Disruptions to system operations, depending on the magnitude and length, could result in significant economic impacts to both system users and to adjacent land uses.

Identify pre-planned detour routes around critical facilities whose disruption or failure would cause major network degradation.

Although Florida already has well-tested emergency response action plans, in light of the results of this study, coordinate with FDOT and emergency responders to identify potential strategies for dealing with the identified risks.

Maintenance

Avoid significant disruptions and maintenance demands by "hardening" such items as sign structures and traffic signal wires.

Given that a great deal of experience has occurred in the study area with the aftermath of hurricanes, implementing agencies are well versed in the types of actions that could be taken to reduce the level of disruption to system operations. This recommendation simply focuses attention on the types of actions that could be taken to minimize the post-storm impact on moving people and traffic on the network. Excessive wind speeds are the source of many failures in signs and signals during storms, and it is often cheaper in the eyes of some public works officials to simply let the failures occur and replace the assets once the storm has passed. From a budgetary perspective this is perhaps the most likely strategy. However, officials should introduce into such calculus the delays and disruptive nature of not having traffic control devices available for some time after a storm. With such a perspective it might be cost beneficial to provide hardened supports or some other means of reducing the probability of failure during a storm.

Keep culverts and drainage structures debris free and maintained to handle flows.

One of the major lessons learned from weather disasters in other parts of the country is that culvert failure often occurred because of debris that was lodged in the culvert, thus reducing the effective water flow. Transportation agencies should therefore systematically monitor the status of culverts to assure they are debris free.

Lessons Learned

This study has produced several lessons learned that would be of use to others considering a similar type of analysis. These lessons learned can be considered in five major areas: data availability and quality, database integration, data analysis, involvement of agencies and groups in the study process, and establishing a long-term commitment to on-going climate adaptation planning.

Data availability and quality: As is true in any planning study, the availability and quality of data is one of the most important factors in the overall success of the study. This was certainly true in this study where climate- , traffic-, and asset-related data were critical to the technical analysis. In many instances, it was the lack of such data that caused reconsideration of analysis approach. Climate adaptation studies need to consider what types of data will be needed, its availability, and what surrogates can be used if it is found to be inadequate or unavailable. In addition, future climate adaptation studies would benefit greatly if certain types of data were collected periodically by transportation or planning agencies, in some cases, as part of normal data collection activities (e.g., asset management systems). For example, an important asset data item that is often not readily available is the size of hydraulic openings for bridges or culverts.

Perhaps the most important and critical data relate to asset exposure to climatic conditions. For this study, several studies had been conducted concerning sea level rise but none had been done regionally on precipitation-induced flooding and storm surge with sea level rise. Furthermore, in most cases, this type of information had not been linked to specific assets and thus it was difficult to assess risks without significant data integration and analysis.

Furthermore, data quality was a concern for the exposure measures. As described above , the existing FEMA flood zones for each county were assessed against newly collected LIDAR topographic data and areas were noted which were inconsistent (i.e., the land elevation exceeded the flood zone elevation but was shown as inundated in the FEMA zone). In order to apply this data it had to be “cleaned” to reflect actual conditions. It was found that cleaning the data can significantly improvement results as it eliminates many false positives that would otherwise show up as impacted.

Data analysis: The approach overall was to generate scores for each variable for each link, applying methods that recognized conditions in the south Florida region. This work required challenging technical processing including the translation of data from linear feature to linear feature (for Average Annual Daily Traffic), the calculation of detour length for each segment, and the derivation of the inundation exposure indices. A significant challenge with conducting a vulnerability assessment of this type in a region of this size is the processing time required to complete some of the spatial analysis identified. Some of the processes created and run to determine scores across the network for given vulnerability variables took multiple days or weeks of computer processing time to run.

Involvement of agencies and groups in the study process: A regional, multi-jurisdictional study such as this creates its own set of challenges, ranging from consistent expectations on study results to obtaining the cooperation of agencies in providing data or other resources for the study. The technical advisory committee provided an important source of input and guidance to the study effort. Having such an opportunity for input is an important aspect of climate adaptation planning. However, marshalling the resources of the many different agencies (even just participating in the planning process) that should be interested in a study such as this can be challenging. A key lesson for the process is that agreements and understandings among the major participants should be put in place as early as possible in the study.

Establishing a long-term commitment to on-going climate adaptation planning: Although the South Florida region is known for its concern for climate adaptation, very few examples exist of where such interest has resulted in an institutionalized approach for incorporating this concern into on-going planning and decision-making processes. This is neither unusual nor unique to this region. Often, adaptation studies are viewed as a one-time process for identifying at-risk assets and the types of mitigation strategies that can be considered. However, the study participants included as part of the study scope a task to identify how climate change concerns can be incorporated into agency decision-making (described in the section *Adaptation Strategies/Linkage to Decision-making*). This study was thus considered a first step toward a full consideration of climate change in planning and agency standard operating procedures. Although the effectiveness of this linkage will be judged at some future date, a key lesson from the study is that given the long time frame and uncertainty of climate change stresses, and the corresponding longevity of many transportation assets, the climate adaptation process cannot be simply a one-time effort, but rather something that needs to part of the normal planning and decision-making process.

Comments on FHWA Framework

The technical approach for this study followed the approach described by the FHWA Vulnerability Assessment Framework. Importantly, the three factors identified by this framework—sensitivity, exposure, and adaptive capacity---were used as the foundation of the scoring process. The study found the overall framework to be quite useful in directing the study team to the types of data and analysis efforts that had to be undertaken. The framework, perhaps necessarily, is defined at a very high level, with little guidance on how the planning effort leads to actual actions. This study found that considerable effort was expended in defining the three factors in ways that were meaningful to the context of the study. Thus, for example, it was not enough to say that a facility or asset was in a 100-year flood plain to say it was vulnerable. More information on the asset design and characteristics such as elevation and drainage mitigation measures had to be part of the study process to understand fully the potentials risks associated with that facility.

In addition, the three factors were used in the vulnerability scoring system with weights attached to each that could be changed by the user. This approach found that the exposure variable was being "overwhelmed" by the contribution to the score of the other two variables. On possible way of modifying the approach in the future might be to first rank the network segments by level of exposure, and once this ranking is established consider a prioritization by sensitivity and adaptive capacity.

Conclusions

The methods to assess climate change-related risks through the processes described above are far easier to describe in a few pages than they are to operationalize in a GIS system. The process of developing scores for each link in the system required the collection, refining, cleaning and clarifying of a diverse set of data sources. The outcome of the GIS work was the derivation of scores for each link in the roadway system based on values collected and translated from existing data sources or calculated from various spatial analysis methods.

From the climate forecasts analyzed as part of this study, the southeast Florida region is one of the most at-risk areas in the country for extreme weather events and long-term climate change. Not surprisingly, it is also an area that has seen a lot of interest in what such threats mean to the businesses and residents of the region. This study has developed an approach for analyzing climate change-related risks to the regionally significant transportation system that can be replicated and updated over time. It uses tools that are available to transportation agencies, e.g., GeoPlan, and relies on available data (although as noted above, this data can be improved). Importantly, the study has recommended actions that can be taken by transportation agencies to make sure that such consideration is incorporated into decision-making. This is perhaps the most important legacy of the study.

