Broward Metropolitan Planning Organization
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COMMITMENT 2045
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Broward Metropolitan Planning Organization
Commitment 2045
Metropolitan Transportation Plan

Technical Report #17

Incorporating Resiliency into Commitment 2045

January 14, 2020

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BrowardMPO.org

MPO MISSION STATEMENT

To collaboratively plan, prioritize, and fund the delivery of diverse transportation options.

MPO VISION STATEMENT

Our work will have measurable positive impact by ensuring transportation projects are well selected, funded, and delivered.

Core Products of the Broward MPO

Table of Contents

List of Tables

List of Figures

List of Maps

Introduction

Resiliency to sea-level rise and a changing climate are not new issues for Broward or South Florida. The region (Broward, Miami-Dade, Monroe, and Palm Beach counties) has collaborated on resiliency issues since the formation of the South Florida Regional Climate Change Compact in January 2010. Broward County adopted its first Climate Change Action Plan (CCAP) in 2010 and updated it in 2015. Beyond planning and coordination, transportation partners have worked to rebuild a coastal road in Broward following damage from a tropical storm combined with a high tide event. Beyond Broward, certain areas of South Florida already experience road flooding during high-tide events and improvements to address these issues have been undertaken, such as the reconstruction of Alton Road in Miami Beach.

The purpose of this document is to review local and regional activities related to resiliency, discuss how resiliency was addressed during the development of *Commitment 2045*, and offer next steps for enhancing the incorporation of resiliency in future updates. Resiliency was required to be considered as part of *Commitment 2045* as an additional planning factor pursuant to the *Federal Strategies for Implementing Requirements for LRTP Updates for the Florida MPOs*, dated January 2018. This document required the addition of a planning factor for "improving the resiliency and reliability of the transportation system and reducing or mitigating stormwater impacts of surface transportation." This factor was incorporated into the goals, objectives, and performance measures for *Commitment 2045*, which will be further discussed in this document.

Background & Prior Studies

Over the past 10 years, a number of plans and studies have been completed that evaluate the vulnerability of South Florida's transportation system, identify tools available to determine impacts, recognize mitigation strategies, and model the potential impacts of sea-level rise (SLR) combined with storm-surge impacts. Although the focus of this document is on Broward, additional information developed by regional partners is referenced.

Broward Climate Change Action Plan

Originally adopted in 2010, an updated version of this document was completed in November 2015 by Broward County. The CCAP consists of nearly 100 strategic actions to address the economic, environmental, and social impacts of climate change. These actions are focused on reducing local greenhouse gas (GHG) emissions, increasing community resiliency, and planning necessary adaptation measures to address local impacts. The strategies are county-wide in scope and are meant to be implemented by local governments, community partners, and residents. The CCAP has two overall goals: reduce GHG emissions by 2% per year by 2020 (with an overall reduction of 80% achieved by 2050) and increase the resilience of our community to the effects of climate change.

The plan identifies strategies in six areas—Policy, Natural Systems, Water Supply, Energy Resources, Built Environment, and Community Outreach. These areas are further described in Table 1. High-priority actions were identified in each area, of which only one was directly related to the transportation system—"Actively pursue the installation of alternative fuel vehicle infrastructure." Additional transportation-related actions in the CCAP are summarized in Figure 1.

Table 1: Broward CCAP Action Areas

CCAP Action Area	Description
Policy	Focus is on creating collaborative intergovernmental practices through joint legislative policies that raise awareness at State and Federal levels of South Florida's vulnerability and that advocate for increased State and Federal funding for mitigation and adaptation projects.
Natural Systems	Concentrate on preserving beaches, the Everglades, and habitats and protecting diverse plant and wildlife to create a balanced community of human habitation and natural ecosystems.
Water Supply	Safeguard the fresh water supply through conservation and adaptation, development of decision support tools, and integrated water resource management.
Energy Resources	Move towards an energy efficient future by increasing sustainable consumption through efficiency and conservation efforts, expand renewable and alternative energy accessibility, and create incentive programs.
Built Environment	Rethink traditional approaches to land use and land management, building and infrastructure siting and design, community planning, and private infrastructure investments, policies and practices.
Community Outreach	Deliver education information to all audiences so as to increase awareness and mobilize action on climate change.

Figure 1: Transportation-Related Actions from 2015 Broward CCAP

Policy Actions

- Contribute to climate planning efforts for transportation – Assist in coordinating transportation-related adaptation policies across jurisdictional boundaries and ensure alignment amongst broader planning and plan implementation efforts.
- Adopt adaptation standards which consider climate change and sea level rise – Ensure that public and private infrastructure, such as street and bridges … are built or rebuilt considering impacts from global climate change, including rising sea levels.
- Address mitigation and adaptation policies in Land Use Plan – Supporting linking the broad range of local and state infrastructure investments to improve and integrate multi-modal transportation and land uses that encourage a reduction in single occupancy vehicle trips and greenhouse gas emissions.
- Promote transit-oriented development – Promote functional, walkable mixed-use development designs and projects around transit stations.

Energy Resources Actions

- Increase share of trips made on transit – Dedicate funding for a sustainable transportation public education program…. Ensure the following specific focal components are included in the program: alternative fuels, vehicle efficiencies, use of mass transit, pedestrian and alternative vehicle uses, and public capacity to bring about change.
- Integrate bike share program with Complete Streets – Seek opportunities to install new and/or enhanced bike facilities, including buffered bike lanes, bicycle signage and pavement markings in transportation projects to improve bike accessibility and safety.
- Reduce fuel consumption of county fleet – Require County fleet vehicles, including transit, airport and port, to use alternative fuels, where not precluded by function. Purchase the most efficient vehicle that meets work requirements. Encourage efficient driving behavior and reduce idling.
- Incentivize employee carpooling and alternative fuel vehicles – Provide incentives … such as fee and/or priority parking for employee carpools, hybrid, and alternative fuel vehicles at county facilities. Increase electric vehicle charging infrastructure at county facilities….

Figure 1: Transportation-Related Actions from 2015 Broward CCAP (cont'd)

Energy Resources Actions

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Built Environment Actions

- Engage private sector to strategize adaptation of vulnerable railroads – Engage private sector to encourage their development of strategies, cost/benefit analyses, and schedules for raising or relocating railroad tracks in anticipation of accelerated sea level rise and other potential effects of climate change.

The Broward CCAP can be downloaded from the County's website on the Environmental Planning and Community Resilience page, or by using this link:

https://www.broward.org/Climate/Documents/BrowardCAPReport2015.pdf.

South Florida Climate Change Vulnerability and Adaptation Pilot Project

FHWA Vulnerability Framework Factors

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 (i.e., sea-level rise, storm surge, and precipitation-induced flooding).

Adaptive Capacity – The ability of the transportation network to deal with the loss of an impacted asset.

In 2013, the Broward MPO, as lead agency on behalf of the region's three MPOs and in partnership with other agencies, received funding for a Federal Highway Administration (FHWA) sponsored climate resilience pilot study. The "South Florida Climate Change Vulnerability and Adaptation Pilot Project" determined the impact of extreme weather on the area's regional transportation network based on the stressors of sea-level rise, storm surge, and precipitation-induced flooding. The focus was to develop a consistent methodology for integrating vulnerability into the MPO transportation decision-making process.

The study used five objectives to guide the GIS-based analysis.

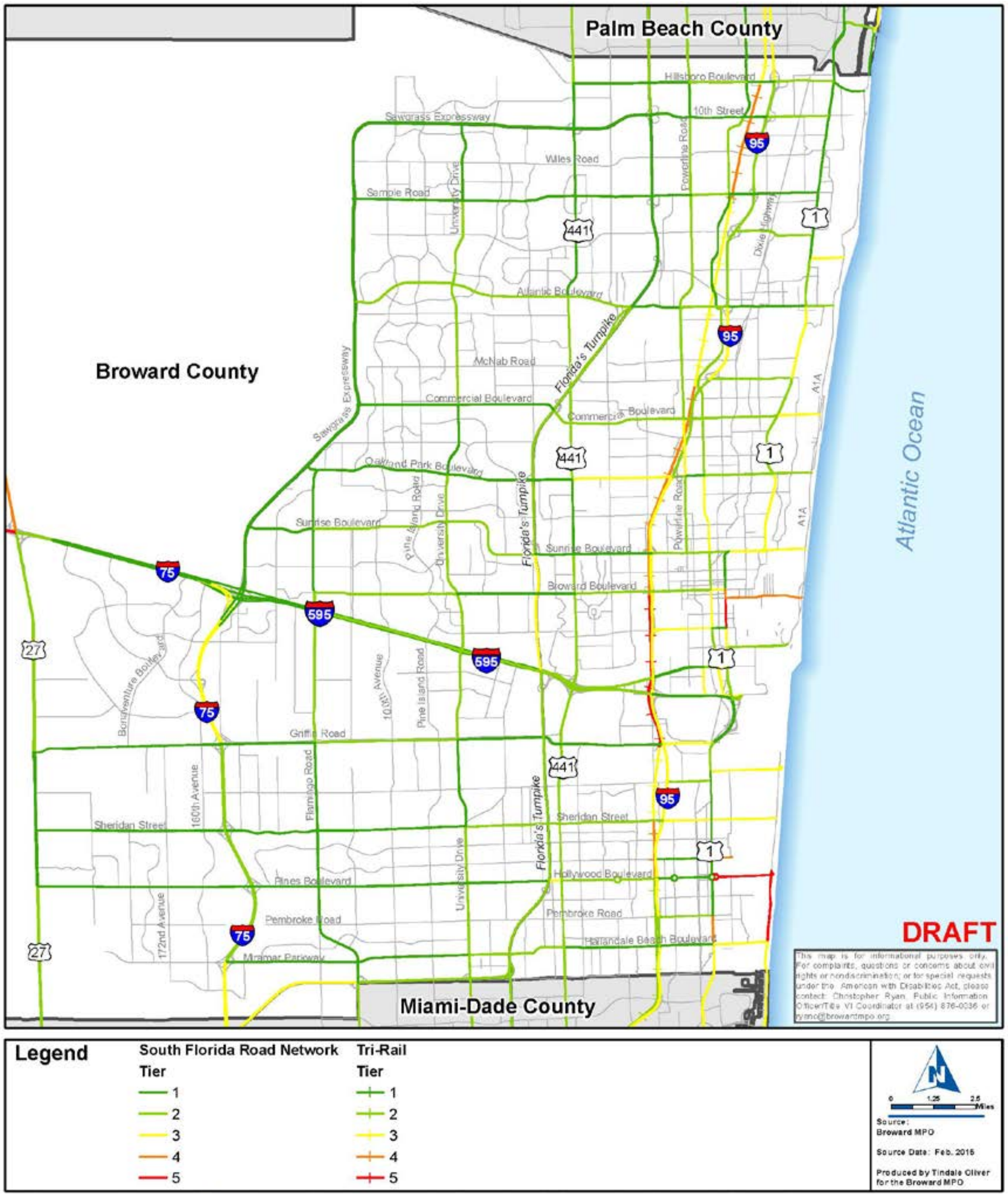
(1) Provide adaptation analysis capability.
(2) Identify adaptation projects and strategies.
(3) Apply a vulnerability framework and provide feedback to the planning process.
(4) Enhance decision support.
(5) Strengthen institutional capacity.

The approach to the vulnerability assessment was based on the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework, which is defined by three factors—exposure, sensitivity, and adaptive capacity. In addition to identifying the vulnerable roadway and rail assets, shown in Map 1, the study recommended 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. The final report identified the vulnerability of both roadway and rail assets, and the results were endorsed by the MPO Board on March 12, 2015, and approved by FHWA on September 29, 2015.

The report can be accessed from the Broward MPO's website from the "Adapting to Climate Change" page on the "What We Do" menu, or by using this link:

http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf.

Map 1: Broward County Vulnerability Assessment Results



Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida

As a follow up to the Pilot Project, the Broward MPO completed “Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida,” which addressed the Broward region’s local/county-level needs. The analysis resulted in the identification of vulnerable facilities and methods for treatment of roadways in areas that might be impacted by sea-level rise, storm surge, and precipitation-induced flooding stressors. The project applied climate change stressors to county and local roadways classified as collectors and above within the Broward region and included an assessment of the locations and elevations of significant roadways and bridges throughout the county compared to current and future flood levels. Map 2 illustrates the roadway classifications, based on level of importance, developed by this study. The future flood levels include sea-level rise values as identified and agreed upon by the Southeast Florida Climate Change Compact.

Whereas this report is not intended to provide project-specific details on potential resiliency upgrades for prioritized segments, Tables 1 through 3 show the general types of impacts and potential mitigation measures for infrastructure in Broward. The study provided an overview of the risks to the transportation system and should help guide policies and investments to ensure that decisions made today consider those future risks. This phase was approved by the MPO Board on October 13, 2016.

The report can be accessed from the Broward MPO’s website from the “Adapting to Climate Change” page on the “What We Do” menu, or by using this link:

http://www.browardmpo.org/images/Final_Report_-_FINAL_Submittal_to_BMPO_161103.pdf.

Map 2: Broward Roadway Transportation Network – Identified Tiers

Table 2: Temperature Effects on Transportation Infrastructure

Potential Impact for Temperature	Areas of Potential Exposure	Mitigation	Associated Issues
Heat Kinks/ Rail Buckling	Along turns, ballated track, track using wooden rail ties, areas of lower rail strength	Carefully consider rail neutral temperature by location and do not default to averages, directly or indirectly measure rail temperature to monitor for stress, monitor areas more prone to kinks/buckling, use concrete (not wood) crossties, maintain ballast to improve stability	Misalignment/ derailment delays, slow orders, halts in service, heavy maintenance.
Overheated Electrical Equipment	Above-ground cables, bare conductors, power control cubicles, signal rooms, etc.	Design systems for temperature increases/ hotter weather	Connection loss, wire expansion, decreased transmission efficiency
Blackouts	Electrical equipment, facilities including stations, stoplights at control points	Build redundancy into system and prepare emergency power generation (FTA, 2011), prioritize energy/efficiency, develop strong emergency response	Operations disruption
Material Expansion and Contraction	Pavements, cements, bridge joints	Choose materials carefully for climate; choose joints careflly for locations, temperatures, expansion limits, and service life; place joints downhill of drains to limit water contact; design decks with few joints; maintain joints and drains annually; consider creating jointless bridge decks by using link slabs	Rutting, asphalt movement, slab buckling, frequent maintenance, joint failure

Table 3: Expected Effects of Sea-Level Rise on Transportation Infrastructure in Broward

Asset	Issue	Concern	Potential Action
Roadways and Rail	Inundated Roadways	Roadways that may be inundated from SLR at all times or intermittently, impacting travelers during times of peak tidal events	Raise profile
	Higher Water Table	Reduced drainage capacity – increased effects during precipitation events	Raise profile, install drainage pumps
		Inundation of pavement during tidal/storm events or at all times	Raise profile
		Inundation of pavement subgrades during tidal events or at all times; erosion of material and increasing need for maintenance	Increase maintenance to maintain
Bridges	Tidal Effects	Tidal effects in areas that previously had no tidal effects and not considered in design	Add erosion control measures
		Undermining of foundations (scour)	Add scour protection measures
		Reduced bridge clearance	Re-build bridge at replacement for higher clearances
		Bridge girder corrosion from saltwater in areas not considered	Add corrosion protection treatment
		Uplift of roadway approaches from inundation	Anchor approaches
		Additional buoyancy on bridge superstructure (timber bridges)	Add buoyancy control measures
		Mechanical system flooding	Protect/move mechanical features
		Inundation of utility connections required to operate mechanical bridges	Seal electrical systems from flooding

Table 4: Potential Effects of Storm Surge on Transportation Assets

Asset	Issue	Concern	Potential Action
Tunnels	Inundation	Loss of service, inundation of sensitive electrical systems, latent damage (reduced life for concrete/structure, etc.)	Obtain/Install temporary or permanent barriers
	Power	Loss of power required to operate the systems – including pumping required to process flooding effectively	Invest in fuel-based pumps
Roadways/Rail	Pavement	Potential for pavement washouts or ballast effects (rail)	Add design features at edges to reduce washouts
		Extended surge area inland, where pavement design would not likely have considered storm surge	Add anchoring during pavement rehabilitation cycles
	Embankments	Erosion of embankments – higher surge levels for structures where surge considered and erosion effects in areas where surge not previously considered	Add embankment erosion control measures
Bridges	Decks	Surge impacts on bridge decks - superstructure floating away, damage to anchoring	Explore anchoring or raise the bridge deck
	Foundation	Increase in flow and velocity undermining foundations through scour for bridges analyzed previously for scour	Add scour protection measures
		Scour potential at bridges where surge not previously considered, impact on erosion walls, etc.	Add scour protection measures
	Approaches	Water flowing over approaches, causing uplift and damaging approaches	Anchor or redesign approaches
		Flowing water washes out approaches to bridges	Re-design approaches

Storm Surge, Sea-Level Rise, and Transportation Network Disruption

Funded by the Florida Department of Transportation (FDOT) and completed in November 2016, this report examines how storm surge (using historic storm tracks) and storm surge plus projected SLR (2040 scenarios) impact regional mobility and infrastructure, including airports and seaports, in the tri-county area (Palm Beach, Broward and Miami-Dade counties). Three historic storm tracks were simulated using the National Oceanic and Atmospheric Administration (NOAA) Sea, Lake, and Overland Surges from hurricanes model. The three historic storms selected impacted each of the three counites—Hurricane Andrew (1992) made landfall in Miami-Dade, the Fort Lauderdale hurricane (1947) made landfall in Broward, and the Delray Beach hurricane (1949) made landfall in Palm Beach.

An additional objective of this study was to evaluate the use of the regional travel demand model for these types of resiliency analyses. The Southeast Florida Regional Model (SERPM) 7.0 was applied to evaluate the extent of impacts on daily roadway trips, transit trips, vehicle miles traveled (VMT), vehicle hours traveled (VHT), vehicle hours of delay, and basic estimated economic impacts. Facilities impacted by storm surge or storm surge plus SLR were assumed to be fully unavailable for an entire day.

The results of this study were summarized in a presentation for the Southeast Florida Florida Standard Urban Transportation Model Structure (FSUTMS) Users Group on November 18, 2016 (see Appendix A). For roadways, the percentage of lane miles (for the tri-county network) disrupted by the storm-surge-only scenario ranged from 2% (Delray hurricane) to over 4% (Hurricane Andrew). When considering storm surge plus SLR, the percentage of lane miles disrupted grew to slightly over 3% (Delray hurricane) to 8% (Hurricane Andrew).

Railway impacts were reported by segments and projected similar impacts in Broward for both the Delray and Fort Lauderdale hurricanes plus SLR scenarios, with impacts to Tri-Rail extending from its Hollywood station to the Pompano Beach station. The Hurricane Andrew plus SLR scenario projected impacts in

Broward from the Hollywood station to the Cypress Creek station, not as far north as the other scenarios. Figures 1 through 4 are from the presentation and show the projected disruption to roadways, railways, airports, and seaports, respectively.

In terms of the regional travel demand model results for the tri-county system, VMT was shown to decrease under all scenarios, with a greater decline occurring in the storm surge plus SLR scenarios. VHT was projected to increase with corresponding increases in vehicle hours of delay and loss of economic productivity, which was measured as lost wages and time lost while sitting in traffic. The number of roadway and transit trips both show decline, with greater losses projected for the storm surge plus SLR scenarios.

The report concludes that SERPM worked well to identify facilities/areas to be prioritized for further study and improvement, allowed for a more robust transportation network analysis, and provided an end-to-end trip perspective since it accounted for alternative routes taken as a result of impacted roadway trips. SERPM could be improved related to the geospatial accuracy of the network, especially from the perspective of elevation data; transit trip rerouting, which was not evaluated; and allowing for model runs to be completed for different times of day.

Figure 2: Disrupted Roadway Links in Broward

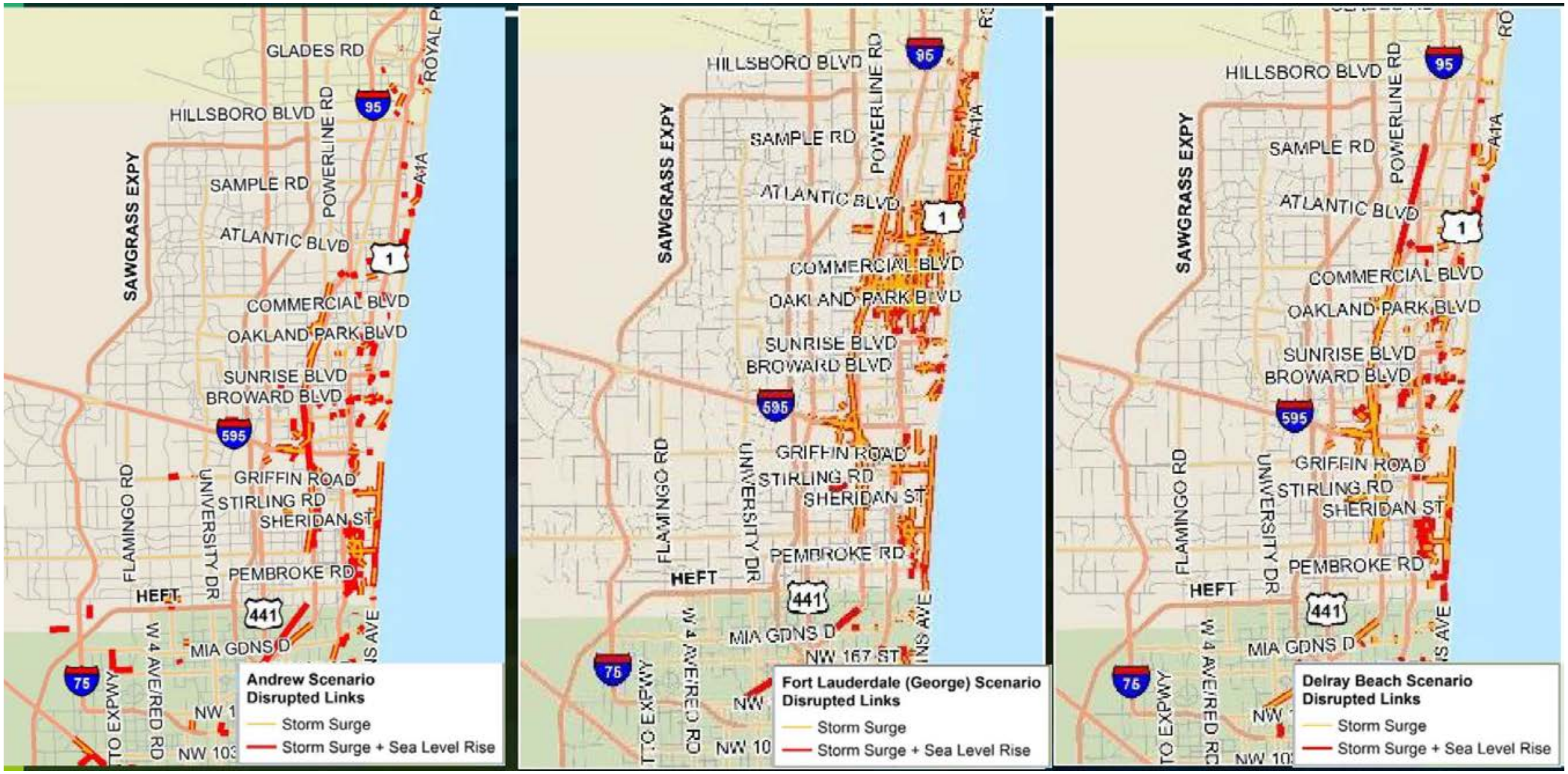


Figure 3: Disrupted Railways in Tri-County Area by Hurricane Scenario

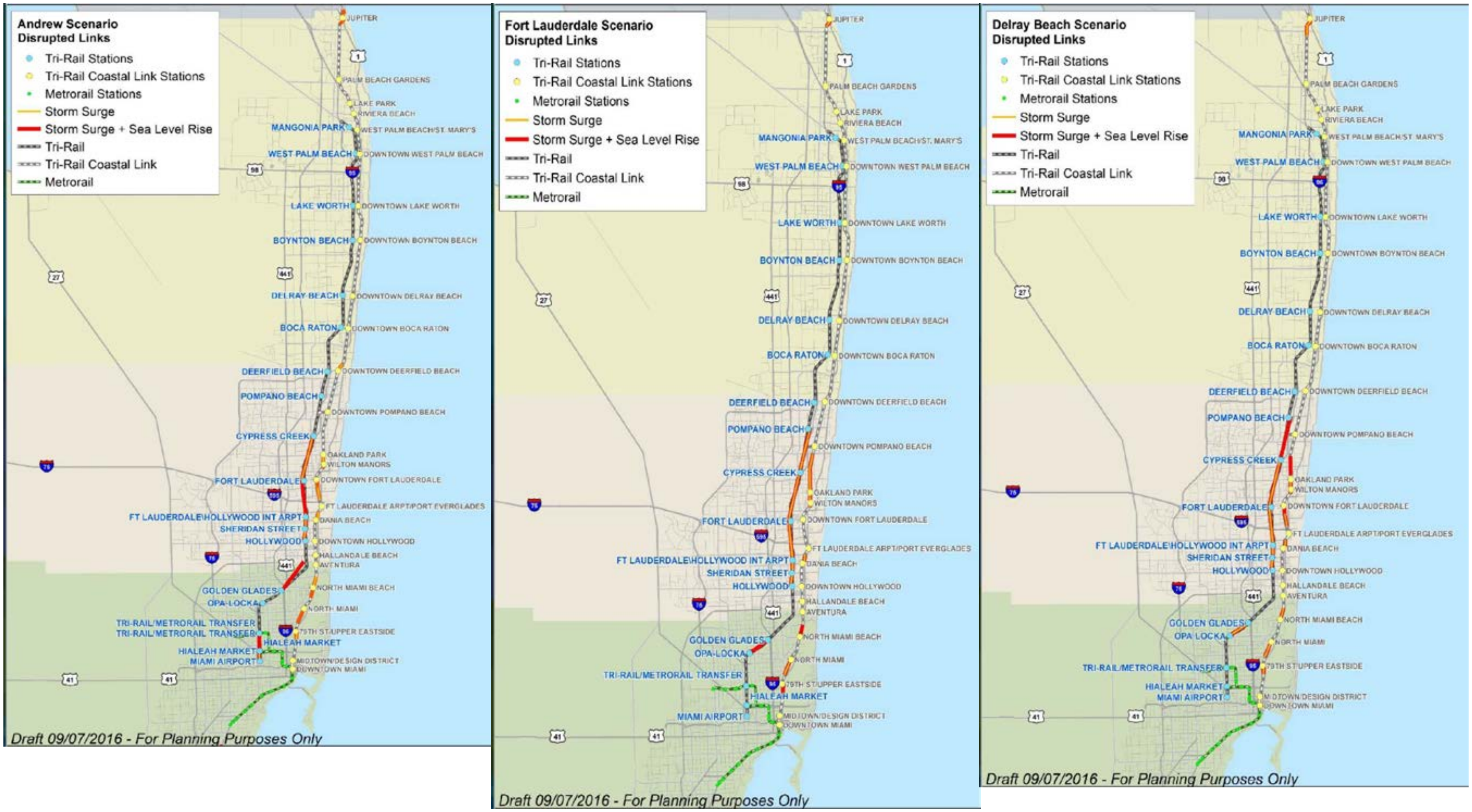


Figure 4: Impacts to Airports

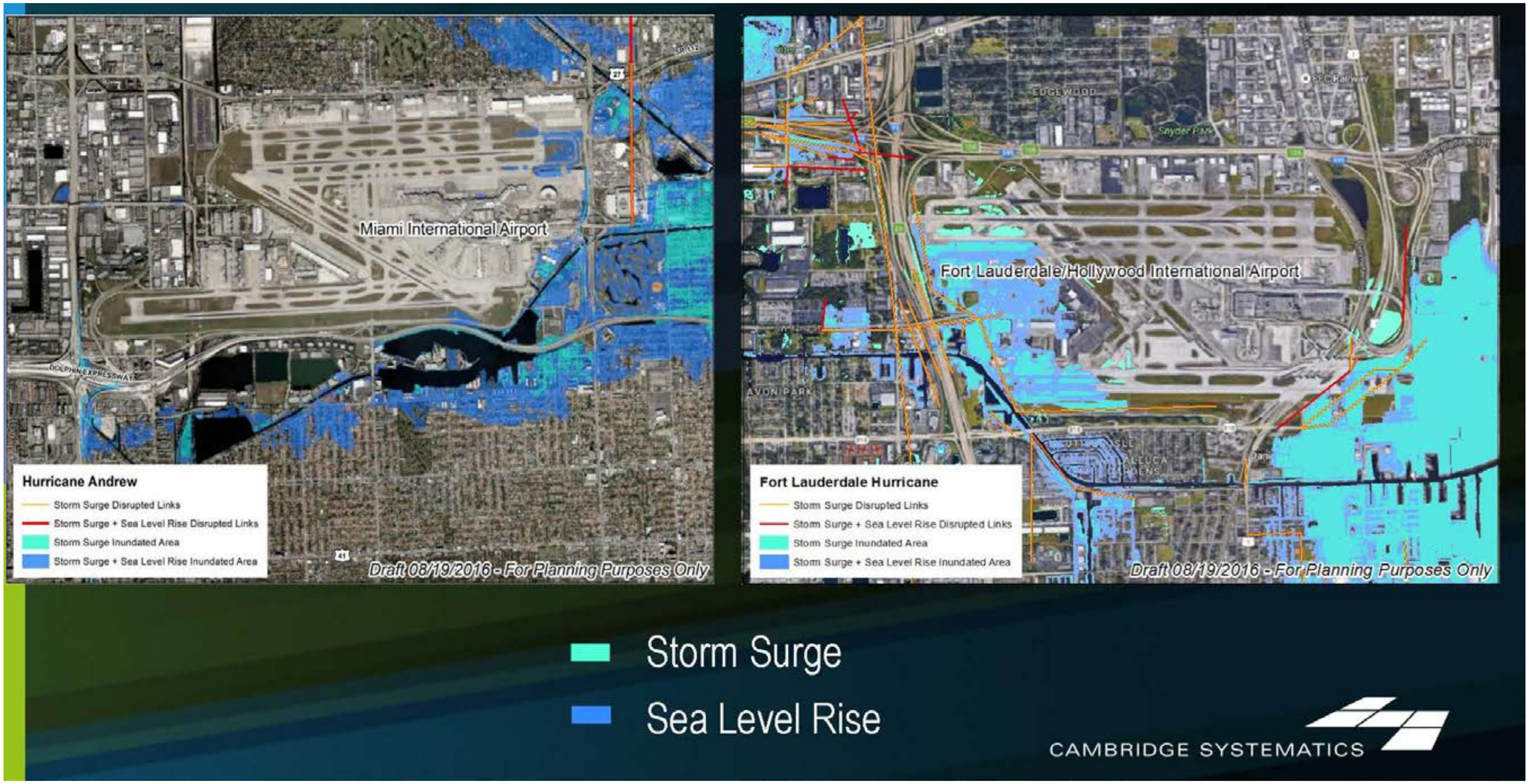


Figure 5: Impacts to Seaports

Assessment of Available Tools to Create a More Resilient Transportation System

In November 2016, Miami-Dade County published a report that reviews the methods and tools available from FHWA and FDOT that assess the vulnerability of transportation facilities to SLR and extreme weather events. The report begins with an assessment of SLR past, present, and projected and discusses how these changes impact the transportation network. The report also reviews recently-completed studies that assessed the vulnerability of the transportation network. Two studies reviewed were the Pilot Project and Storm Surge, Sea-Level Rise, and Transportation Network Disruption Impacts previously described in this document. The third study reviewed was conducted by the Southeast Florida Regional Climate Change Compact that classified the vulnerability of regional assets to SLR, which resulted in similar information identified by "Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida."