Appendix A: Current FEMA 100-Year Flood Road Segment Inundation

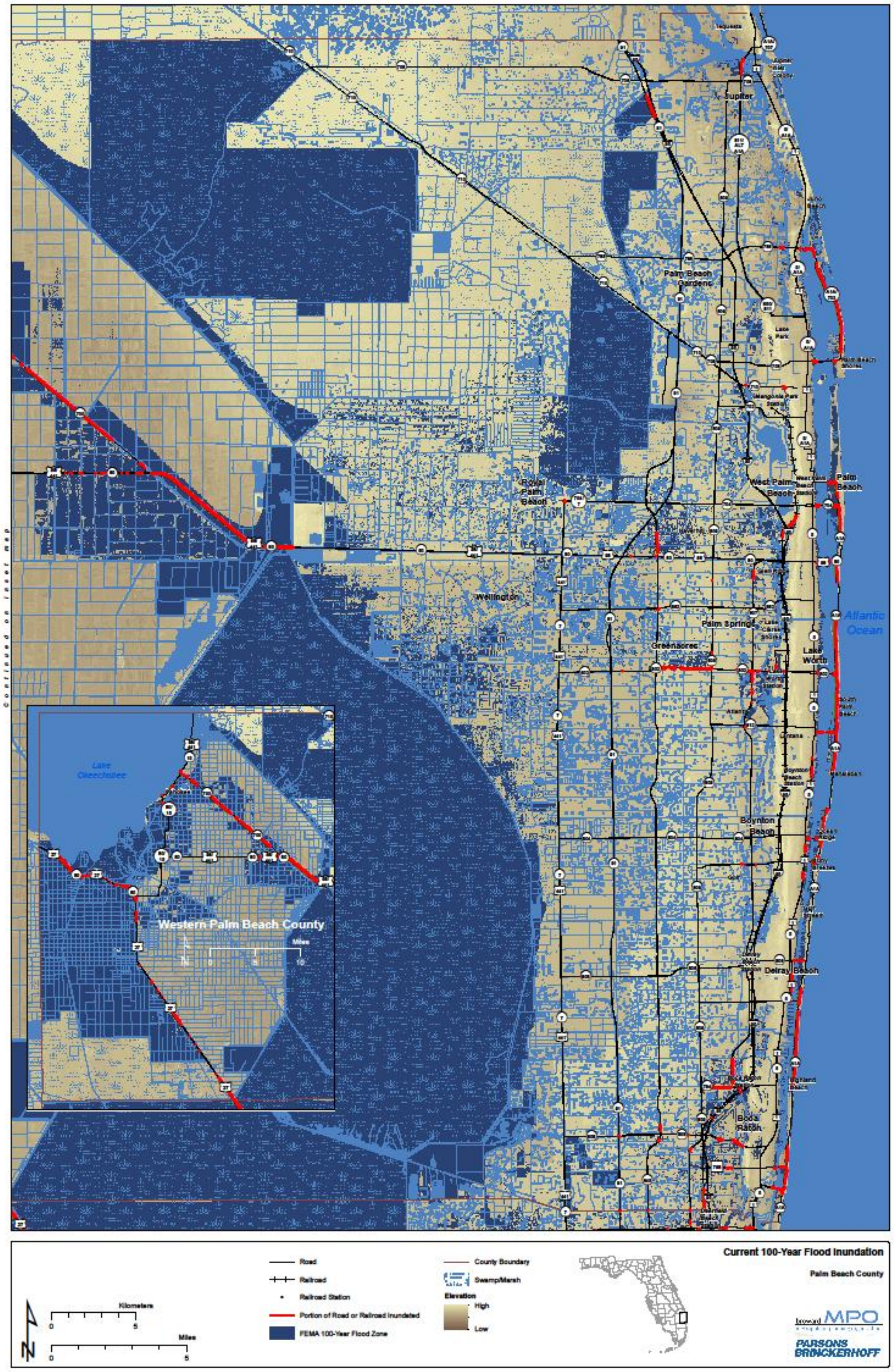


Figure 21: Current FEMA 100-Year Flood Road Segment Inundation, Palm Beach County

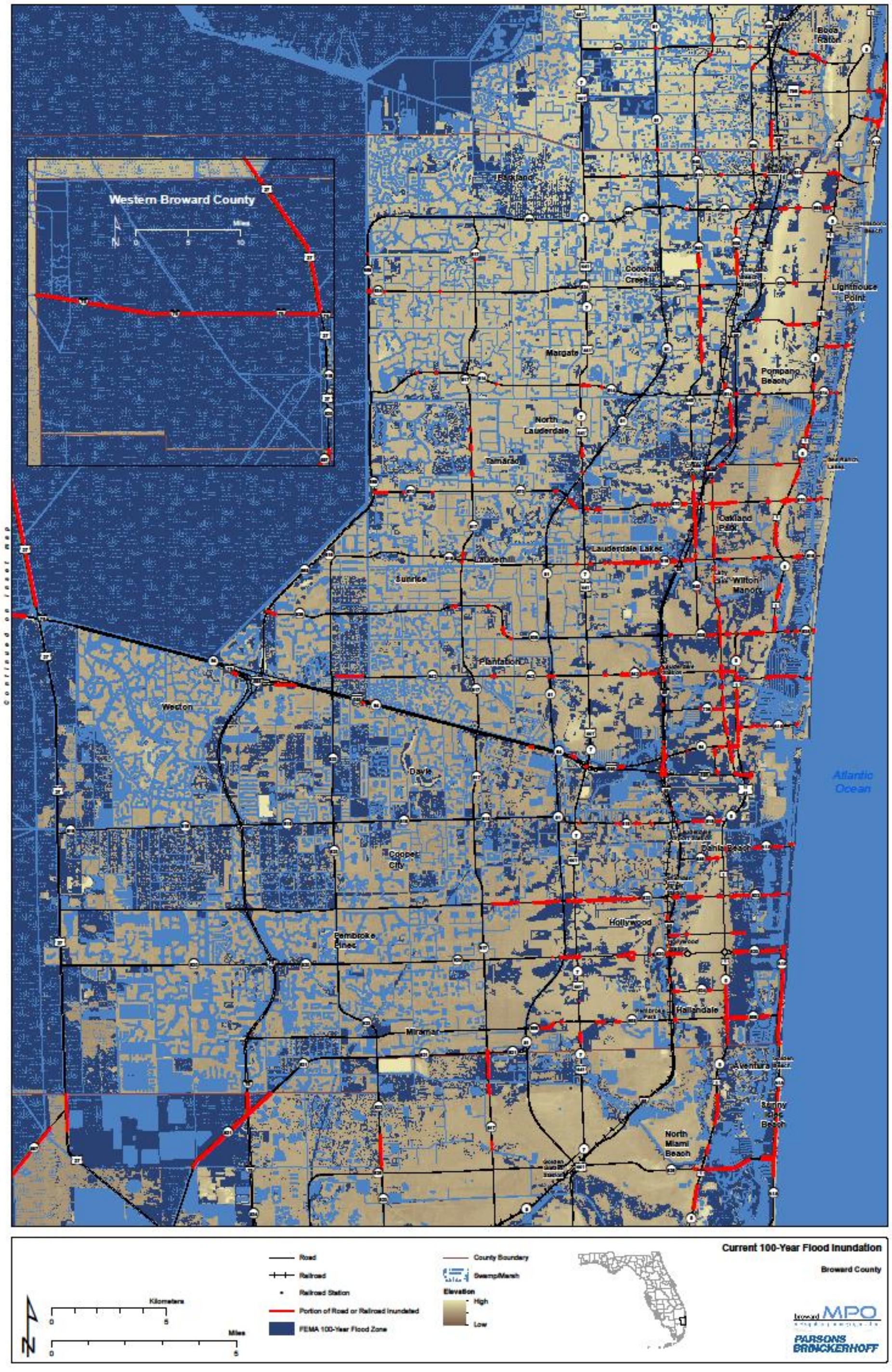


Figure 22: Current FEMA 100-Year Flood Road Segment Inundation, Broward County

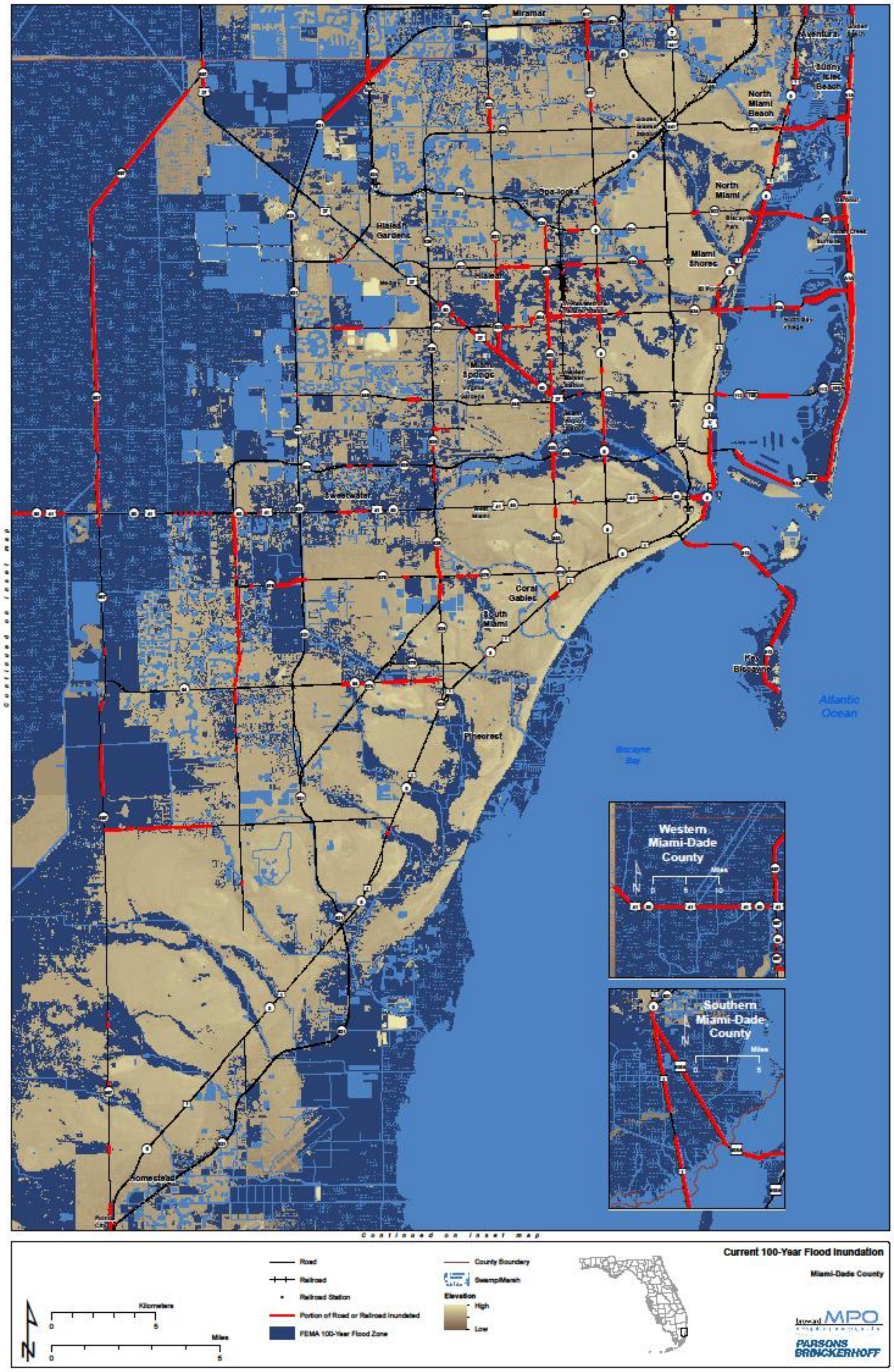


Figure 23: Current FEMA 100-Year Flood Road Segment Inundation, Miami-Dade County