The document identifies several resources available from FHWA and the University of Florida (created in conjunction with FDOT), including guidance, tools, and webinars. A brief description of each of these resources is provided in Table 5 along with an assessment of the cost associated with their use. A copy of the report is provided in Appendix B.

Table 5: Resources Available from FHWA and University of Florida

Resources Available from FHWA	
Sensitivity Matrix	Webinar Session 4: Hurricane Sandy – Lessons Learned
Guide to Assessing Criticality in Transportation Adaptation Planning	Webinar – Understanding Criticality and Sensitivity
CMIP Climate Data Processing Tool	Webinar – Developing Scenarios of Future Temperature and Precipitation Conditions
Vulnerability Assessment Scoring Tool (VAST)	Webinar – Engineering Roads and Other Transportation Assets to be Resilient to Climate Change
Updated Hydraulic Engineering Circular 25: Highways in the Coastal Environment	Webinar – Developing Future Sea Level Rise and Storm Surge Scenarios
Updated Riverine Hydraulic Engineering Circular	Webinar – Assessing Vulnerability with VAST
Green Infrastructure Techniques for Improving Coastal Highway Resilience	Webinar – Climate Resilience Pilots: Results from Oregon DOT, WSDOT, Caltrans, and MTC
Webinar Session 1: Getting Started	Webinar – Climate Resilience Pilots: Results from CT DOT, Maine DOT, NYSDOT, and MassDOT
Webinar Session 2: System-Level Vulnerability Assessments	Webinar – Climate Resilience Pilots: Results from MnDOT, Michigan DOT, Iowa DOT, and Alaska
Webinar Session 3: Applying the Results	Webinar – International Climate Resilience: Practices from Denmark, Norway and more
Resources Available from University of Florida	
Quick Start Guide for the SLR Sketch Planning Tool	Map Viewer User Guide
SLR Inundation Surface Calculator User Guide	Webinar Recordings

Resiliency and *Commitment 2045*

As noted in the Introduction, resiliency is identified as one of the planning factors to be considered as part of this Metropolitan Transportation Plan. As such, it was included in the development of *Commitment 2045* in several ways:

- Emerging issue
- Scenario planning analysis
- Identification of needs
- Project prioritization process
- Cost feasible plan
- Public comments

This section reviews each of these portions of the *Commitment 2045* development process and discusses how resiliency was incorporated into each.

Emerging Issue

Although resiliency is not an emerging issue in Broward, having been part of the conversation for at least the past 10 years, it was included in the MTP as such since it was not addressed in prior plans. This section reviews the studies completed by the Broward MPO (Pilot Project, "Extreme Weather and Climate Change Risk to the Transportation System") and summarizes the other portions of the MTP influenced by these findings.

Scenario Planning Analysis

As part of this MTP, the Broward MPO elected to conduct a scenario planning analysis that considered five different approaches to the transportation network:

- **Trend –** improvements and investments continue as per previous plan
- **Compact Development –** includes greater investment in transit and a refocusing of projected growth to high-capacity transit corridors
- **Technology** – model variables modified to reflect automation of the vehicle fleet, including increasing the percentage of telecommuters

- **Community Vision** – applied improvements identified through the Call for Projects
- **Resiliency** – removed any proposed improvements to facilities identified as vulnerable by the "Extreme Weather and Climate Change Risk" report to determine the impact this approach would have on the network and travel

The scenarios were evaluated using criteria to determine the impact of each on mobility, accessibility, safety, equity, environmental stewardship, and economic vitality based on information obtained from the regional travel demand model. More information about the Scenario Planning Analysis and its results are provided in Technical Report #13.

Ultimately, the Resiliency scenario was not modeled and compared against the others, as there were no improvements proposed to vulnerable facilities (as part of the Trend network) that could be coded into the model. One of the objectives of the Scenario Planning Analysis was to assist in identifying additional needs for inclusion in the plan. Given the lack of projects identified through the Resiliency scenario, the Broward MPO focused on other methods for identifying projects that could be included in the MTP to address resiliency.

Identification of Needs

Full details of how the list of needs for *Commitment 2045* was developed are provided in Technical Report #13. The majority of the projects identified in the needs resulted from the Broward MPO's Call for Projects, which requested that planning partners submit capital projects eligible for MTP funding. Additional projects were identified based on the results of the Scenario Planning Analysis, a review of the prior long-range plan and other similar documents, a review of the Existing + Committed travel demand model results, and the Transit Vision. For the purposes of identifying projects to address resiliency, the Broward MPO coordinated with FDOT District 4.

As a starting point, the vulnerable facilities identified in the "Extreme Weather and Climate Change Risk" report were gathered (see Appendix C). Table 6 provides the top 10 ranked roadway and top 4 ranked railway segments.

Table 6: Top Vulnerable Roadway and Railway Facilities in Broward

	Name	Length (mi)	From Road	To Road	Rank*
Roadways	SR-A1A	3.4	S of Arizona St	SR-858/ Hallandale Beach Blvd	5
	I-75	54.7	Collier County Line	US-27	6
	SR-820/ Hollywood Blvd	3.2	US-1/SR-5	SR-A1A	9
	US-1/SR-5	1.6	E Las Olas Blvd	SR-736/ Davie Blvd	10
	US 27	81.6	SR-15/SR-80	I-75	18
	E Las Olas Blvd	3.0	US-1/SR-5	SR-A1A	20
	Johnson St	0.6	US-1/SR-5	N 14th Ave	22
	US-1/SR-5	0.4	SR-842/Broward Blvd	E Las Olas Blvd	33
	US-1/SR-5	1.5	SR-824/Pembroke Rd	SR-858/ Hallandale Beach Blvd	35
	SR-858/ Hallandale Beach Blvd	2.9	US-1/SR-5	SR-A1A	40
Railways	Tri Rail Mainline	4.1	Fort Lauderdale-Hollywood Intl Airport	Fort Lauderdale	1
		5.8	Fort Lauderdale	Cypress Creek	2
		1.5	Hollywood	Sheridan Street	3
		3.1	Pompano Beach	Deerfield Beach	5

*Vulnerability rank based on region, not Broward alone.
Source: "Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida," Broward MPO, October 2016.

The results from the "Extreme Weather" report were used in lieu of the facilities identified through the "Storm Surge, Sea-Level Rise, and Transportation Network Disruption" for two reasons. First, the results of the "Extreme Weather" report were based on the Pilot Project approved by FHWA and used FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework. Second, the disrupted roadway segments identified in FDOT's report include segments that are disrupted for an unknown period of time as a result of storm surge, and these segments may or may not require improvements to address these impacts, as the severity of those impacts were not identified in the report. Finally, due to the time constraints associated with the MTP process, it was not possible for the MPO to complete an updated review of these efforts.

Through coordination with FDOT, it was agreed that Strategic Intermodal System (SIS) facilities would not be included in the MPO's list of resiliency projects since FDOT has a policy to handle these facilities; they are included as part of the program of SIS projects FDOT provides to the MPO. As a result of this agreement, vulnerable railway segments were not included as they are also part of the SIS. The MPO also learned that FDOT considers resiliency to be part of its Project Development & Environment (PD&E) studies, which are conducted whenever improvements to State roadways are proposed that require an environmental review pursuant to State and/or Federal guidance.

In reviewing the list of vulnerable facilities, it was determined that the best approach was to include these projects as studies so that the most appropriate long-term solution for the facilities could be determined in conjunction with the MPO's planning partners and facility owners. After removing SIS facilities, the list of studies was reduced to the following eight roadway segments:

- SR-A1A from S of Arizona St to SR-858/Hallandale Beach Blvd
- SR-820/Hollywood Blvd from US-1/SR-5 to SR-A1A
- US-1/SR-5 from E Las Olas Blvd to SR-736/Davie Blvd
- E Las Olas Blvd from US-1/SR-5 to SR-A1A
- Johnson St from US-1/SR-5 to N 14th Ave
- US-1/SR-5 from SR-842/Broward Blvd to E Las Olas Blvd
- US-1/SR-5 from SR-824/Pembroke Rd to SR-858/Hallandale Beach Blvd
- SR-858/Hallandale Beach Blvd from US-1/SR-5 to SR-A1A

Project Prioritization Process

Resiliency was incorporated into the project prioritization process in part to comply with the required planning factor previously discussed, but also in recognition of the public's desire to see this issue addressed, as documented in the Online Survey results in Technical Report #1, and through interactions with the MPO's Technical Advisory and Citizen Advisory committees. Two criteria were included as part of the project prioritization process, under the Environmental Stewardship factor, which considered resiliency. Table 7 shows the prioritization criteria for the Environmental Stewardship factor, with criteria related to resiliency highlighted in **bold**.

Table 7: Environmental Stewardship Prioritization Criteria

Category	Points	Assessment Scoring Description
SLR Mitigation/Extreme Weather Resiliency	**+2**	**Project located within SLR vulnerability area (Tiers 1–3), will mitigate infrastructure in area**
	+1	**Project will result in infrastructure more resilient to extreme weather events**
	0	**Project not located within SLR inundation area**
GHG and Precursor Emissions	**+2**	**Project will reduce GHG emissions**
	+1	**Project may reduce GHG emissions**
	0	**Project has no impact on GHG emissions**
	-1	**Project may increase GHG emissions**
Wetlands and Natural Habitats	+1	Project may improve wetlands, floodplains, natural habitats or historic resources
	0	Project has no impact wetlands, floodplains, or natural habitats
	-1	Project may likely impact wetland, floodplains, or natural habitats
Historic Preservation	0	Project has no impact to buildings or areas identified on National Historic Register
	-1	Project may likely impact buildings or areas identified on National Historic Register

Cost Feasible Plan

The eight resiliency studies listed in the Identification of Needs section were included in the Cost Feasible Plan. As the prioritization process noted above was not appropriate for prioritizing these studies, a separate process was developed for them based on projected year of inundation and their vulnerability ranking. All eight studies are shown in first five-year implementation time band, 2026 to 2030, and are listed in the following priority order:

(1) SR-820/Hollywood Blvd from US-1/SR-5 to SR-A1A
(2) SR-A1A from S of Arizona St to SR-858/Hallandale Beach Blvd
(3) US-1/SR-5 from E Las Olas Blvd to SR-736/Davie Blvd
(4) US-1/SR-5 from SR-842/Broward Blvd to E Las Olas Blvd
(5) E Las Olas Blvd from US-1/SR-5 to SR-A1A
(6) US-1/SR-5 from SR-824/Pembroke Rd to SR-858/Hallandale Beach Blvd
(7) SR-858/Hallandale Beach Blvd from US-1/SR-5 to SR-A1A
(8) Johnson St from US-1/SR-5 to N 14^{th} Ave

Public Comments

A draft of the MTP document was published for review on October 10, 2019, with comments requested by November 1, 2019, to allow sufficient time to address any necessary changes prior to the MPO Board's adoption on December 12, 2019, consistent with Federal requirements. Three agencies provided comments specific to the resiliency efforts documented in the MTP—the City of Fort Lauderdale, FDOT, and Broward County's Environmental Planning and Community Resilience Division. Appendix D provides the specific comments received from each of these agencies, which are summarized below.

City of Fort Lauderdale

The City's comments were focused on the resiliency studies located within their municipal boundaries, and the concern was related to how these projects were identified and included in the Cost Feasible Plan. A response to these comments was provided by the MPO.

FDOT

FDOT's comments were focused on the Resiliency scenario and requested additional explanation as to why the vulnerable facilities identified were based on prior studies as opposed to other available information. The comments specifically referenced the "Storm Surge, Sea-Level Rise, and Transportation Disruption" report and the resources available from the University of Florida. The MPO provided a response to these comments, and this document serves to address these comments, as it was not possible to do so as part of the MTP document due to time constraints. Specifically, this document provides a review of the resources referenced by FDOT and explains the MPO's rationale for using the vulnerable facilities identified in the 2015 and 2016 studies.

Broward County

Broward County's Environmental Planning and Community Resilience Division provided written comments on December 2, 2019, with comments focused on the Resiliency scenario, the roadway plan and timeframes, and general coordination. The MPO provided a response to these comments, which is included in Appendix D. The County took exception to the scenario planning approach for resiliency;

whereas their concerns are noted, it is not possible at this point to revise the effort as suggested. The County's concerns about the roadway plan and timeframes are focused on their desire to have additional studies and projects included in the plan and to have all projects in the MTP reviewed for vulnerability to SLR. The recommendations in the Next Steps section of this document address many of these comments. The County's concerns and recommendations regarding coordination are also addressed in the Next Steps section.

Next Steps

Commitment 2045 is a "living" document. Although the MPO was required to adopt it by December 12, 2019, the Cost Feasible Plan remains in effect for the next five years until the next MTP update is adopted in 2024. As such, amendments to the Cost Feasible Plan are anticipated and are a key means to address resiliency concerns in Broward. For a project to be included in the Cost Feasible plan for construction, it must have a defined scope, defined "to and from" limits, and a cost estimate. For this reason, resiliency projects were identified as studies and not as construction projects, as the necessary improvements are not fully defined at this point. Through coordination with Broward County, FDOT, and municipalities, these studies could be modified or added to through the MTP amendment process. If construction projects are already identified, these projects may also be added through the amendment process.

The project prioritization process developed for the MTP includes a significant focus on safety as one of the six planning factors identified for the evaluation. As reviewed in this document, there are also criteria related to resiliency projects. Therefore, the County's concern about prioritizing safety already has been addressed. Unfortunately, there were no resiliency-related construction projects submitted for inclusion in the MTP; therefore, it is not possible to assess how well the established criteria and process performed. For the next MTP update or as the current one moves forward, the MPO will reconsider the prioritization criteria, specifically the weighting factors applied as part of the prioritization process. These weights were established through coordination with the MPO's committees and Board. Environmental Stewardship, where the resiliency criteria are located, received the lowest weighting of the six factors, at 12.8, compared to the 20.5 established for Mobility. Moving forward, it may be advisable to rename this factor Resiliency and Environmental Stewardship. It also may be prudent to establish a seventh factor that focuses solely on resiliency and climate change criteria, thus allowing its own weighting factor outside of the natural and built environmental consideration.

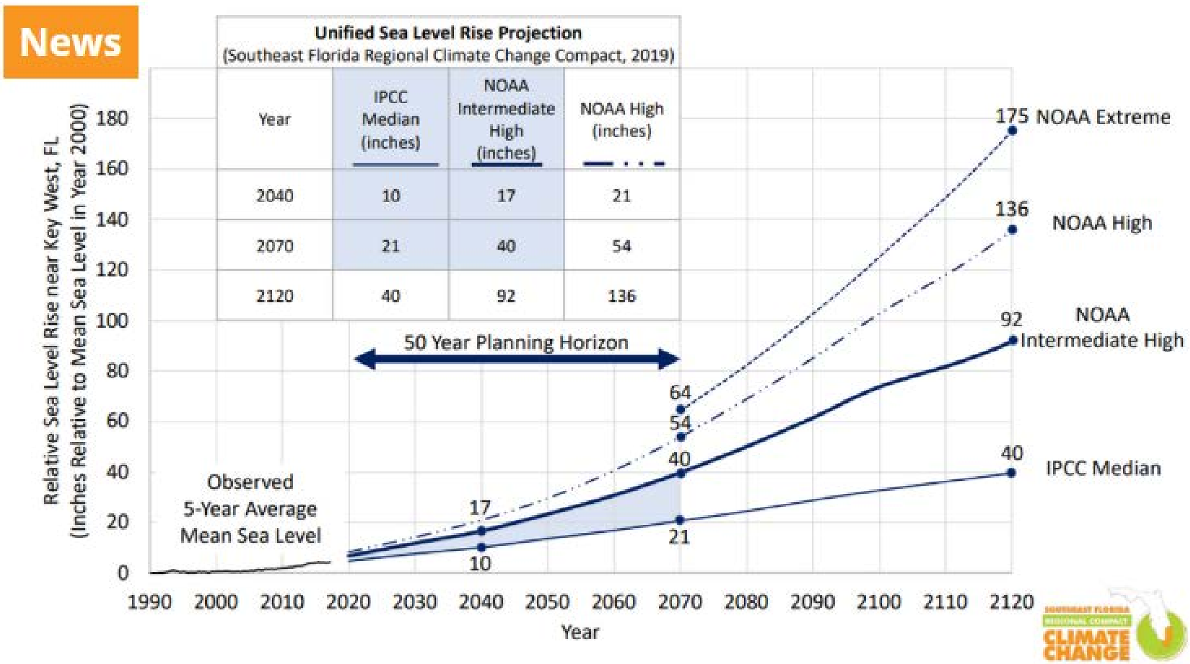
The inclusion of a project in the Cost Feasible Plan is not the end of its review and evaluation; rather, it is the beginning. Projects identified in the roadway portion of the MTP will undergo a PD&E phase, which, per FDOT's policies, will include an evaluation for resiliency. These PD&E studies will be coordinated with the local community, roadway owner(s), affected stakeholders, and technical experts. The MPO will not lead these studies but will ensure that coordination is occurring.

Commitment 2045 served as a useful means for engaging the MPO's partners in a discussion about how the MTP should address resiliency and climate change. The comments received for this MTP will be maintained and used by the MPO as it develops the scope for the next MTP update. To the extent feasible, the MPO will ensure that the next MTP document adequately addresses the concerns raised during the review of *Commitment 2045*.

Finally, it is anticipated that vulnerability assessments and future conditions projections will be updated, requiring updates to previously-completed studies. For example, a new Southeast Florida Unified Sea-Level Rise Projection was released on December 4, 2019 (see Figure 6). Compared to 2015 projections, this update indicates that instead of the approximately 9–15 inches of SLR projected for 2040, 10–17 inches are now anticipated. Similarly, projections for 2060 grew from approximately 14–26 inches to 20–40 inches. Unfortunately, it appears that updates to the Unified SLR Projections will entail the required adoption of the MTP, as the next update to both are anticipated in December 2024, meaning that the 2050 MTP will be using the 2019 SLR projections.

Given the cyclical nature of SLR projection updates, the MPO may consider establishing a program to ensure that vulnerability assessments are re-evaluated every five years, pending available funding. The MPO will work with its partners to identify potential funding sources that may be used to update the efforts completed in 2015 and 2016, as well as any other efforts deemed necessary to ensure the resiliency of Broward's transportation network.

Figure 6: 2019 Southeast Florida Unified Sea Level Rise Projection



Source: Southeast Florida Regional Climate Change Compact, accessed on January 3, 2020

Appendix A: FDOT's "Storm Surge, Sea-Level Rise, and Transportation Network Disruption" Report & Presentation

Storm Surge, Sea Level Rise, and Transportation Network Disruption

prepared for

Southeast Florida Planning Partners

funded by

Florida Department of Transportation

prepared by

Cambridge Systematics, Inc.

with support from

Keren Bolter, PhD

report

Storm Surge, Sea Level Rise, and Transportation Network Disruption

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prepared by

Cambridge Systematics, Inc.
2101 West Commercial Boulevard, Suite 3200
Fort Lauderdale, FL 33309

date

November 2016

Table of Contents

List of Tables

List of Figures

Executive Summary

> This project contributes to a more robust understanding of potential sea level rise and storm surge impacts on regional mobility and infrastructure.

The Federal Highway Administration (FHWA) funded South Florida Climate Change and Vulnerability Assessment and Adaptation Pilot Project (Pilot Project) shows that the transportation network in Miami-Dade County, Broward County, and Palm Beach County is vulnerable to coastal and inland flooding, and future flooding from sea level rise (SLR) and other climate trends. This project supplements the FHWA-funded South Florida Climate Change and Vulnerability Assessment and Adaptation Pilot Project by **contributing to a more robust understanding of potential SLR and storm surge impacts on regional mobility and infrastructure, including from an emergency management standpoint**. A scenario approach was used to simulate storm surge associated with the simulation of three historic storm tracks, with a storm making landfall in each of the three counties. Three storms were simulated using the National Oceanic and Atmospheric Administration (NOAA) Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model: Hurricane Andrew (1992), Fort Lauderdale Hurricane (1947), and Delray Beach Hurricane (1949). **For each historic track, current and 2040 sea level rise scenarios were simulated**, using a linear amplification of SLR on storm surge despite research indications that the effects may be larger. Section 2.0 describes the details of storm surge simulation.

Another objective of this project was to evaluate the use of the regional travel demand forecasting model for these types of analysis. Section 3.0 discusses the methodology for identifying effecting infrastructure and results of transportation network disruption and modeling. The Southeast Florida Regional Model (SERPM) 7.0 was applied to evaluate the extent of impacts in terms of daily Roadway Trips, Transit Trips, Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), Vehicle Hours of Delay (VHD), and basic estimated economic impacts. Facilities impacted by storm surge or storm surge plus SLR were assumed to be fully unavailable for an entire day. Findings are summarized as follows:

- This project builds on the FHWA Pilot project in several ways. The Pilot identified facilities vulnerable to SLR and **this project focuses on those facilities that are vulnerable to storm surge as well as SLR**, thereby helping to identify facilities/areas to be prioritized for further investigation and improvements. It also identified areas that are isolated as the result of storm events, highlighting communities where more in depth evaluation is needed to ensure access to critical goods and services. This project relied on SERPM to account for traveler preferences to take alternate routes for impacted trips, providing **an end-to-end trip perspective of adaptive capacity**. Using SERPM also allowed for many more roads to be analyzed and included transit impacts.

- **Simulated storms predict a reduction of daily VMT in the transportation network**. When coupled with sea level rise, these storms will reduce system-wide daily VMT by five to 11 percent. These reductions are **due to trips that cannot be completed due to isolated origination or destination areas**. Total daily VHT in all three counties are predicted to increase with the simulated storm and storm plus SLR events. The increase of VHT (as compared to baseline 2040 conditions) varies in the three counties and by storm track, and increases range from 19 percent to more than 300 percent. The **additional hours of delay results in $49 million to more than $700 million in the value of drivers' time spent traveling**. These ranges show that while addressing storm surge and SLR is a regional challenge, different parts of the region may be more affected for any given circumstance.

- The regional nature of travel patterns in Southeast Florida means the loss of access to an economic or employment center results in the inability of trips to be completed throughout the three counties. These are termed "lost trips" because the origination or destination is inaccessible, and no rerouting (or adaptive capacity) is possible. In the scenarios with storm surge only up to 11 percent (one in nine) of all trips cannot be completed due to lack of access at the originating or terminating end. **For the storm surge plus SLR scenarios, up to 15 percent of trips are lost (one in seven). This includes both transit and non-transit trips**. Miami-Dade County is impacted the most; however, there are locations in each of the three counties that become inaccessible, or isolated, due to storm surge and SLR.

- **Potential impacts are not limited to roadways**. Several Tri-Rail, Tri-Rail Coastal Link, Metrorail, and fixed route bus segments are vulnerable to storm surge and storm surge plus sea level rise. Total transit trips in the three counties is predicted to be reduced up to 16 percent with storm surge only and up to 22 percent with storm surge plus SLR. In the worst case scenarios, Miami-Dade County and Broward County may see up to 32 percent and 31 percent of transit trips lost, respectively[1]. The lack of transit adaptive capacity in SERPM means the results here over emphasize the impacts to transit. In practice, transit service, if able to run, would rely on alternate facilities to circumvent disrupted segments.

- **Small areas of Miami International Airport and Fort Lauderdale/Hollywood International Airport are predicted to be inundated** in various scenarios. Access to these airports also is impacted. **PortMiami, Port Everglades, and Port of Palm Beach each have areas inundated** due to storm surge and storm surge plus SLR. The facilities are critical economic engines for the region and provide important access after a storm event.

- The storm surge project demonstrates **the most vulnerable areas are those with hydrological connections to the coast**, such as inlets and areas near the Miami River, Middle River, and Loxahatchee River. If not already part of transportation related emergency management preparations, operational strategies to protect hydrologically vulnerable areas and to reduce storm surge impacts should be identified.

- The basic economic information provided by this project helps foster a conversation about the costs of incorporating adaptation strategies into transportation infrastructure. The high level figures show the extent of traveler delay and lost trips – two major impacts. However, impacts on the economy as a result of the disruption is not included, nor are impacts associated with seaport and airport disruptions. **More robust economic analyses would help to evaluate the benefits and costs of implementing adaptation strategies in the future**.

In addition to identifying potentially vulnerable areas and evaluating the extent of disruption, this project offers multiple recommendations, such as:

- **Regional partners should continue to address recommendations from this project and other ongoing initiatives** (e.g., FHWA Pilot and Regional Compact). Planning partners should prioritize resiliency and emergency management considerations for highly vulnerable areas, namely those areas impacted by all three storm tracks. FDOT or other agencies should consider applying a similar storm surge and SLR scenario approach to evaluating transportation implications to other areas of the region

[1] As noted in Section 4.3.2, transit trips on Tri-Rail Coastal Link are not part of the total.

and state. Performing a more thorough economic analysis (using REMI) would provide more detailed information to support benefit cost discussions.

- Parties are encouraged to use the results of this project and enhance tools that support planning and operational decision making. **Resiliency considerations should be incorporated in transportation planning, engineering, design, maintenance, operations, and emergency management processes and procedures.** For example, FDOT should take steps to improve the geospatial accuracy of the travel demand forecasting model to allow easier identification of vulnerable roadway segments and transit facilities. Another suggestion is to enhance the environmental screening tool (FDOT's Efficient Transportation Decision Making (ETDM) process) initially for internal use as a resource to identify vulnerable facilities. Providing additional vulnerability assessments helps develop comprehensives list of at risk roadways and transit facilities, particularly for pre-event planning. Another recommendation is to create a sketch level resource to identify potential transportation facilities in the path of an impending storm to support road closure/detour planning.

- **More robust assessment of airport and seaport impacts**, including impacts on access to these facilities and estimations of economic cost, are appropriate through airport and seaport master planning processes. Similarly, **transit agencies plans should consider potential disruptions** noted here, as well as on maintenance facilities, as part of continuity of operations plans. Another next step in transportation/transit planning would be to repeat this analysis utilizing the six SMART Plan Corridors and the BERT express Bus Routes inclusive of their terminals to better plan for adaptation strategies for these projects.

- **Regional partners should continue to collaborate on transportation related storm surge and storm surge plus SLR related emergency management data, planning, operations, maintenance, and response activities**. The coordination can be broadened for the protection of transportation infrastructure and operations to include public works, water management and drainage districts officials. Furthermore, the partners should encourage the creation of a guideline/handbook which summarizes methods, findings, and applications of various storm surge and sea level rise projects, including this project, the South Florida FHWA Pilot Project, and the Florida Sea Level Scenario Sketch Planning Tool.

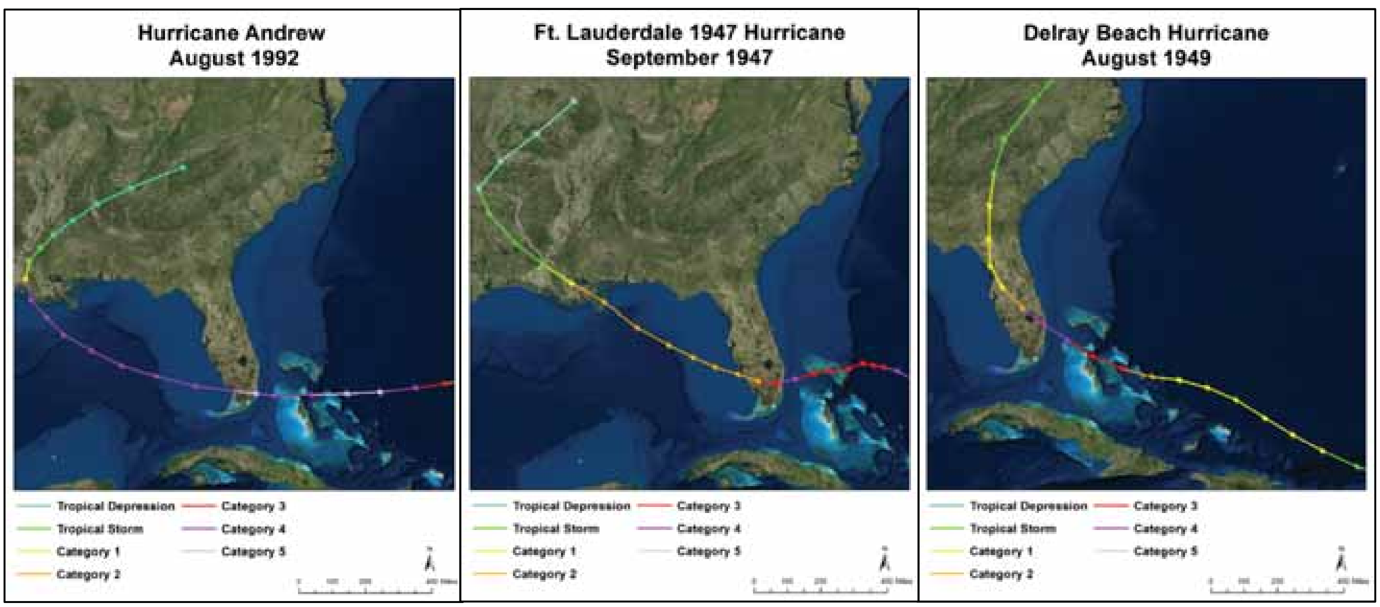
- The Fixing America's Transportation Act (FAST) requires the planning process to consider projects/strategies to: improve the resilience and reliability of the transportation system, stormwater mitigation, and enhance travel and tourism. The region is ahead on the issues given the work of the FHWA Pilot Project and the Climate Compact. However, given the regions susceptibility to storm surge and SLR, incorporating resiliency in all stages of project planning, programming, engineering, construction, and maintenance should be considered. **Steps would be to incorporate objectives and evaluation criteria in decision making or mainstream adaptation strategies in the next round of long range transportation plans**, such as setting aside funding to allow adaptation strategies to be included in projects. **Local governments are encouraged to incorporate considerations of storm surge and sea level rise in their Comprehensive Plans, Capital Improvement Plans, and Emergency Management Plans**.