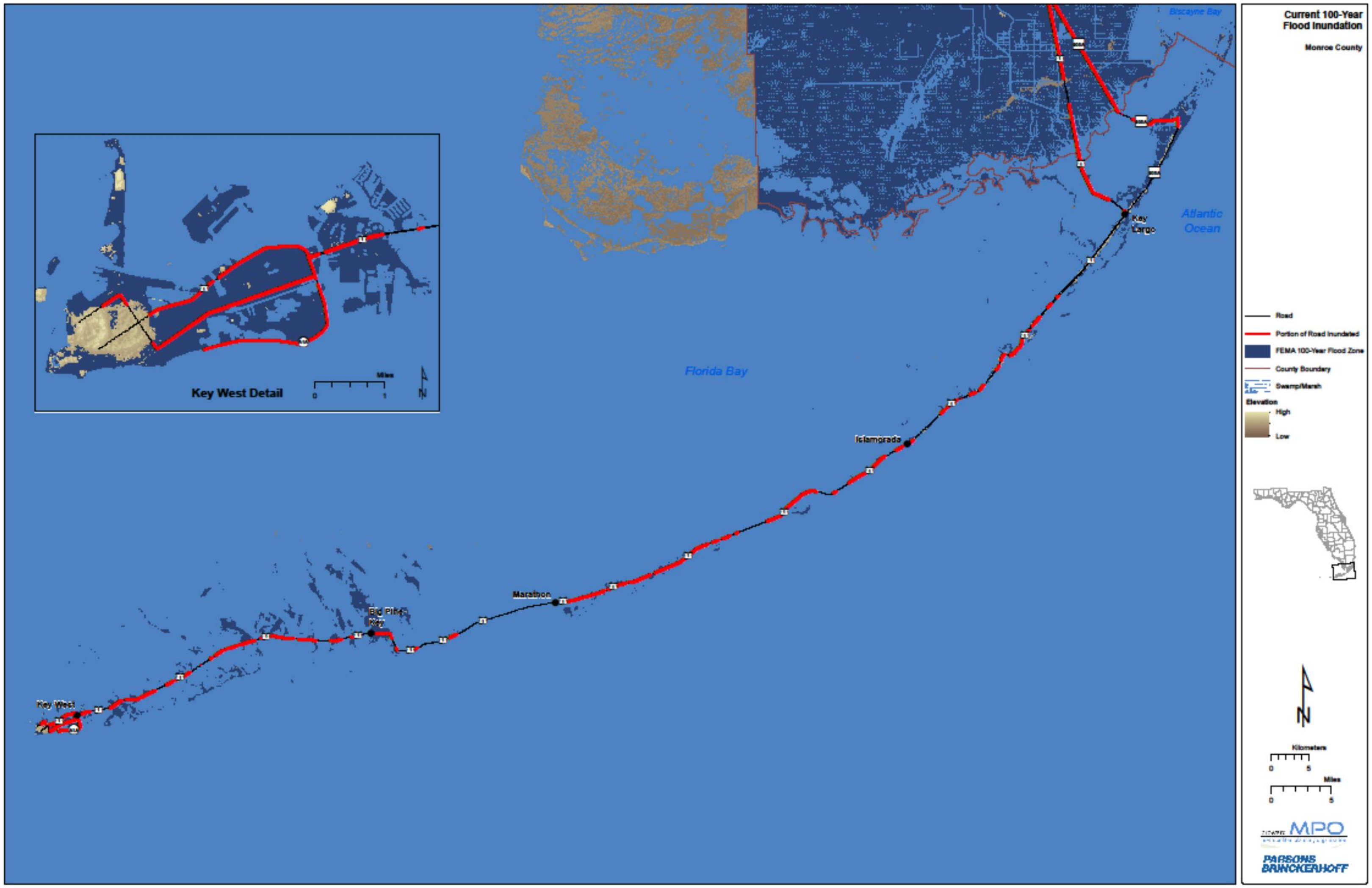


Figure 24: Current FEMA 100-Year Flood Road Segment Inundation, Monroe County

Appendix B: Permanent Sea Level Rise Road Segment Inundation

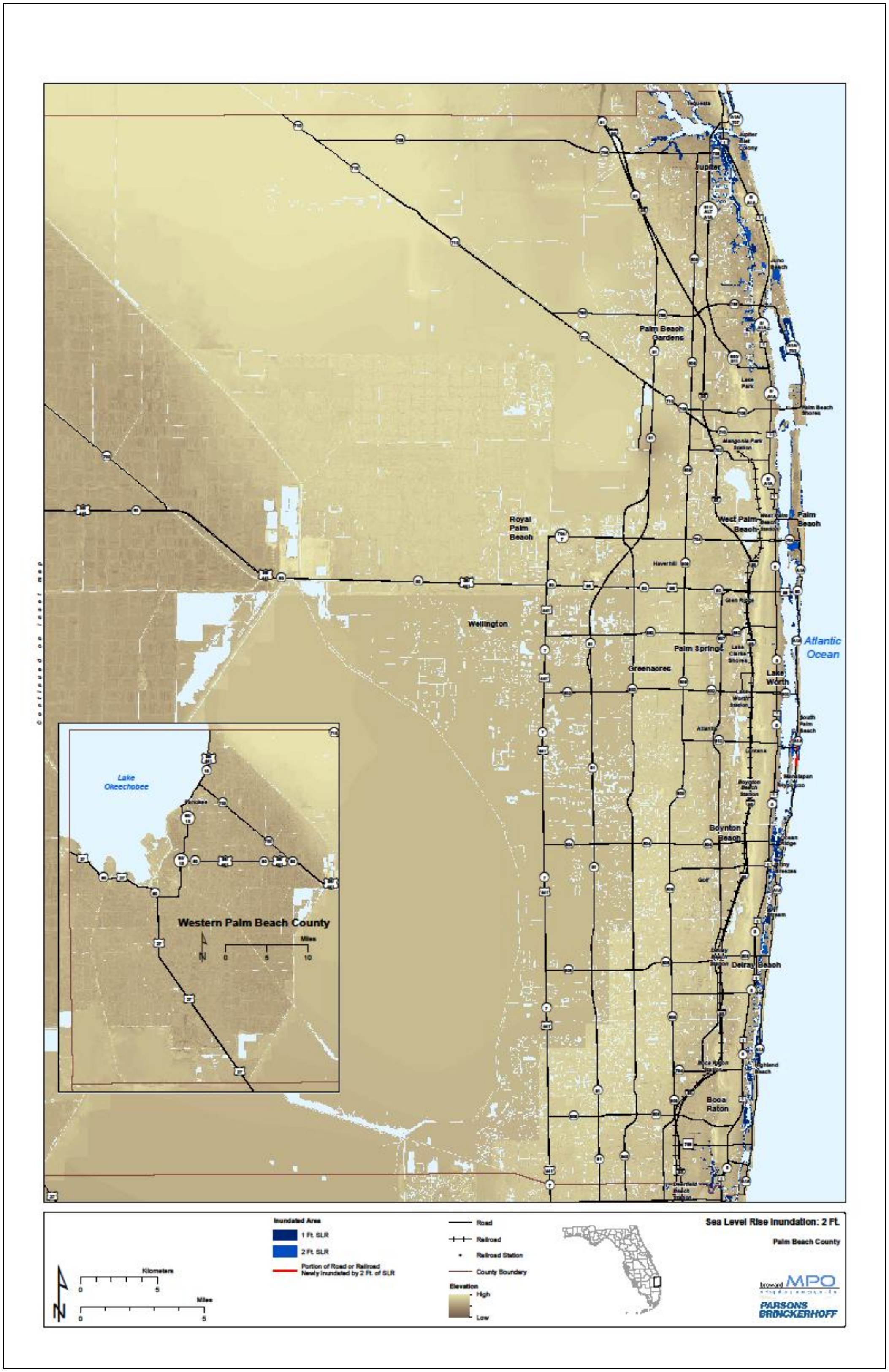


Figure 25: Permanent 2-foot Sea Level Rise Road Segment Inundation, Palm Beach County

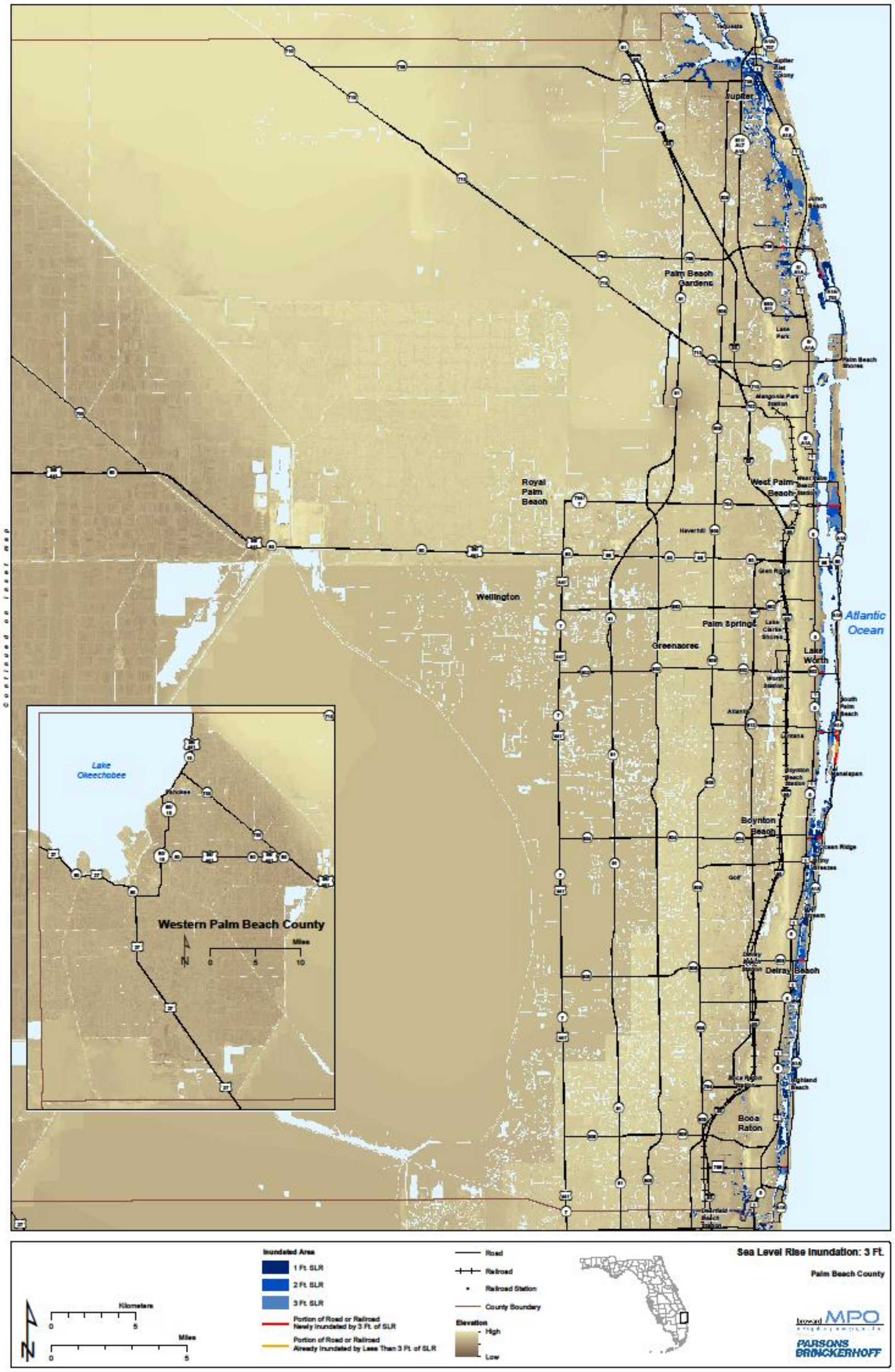


Figure 26: Permanent 3-foot Sea Level Rise Road Segment Inundation, Palm Beach County

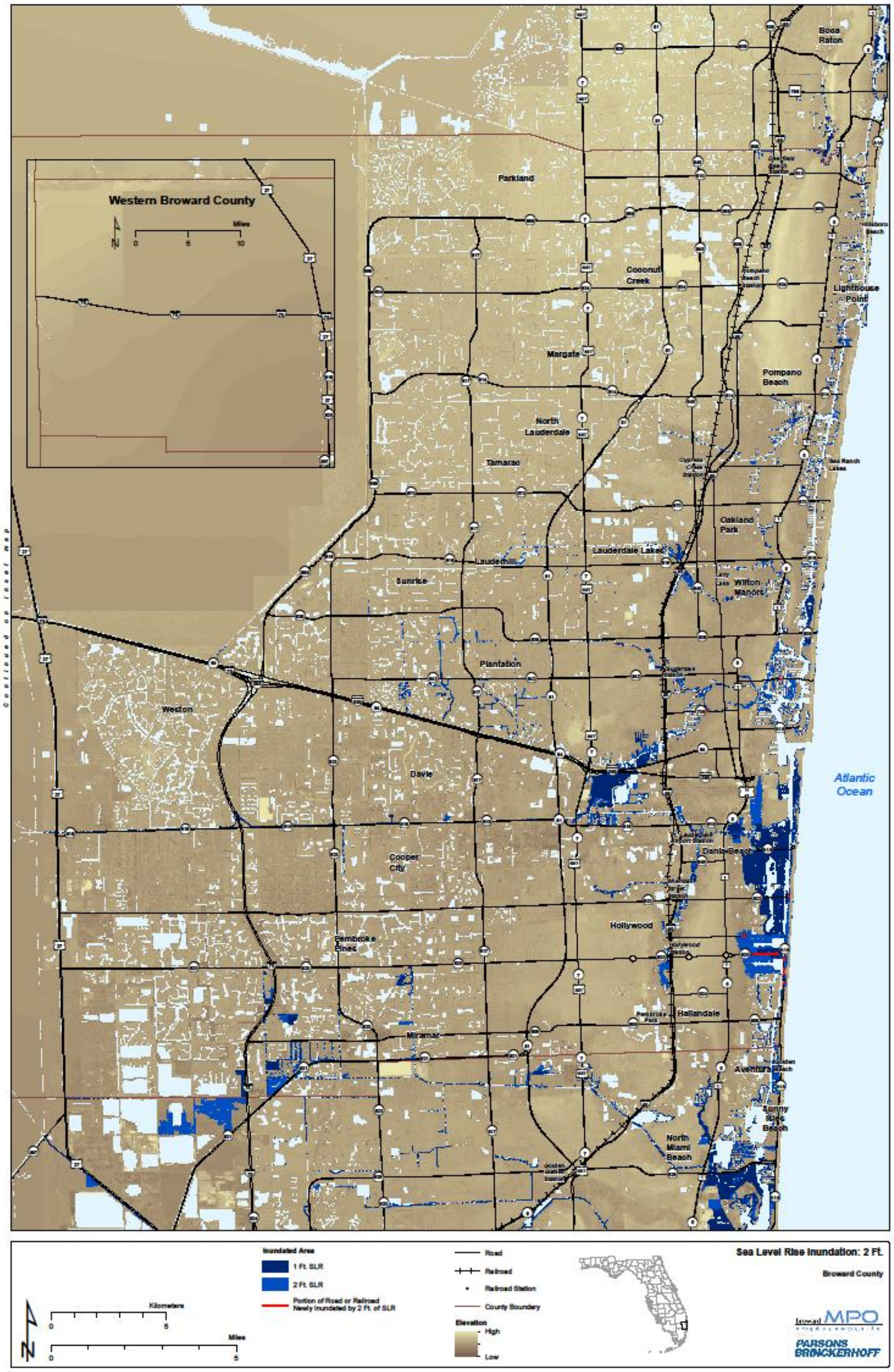


Figure 27: Permanent 2-foot Sea Level Rise Road Segment Inundation, Broward County