1.0 Project Approach

The FHWA South Florida Climate Change and Vulnerability Assessment and Adaptation Pilot Project[2] (Pilot Project) indicates the transportation network in Miami-Dade County, Broward County, and Palm Beach County is vulnerable to sea level rise and other climate trends. The Pilot Project was not able to consider the compound effect of sea level rise and storm surge, or consider the potential network-level implications of a storm surge-related disruption. This project performs additional analysis in these areas to provide transportation and emergency management personnel additional tools to evaluate potential impacts to infrastructure – and by extension people – to storm surge and storm surge plus SLR. The study area includes transportation networks in Miami-Dade County, Broward County, and Palm Beach County.

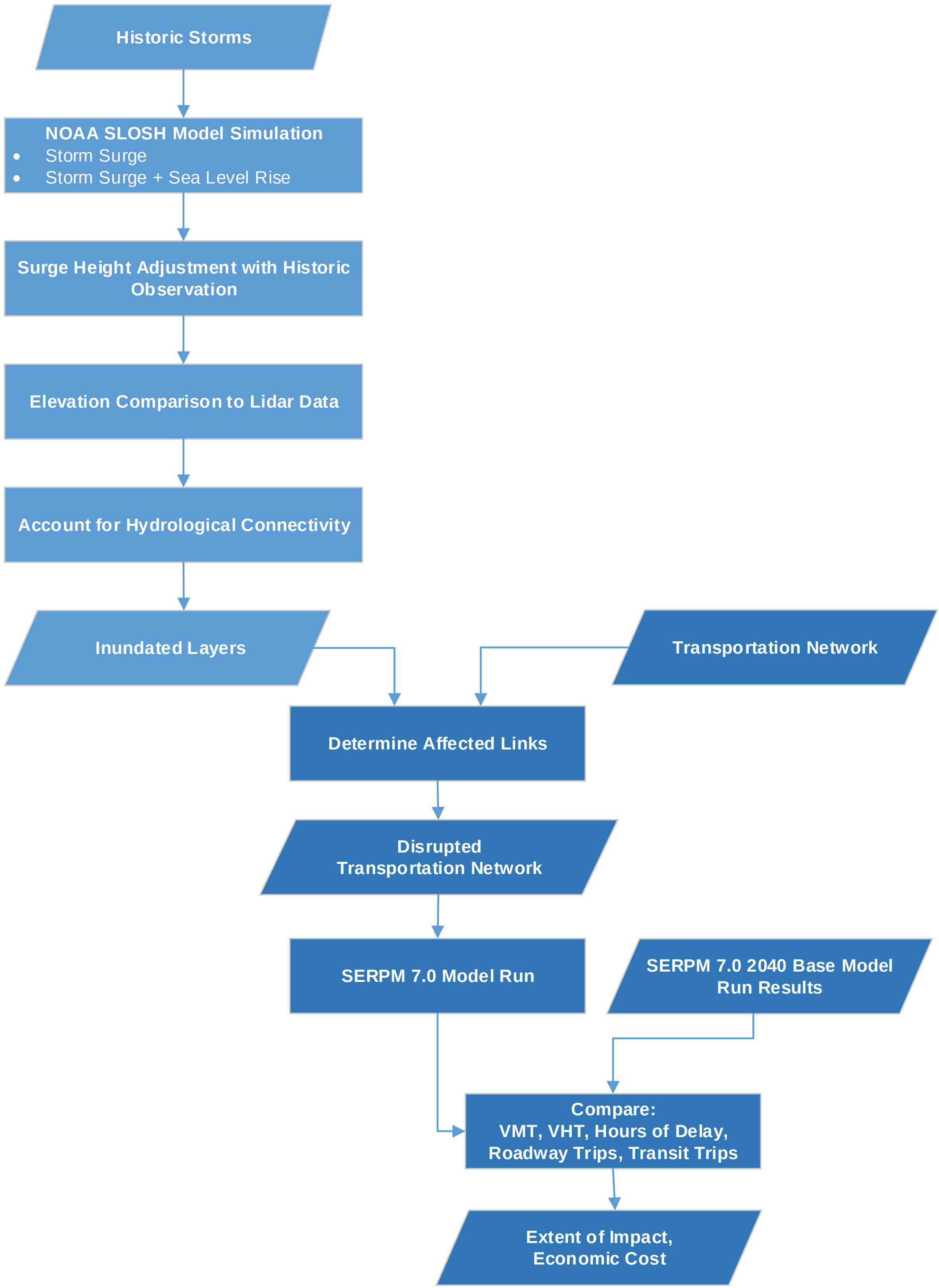
Three storms were simulated using NOAA's SLOSH model: Hurricane Andrew (1992), the Delray Beach Hurricane (1949), and the Fort Lauderdale Hurricane, also called Hurricane George (1947), each under current and 2040 sea level rise scenarios. A projection of 14.52 inches, equating to USACE high projections consistent with the Climate Compact 2015 Unified Sea Level Rise Projections, was used. The Southeast Florida Regional Model (SERPM) 7.0 was applied to estimate travel condition in each storm scenario. Model results are compared to those in the baseline condition (without any storm) to evaluate the extent of impacts in terms of Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), Vehicle Hours of Delay, Roadway Trips, Transit Trips, and to develop estimated economic impacts.

Figure 1.1 Historical Storm Tracks



2 The report is available at http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf

Figure 1.2 Methodology



2.0 Storm Surge and Sea Level Rise Simulation

In order to provide crucial information on changes in storm surge vulnerability resulting from projected sea-level rise (SLR) to three counties in Southeast Florida (Palm Beach, Broward, and Miami-Dade), a series of Sea, Lake, and Overland Surges from Hurricanes (SLOSH) models were enhanced with increments of SLR to compare storm surge baseline to SLR projections based on three historic hurricanes. Actual storms were used rather than SLOSH Maximum of Maximum (MoM) grids to allow for more realistic and reliable results. The three storms were Hurricane Andrew (1992), the Delray Beach Hurricane (1949), and the Fort Lauderdale Hurricane, also called Hurricane George (1947). Hurricane Andrew made landfall at high tide, bringing a pointed maximum surge of 16.9-feet in central Biscayne Bay. Areas to the north and south experienced surges between four and six feet. The most damage from the Delray Beach Hurricane resulted from both the wind and surge in the coastal communities of Palm Beach, Jupiter and Stuart. However, hurricane force winds were felt from Miami Beach to St. Augustine. Hillsboro Beach, Florida (Barnes, pp. 170-171). At the same location, the surge was measured to be 11 feet above mean low tide with extreme surges stretching from Fort Lauderdale to Palm Beach, Florida (Barnes, pp. 172).

To analyze these three storms accurately, SLOSH data was fused with historic measurements. The National Hurricane Center (NHC) has produced SLOSH grids which indicate surge heights across Biscayne Bay and spanning north to Broward and Palm Beach Counties. Local inundation levels can be measured on a more granular level by comparing the surge heights to higher resolution elevation data. The SLOSH grids were analyzed with respect to LiDAR elevation to allow for higher resolution in estimating baseline risk.

In addition to the confidence gained by using a single historic storm and by increasing granularity, real-time observations were integrated. Upon comparing the SLOSH results to historic observations, it was clear that the simulations were underestimating the surge height. Data fusion was used to improve the modeled results, as the observations were limited to credible sources, namely National Oceanic and Atmospheric Administration (NOAA) and U.S. Army Corps of Engineers (USACE). The results from the SLOSH grid were rectified at areas with true observations to allow for reduced error. The new SLOSH grid's surge heights were interpolated using the spline tool in GIS. Once the advanced surge height layer had been created, it was compared to the most recent LiDAR elevation. Areas of land in which the surge height surpassed the ground elevation were delineated into a layer which were identified as "wet". However, there were many areas that were not hydrologically connected to the coastline and therefore were likely to remain dry. Therefore, a shoreline buffer was created to only select areas that maintained a level of connectivity within 20 feet of the shoreline or another "wet" area that was within the buffer. These final connected polygons specified the spatial extent of the study area impacted by storm surge. Once the baseline layer had been created, the USACE 2040 sea-level rise projection was created using similar methods. An additive 1.21 feet (14.52 inches) was used to enhance the surge heights from the rectified SLOSH grid. (Section 3 provides figures showing results.)

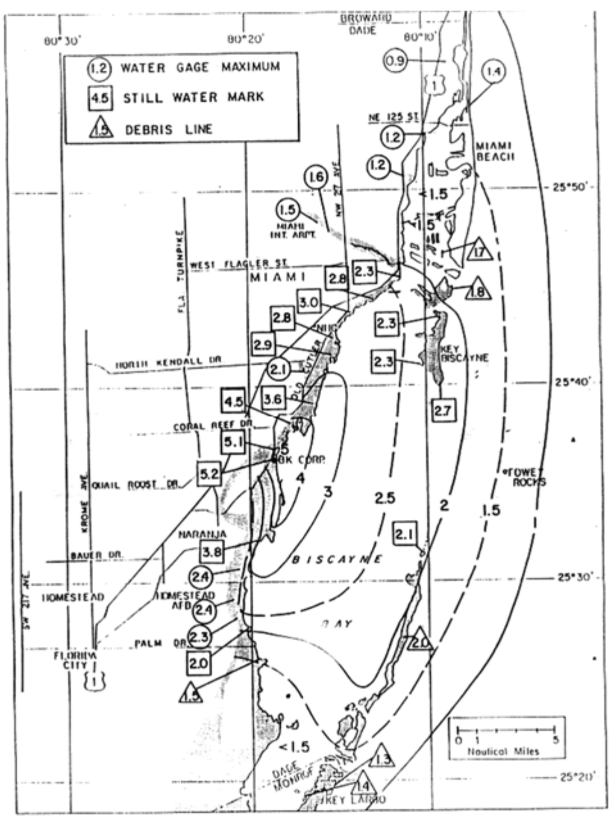
2.1 Data collection and Literature Review for Historic Storm Observations and Measurements

The storms chosen had recorded, real-time data available about the historic storm track and surge and tide impacts. They also are storms that resulted in higher surges than others. The amount of data points for each storm as well as the credibility of each data source were taken into consideration when selecting the recommended storms. Storm surge data are provided by SURGEDAT, a global storm surge database (Needham et al., 2015). SURGEDAT provides more than 8,000 high-water marks from 350 tropical cyclones that have struck the United States since 1880. SURGEDAT data are constructed from all available sources, including federal government documentation, numerous academic sources, and newspaper archives from daily periodicals (Needham and Keim, 2012). Appendix F shows illustrations of the tracks and categories for the three storms analyzed. As Hurricane Andrew was the most recent, there was much more data for surge heights.

2.1.1 Hurricane Andrew (1992)

The peak surge for Andrew was extremely localized and had a maximum value recorded via still water mark at 16.9 feet (5.2m) on the location of the Burger King International Headquarters (Rappaport, 1993). Occurring at high astronomic tide, the surge height decreased to 4 to 6 feet moving north along Biscayne Bay and to 4 to 5 feet towards the south of the maximum (Mayfield, Avila, & Rappaport, 1994; Schmidt, Taplin, & Clark, 1993; Rappaport, 1993). Figure 2.1 illustrates locations where various forms of surge heights were observed, mainly in the form of still water marks, but also with several water gage maximums as well as debris lines. These and other observations from NOAA and USACE are recorded with specific latitude and longitude coordinates in the metadata section for historic observations (Appendix B).

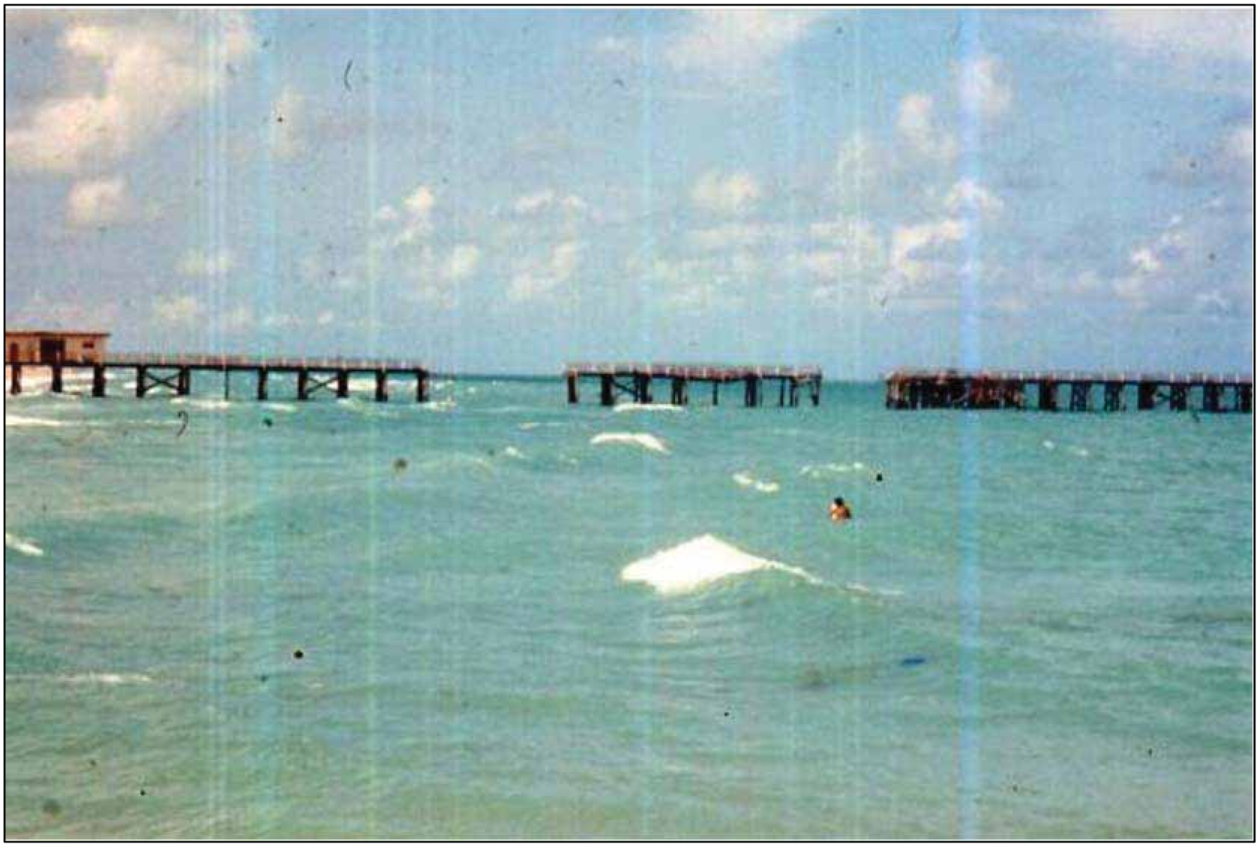
Figure 2.1 Maximum Storm Tide (NGVD) During Andrew's Landfall in Florida (Meters)



Source: Rappaport, 1993

In addition to historic measurements, there is imagery to reflect Andrew's surge damage. The Haulover Beach Pier in northern Dade County sustained major structural damage due to storm waves and a storm tide measured to be +6.1 feet NGVD at Bakers Haulover Inlet (Clark, 2010), Figure 2.2 illustrates how two sections of the pier were destroyed. The pier was removed rather than repaired.

Figure 2.2 Hurricane Andrew's Damage to Haulover Beach Pier in Northern Dade County

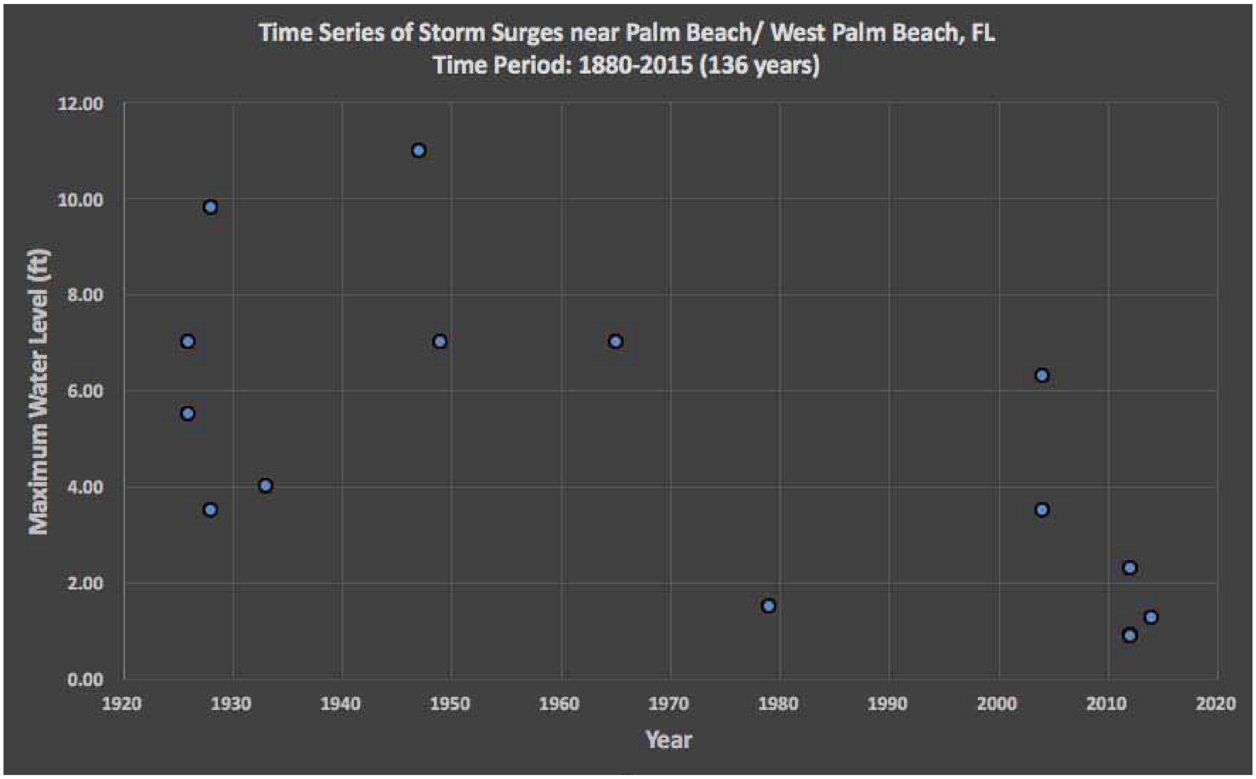


Source: Clark, 2010

2.1.2 Fort Lauderdale Hurricane of 1947 (Hurricane George)

The Fort Lauderdale Hurricane of 1947 was also named Hurricane George by the U.S. Weather Bureau but was not the formal name as naming hurricanes did not occur until the beginning of the 1950s (NOAA, 2015a). The storm went over the Bahamas and made landfall in Fort Lauderdale on September 17th, 1947. The highest wind speed that was recorded for the storm was 155 mph at Hillsboro Lighthouse in Hillsboro Beach, Florida (Barnes, pp. 170-171). At the same location, the tide was measured to be 11 feet above mean low tide, with extreme tides along Florida's Atlantic coastline. This storm brought the highest surge ever recorded in Palm Beach County, at 11 feet. Figure 2.3 illustrates the surge height of this storm as surpassing all subsequent storms by at least 4 feet.

Figure 2.3 Time Series of Storm Surges near Palm Beach/West Palm Beach 1880 to Present



Source: Hal Needham, 2016

The Fort Lauderdale Hurricane was incredibly large with hurricane force winds stretching from Key Largo to Cape Canaveral in North Central Florida. It not only produced high winds, but brought two feet of rainfall to the Fort. Lauderdale area (Sumner).

2.1.3 Delray Beach Hurricane (1949)

In August of 1949, the Delray Beach Hurricane became a hurricane while crossing the Bahamas and made landfall near Delray Beach. This storm produced extreme precipitation and therefore compound flooding as rainfall pooled upon high tide and surge. This hurricane had a very similar path to that of the Okeechobee Hurricane, but since the Herbert Hoover Dike had been built to prevent another disaster, the dike successfully prevented the catastrophic flooding that occurred during the 1928 storm. However, the lake did rise to 12 feet. In Palm Beach County, the surge moved piers off their pilings and threw them onshore. Coastal communities were covered in sand as the impact caused erosion and overtopping.

2.2 Data Fusion, SLOSH modeling and Sea-Level Rise Addition

While these methods are described as they were applied for Hurricane Andrew, the same methods were employed for the other two storms, unless noted otherwise. Figures showing the data for the other storms will also be referenced.

2.2.1 Data Fusion

Data fusion is a method of comparing historical observations with modeled results and adjusting to fill gaps and create the most realistic results. This form of data integration is useful because real-world observations increase accuracy of models (Emanuel, Ravela, Vivant, & Risi, 2006). The National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model is a dynamic model which estimates storm surge heights resulting from historical, hypothetical, or predicted hurricanes. It considers conditional variables including atmospheric pressure, size, forward speed, and track data. It also takes into account parameters specific to the location's shoreline, including bathymetry, water bodies, elevation, and certain infrastructure such as roads and levees.

2.2.2 SLOSH Model and Maximum Envelopes of Water (MEOWs)

The SLOSH model has been used for over 25 years, and it has developed immensely in line with major advancements in computer technology, particularly GIS and GPS. The SLOSH model's resulting grid carries uncertainty due to the relatively coarse resolution, but comparing it to LiDAR elevations can give a better understanding of depths of inundation.

In many cases, a composite approach is used, in which SLOSH simulates Maximum Envelopes of Water (MEOWs) and the Maximum of MEOWs (MOMs) by running several thousand times with hypothetical hurricanes under different storm conditions. The SLOSH grids generated from this approach are predicting worst-case scenario surge heights, and therefore might not be as realistic as actual storms which have occurred. These may be used as a reference to compare historic storm results against as well. Historical SLOSH runs are based on the best post-storm estimates of track, intensity, and size for the historical hurricane. [3]

2.2.3 Linear Addition of Sea-Level Rise to SLOSH

Many studies use SLOSH results to linearly add sea-level rise increments to the grid cell surge heights before interpolating the resulting grids (Frazier et al., 2010; Kleinosky et al., 2007; Shepard et al., 2012; Wu et al., 2002). The linear addition method of adding sea-level rise to surge height may not be applicable for Southeast Florida. Zhang et al. (2013) found that this method leads to large errors in terms of overestimating inundation for the mainland. With a case study for Hurricane Andrew, the magnitude of actual wave height was 22-24% higher and the extent of inundation was 16-30% more expansive, when compared to numerical simulations. Adjusting the modeled surge heights with observed values dramatically reduces this error, while maintaining the modeled slope of the surge height surface. The error was also reduced by adding a series of points inland that had a surge height of zero, explained in a later section.

2.3 GIS Modification of SLOSH Results with Historic Data Observation

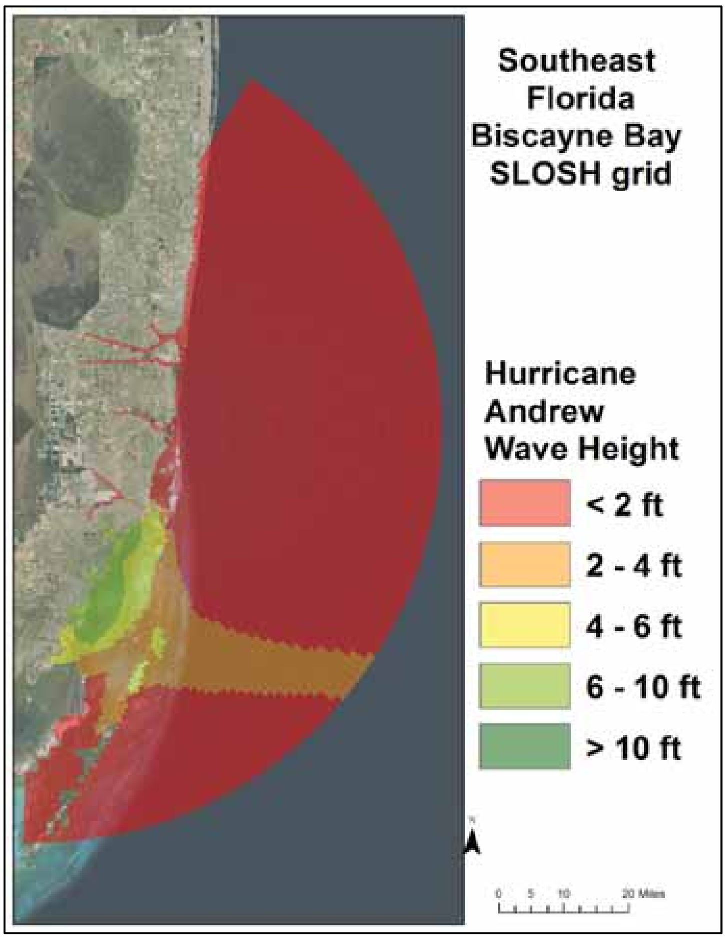
There is a phenomenon of surge in which it increases moving inland. In most cases, the land elevation increase moving from the coast surpasses the increasing surge height at a particular point and this is where the water can no longer move inland. The variations of surge heights modeled within SLOSH are not only attributed to characteristics that are specific to this particular storm (maximum sustained winds, storm size, forward speed),

[3] Available from https://slosh.nws.noaa.gov/sdp/ Both the MOMs and historic surge shapefiles for the hurricane were accessed at the SLOSH Display Web page at https://slosh.nws.noaa.gov/sdp using the user name of: Gustav2008 and a password of: Ike2008.

but there are also general coastal features that influence the height of storm surge that is generated. Coastal features include bathymetry, coastal shape (smooth versus protruding), and coastal aspect (the direction the storm is facing determines the angle of track in relation to coastline).

The SLOSH grid has cells that can be up to half a mile in length and width, with a single value for surge height is assigned to each cell. Figure 2.4 illustrates surge heights that were modelled by SLOSH for Hurricane Andrew. It is clear that the highest surge offshore follows the hurricane track offshore. There is a distance around 20 miles along the shore that has surge heights which exceed 2 feet (NAVD88). There are increases that exceed 13 feet (NAVD88) concentrated around the Deering Estate in Cutler Bay. The surge heights decreased dramatically within a few miles from this peak surge.

Figure 2.4 Hurricane Andrew Surge Heights Modelled Using SLOSH



2.3.1 Mapping Historic Observations to Compare with SLOSH

Figure 2.5 shows the spatial variation of actual Hurricane Andrew surge heights which were recorded in Miami, at coordinates within corresponding cells of the SLOSH grid.

With the objective of using data fusion to compare observed storm contours to grid results, this task required creating new SLOSH grid cells using the historic measurements. The metadata for Hurricane Andrew's surge heights shows 32 observation points with coordinates, all in the datum of NGVD (Some of these are illustrated in

Figure 2.5). These coordinates were geocoded in GIS to allow for the corresponding grid cells to be adjusted with the observed values. For example, the maximum surge height recorded for Hurricane Andrew is 16.9 feet NGVD. However, the value in the modeled SLOSH grid was 13.1 feet NGVD. There were other discrepancies between modeled and observed results along Biscayne Bay in which the modeled results were underestimating the actual measurements by 1 to 3 feet.

Figure 2.5 Historic Points from Hurricane Andrew

2.3.2 Fusing Historic Observations with SLOSH Grid and Interpolation

Various adjustment options were explored to determine the most realistic and consistent way for maintaining the most constant slope in adjusting the grid cell heights to fit the observed values. Testing and researching methods for data fusion of observed and modeled results allowed for a Spline interpolation with variables and settings that smoothed out the new storm surge surface. The Spline tool in ArcGIS interpolates points using a two-dimensional minimum curvature spline technique to produce a raster surface. The resulting smooth surface passes exactly through the input points. The tension function was used to tune the stiffness of the interpolant according to the character of the modeled phenomenon. This technique is popular when interpolating SLOSH grids and the NOAA Primer on Mapping Coastal Inundation[4] outlines methods for interpolating SLOSH grid cells as well as for interpolating observed high water marks. It also lays out the steps to compare surge heights to LiDAR elevation in order to obtain depth of inundation. These steps include transforming the grid cells to points, interpolating the points using the spline method and comparing surge heights to LiDAR elevations to determine inundated areas. The procedure used here relies on this guidance, which is summarized below:

According to the *Mapping Coastal Inundation Primer* (p.20), to adjust the values for Hurricane Andrew's 32 observed points, the values of the cell which contained the new surge height was increased to the recorded value, and the surrounding 24 cells had their values removed so that there would be a continuous slope based on cells that were about a mile away. Figures 2.6 and 2.7 illustrate the location and spacing of the grid cells, which led to this optimal distance of approximately 2 miles (red bar) within which the slope of increase or decrease would be continued from the modeled results (grid cells outside of the 24 highlighted cells) until the measured value (the solid purple/pink cells).