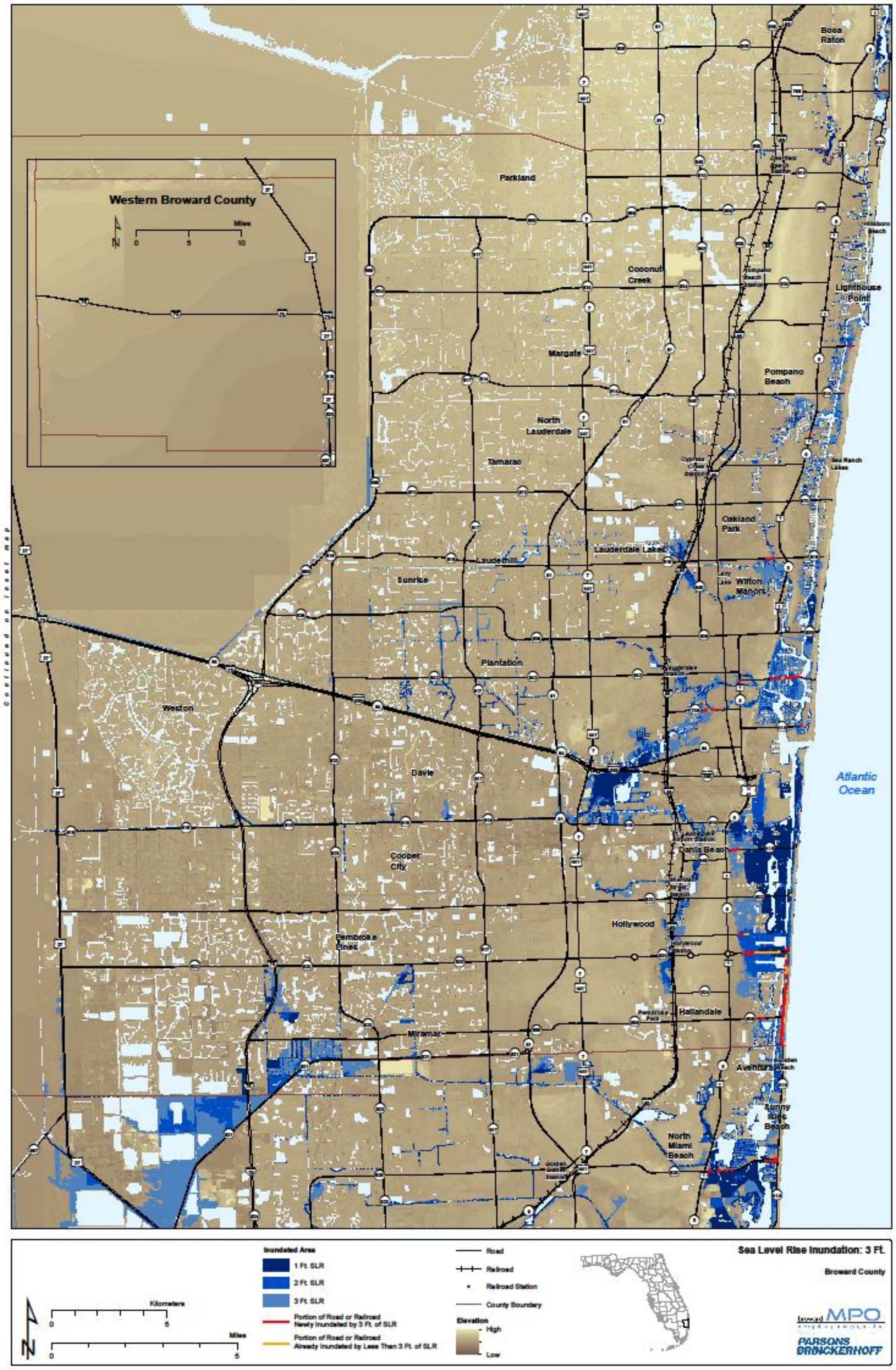


Figure 28: Permanent 3-foot Sea Level Rise Road Segment Inundation, Broward County

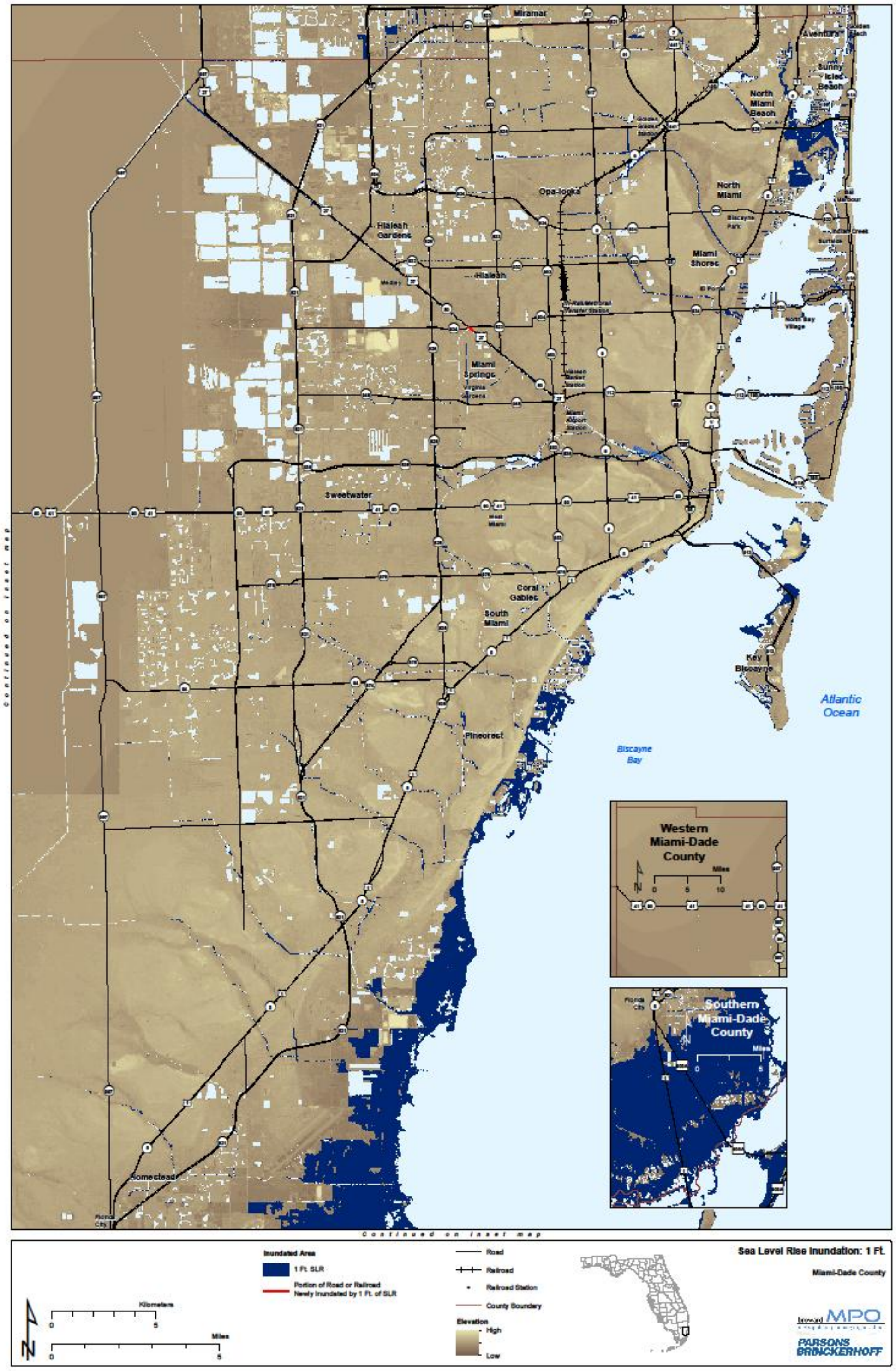


Figure 29: Permanent 1-foot Sea Level Rise Road Segment Inundation, Miami-Dade County

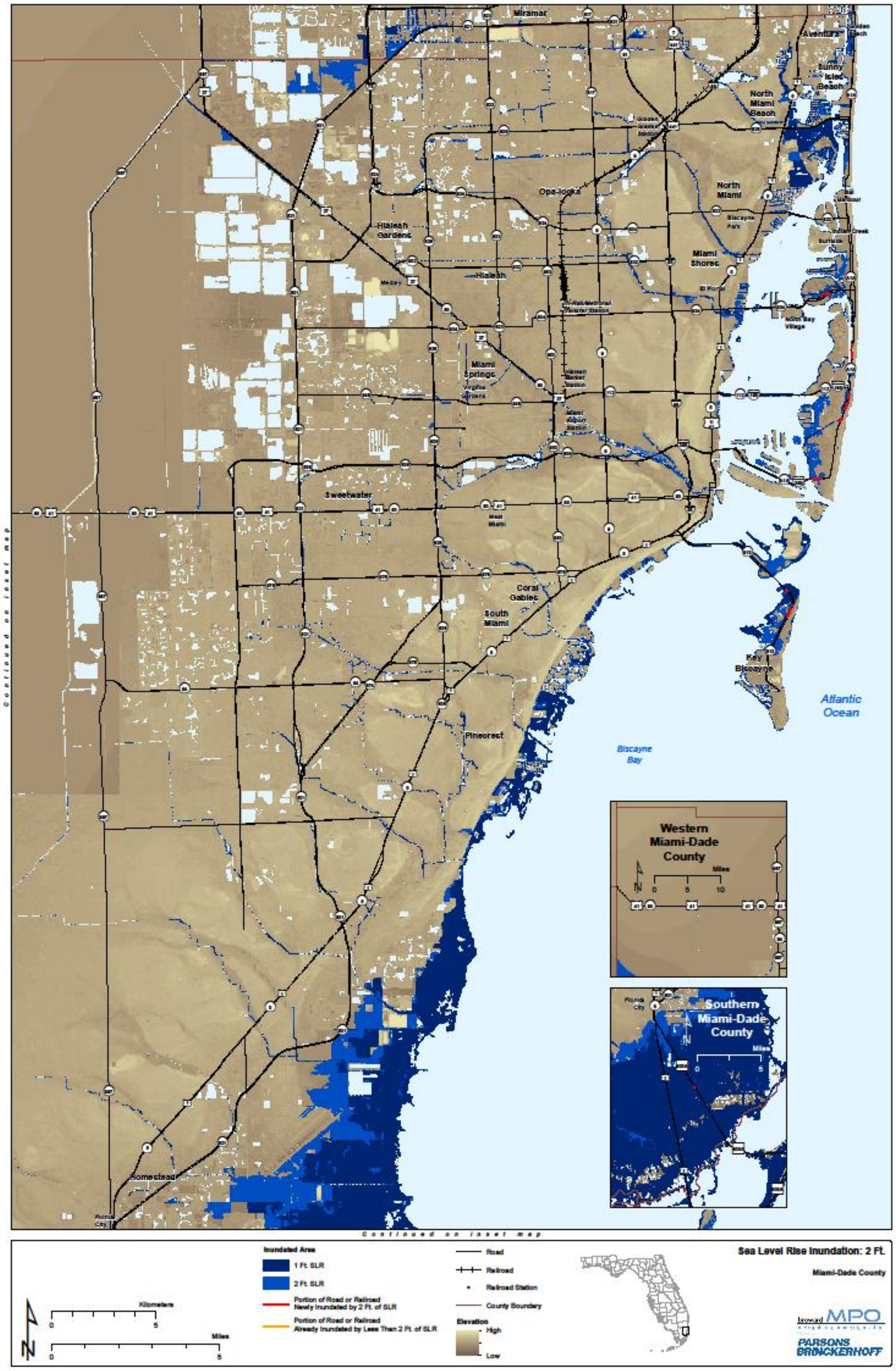


Figure 30: Permanent 2-foot Sea Level Rise Road Segment Inundation, Miami-Dade County

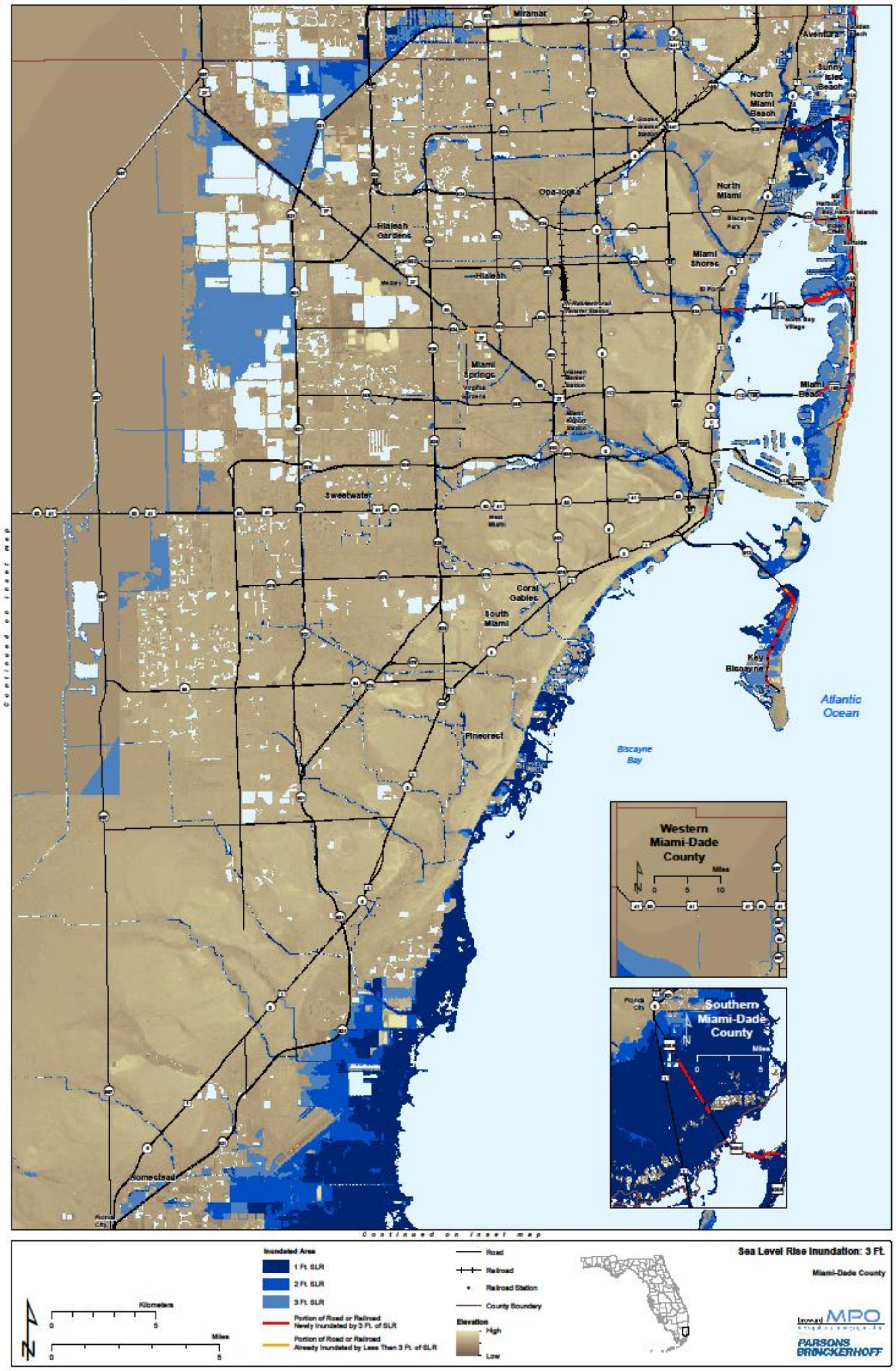


Figure 31: Permanent 3-foot Sea Level Rise Road Segment Inundation, Miami-Dade County