As shown in Figure 2.6, the SLOSH grid cell near Biscayne Park had a value which was about 1 foot lower than the observed height. The adjustment was made to the purple cell and the cells highlighted in cyan had their values removed so that the interpolation would smooth this adjustment.

While the SLOSH grid values and the LiDAR Digital Elevation Model (DEM) were in NAVD88, the observational points were in NGVD. Therefore, a conversion tool[5] was used to translate the historic surge heights to NAVD88 before they were used to adjust the SLOSH grid.

Figure 2.8 shows areas with denser clustered observation points had 8 cells adjusted rather than 24.

[4] Available at https://coast.noaa.gov/digitalcoast/_/pdf/guidebook.pdf
[5] This tool can be found at http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl.

Figure 2.6 SLOSH Grid Cell 1

Figure 2.7 SLOSH Grid Cell 2

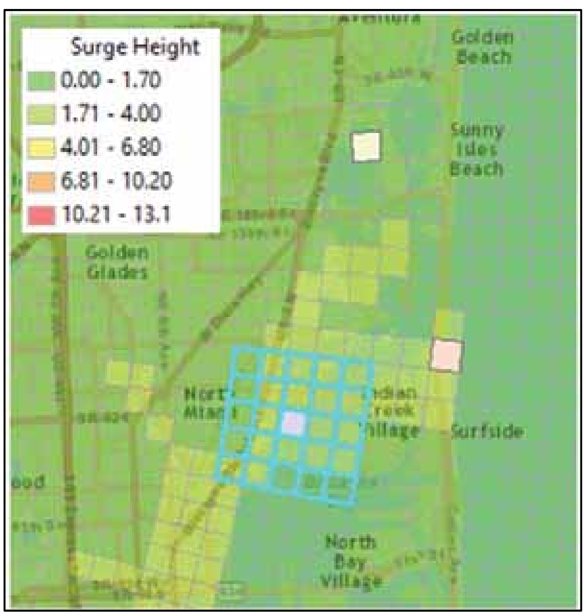
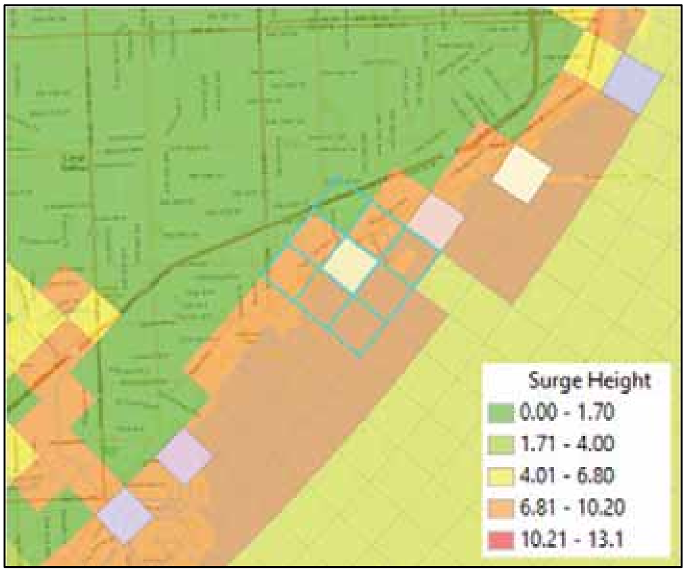


Figure 2.8 SLOSH Grid Cell 3



2.4 GIS Surge Inundation Mapping

2.4.1 Interpolation of SLOSH grid with Inland Adjustments

Before the newly revised SLOSH grid could be interpolated (via spline method), the grid cells must be converted to points using the feature to point tool. In addition, certain grid cells needed to be removed and adjusted. Cells that are “dry” are assigned a value of 99.9. This signifies that the surge height in this area is zero. These cells were removed. In the SLOSH grid, there can be a “wet” cell with a value of zero feet next to a value of 7.5 feet. Figure 2.9 shows the dramatic and harsh magenta line which separates wet cells (east of the line) from dry ones (west of the line) As explained in p.19 of NOAA’s primer, it is appropriate to remove the dry cells. However, with the unique topography in Southeast Florida, it causes dramatic errors to simply remove dry cells. One reason for the errors is that these methods work under the assumption that the storm water piles up as it pushes against the increasing elevation of the topography moving inland. In most areas, this is the case; however, in Southeast Florida, the highest elevations are along the Atlantic Coastal Ridge, with land dipping down as it goes west towards the Everglades. The ridge is cut through by low-lying transverse glades, cut by the historic flow of the Everglades, through which many canals and rivers still run. A moderate storm surge can easily travel west of the Ridge via these transverse glades. Once the storm surge has moved inland of the narrow transverse glades, there is land dissipation effect in which the storm surge spreads out and thus the water height is dramatically lowered (Condon & Sheng, 2012). Therefore, it was essential to create inland points with a value of zero in a way which allows the surge heights to naturally taper off.

As shown in Figure 2.9, the magenta line indicates the interface between inundated and dry cells in the Hurricane Andrew SLOSH grid. Figure 2.10 shows the blue highlighted grid cells which were assigned values of zero. Inland cells which were modelled as dry were removed, but the cells highlighted in cyan were assigned values of zero. Figure 2.11 shows the surge heights that resulted from the data fusion and SLOSH interpolation.

Figure 2.9 Interface between Inundated and Dry Cells - Hurricane Andrew

Figure 2.10 Processing Grids

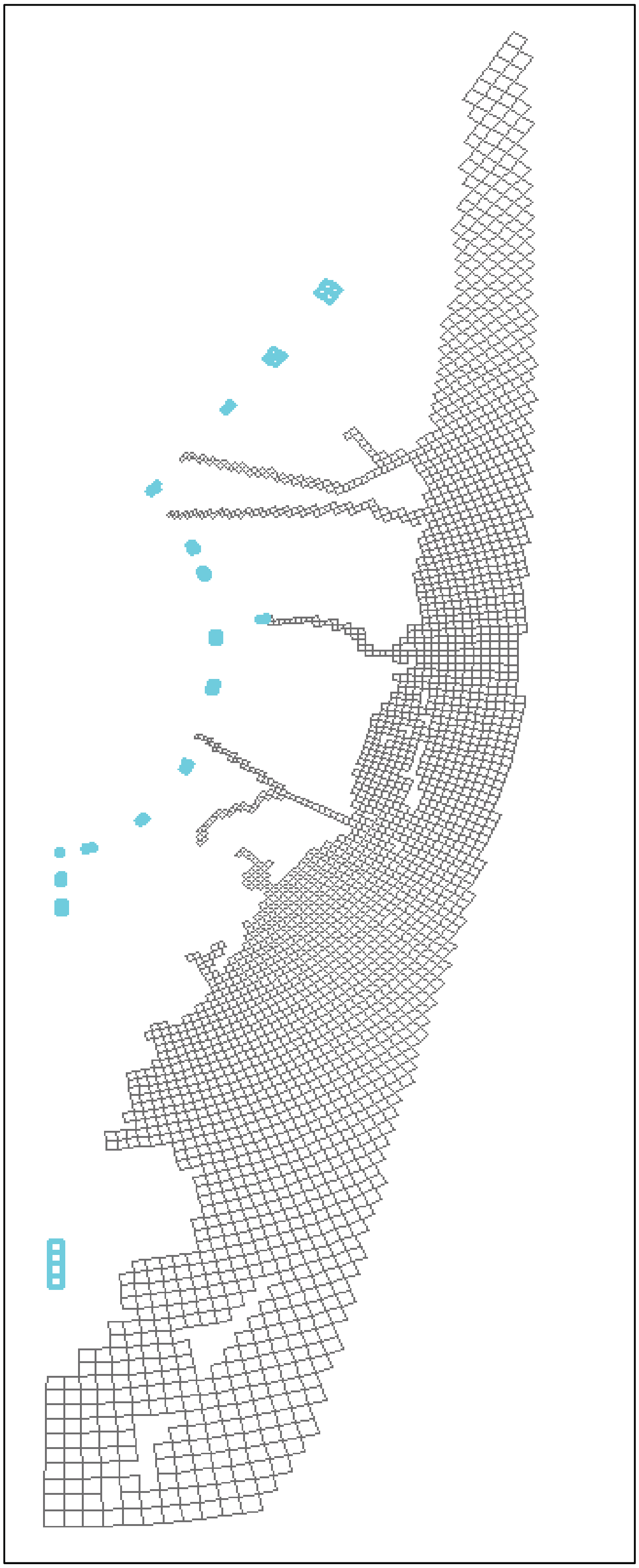
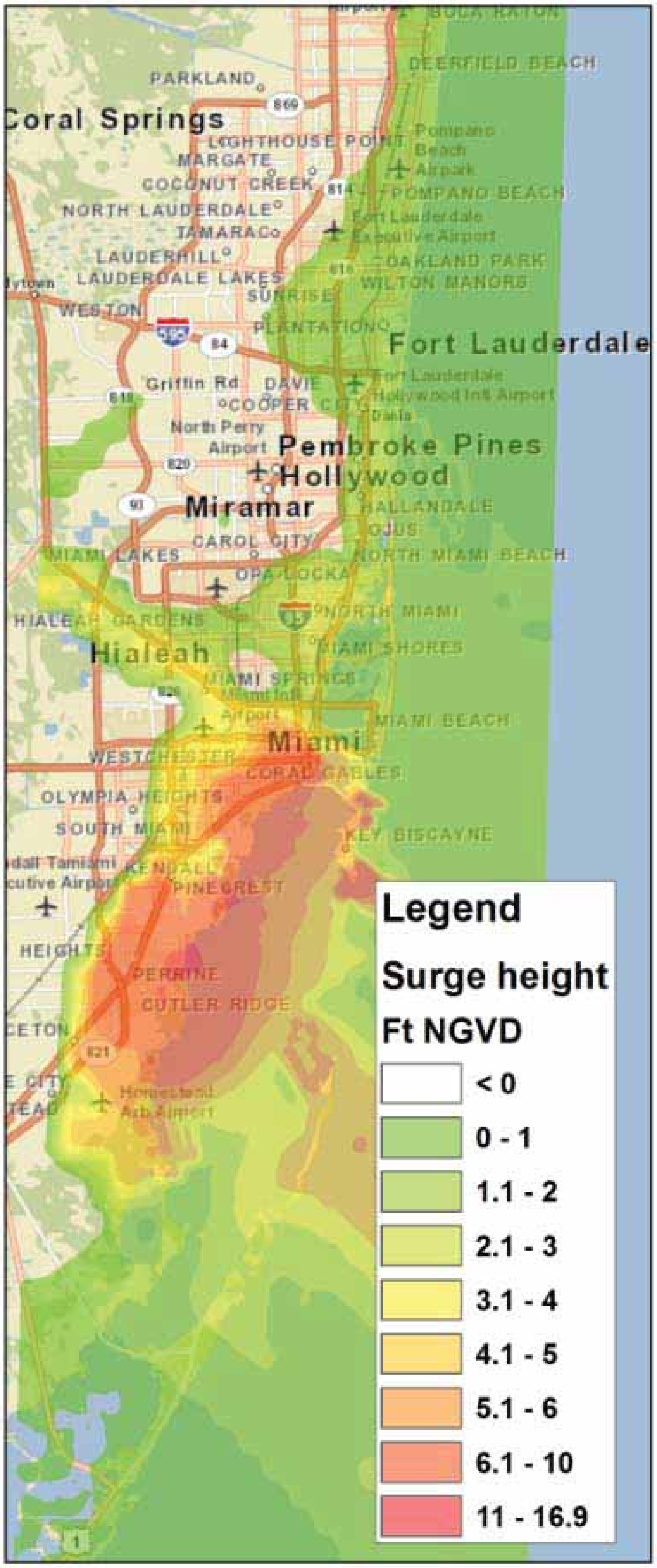


Figure 2.11 Surge Heights after Data Fusion and SLOSH Interpolation



2.4.2 Integration of LiDAR Elevation to Estimate Depth of Water Based on Surge Height Compared to Land Elevation

It was important to project the SLOSH layer to match the projection of the LiDAR elevation layer. The SLOSH points were also interpolated at a resolution that matched the LiDAR elevation layer. Another step to adjust the LiDAR DEM required removing areas which did not represent land. The most up-to-date water layer was downloaded from each of the counties' GIS websites in order to mask out small lakes and canals.

Finally, the raster calculator was used to subtract the LiDAR DEM from the interpolated water surface. In the resulting layer, the aggregated values representing inundation were positive values (including zero). Any negative values indicate that the land elevation is higher than the surge height, and therefore the land is dry. The reclassify tool was used to assign “no data” to the raster pixels which were negative. The resulting “wet” raster layer was converted to polygons. However, many of these seemingly wet polygons were not hydrologically connected to the coastline, and therefore would not necessarily be inundated (unless there was a groundwater component). To account for this, a coastline vector layer was added to the interface (Figure 2.12).

Multiple iterations took place in which “wet” polygons we selected if they were within 10 feet of the shoreline. For example, a chain of polygons could occur in which one “wet” polygon was touching another “wet” polygon which was touching the coastline. As shown in Figure 2.14, inland cells which were modelled as dry were removed, and the new red layer indicates hydrologically connected areas which were more likely inundated by Hurricane Andrew. The resulting layer illustrated in Figure 2.13 compares to that in Figure 2.14 showing that the wet areas were significantly reduced to coastal areas. The base map was useful here because in many areas the “land” was a wetland and therefore hydrological connectivity can be assumed. Figure 2.15 illustrates the LiDAR Elevations that were used for the analysis for all 3 storms.

Figure 2.12 Hydrologically Connected Shorelines for Southeast Florida

Figure 2.13 Inundated Areas by the Hurricane Andrew (1992)

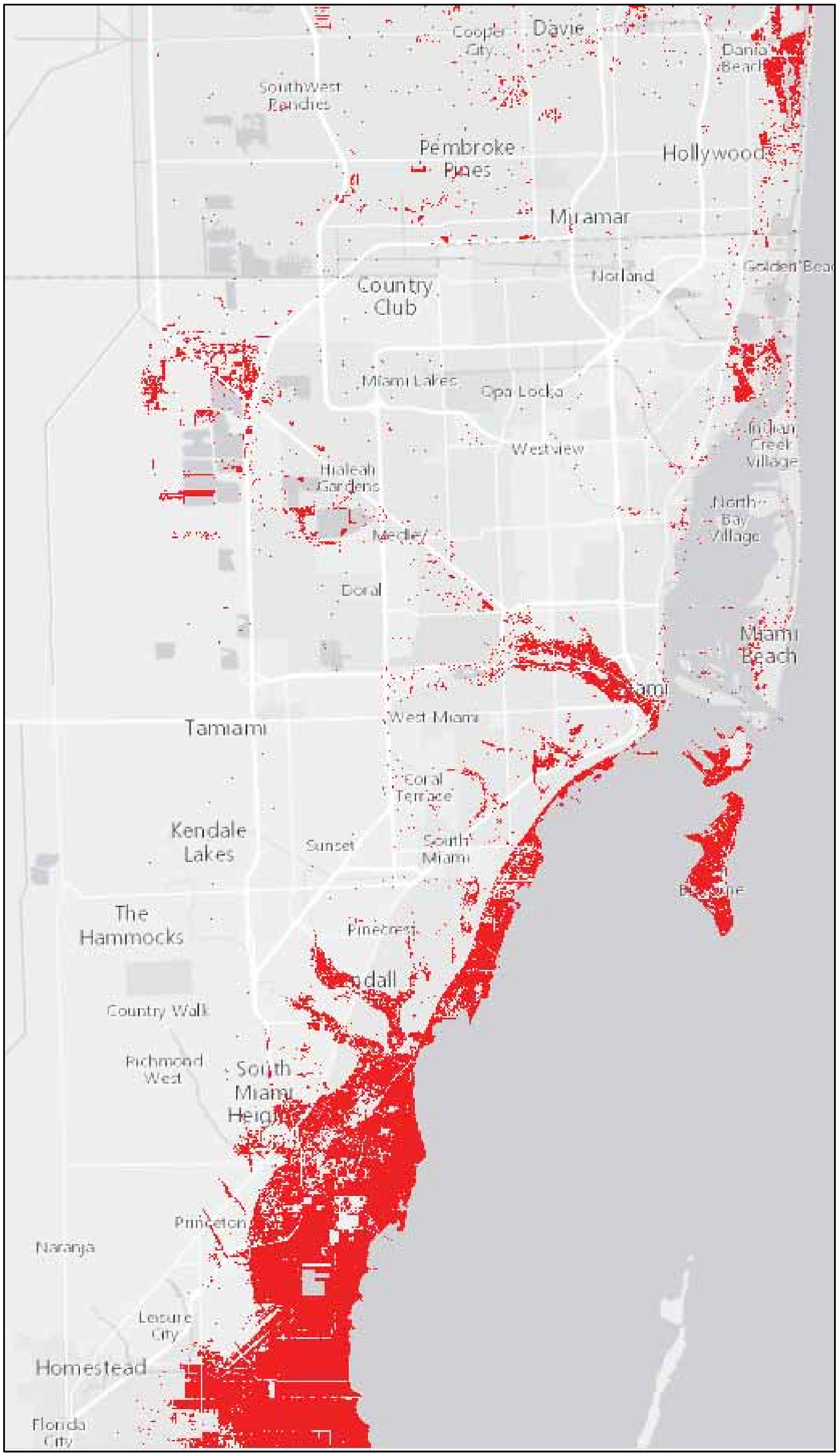


Figure 2.14 Inundated Areas by the Hurricane Andrew – Hydrologically Adjusted

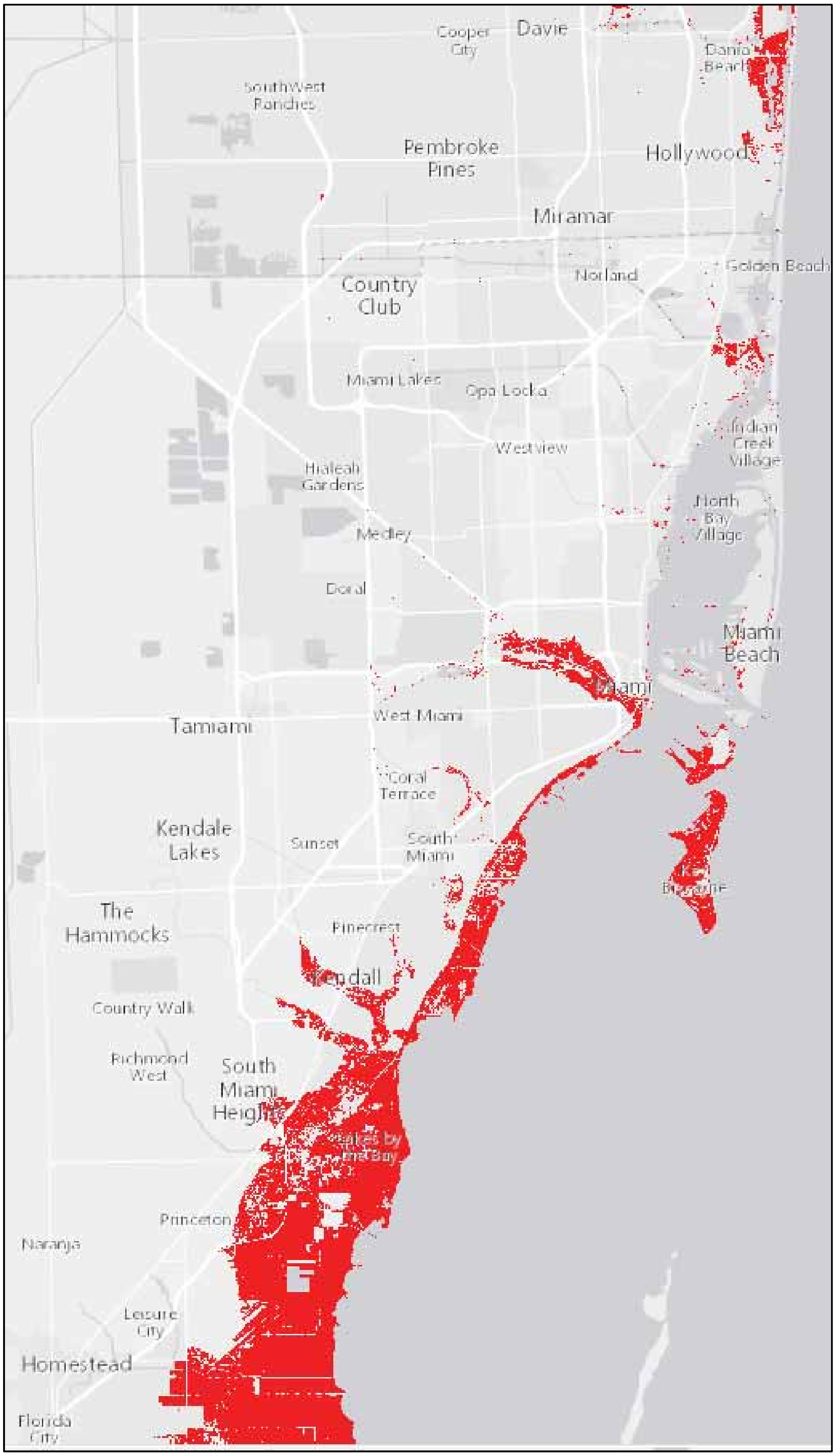
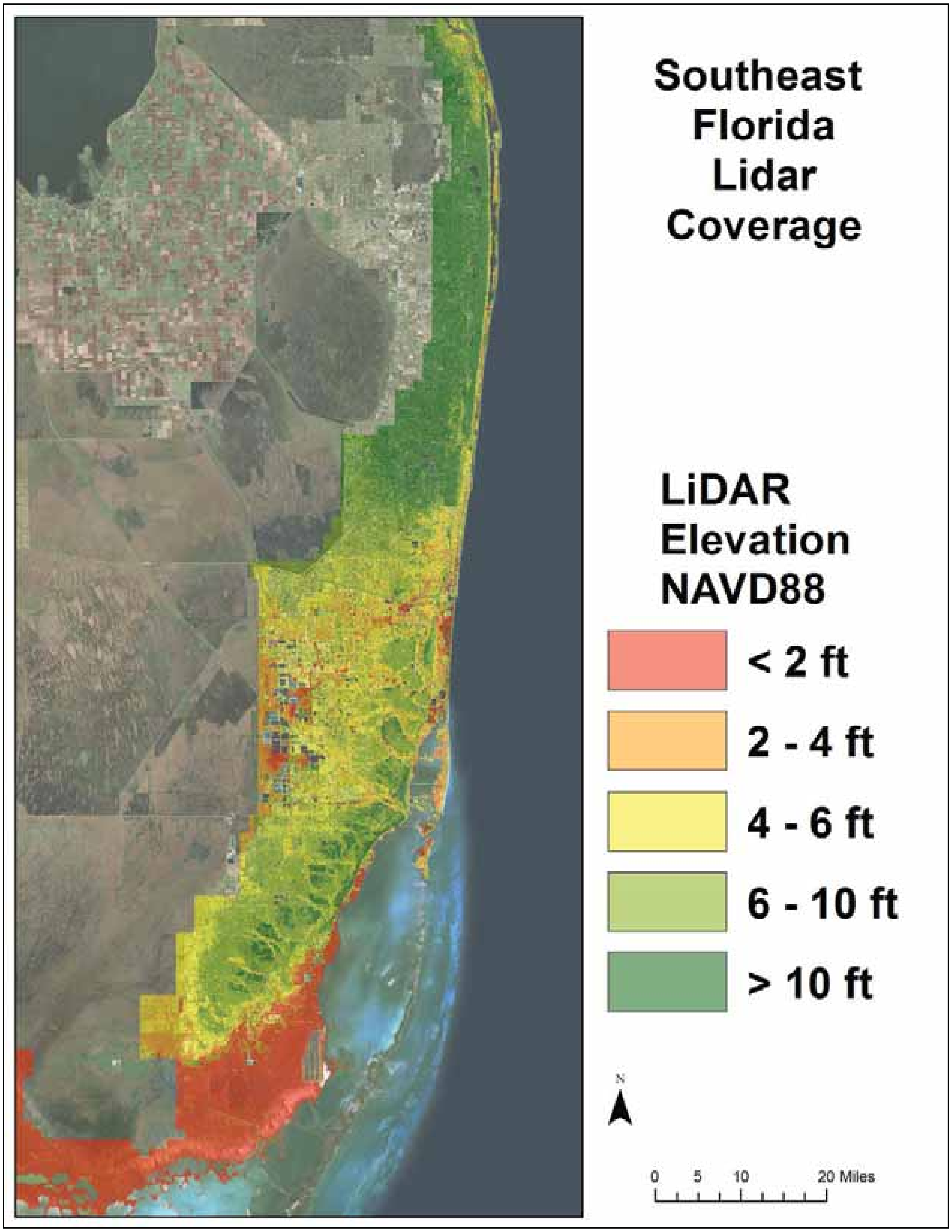


Figure 2.15 LiDAR Elevations for Southeast Florida



Source: South Florida Water Management District (SFWMD)

2.5 Analysis Steps for Delray Beach Hurricane (1949) and the Fort Lauderdale Hurricane, or Hurricane George (1947)

The Delray Beach Hurricane (1949) and the Fort Lauderdale Hurricane, or Hurricane George (1947), hereafter referred to as the 1947 and 1949 storms, respectively, were more complex to model. They both had significantly less data points, and hit in areas that have an overlap between two slosh grids. Therefore, a new grid was created which stemmed from a larger SLOSH grid within the SLOSH program. Figure 2.16 illustrates the 1949 hurricane surge values that were modelled using SLOSH. As the peak surge was recorded to be 7 feet (5.5 feet NAVD88) in West Palm Beach, there is a significant increase in the observed values. Figure 2.17 shows how the new data-fused, interpolated surface maintains the trends in, with the heights decreasing moving south, but the values have been adjusted to reflect historic observations.

Figure 2.18 illustrates the 1947 hurricane SLOSH surge values as the original grid cell output. Again, the values are much lower than observed values. Values increased significantly, particularly where 11 feet surges (adjusted to 9.45 feet NAVD88) were recorded at Hillsboro Lighthouse, Boynton Beach, and Palm Beach. Figure 2.19 and Figure 2.20 show the surge height surface that resulted from interpolating the data fused grid from the 1949 storm for Palm Beach County and Broward, respectively.

After the Hurricane Andrew storm surge scenarios were completed, results were shared with partner agencies in the region. Miami-Dade County noted they prepared more refined LiDAR Data, which was subsequently used for the remaining four scenarios. A comparison of the two LiDAR coverages showed minor differences in the areas affected. These areas were smaller and were predominately associated with wetlands. For a regional level planning analysis, using different elevation data will have minimal, if any, affect on results.