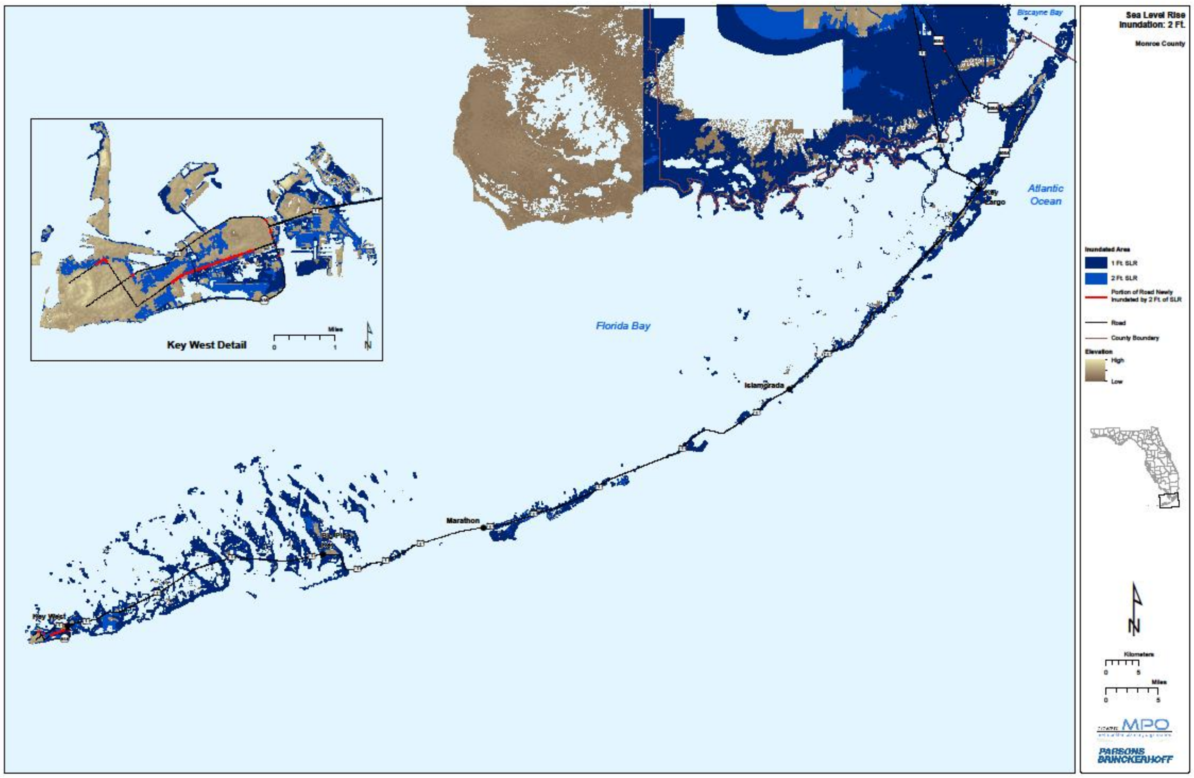


Figure 32: Permanent 2-foot Sea Level Rise Road Segment Inundation, Monroe County

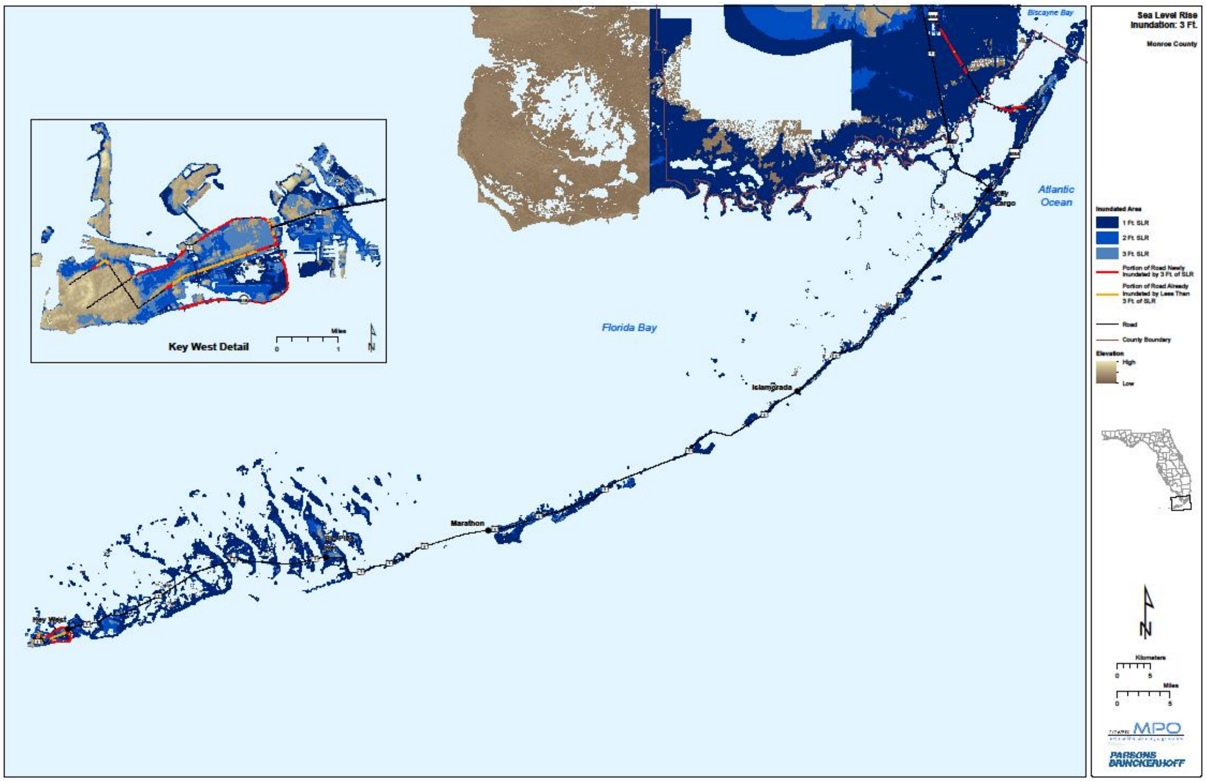


Figure 33: Permanent 3-foot Sea Level Rise Road Segment Inundation, Monroe County

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