Figure 2.16 Current SLOSH Grid Surge Heights for Delray Hurricane (1949)

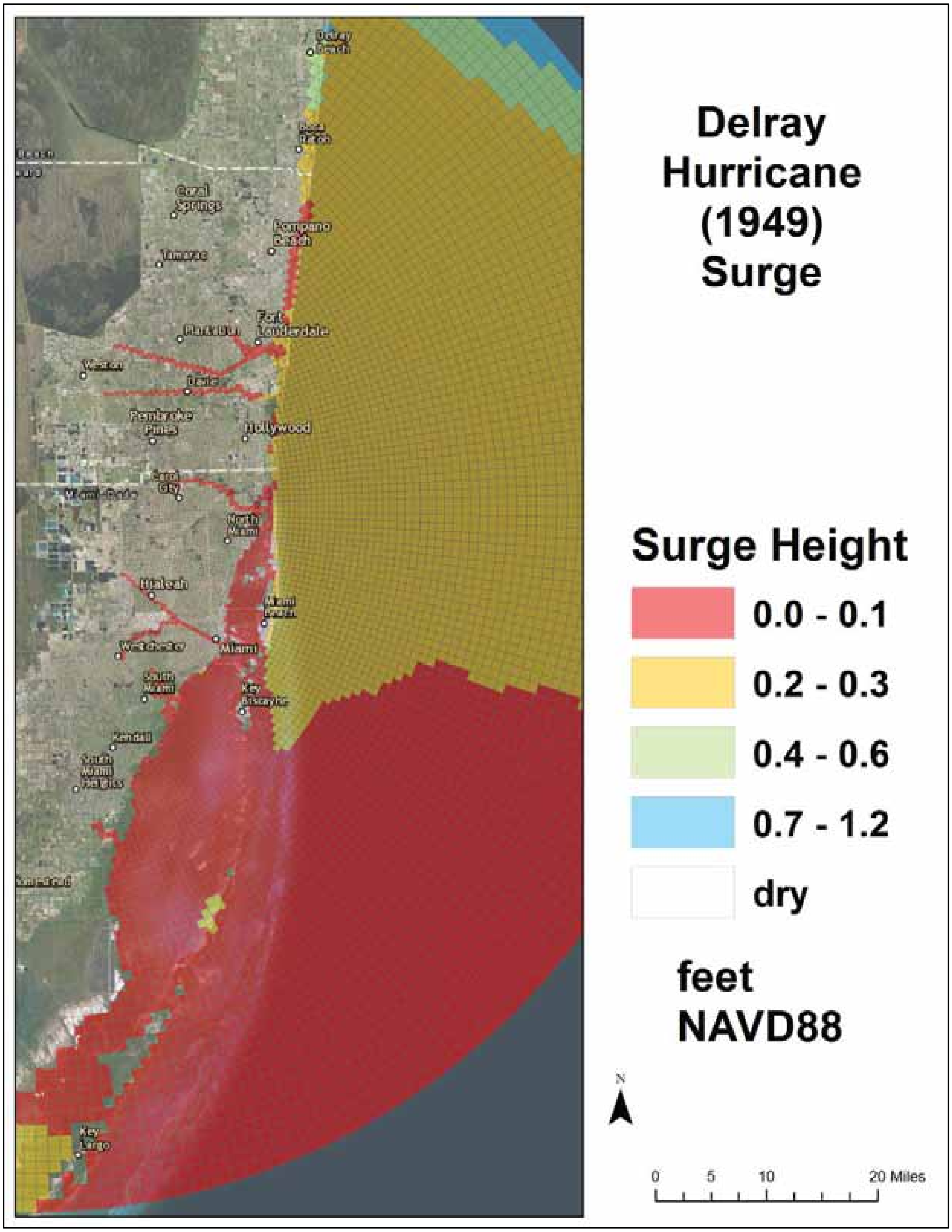


Figure 2.17 Current Surge Heights for Delray Beach Hurricane (1949)

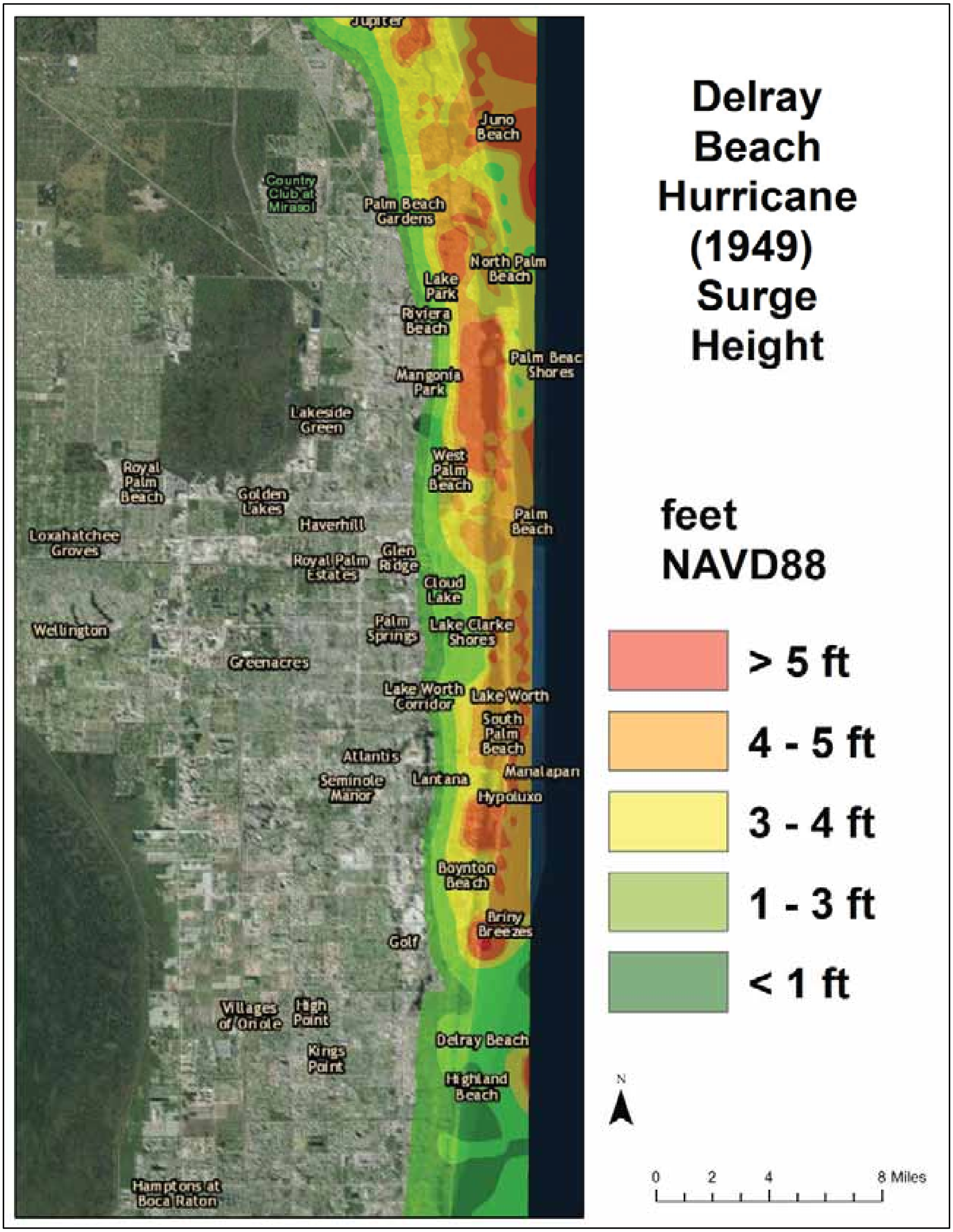


Figure 2.18 Current SLOSH Grid Surge Heights for Hurricane George (1947)

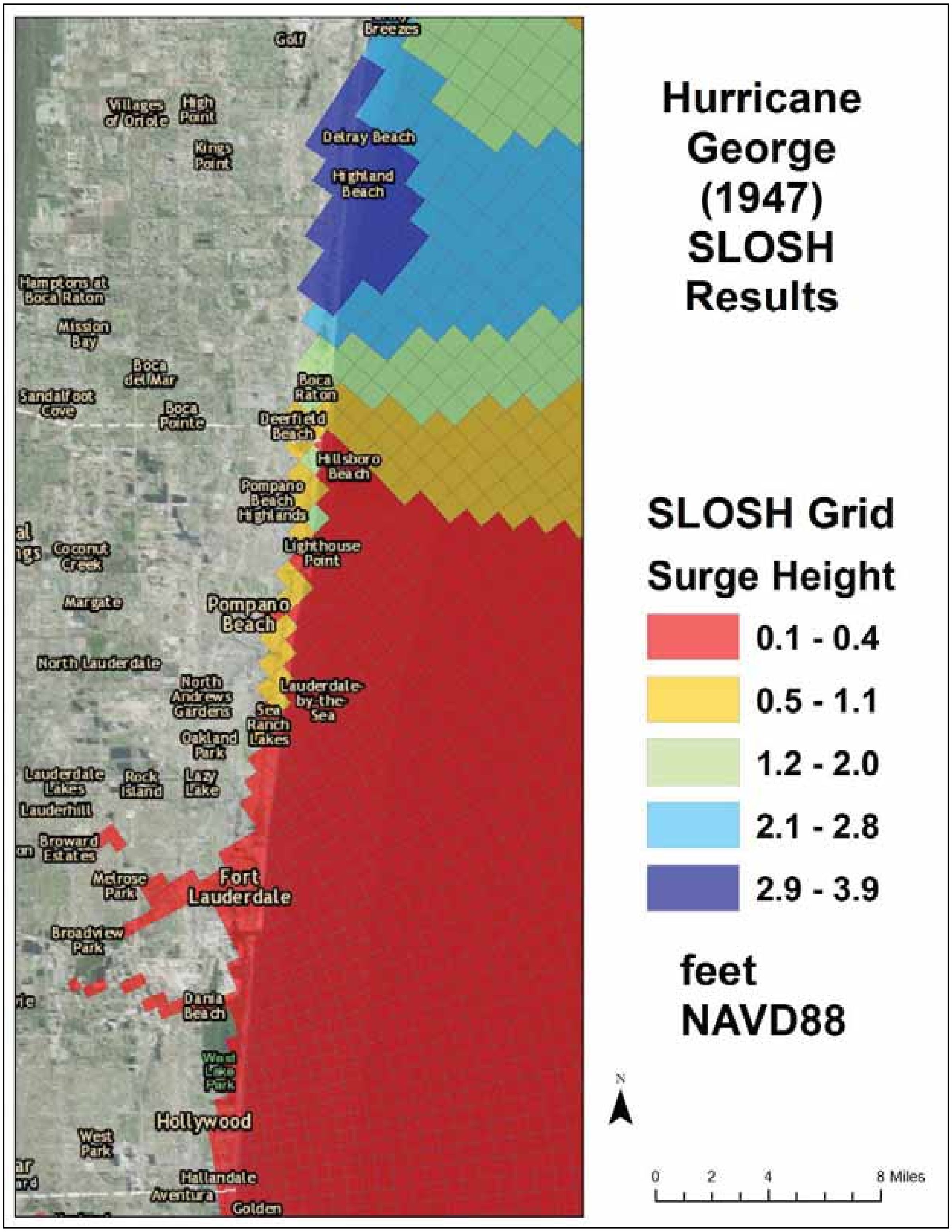


Figure 2.19 Current Surge Heights for Hurricane George (1947) in Palm Beach County

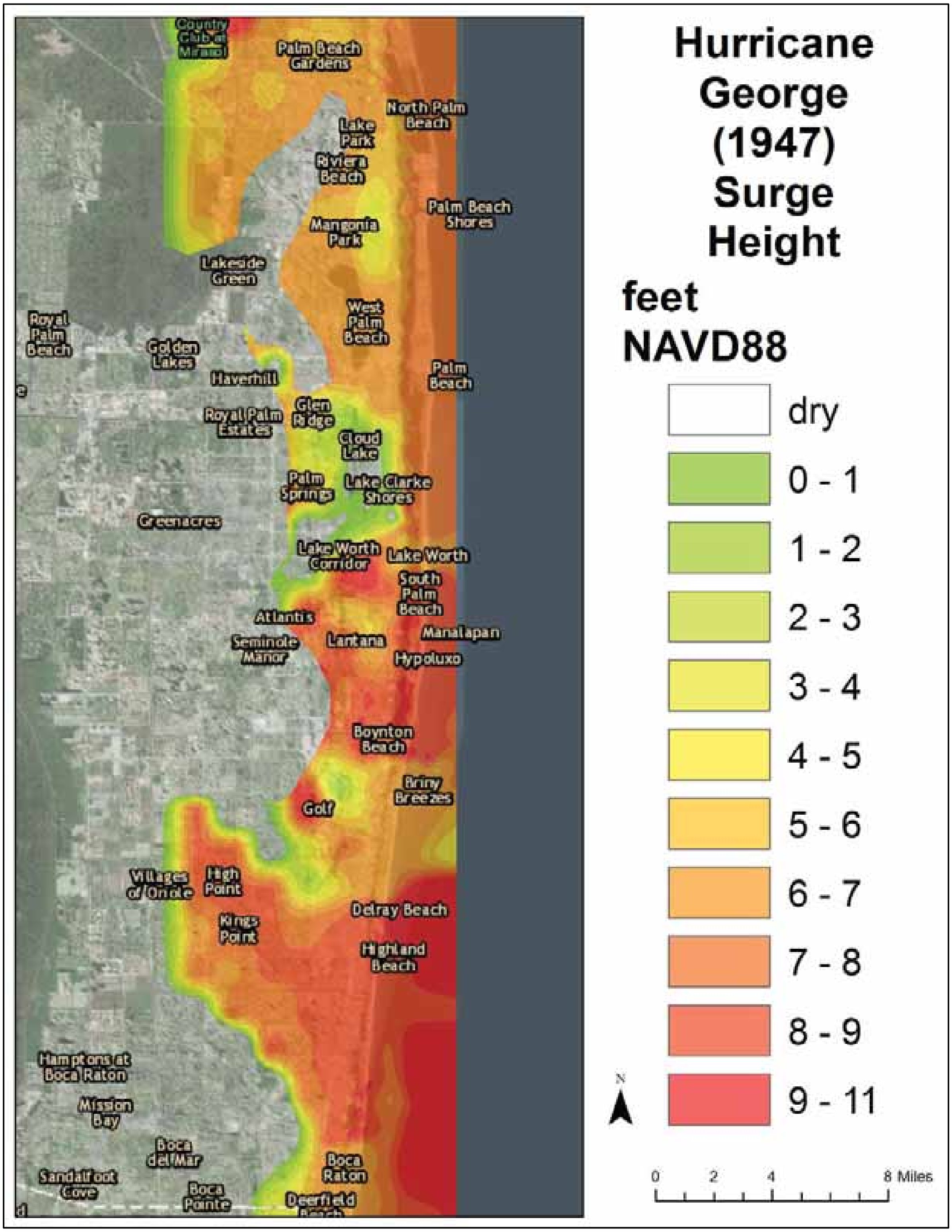
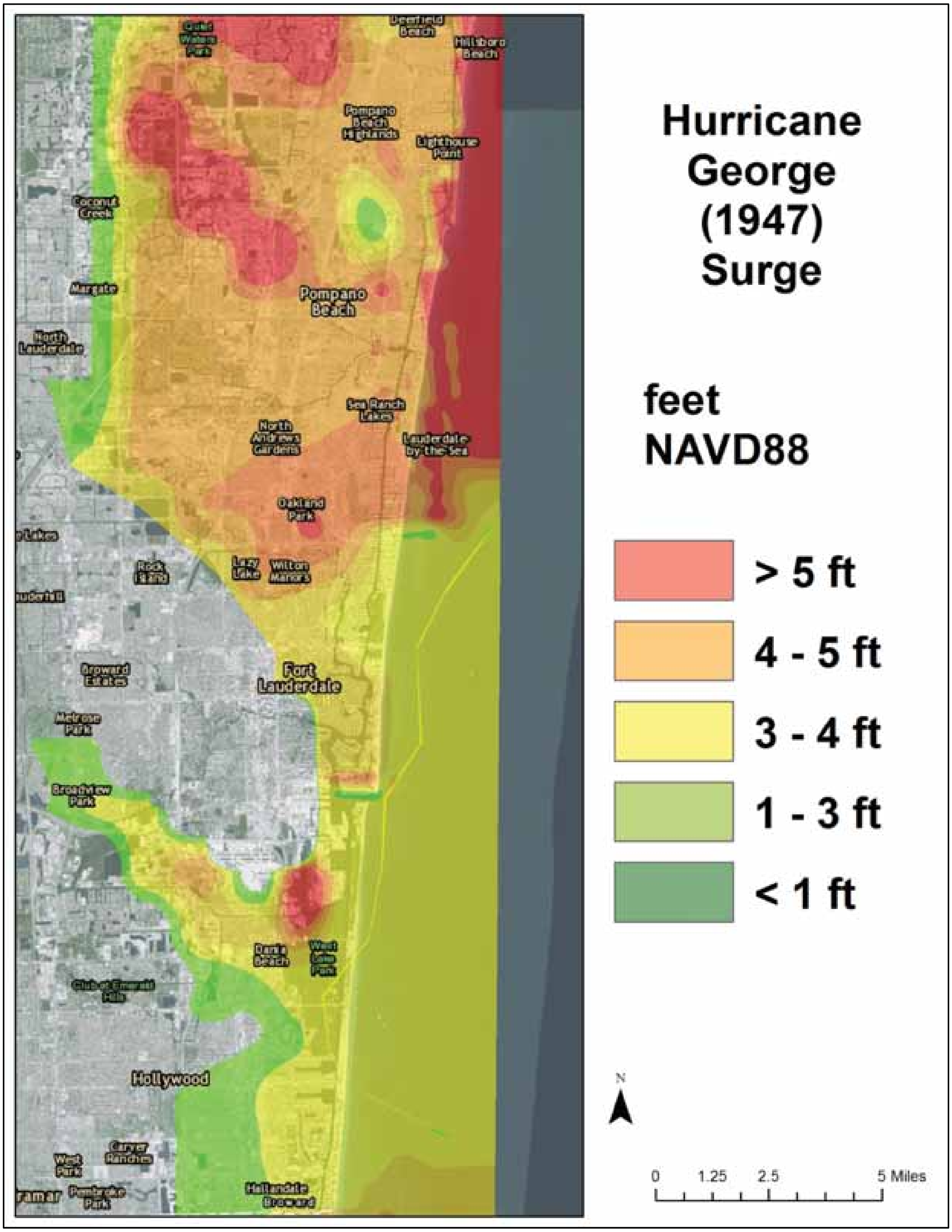


Figure 2.20 Current Surge Heights for Hurricane George (1947) in Broward County



3.0 Transportation Modeling

The transportation modeling analysis was conducted to evaluate the performance of the transportation network in the region of six storm surge scenarios. Two precursor investigations were conducted to inform the transportation modeling analysis, including the “Inventory” task which researched storm surge modeling information and tools in the Southeast Florida region, and the “Network Preparation” task which investigated and reconciled the spatial misalignments issues of SERPM model network. Details of the precursor investigations are include in the Appendix G.

As describe in Section 2, three storms were used in the analysis: Hurricane Andrew in August 1992, Fort Lauderdale Hurricane in September 1947, and Delray Beach Hurricane in August 1949. Each storm has two associated scenarios: storm surge and storm surge plus sea level rise. The inundated areas of these scenarios from SLOSH analyses are shown in Figure 3.1, Figure 3.2, and Figure 3.3. For each storm surge scenario, there are two main steps in the transportation modeling analysis: network disruption and modeling.

3.1 Network disruption

Network disruption identified and removed facilities in the 2040 transportation network that are disrupted by the storm. In the SERPM model transportation network, transportation facilities are divided by traffic breakpoints into smaller segments (links), and are represented by polylines in the transportation network shapefiles. The project team used ArcGIS to overlay the shapefile of transportation network with the shapefile of inundated areas by each storm. Segments of facilities that were intersected with the inundated areas by a storm were considered not able to carry traffic and were removed from the transportation network shapefiles.

There is an exception in the network disruption process for bridges. Bridges are considered inundated when a footer is intersected by the inundated areas. A manual examination was conducted to determine if a bridge should be removed or kept in the transportation network, using a polygon of bridges’ true shape from the FDOT’s Transportation Statistics Office.

3.2 Transportation Modeling

In the modeling process, the Southeast Florida Regional (SERPM) 7.0 Model was utilized and only those projects listed under the cost feasible plan of the 2040 Long Range Transportation Plan (LRTP) were loaded into the model. The disrupted transportation network was used to obtain transportation information, including Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), Vehicle Hours of Delay, and number of trips. The SERPM Model is an expanded application of the regional travel demand model. The transportation network in the SERPM Model contains interstate highways, state roads, county roads, and local facilities. Using the SERPM Model help foster greater understanding of the role of critical evacuation routes in the broader network as an aid to emergency management and other planners in Southeast Florida.

Three storm scenarios were considered during this analysis. These are Hurricane Andrew in August 1992, Ft. Lauderdale Hurricane in September 1947, and Delray Beach Hurricane in August 1949. Each scenario was considered to have two impacts, storm surge and storm surge plus sea level rise. Model results without any storms were used as a baseline for comparison.

After inundated links were removed from the transportation network in the network disruption process, a skimming process was run to identify which origin-destination Traffic Analysis Zones (TAZs) will lose trips. Trips originating or terminating in in TAZs for which no entrance/exit route is available is considered “lost,” and quantified by trip types using the trip table created after mode choice. These trips are subtracted from the original trips to create another set of trip tables which are then used during the assignment procedure. The trip generation, distribution and mode choice processes were run without disabling those zones as baseline. This created an original trip table without any lost trips. The project team then subtracted trips from those zones that are under water identified during the skimming process to create a final trip table that had fewer trips compared to original trip table. Since the model has five time period trip tables, all trip tables were modified to account for the daily effect of each scenario. The trip assignment process was then performed using the modified trip tables for all five time periods by disabling all links inundated by storm surge. After each scenario was run, the output data was summarized to extract transportation information, including Vehicle Miles Traveled (VMT), Vehicle Hours Traveled (VHT), Vehicle Hours of Delay, and number of trips.

3.3 Limitations

Several limitations of this analysis should be noted. The SERPM model transportation network was originally developed to represent transportation facilities in a roughly accurate geographic scale that can serve modeling purposes. However, it is not precisely consistent with the true shape of the transportation facilities in the real world. Due to the geospatial imprecision, it is possible that some transportation facilities are considered inundated in the analysis when they are not impacted by storms, and some transportation facilities are not considered inundated in the analysis when they are impacted by storms.

Using the same method of network inundation, transit links that are intersect by the inundated areas of storms are removed from the SERPM transportation network. Transit rerouting was not conducted in the modeling step as it would require coding a rerouted transit network into the model. The impact of storms to transit travel could be overestimated, because in practice transit rerouting would occur where feasible.

The SERPM model only estimates transportation conditions in the three-county region of Miami-Dade, Broward, and Palm Beach. It is possible that the storm scenarios impact other counties, e.g. Martin County and Monroe County. Future study should be conducted to have a comprehensive estimation of storm scenarios’ impact.

Figure 3.1 Inundated Area – Hurricane Andrew Scenarios

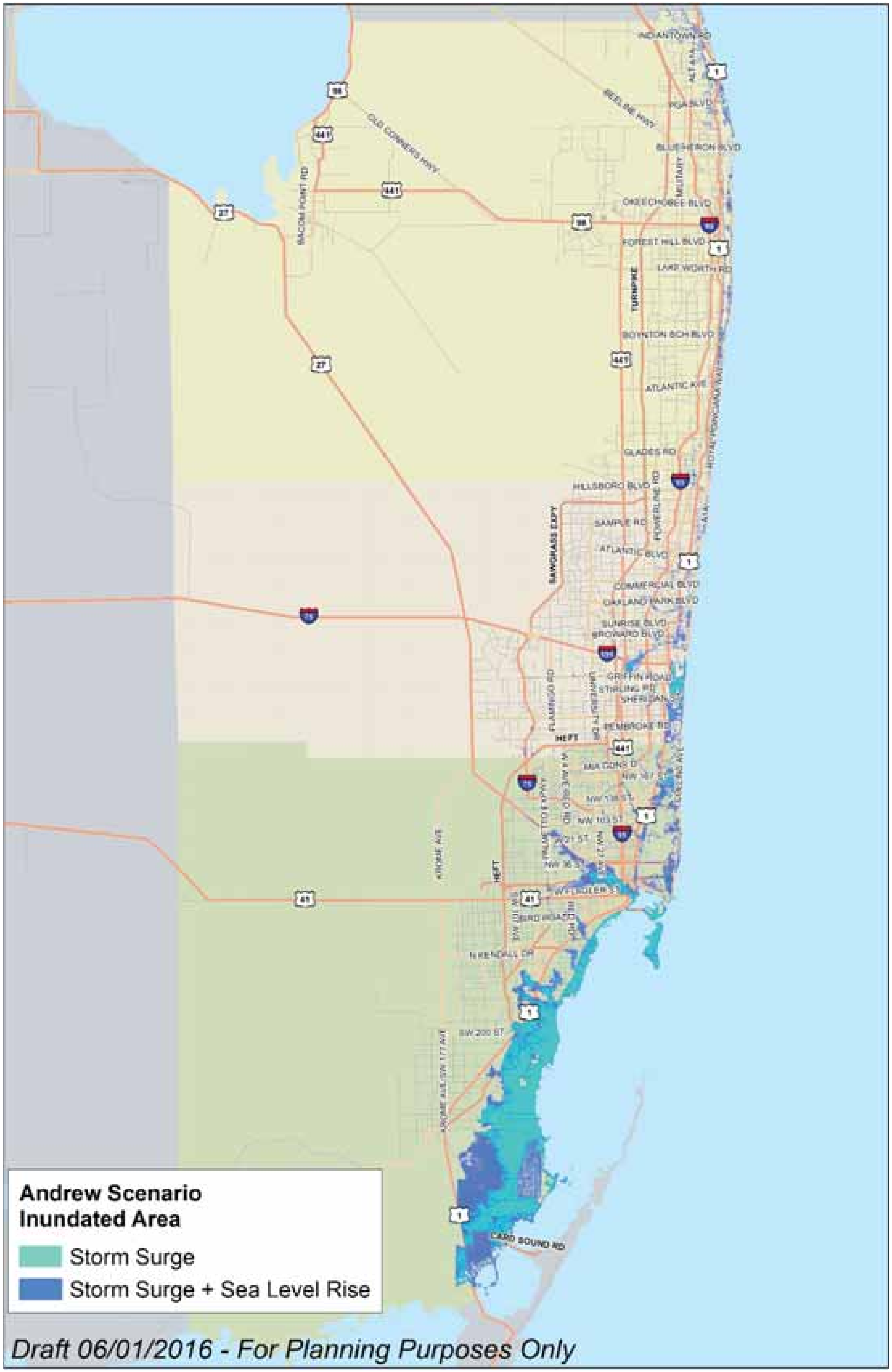


Figure 3.2 Inundated Area – Fort Lauderdale Hurricane Scenarios

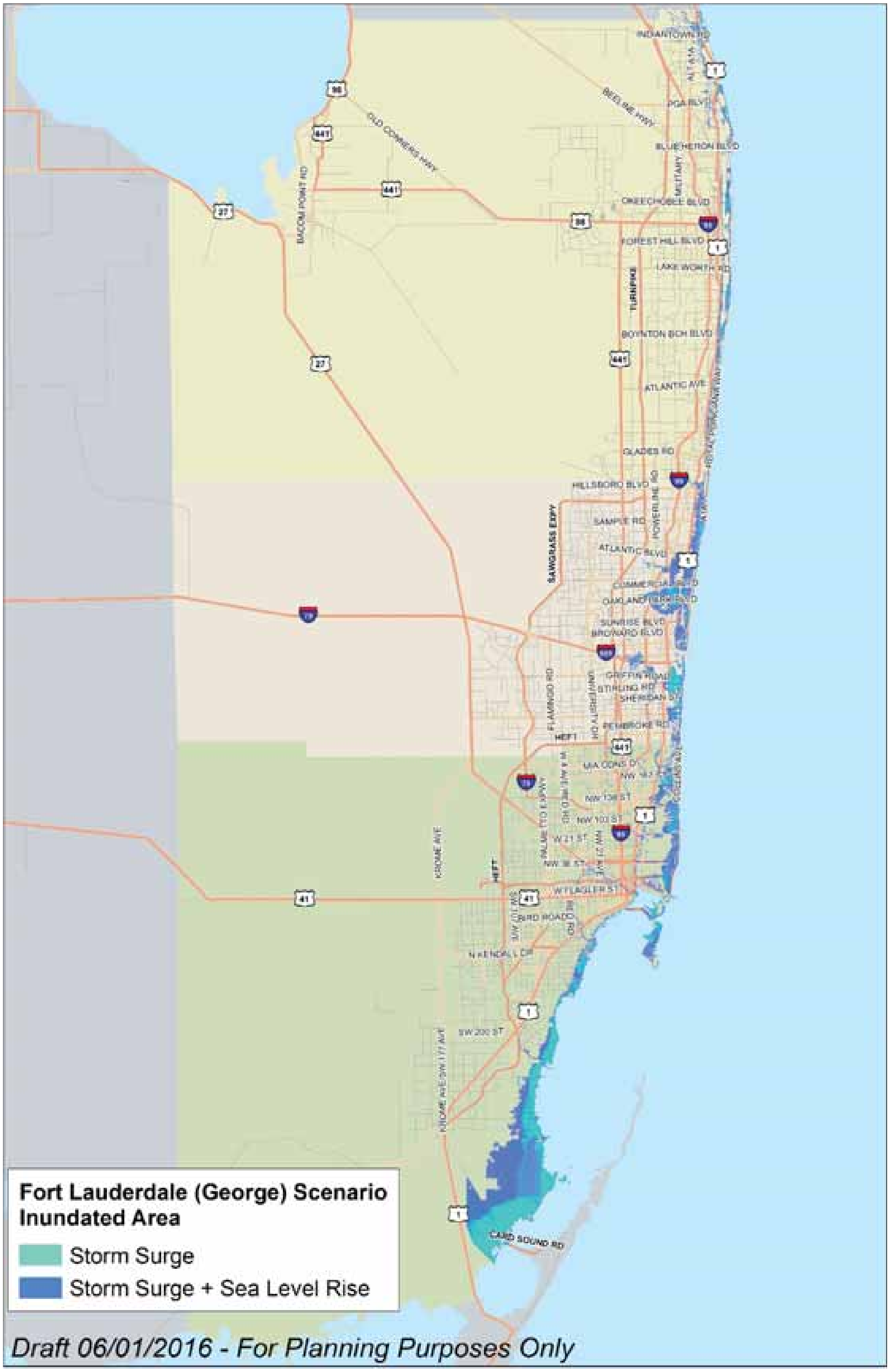
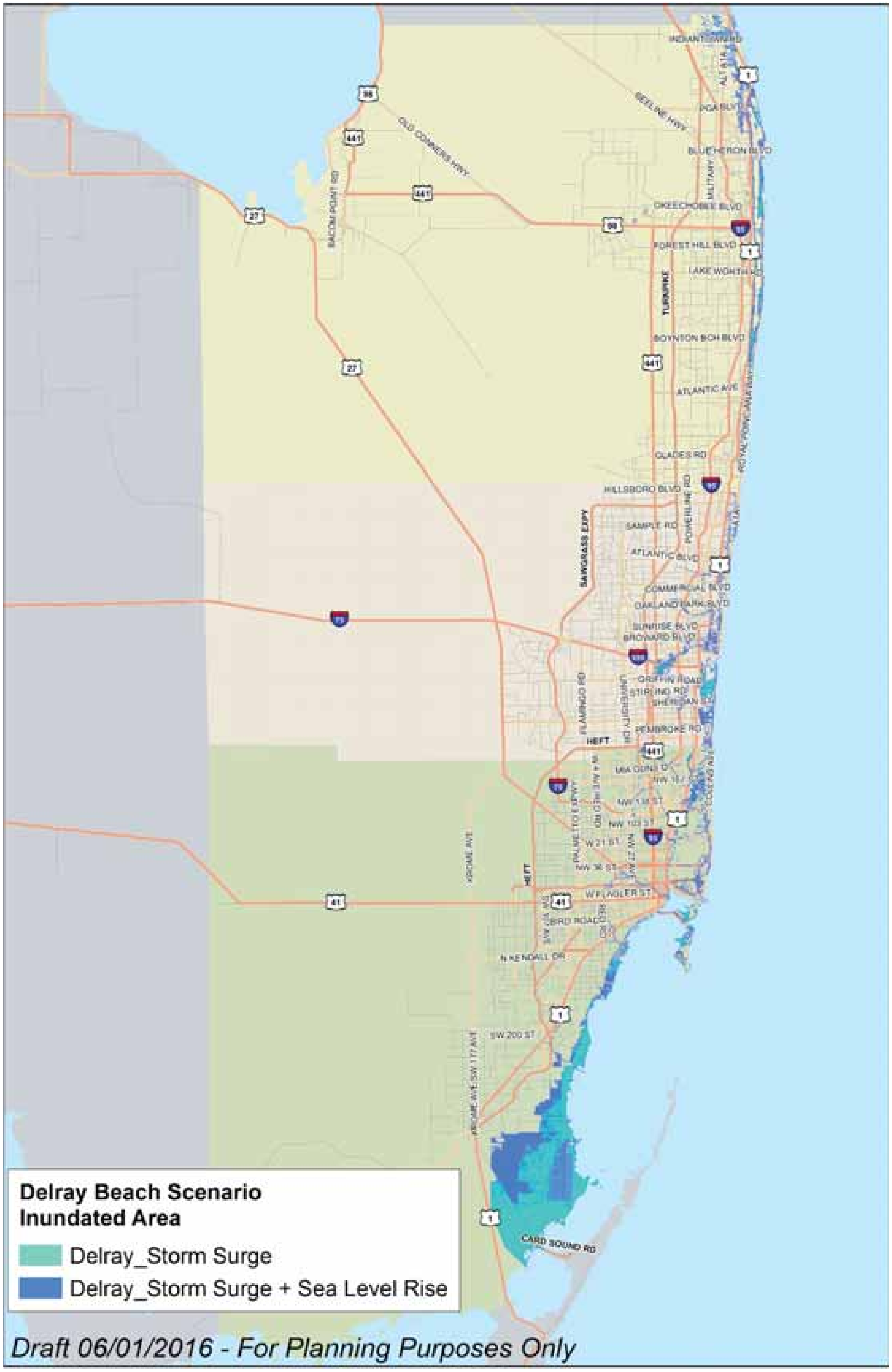


Figure 3.3 Inundated Area – Delray Beach Hurricane Scenarios



4.0 Results

4.1 Network Disruption

The results of network disruption analysis are shown in Table 4.1 and Figure 4.1. Links are the polyline segments in the SERPM model network used to represent transportation facilities for modeling purposes. Centerline miles are the total length of a given road from its starting point to its end point, without considering number and size of the lanes on that road. Lane miles represents the total length and lane count of a given highway or road. Lane miles can be calculated by multiplying the centerline mileage by the number of lanes of the road. Figures 4.2, 4.3, and 4.4 display the disabled links for the three storm tracks. Of note is that roads in all three counties are impacted regardless of storm scenario.

Hurricane Andrew is predicted to have the greatest impact on the regional transportation network. Under the Hurricane Andrew storm surge scenario more than two thousand links were disabled in the transportation network, which equates to about 4 percent lane mileage of the facilities. Hurricane Andrew's impact is doubled with sea level rise, in which about 8 percent lane mileage of transportation facilities was disrupted. For the Fort Lauderdale Hurricane 3.6 percent and 4.6 percent of lane mileage are disabled in the storm surge and storm surge plus sea level rise scenarios respectively. The Delray Beach Hurricane has the smallest impact in terms of disrupted lane mileage.

Table 4.1 Disrupted Network of Scenarios

Scenarios	Andrew		Fort Lauderdale		Delray Beach	
	Storm Surge	Storm Surge + Sea Level Rise	Storm Surge	Storm Surge + Sea Level Rise	Storm Surge	Storm Surge + Sea Level Rise
Disrupted Links	2,172	4,140	1,834	2,358	893	1,741
Disrupted Lane Mileage	588	1,057	547	680	263	467
Disrupted Center Line Mileage	363	635	334	398	163	275

Figure 4.1 Disrupted Network of Scenarios

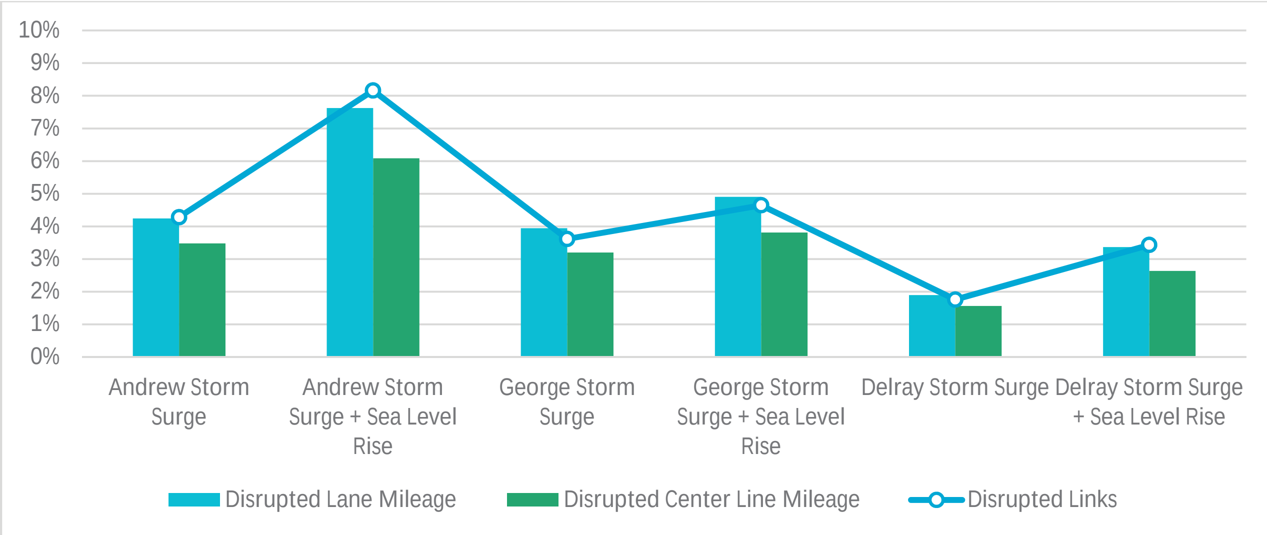


Figure 4.2 Disrupted Links – Hurricane Andrew Scenarios

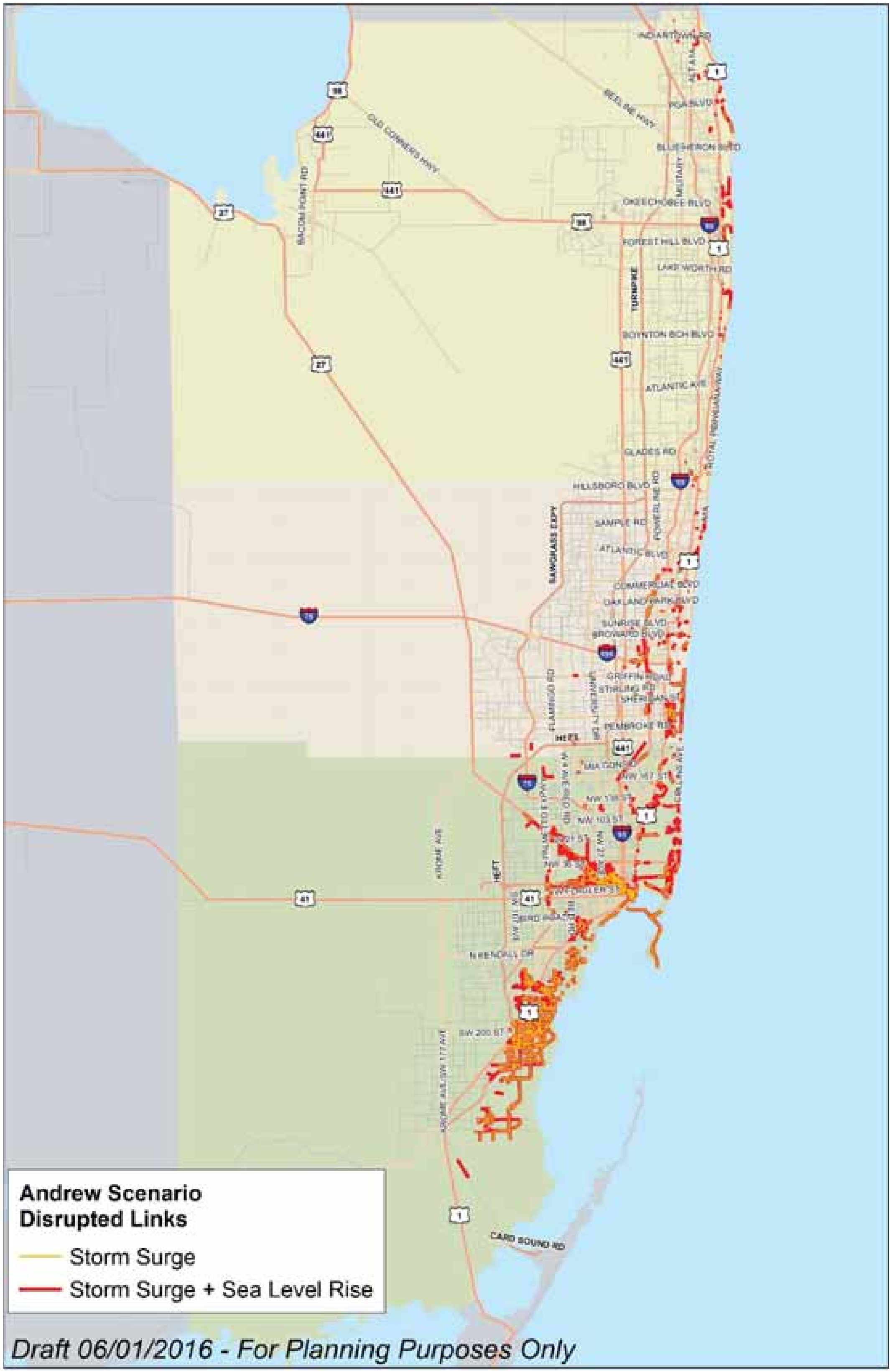


Figure 4.3 Disrupted Links – Fort Lauderdale Hurricane Scenarios

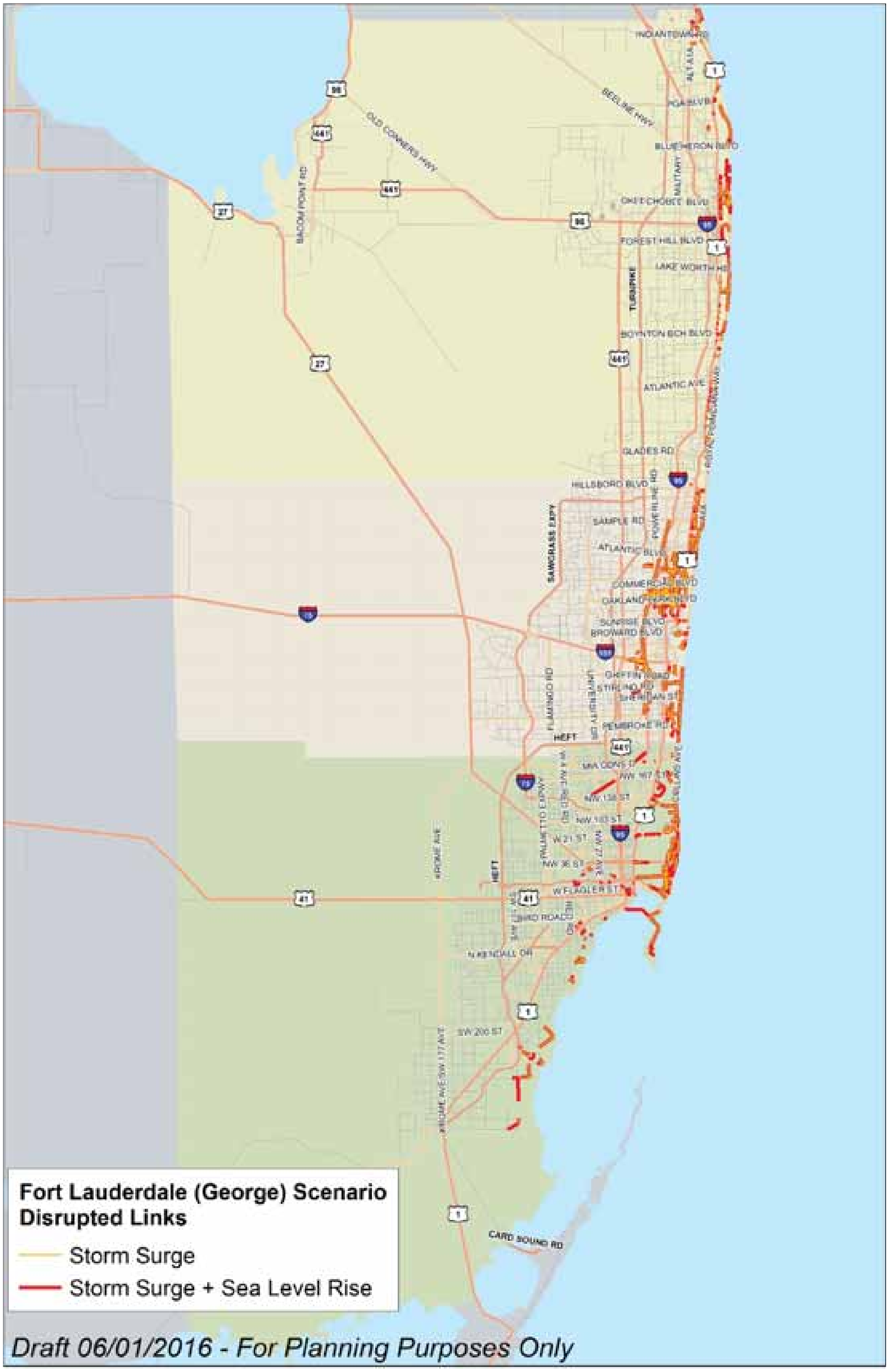
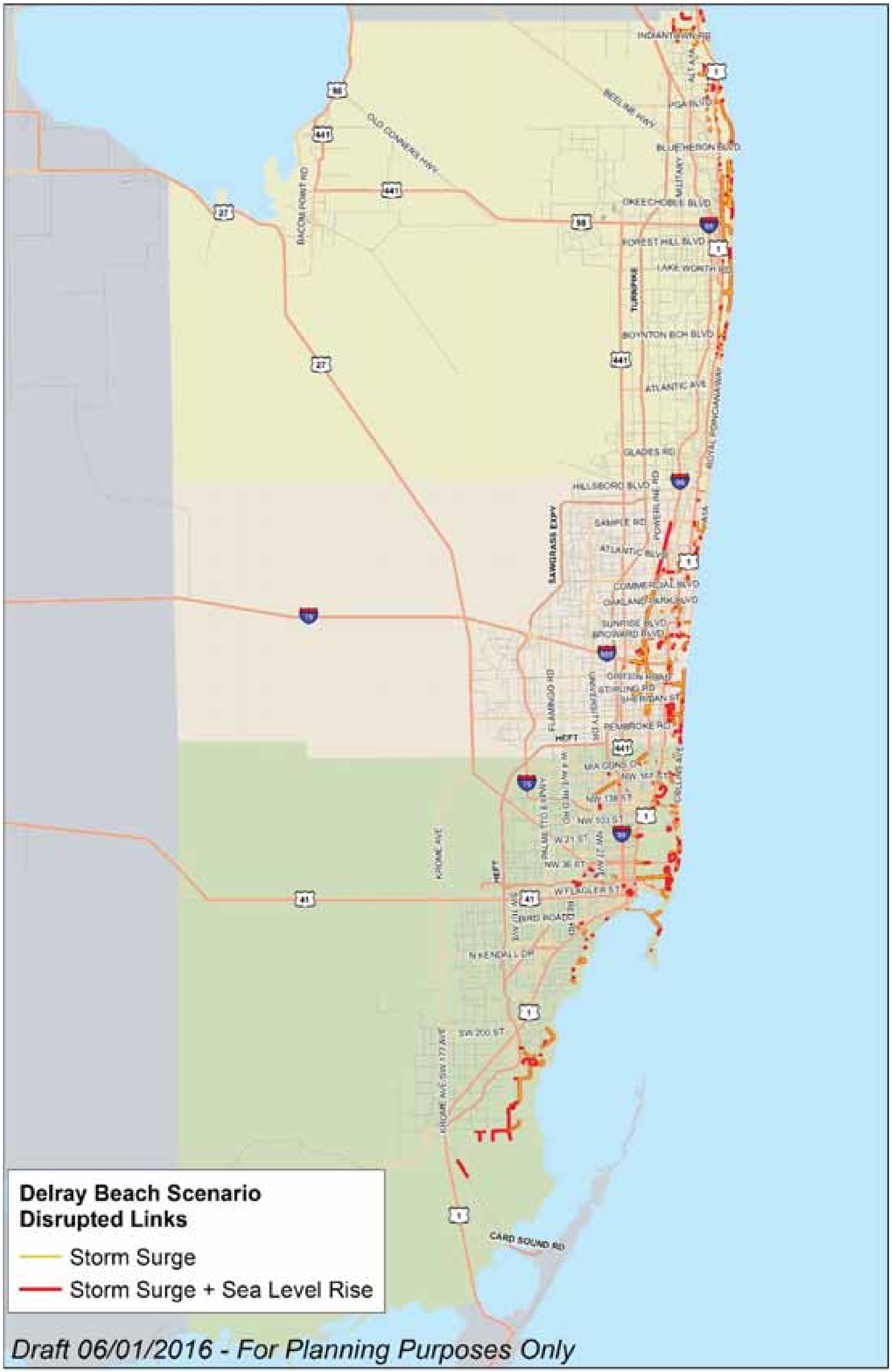


Figure 4.4 Disrupted Links – Delray Beach Hurricane Scenarios



4.2 Impact to Roadway Travel

This section addresses storm scenarios' impacts to roadway travel in terms of changes in vehicle miles traveled (VMT), Vehicle Hours Traveled (VHT), Vehicle Hours of Delay, and number of trips. Model results were used as a baseline for comparison. As noted earlier, this project assumed a one-business-day of impacted facilities to estimate and compare the extent of impacts. One day may not be the actual time when transportation facilities are impacted in the real world - some facilities with smaller impact may be able to carry traffic again in less than one day, while some other facilities with more serious damage may need to close for longer periods.

4.2.1 Daily Vehicle Miles Traveled (VMT)

Vehicle miles of travel or vehicle miles traveled (VMT) is the miles traveled by all vehicles within a specified region for a specified time period (FHWA, 2012). The total daily VMT in a region is associated with two factors, the total number of trips traveled and the average distance of those trips. When transportation facilities are inundated by storms or sea level rise, rerouting is likely to increase the average distance of trips and therefore increase total daily VMT. However, the inundation of transportation facilities could also make people unable to travel to some areas and have to cancel their trips, which will decrease the total daily VMT in the region. When the amount of increased VMT caused by longer average trip distances is greater than the decreased VMT caused by lost trips, the total daily VMT in a storm or sea level rise scenario will be greater than that in the baseline model. On the contrary, when the amount of increased VMT caused by longer average trip distances is less than the decreased VMT caused by lost trips, the total daily VMT in a storm or sea level rise scenario will be less than that in the baseline model.

The differences of Daily VMT compared to baseline model results are shown in Figure 4.5. SERPM model output of Daily Vehicle Miles Travel (VMT) under storm surge and storm surge plus sea level rise scenarios are shown in Figure 4.6 and Figure 4.7, respectively. System-wide, all three storms are predicted to reduce daily VMT. When coupled with sea level rise, these storms reduced system-wide Daily VMT by 5 to 11 percent. The extent of each scenario's impact varies in three counties. Miami-Dade County is expected to have the greatest Daily VMT decrease in most scenarios, with an exception of the Andrew Storm Surge Scenario, in which Daily VMT in Miami-Dade County is predicted to increase slightly (0.4%). The increasing Daily VMT is likely caused by additional mileage of detour trips. Broward County is expected to have less Daily VMT in the Andrew and Fort Lauderdale scenarios, and more Daily VMT in Delray Beach Scenarios. The scales of impact in Broward County range from 5 percent of increase to 12 percent of decrease. Daily VMT in Palm Beach County is expected to decrease by 2 to 8 percent.

Figure 4.5 Difference of Daily VMT – All Scenarios

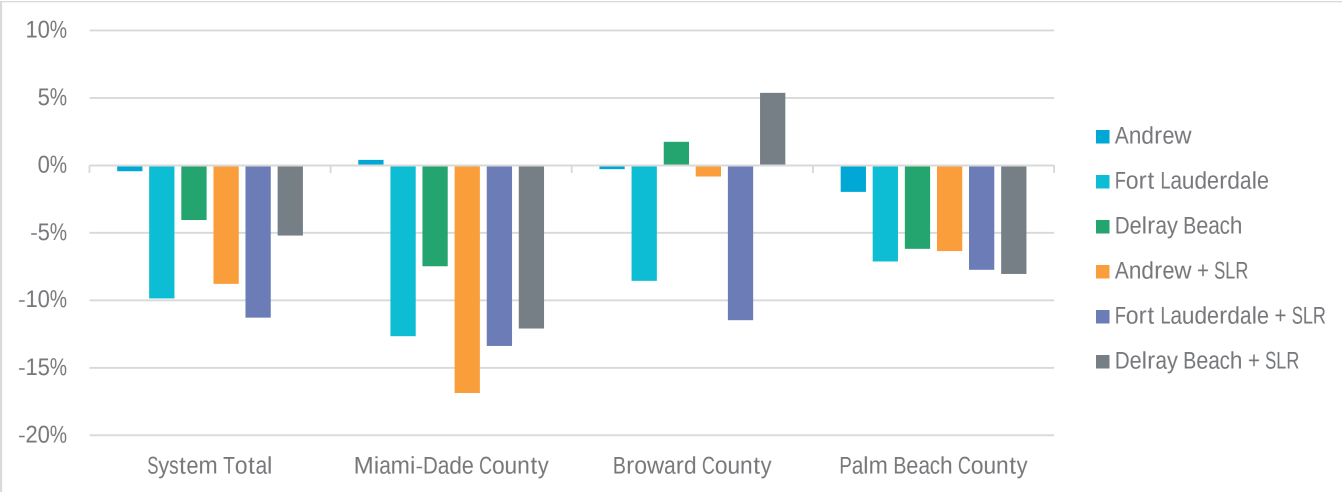


Figure 4.6 Daily VMT - Storm Surge

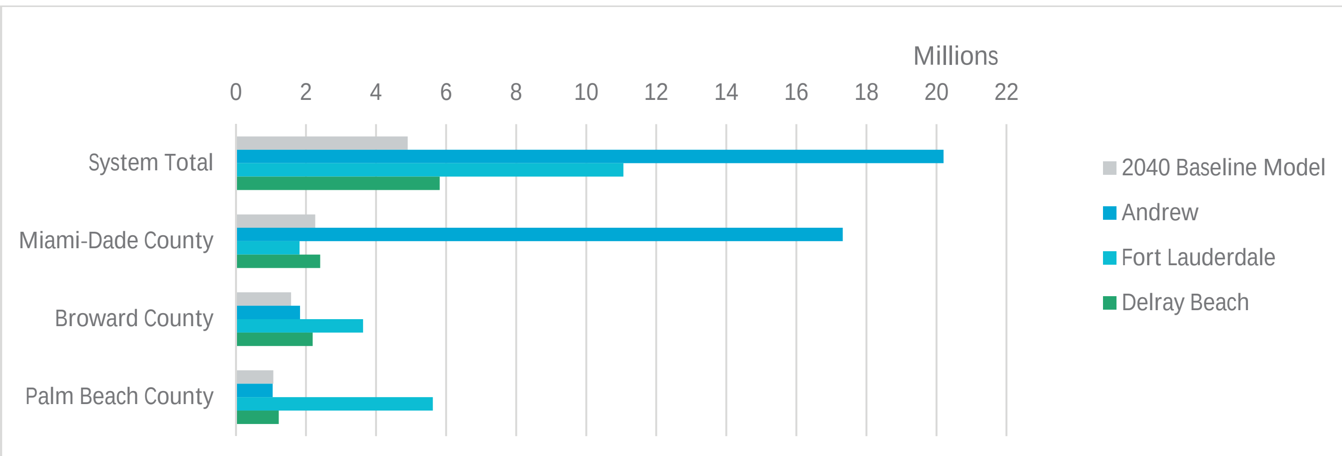
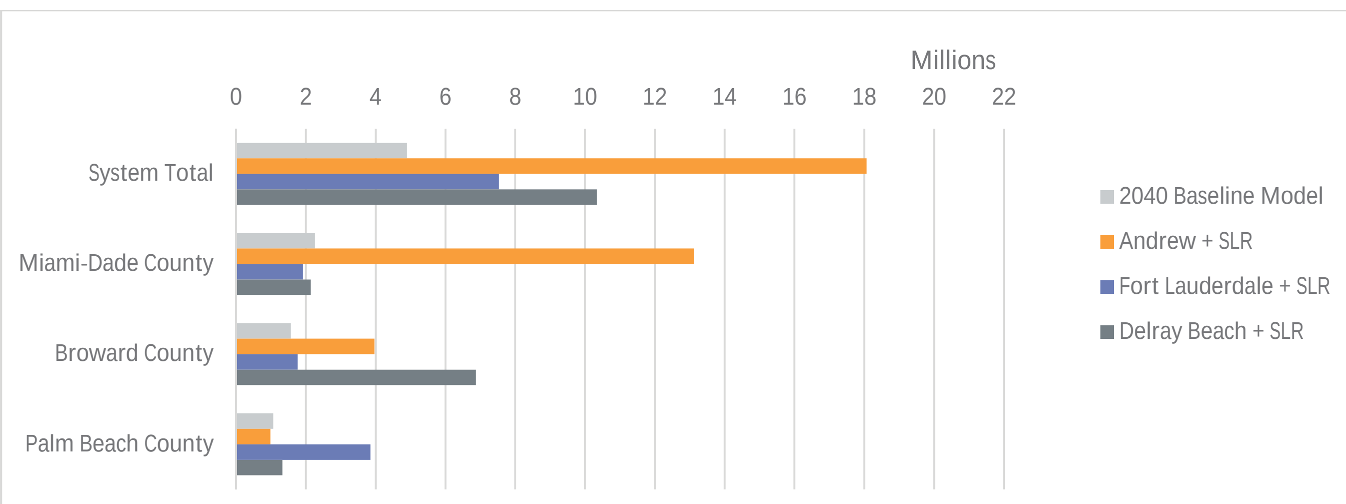


Figure 4.7 Daily VMT - Storm Surge + Sea Level Rise



4.2.2 Daily Vehicle Hours Traveled (VHT)

Vehicle Hours Traveled (VHT) is the total vehicle hours that travelers spend on the roadway network in a specified area during a specified time period (FHWA, 2012). Similar to the total Daily VMT, the total Daily VHT in a region is also associated with both the total number of trips traveled and the average hours traveled of those trips. When transportation facilities are inundated by storms or sea level rise, travelers will have to reroute and travel on the remaining facilities, which likely increases t travel time of their trips and therefore increases total daily VHT. However, the inundation of transportation facilities could also make people unable to travel to some areas and have to cancel their trips, which will decrease the total daily VHT in the region. When the amount of increased VHT caused by longer average hours traveled are greater than the decreased VHT caused by lost trips, the total daily VHT in a storm or sea level rise scenario will be greater than that in the baseline model. On the contrary, when the amount of increased VHT caused by longer average hours traveled are less than the decreased VHT caused by lost trips, the total daily VHT in a storm or sea level rise scenario will be less than that in the baseline model.

The differences of Daily VHT compared to baseline model results are shown in Figure 4.8. SERPM output of Daily Vehicle hours Travel (VHT) under storm surge and storm surge plus sea level rise scenarios are shown in Figure 4.9 and Figure 4.10. System total Daily VHT is predicted to increase by 19 percent to more than 300 percent. VHT in Miami-Dade County is predicted to be increased by Hurricane Andrew by more than 4 to 6 times compared to that in baseline model. Fort Lauderdale Hurricane scenario results in increased Daily VHT by about more than 100 percent in Broward County and 200 to 400 percent in Palm Beach County. Broward County is also predicted to be impacted by the Delray Beach Hurricane with sea level rise significantly, which will increase its Daily VHT by more than 300 percent.

Figure 4.8 Difference of Daily Vehicle Hours Traveled

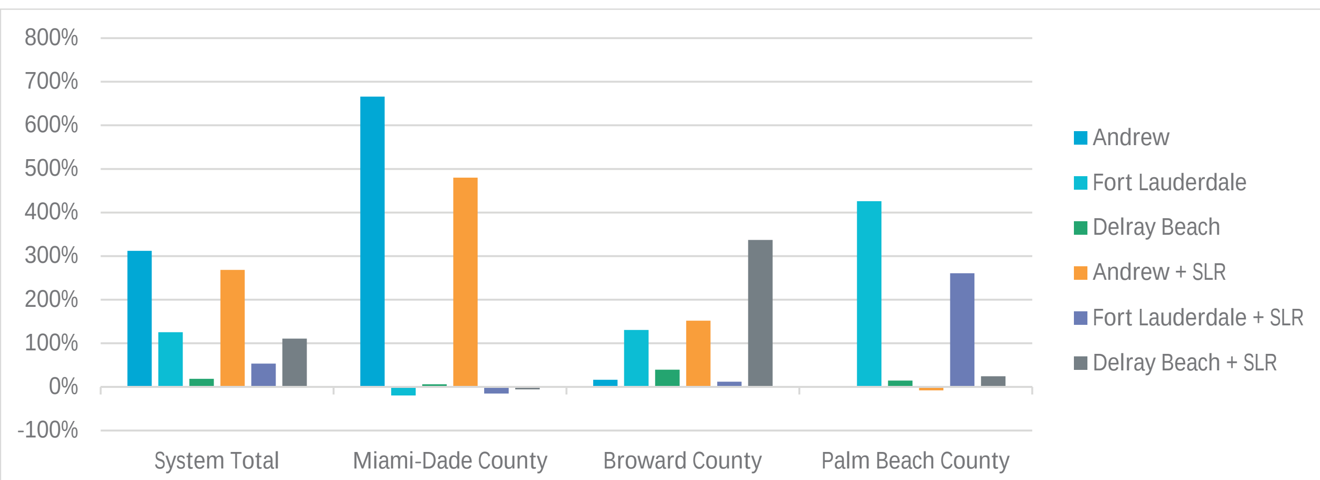


Figure 4.9 Daily Vehicle Hours Traveled – Storm Surge

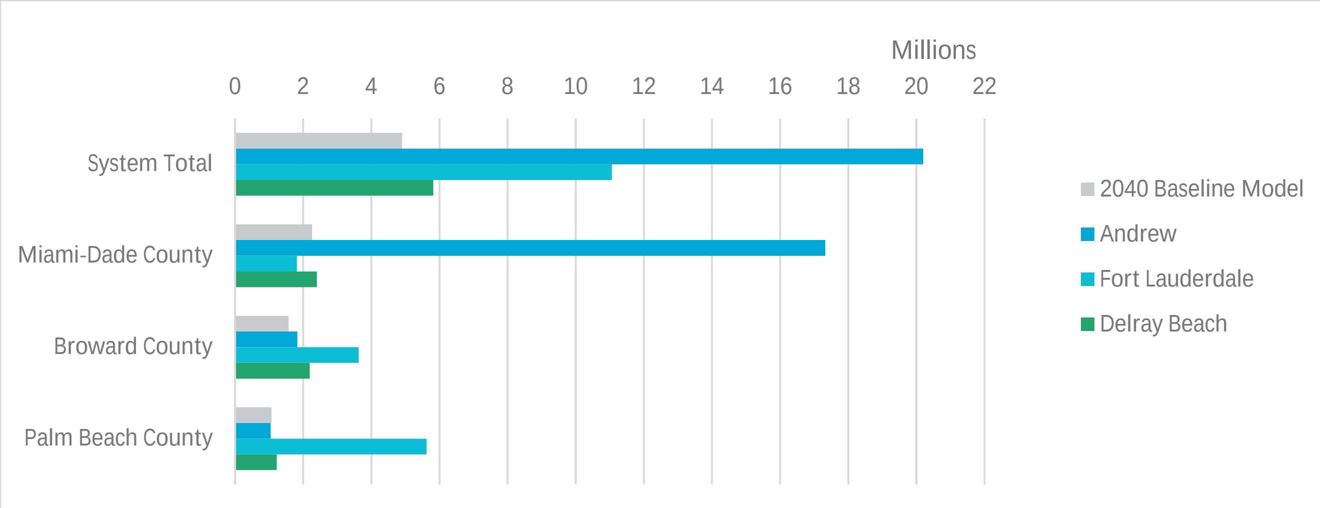
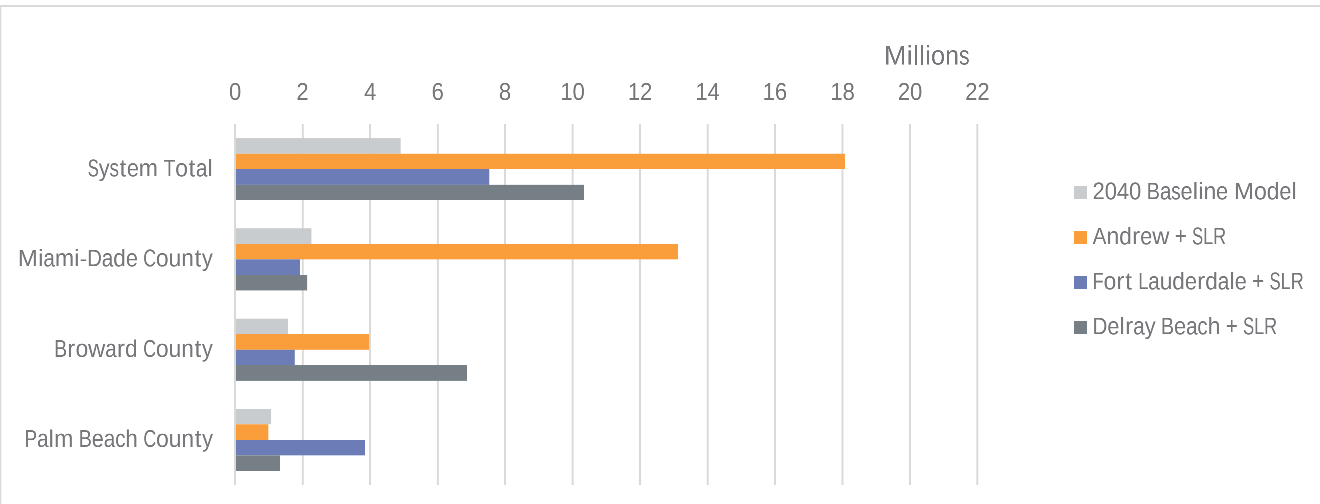


Figure 4.10 Daily Vehicle Hours Traveled – Storm Surge plus Sea Level Rise



4.2.3 Daily Vehicle Hours of Delay

Daily vehicle hours of delay is the difference between the estimated travel time under congested conditions and under free flow conditions. Similar to the total Daily VMT, the total Daily vehicle hours of delay in a region is also associated with both the total number of trips traveled and the average hours of delay of those trips. When transportation facilities are inundated by storms or sea level rise, travelers will have to reroute and travel on the remaining facilities, which is likely to cause congestion and therefore increase total daily vehicle hours of delay. However, the inundation of transportation facilities could also made people unable to travel to some areas and have to cancel their trips, which will decrease the total daily vehicle hours of delay in the region. When the amount of increased vehicle hours of delay caused by longer average hours of delay are greater than the decreased vehicle hours of delay caused by lost trips, the total daily vehicle hours of delay in a storm or sea level rise scenario will be greater than that in the baseline model. On the contrary, when there are more transportation facilities inundated, for example with sea level rise, the amount of increased vehicle hours of delay caused by longer average hours of delay are less than the decreased vehicle hours of delay caused by lost trips. The total daily vehicle hours of delay in a storm or sea level rise scenario will be less than that in the baseline model.

The differences of Daily Vehicle Hours of Delay compared to baseline model results are shown in Figure 4.11. SERPM output of Daily Vehicle Hours of Delay under storm surge and storm surge plus sea level rise scenarios are shown in Figure 4.12 and Figure 4.13. The Fort Lauderdale Hurricane is predicted to cause significant increase in Vehicle Hours of Delay in Palm Beach County and Broward County. The largest growth in Vehicle Hours of Delay in Miami-Dade County is expected to be caused by Hurricane Andrew.

Figure 4.11 Difference of Vehicle-Hours of Delay

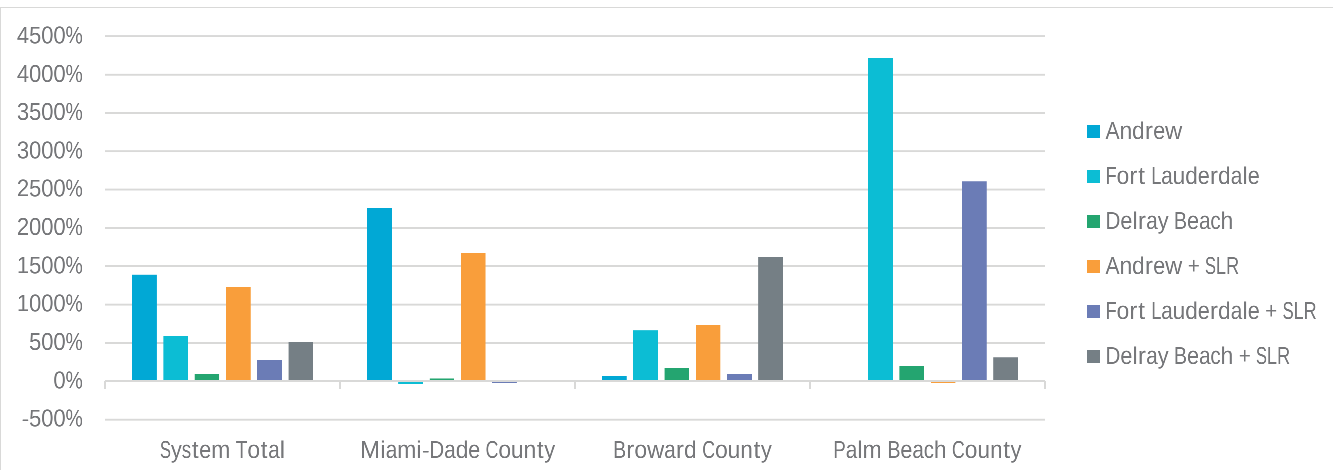


Figure 4.12 Vehicle-Hours of Delay - Storm Surge

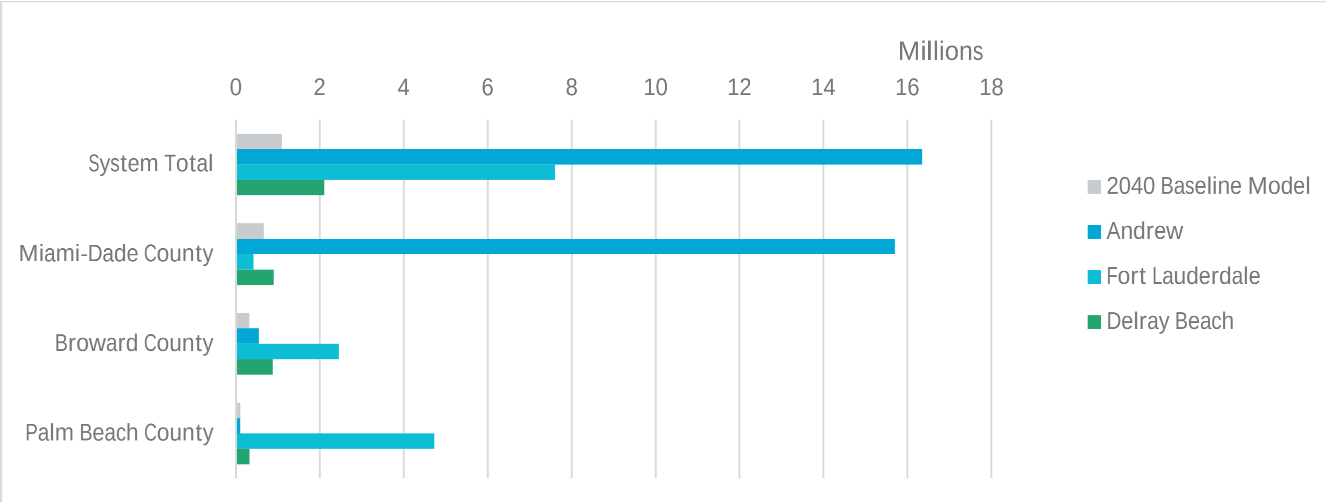
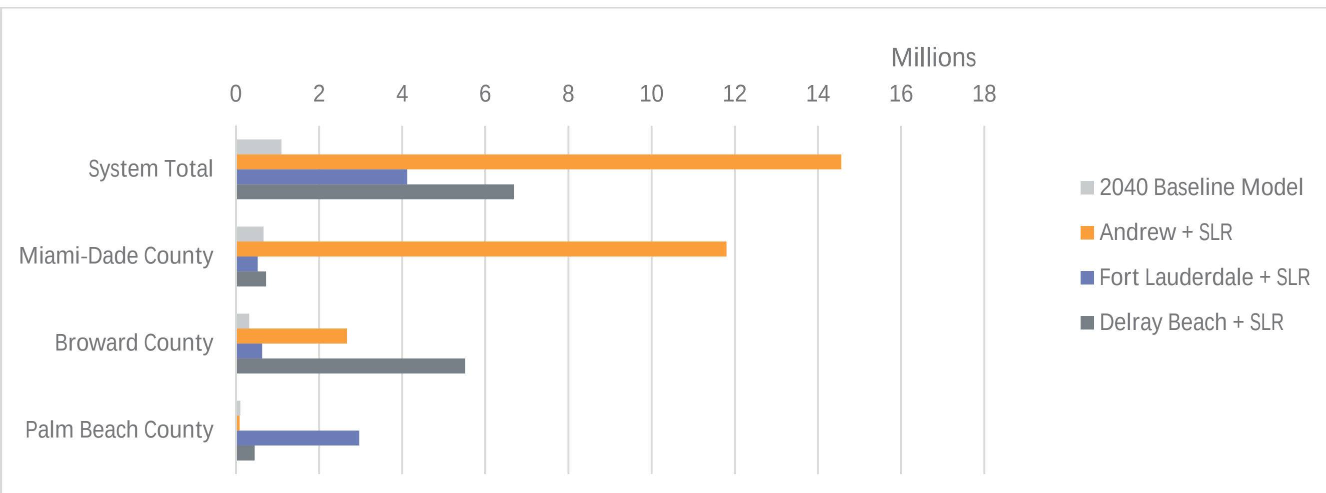


Figure 4.13 Vehicle-Hours of Delay Storm Surge + Sea Level Rise



4.2.4 Daily Roadway Trips

The numbers of roadway trips as compared to baseline model results are shown in Table 4.2.

Figure 4.14 shows the roadway trips that cannot be made (are "lost") for each of the six scenarios. SERPM output of numbers of roadway trips made for storm surge and storm surge plus sea level rise scenarios are shown in Figure 4.15 and Figure 4.16.

System-wide, the three counties are predicted to lose up to 11 percent of roadway trips in storm surge only scenarios, and up to 15 percent roadway trips in storm surge and sea level rise scenarios. Miami-Dade County is predicted to be impacted the most among the three counties, where the Hurricane Andrew scenario results in 13 percent roadway trips lost without sea level rise, and 27 percent roadway trips lost with sea level rise. Broward County is projected to be impacted the heaviest by the Fort Lauderdale hurricane, which will cause 16 and 17 percent decrease of roadway trips without and with sea level rise, respectively. Palm Beach County is predicted to have the greatest roadway trip lost when hit by the Delray Hurricane, which results in 7 and 9 percent roadway trips lost without and with sea level rise, respectively.

Table 4.2 Roadway Trips Lost

	Andrew	Fort Lauderdale	Delray Beach	Andrew + SLR	Fort Lauderdale + SLR	Delray Beach + SLR
System Total	-1,207,548	-1,992,788	-957,435	-2,797,861	-2,211,993	-1,576,847
Miami-Dade County	-1,007,128	-723,233	-446,198	-2,121,002	-792,729	-735,881
Broward County	-142,155	-966,579	-178,270	-416,884	-1,035,551	-386,865
Palm Beach County	-58,265	-302,976	-332,967	-259,975	-383,713	-454,101

Figure 4.14 Roadway Trips Lost

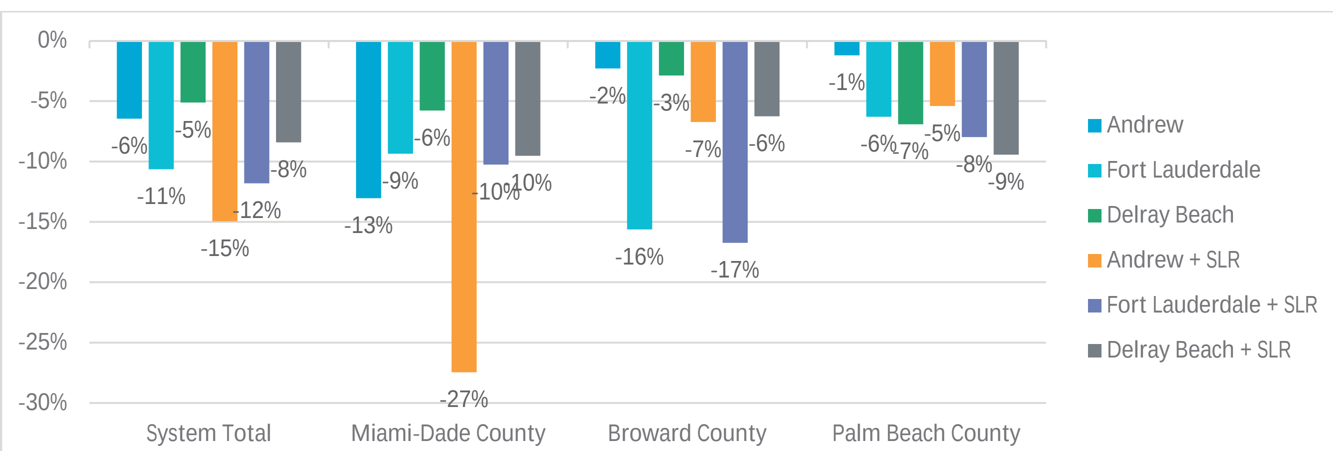


Figure 4.15 Roadway Trips – Storm Surge

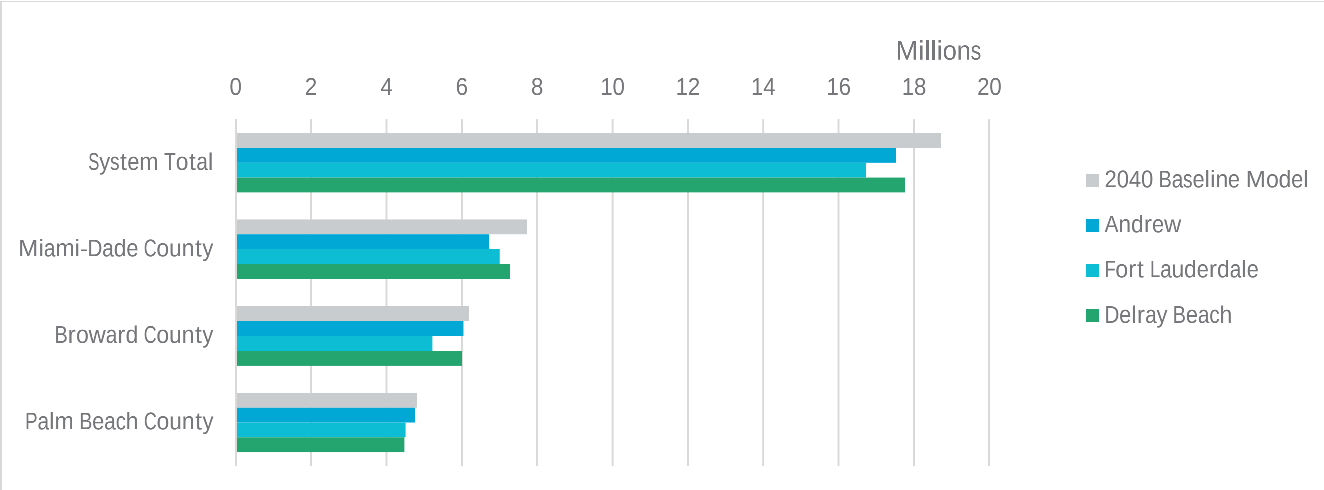


Figure 4.16 Roadway Trips - Storm Surge + Sea Level Rise

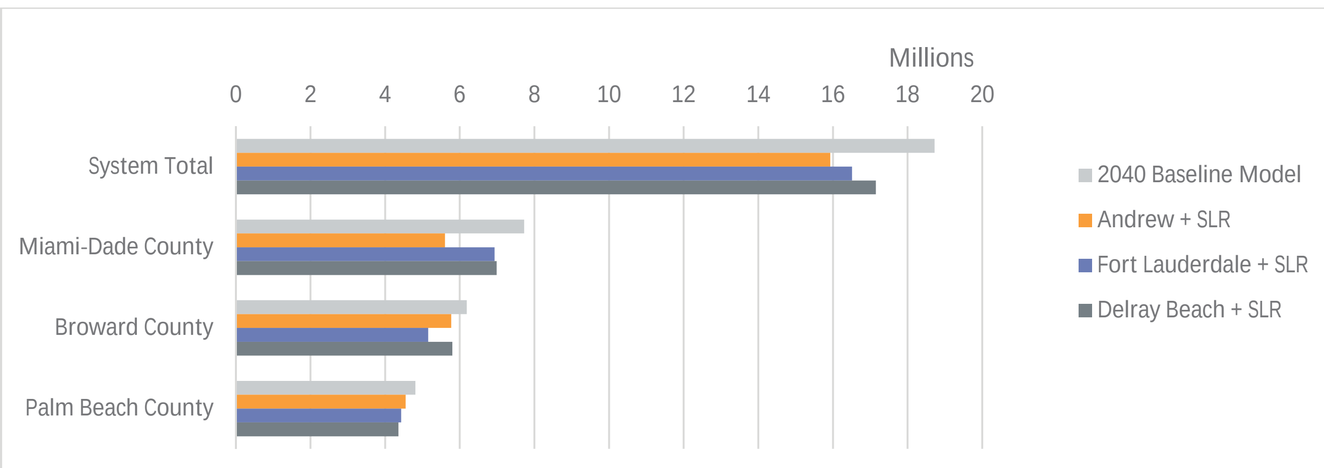


Figure 4.17 and Figure 4.18 illustrate Traffic Analysis Zones (TAZs) for which all access to the zones is cut off from inundation in one, two, or three storm tracks. Areas that are predicted to be impacted by all scenarios can be considered at higher risk than the others. There are sites in all three counties impacted, primarily areas hydrologically connected to the ocean.

Figure 4.17 Inundated TAZ – Storm Surge Only

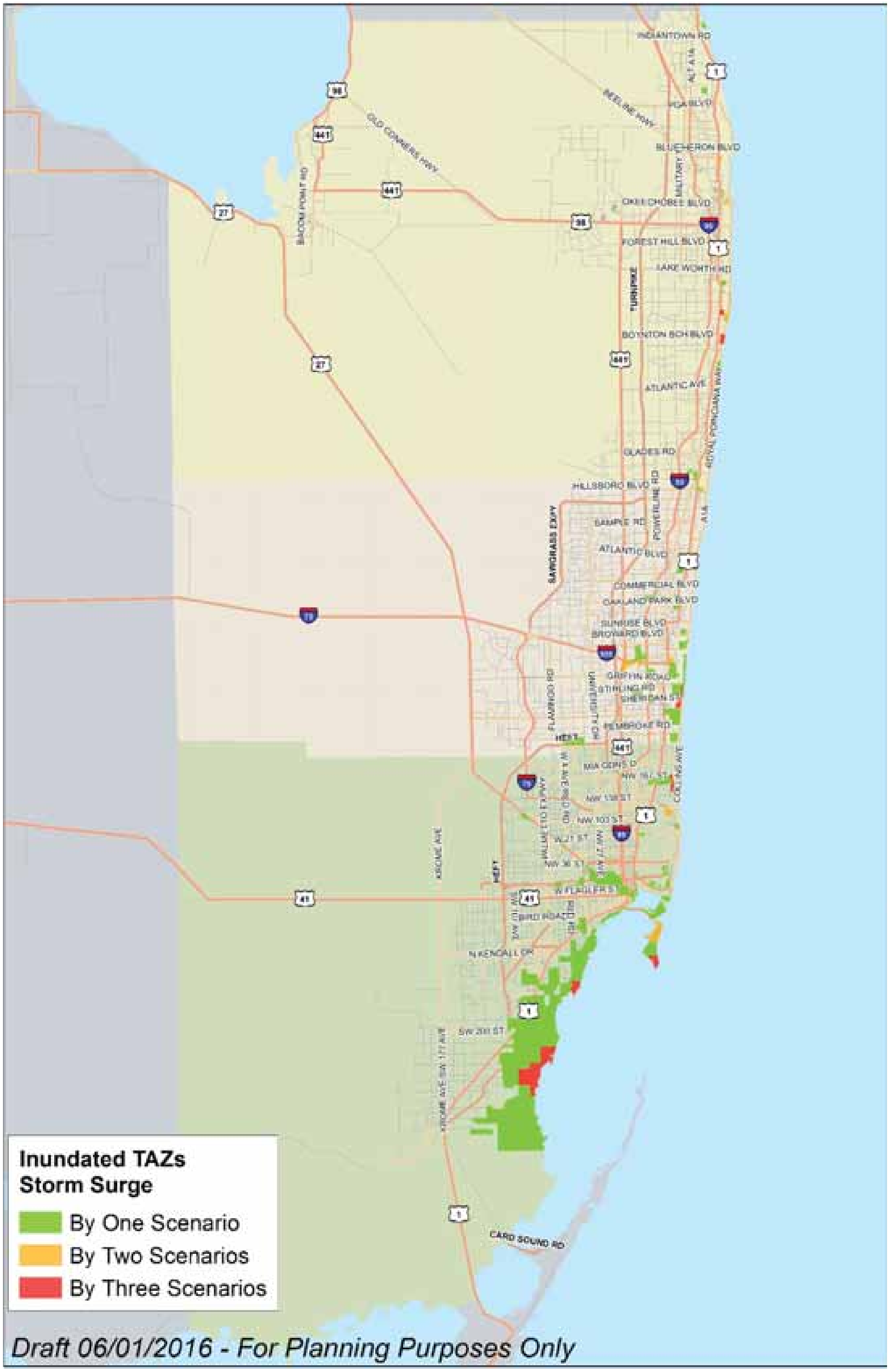
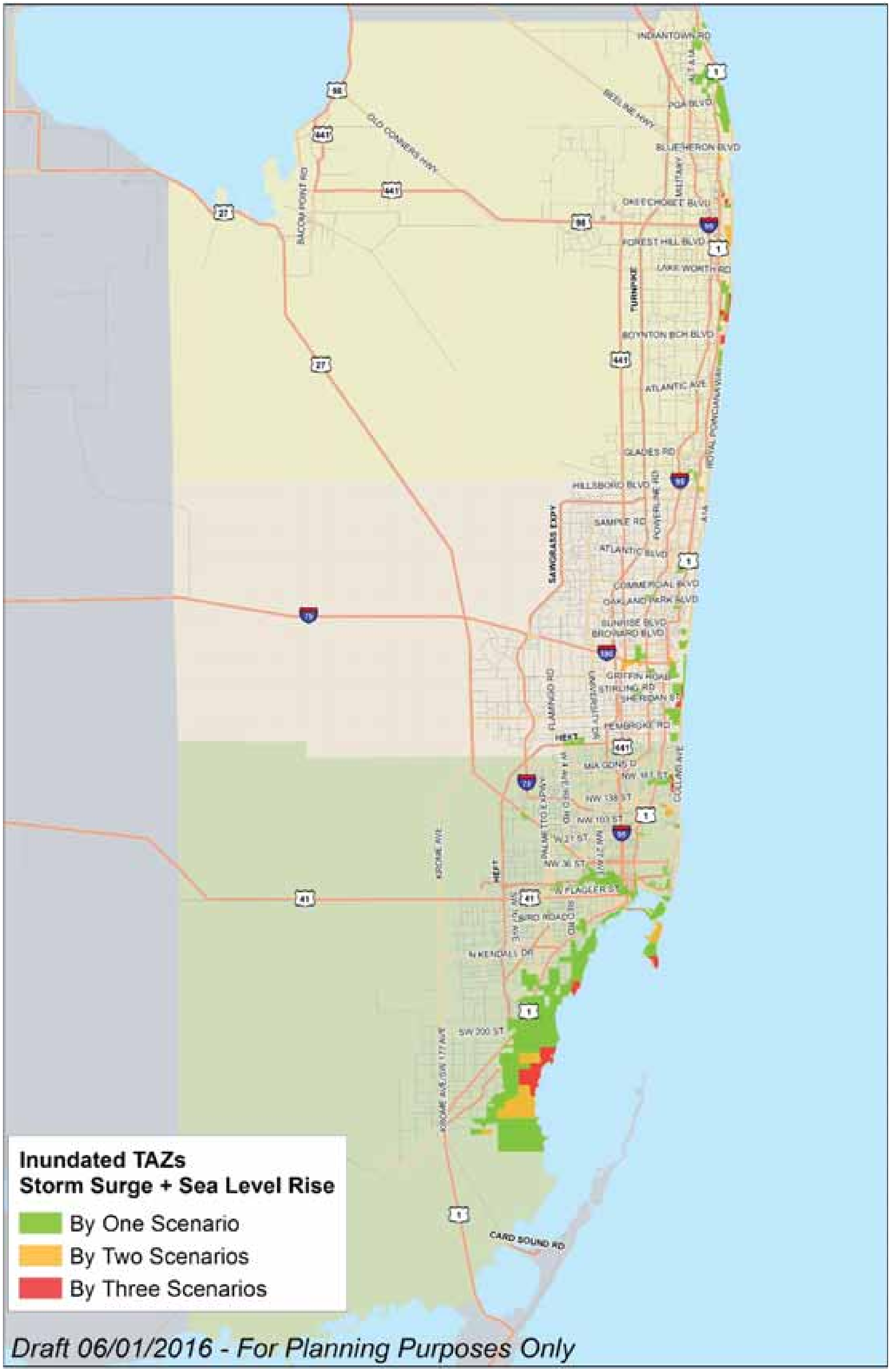


Figure 4.18 Inundated TAZ – Storm Surge and Sea Level Rise



4.3 Impact to Transit Travel

4.3.1 Daily Transit Trips

Using a method similar to that for estimating roadway lost trips, and transit trips that are scheduled on inundated facilities, are removed in the model for each scenario. Transit rerouting was not conducted in the modeling step as it will require coding a rerouted transit network into the model. The differences of transit trips compared to baseline model results are shown in Table 4.3 and Figure 4.19, which reflects the transit trips that are not able to be made because of storms. SERPM output of transit trips under storm surge and storm surge plus sea level rise scenarios are shown in Figure 4.20 and Figure 4.21.

Transit trips in the three counties are projected to be reduced up to 16 percent with storm surge only and up to 22 percent with sea level rise. In the worst case, Miami-Dade County is predicted to lose 32 percent of transit trips for a Hurricane Andrew storm track with projected sea level rise. The Fort Lauderdale Hurricane will see a reduction of 31 percent transit trips in Broward County. The Delray Beach Hurricane with projected sea level rise results in a loss of about 19 percent transit trips in Palm Beach County.

Table 4.3 Transit Trips Lost

	Andrew	Fort Lauderdale	Delray Beach	Andrew + SLR	Fort Lauderdale + SLR	Delray Beach + SLR
System Total	-64,186	-83,666	-65,502	-112,988	-89,430	-97,564
Miami-Dade County	-36,590	-30,482	-26,142	-64,706	-32,624	-37,552
Broward County	-18,206	-33,180	-18,602	-25,004	-34,272	-22,930
Palm Beach County	-9,390	-20,004	-20,758	-23,278	-22,534	-37,082
System Total	-64,186	-83,666	-65,502	-112,988	-89,430	-97,564

Figure 4.19 Transit Trips Lost

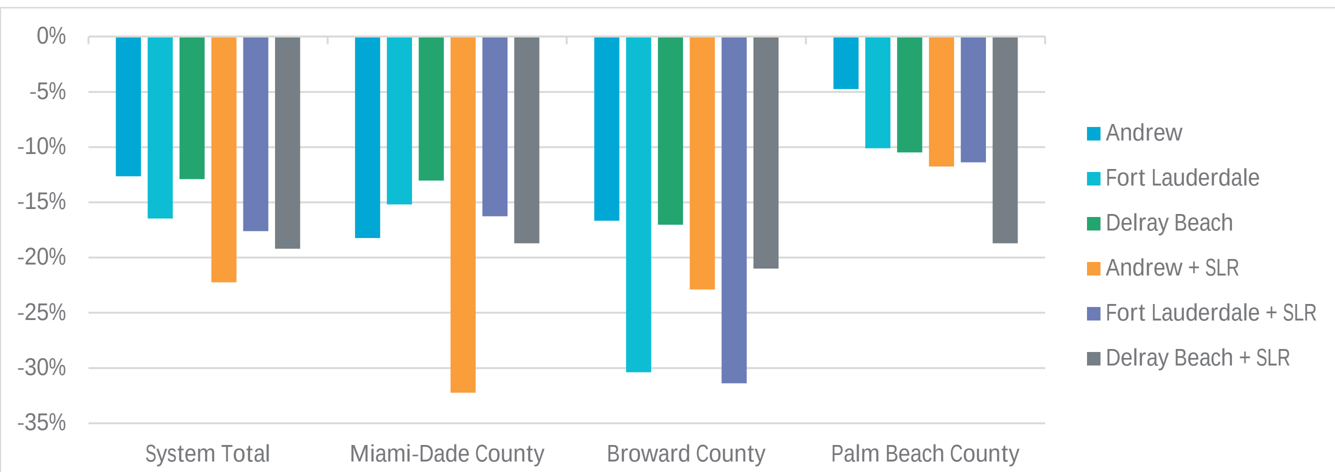


Figure 4.20 Transit Trips Storm Surge

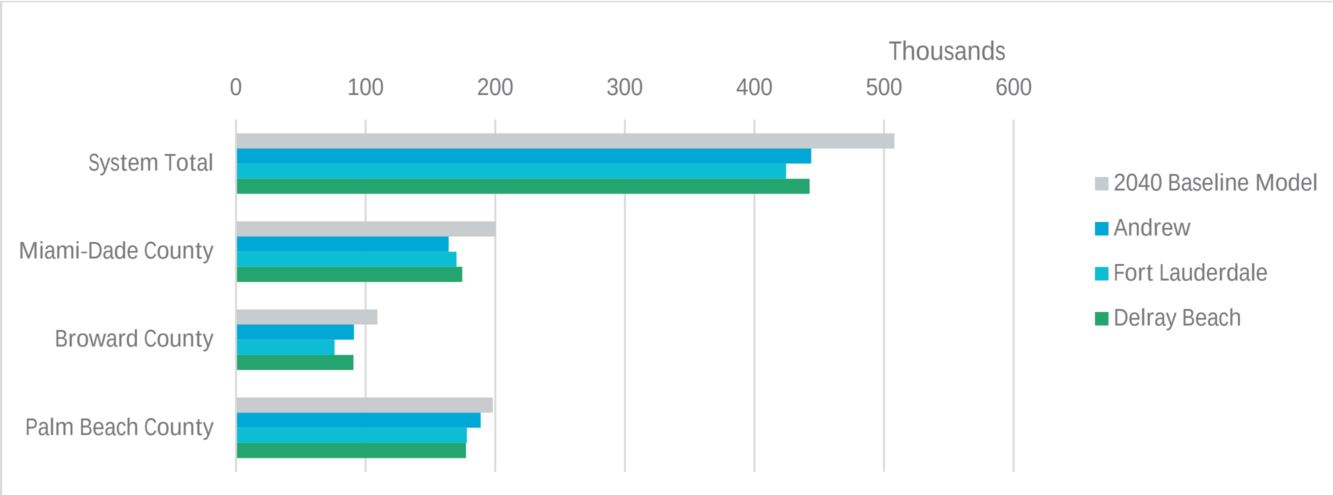
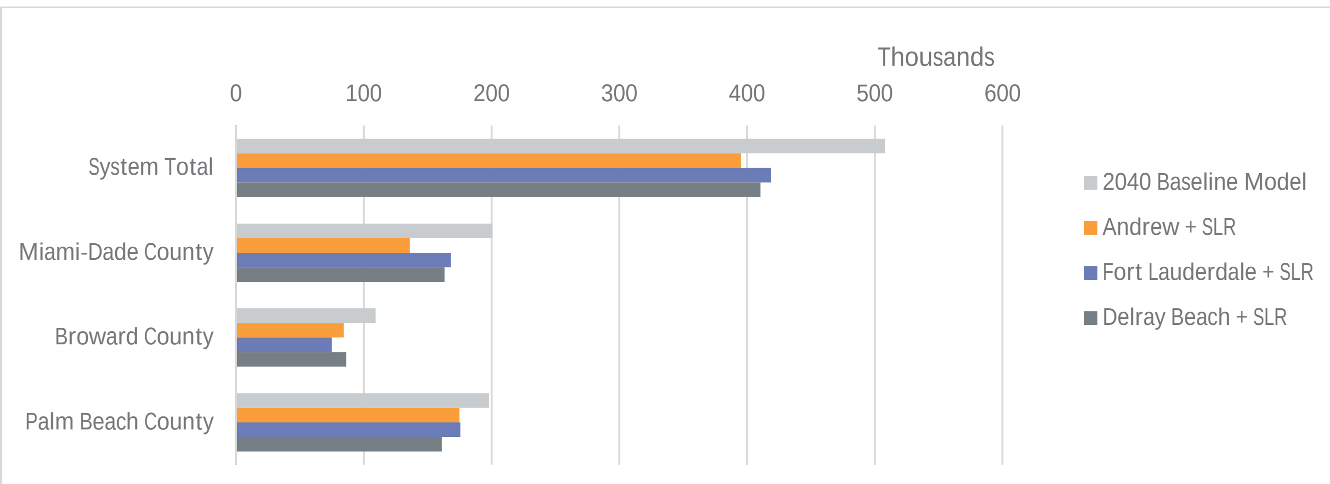


Figure 4.21 Transit Trips Storm Surge + Sea Level Rise



4.3.2 Passenger Rail

Operated by the South Florida Regional Transportation Authority (SFRTA), Tri-Rail provides commuter rail service in the three-county region of Miami-Dade, Broward, and Palm Beach. The service is planned to be expanded on the FEC rail corridor and will be named Tri-Rail Coastal Link. Miami-Dade County operates Metrorail which provides heavy rail service within Miami-Dade County. In SERPM, a rail link is the alignment between two adjacent stations. When the simulated storm water intercepts with rail service at a certain point, the entire link between the two nearest stations of the intercept point is considered disrupted. The planned Tri-Rail Coastal Link was not considered in the SERPM runs of inundated scenarios. While inundation analysis was performed to identify vulnerable segments, inundated trips of the planned Tri-Rail Coastal Link service were not included in the total transit lost summarized in section 4.3.1. Even so, the total transit trips lost are likely to be overestimated numbers given that transit trip rerouting was not considered.

As shown in Figure 4.22, the Hurricane Andrew is projected to impact Tri-Rail at segments between Cypress Creek Station and Golden Glades Station, and the segment from Tri-Rail Metrorail transfer Station to Miami International Airport Station. The Tri-Rail Coastal Link[6] is projected to be impacted at segments near Jupiter Station, Downtown Deerfield Beach Station, on a segment from Oakland Park to Dania Beach, and a segment from Aventura to 79th Street. Although the elevated tracks of the Metrorail system will not be inundated, access at ground level of several stations is projected to be impacted, including at the Brickell Station, the Civic Center Station, and the Miami Airport Station.

The Fort Lauderdale Hurricane's impact on Tri-Rail are illustrated in Figure 4.23. Two Tri-Rail segments are inundated, including segment from Pompano Beach Station to Hollywood Station, segments from Golden Glades Station to Opa-Locka Station. Several segments of the Tri-Rail Coastal Link are predicted to be impacted, including segments near the Jupiter Station, segment between Downtown Pompano Beach and Wilton Manors, segment between the Fort Lauderdale/Hollywood International Airport and Dania Beach, segment between Aventura and North Miami Beach, and segment between North Miami to 79th Street. Metrorail is not impacted in this scenario.

Figure 4.24 shows the Delray Beach Hurricane's impact on Tri-Rail. Inundated Tri-Rail and Metrorail segments are predicted to be similar to those in the Fort Lauderdale Hurricane scenario, including a Tri-Rail segment from the Pompano Beach Station to the Hollywood Station, and a segment from the Golden Glades Station to the Opa-Locka Station. Impacts to the Tri-Rail Coastal Link are slightly different compared to other scenarios. Inundated segments of the Tri-Rail Coastal Link are a segment between Downtown Pompano Beach and Dania Beach, a segment between Aventura and North Miami Beach, and a segment between North Miami to 79th Street. Metrorail is not impacted in this scenario.

[6] Station locations were approximated based on station name.

Figure 4.22 Hurricane Andrew's Impact on Tri-Rail and Metrorail

Figure 4.23 Fort Lauderdale Hurricane's Impact on Tri-Rail and Metrorail

Figure 4.24 Delray Beach Hurricane's Impact on Tri-Rail and Metrorail

4.4 Impact to Other Modes

4.4.1 Airports

There are three Strategic Intermodal System (SIS) airports in the study area: the Miami International Airport, Fort Lauderdale/Hollywood International Airport, and Palm Beach International Airport. Table 4.4 presents the percentage of inundation of airports by each scenario. The method used to identify percentage of inundation is consistent with the Southeast Florida Climate Compact Vulnerability Assessment.

Table 4.4 Percentage of Inundation – SIS Airports

SIS Facility Name	Total Acres	Storm Surge			Storm Surge and Sea Level Rise		
		Andrew	Fort Lauderdale	Delray Beach	Andrew	Fort Lauderdale	Delray Beach
Miami International Airport	2,827	1%	0%	0%	4%	0%	0.1%
Fort Lauderdale/Hollywood International Airport	1,351	0.4%	7%	0%	1%	14%	1%
Palm Beach International Airport	1,894	0%	0%	0%	0%	0%	0%

Hurricane Andrew is predicted to have the greatest impact on Miami International Airport, with 0.5 percent of its total area being inundated in storm surge scenario, and about 4 percent inundated in the storm surge plus sea level rise scenario. Figure 4.25 shows the inundated area by Hurricane Andrew of Miami International Airport. Although runways and access to the airport are not impacted, some areas in the east of the airport are inundated. Future analysis is needed to better evaluate and address the impact.

Fort Lauderdale/Hollywood International Airport is projected to be impacted by the Fort Lauderdale Hurricane the most, with more than 7 percent of its total area being inundated in the storm surge scenario, and 13.58 percent inundated in the storm surge and sea level rise scenario. As shown in Figure 4.26, inundated areas are on the west side of the airport, including some connecting roadways to the airport. Future analysis is needed to better evaluate and address the impact.

Palm Beach International Airport is not impacted in any scenario.

Figure 4.25 Hurricane Andrew's Impact on Miami International Airport

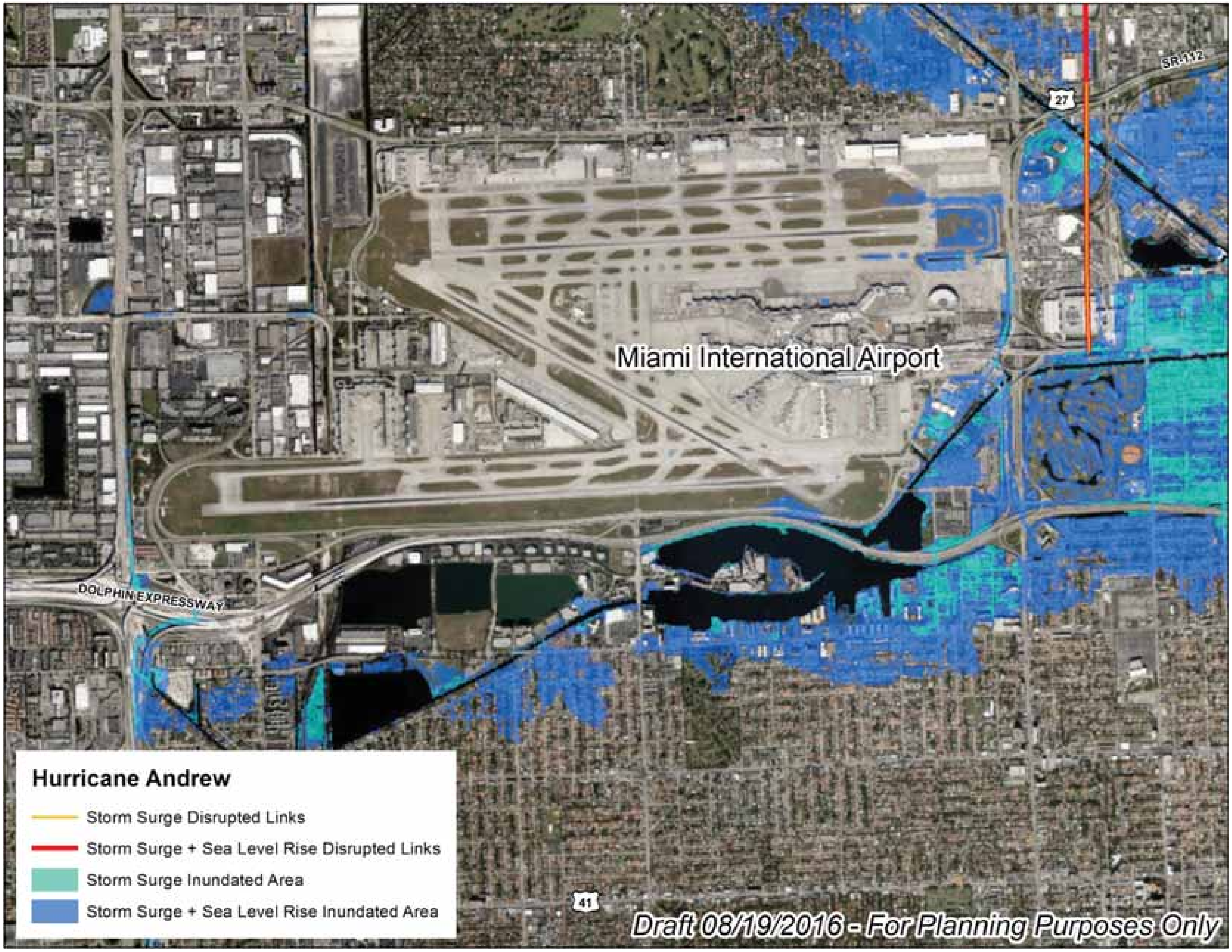
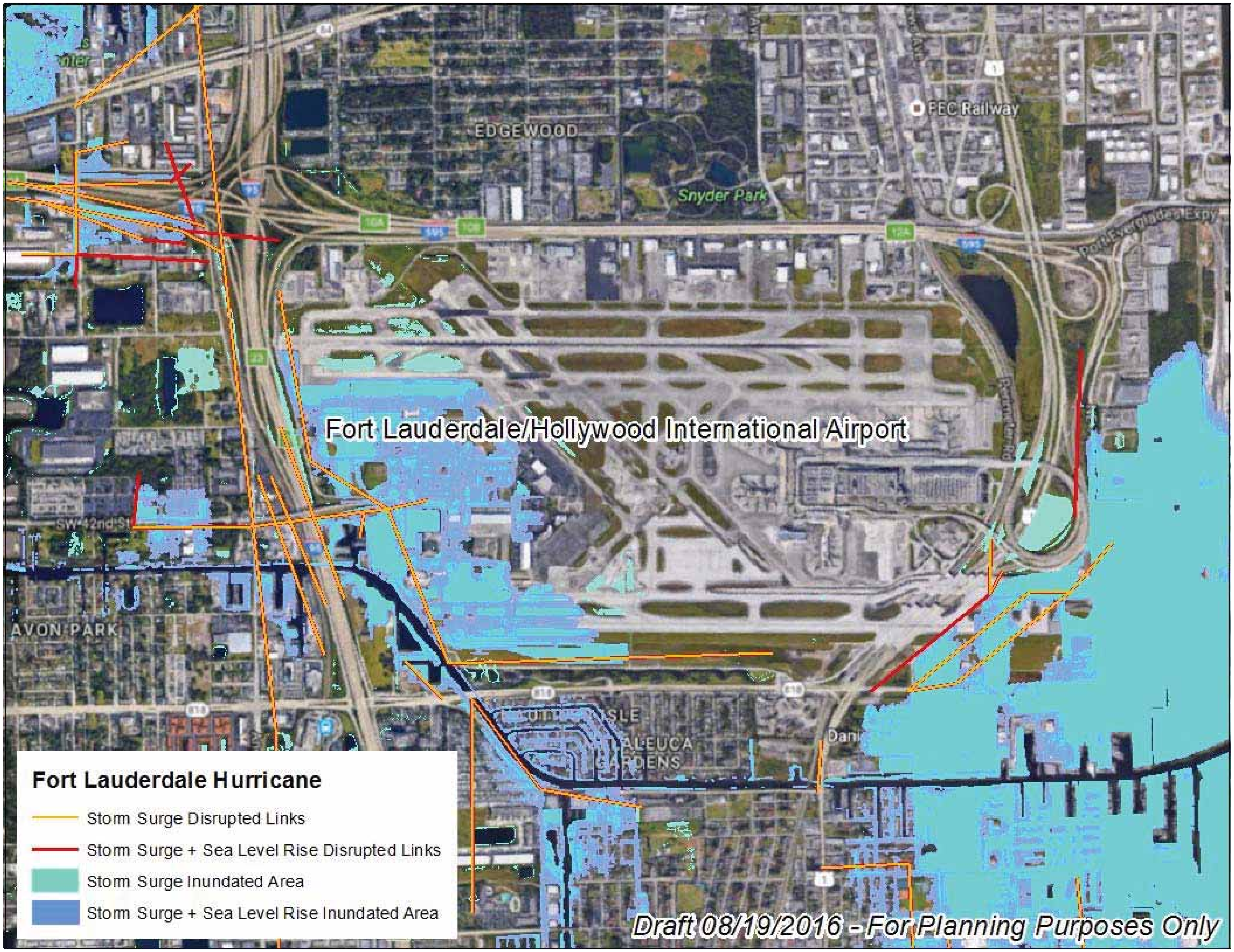


Figure 4.26 Fort Lauderdale Hurricane's Impact on Fort Lauderdale/Hollywood International Airport



4.4.2 Seaports

There are three SIS seaports in the study area: PortMiami, Port Everglades, and Port of Palm Beach. Table 4.5 presents the percentage of inundation of seaports by each scenario.

Table 4.5 Percentage of Inundation – SIS Seaports

SIS Facility Name	Total Acres	Storm Surge			Storm Surge and Sea Level Rise		
		Andrew	Fort Lauderdale	Delray Beach	Andrew	Fort Lauderdale	Delray Beach
Port Miami	521	0.2%	**0%**	0.2%	**3%**	0.4%	0.4%
Port Everglades	1,882	9%	**13%**	8%	11%	**15%**	11%
Port of Palm Beach	163	0.2%	0.1%	**0%**	0.3%	0.1%	**3%**

A Hurricane Andrew scenario has the largest impact on PortMiami, with about 3.42 percent inundated in the storm surge and sea level rise scenario. Figure 4.27 shows the inundated area by the Hurricane Andrew in PortMiami. While roads directly connected to the port are not inundated, facilities leading to the port are affected.

The Fort Lauderdale Hurricane has the largest impact on the Port Everglades among the three storms. As shown in Figure 4.28, about 13 percent of the total area of the Port Everglades is predicted to be inundated by the Fort Lauderdale Hurricane storm surge scenario, and about 15 percent is predicted to be inundated in the storm surge and sea level rise scenario. Some roadways connecting to the south side of the Port Everglades are predicted to be impacted.

The inundated area in the Port of Palm Beach is relatively small. The Delray Beach Hurricane has the largest impact on the Port of Palm Beach, with 0.42 percent of its total area being inundated in the storm surge scenario, and about 2.85 percent inundated in the storm surge and sea level rise scenario. Figure 4.29 shows the inundated area by the Delray Beach Hurricane in Port of Palm Beach. No access to the Port of Palm Beach is projected to be impacted.

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Figure 4.27 Hurricane Andrew's Impact on Port Miami

Figure 4.28 Fort Lauderdale Hurricane's Impact on Port Everglades

Figure 4.29 Delray Beach Hurricane's Impact on Port of Palm Beach

4.5 Estimated Economic Impacts

A preliminary analysis was conducted to estimate the economic impacts associated with each scenario. Economic impacts were estimated in two perspectives, wages lost caused by lost work trips and cost of increased hours of delay. These calculations represent the impact of lost trips and workers production but do not address the impact on the movement of goods.

4.5.1 Cost of Lost Work Trips

The cost of lost work trips is the production of lost work related roadway and transit trips and median wages for workers in Florida. The percentage of work related trips[7] are also applied in the calculation.

$$Lost\ Highway\ Trips\ Cost = Lost\ Highway\ Trips\ x\ Percentage\ of\ Work\ Related\ Highway\ Trips \times Median\ Wages\ for\ Workers \times 8\ Hours$$

$$Lost\ Transit\ Trips\ Cost = Lost\ Transit\ Trips\ x\ Percentage\ of\ Work\ Related\ Transit\ Trips \times Median\ Wages\ for\ Workers\ x\ 8\ Hours$$

- $Percentage\ of\ Work\ Related\ Roadway\ Trips = 18.6\%$
- $Percentage\ of\ Work\ Related\ Transit\ Trips = 33.5\%$
- $Median\ Wages\ for\ workers = \$13\ per\ Hour$

As shown in Table 4.6 and Table 4.7, lost of work related trips is predicted to cause about $75 million to more than $100 million economic impact to the three-county area for a single day. Miami-Dade County is projected to have the greatest financial loss associated with lost work trips among the three counties. Although this analysis estimates the total economic impact related to lost work trips, it is noted that salary workers may not see a loss of wages associated with similar scenarios, but hourly workers may not get paid if they can not get to work.

Table 4.6 Cost of Lost Work Trips - Storm Surge

	Andrew	Fort Lauderdale	Delray Beach
Miami-Dade County	$ 38,072,769	$ 27,494,033	$ 17,230,029
Broward County	$ 5,849,652	$ 36,469,231	$ 7,181,501
Palm Beach County	$ 2,467,921	$ 11,781,672	$ 12,903,188
System Total	$ 46,390,341	$ 75,744,936	$ 37,314,719

7 Source: National Household Travel Survey

Table 4.7 Cost of Lost Work Trips - Storm Surge + Sea Level Rise

	Andrew		Fort Lauderdale		Delray Beach	
Miami-Dade County	$	79,730,305	$	30,107,245	$	28,213,306
Broward County	$	16,119,200	$	39,025,027	$	14,948,511
Palm Beach County	$	10,332,509	$	14,819,087	$	17,917,384
System Total	$	106,182,015	$	83,951,360	$	61,079,202

4.5.2 Cost of Increased Hours of Delay

Increased hours of delay is calculated by comparing hours of delay in each scenario to that in the baseline model. Scenarios of storms usually cause road closures and, trip rerouting leading to congestion that increases hours of delay in the remaining network. However, in an area where there is significant trips lost, the total hours of delay could be less than in the baseline model. The cost of increased hours of delay by personal vehicles and trucks are calculated using the following equations. Average value of person time and commercial time in the Miami metropolitan area are applied to the calculation[8].

$$\begin{aligned} &Cost\ of\ Increased\ Personal\ Vehicle\ Hours\ of\ Delay \\ &\quad = (Vehicle\ hours\ of\ Delay_{Scenario} - Vehicle\ hours\ of\ Delay_{Baseline}) \\ &\quad \times Average\ Vehicle\ Occupancy \times Value\ of\ Person\ Time \end{aligned}$$

$$\begin{aligned} &Cost\ of\ Increased\ Truck\ Hours\ of\ Delay \\ &\quad = (Truck\ hours\ of\ Delay_{Scenario} - Truck\ hours\ of\ Delay_{Baseline}) \times Value\ of\ Commecial\ Time \end{aligned}$$

- $Average\ Vehicle\ Occupancy = 1.25\ Person\ per\ Vehicle$
- $Value\ of\ Person\ Time = \$17\ per\ Hour$
- $Value\ of\ Commercial\ Time = \$94\ per\ Hour$

As shown in Table 4.8 and Table 4.9, the additional hours of delay are predicted to cause about $49 million to more than $700 million financial loss to the three-county area. Miami-Dade County is projected to have the greatest economic impact associated with hours of delay among the three counties. Negative numbers mean that the total hours of delay were less than those in the baseline model, indicating that there were likely significant lost of trips in those areas.

Table 4.8 Cost of Increased Hours of Delay - Storm Surge

	Andrew		Fort Lauderdale		Delray Beach	
Miami-Dade County	$	732,332,349	$	(12,532,450)	$	11,236,390
Broward County	$	10,632,246	$	100,880,793	$	26,367,536
Palm Beach County	$	(411,691)	$	274,458,326	$	11,663,867
System Total	$	742,552,904	$	362,806,669	$	49,267,793

[8] Source: TTI's 2015 Urban Mobility Report. Texas A&M Transportation Institute.

Table 4.9 Cost of Increased Hours of Delay - Storm Surge + Sea Level Rise

	Andrew	Fort Lauderdale	Delray Beach
Miami-Dade County	$ 585,118,962	$ (7,338,465)	$ 2,359,974
Broward County	$ 111,510,043	$ 14,482,210	$ 244,862,744
Palm Beach County	$ (1,342,415)	$ 171,699,216	$ 18,807,119
System Total	$ 695,286,590	$ 178,842,961	$ 266,029,837

5.0 Findings and Recommendations

The results of this project build on the FHWA Pilot project in several ways. The Pilot identified facilities vulnerable to SLR and this project focuses on those facilities that are vulnerable to storm surge as well as SLR, thereby helping to identify facilities that can be prioritized for further investigation and improvements. It also identified areas that are isolated as the result of storm events, highlighting communities where more in depth evaluation is needed to ensure access to critical goods and services. The Pilot incorporated adaptive capacity into the vulnerability ratings through a process of identifying detours. This project relied on SERPM to account for traveler preferences to take alternate routes for impacted trips, providing an end-to-end trip perspective. Using SERPM allowed for many more roads to be analyzed and included transit effects.

SLOSH overestimates potential impacts by using a maximum height of the worst case (maximum) storm for each grid cell analyzed. Using a scenario approach eliminated the “second” maximum by looking at the worst case for a single historic storm track. This refinement helped to localize associated impacts. This project further enhanced SLOSH results by calibrating them against recorded surge heights. Using historic storm tracks allows for calibration. Basin-wide techniques also might provide broader project storm surge impacts and i may also be feasible to use a single track that is moved north and south, and given different intensities, to provide some consistency for comparison purposes.

A consideration for future enhancement is the geospatial accuracy of the transportation network. The SERPM GIS network deviates from the true road and rail network. As such, some areas that are noted as inundated could be dry during a storm event, and vice versa. Digital elevation mapping tools are improving rapidly. By enhancing the transportation network GIS representations it will be possible to incorporate new elevation data in the future.

As mentioned above, SERPM allows for rerouting of roadway trips. To support rerouting (or detours) for transit trips would require coding the detoured routes in the SERPM network. The effort to make the SERPM changes to support transit adaptive capacity likely is not offset by the low mode share of transit usage. However, supporting changes in Miami-Dade County, which sees higher transit ridership, and where the six SMART Corridors are being planned, should be considered. The lack of transit adaptive capacity means that the results here over emphasize the impacts to transit. In practice, transit service, if able to run, would rely on alternate facilities to circumvent disrupted segments.

Combining the two modeling efforts (transportation and water) provides robust results that can be replicated elsewhere in the state. It is tempting to wait for data, or repeat tests, as new data becomes available. This project was no exception as new elevation data became available after two scenarios were completed. A comparison of the changes was performed, and for a planning level analysis, it was determined that moving forward with different sources of elevation data did not significantly skew overall results. Several partners are undertaking enhanced water related modeling studies that can be incorporated in future assessments. For example, the impacts of SLR on groundwater, and ultimately surface water, is being studied and can be addressed in future transportation planning and emergency management discussions. Much research is underway, including by universities in Florida, on data, tools, and climate science. Periodically assessing the risks to transportation infrastructure should be pursued.

Two questions were frequently raised when sharing the project’s results: how deep is the inundation, and how long it will last. This project assumed any facility touched by storm surge was not available for use for an entire day. Applying elevation data to the inundated areas may prove useful in answering the depth question for future investigations. The time duration question is more difficult to answer and could be addressed by collaborating with storm water management and public works officials familiar with local conditions. The FHWA Pilot flooding hotspot information could serve as a proxy for work on a regional level.

The basic economic information provided by this project helps foster a conversation about the costs of incorporating adaptation strategies into transportation infrastructure. The high level figures show the extent of delay and lost trips – two major impacts. However, impacts on the economy as a result of the disruption are not included, nor are impacts associated with seaport and airport disruptions. More robust economic analyses may be warranted to evaluate the benefits and costs of implementing adaptation strategies in the future.

The regional nature of travel patterns in Southeast Florida means the loss of access to an economic or employment center results in the inability of trips to be completed throughout the three counties. These are termed “lost trips” because the origination or destination is inaccessible, and no rerouting (or adaptive capacity) is possible. In the scenarios with storm surge only, up to 11 percent (one in nine) of all trips cannot be completed due to lack of access at the originating or terminating end. For the storm surge plus SLR scenarios, up to 15 percent of trips are lost (one in seven). This includes both transit and non-transit trips. Miami-Dade County is impacted the most by the three storm events and SLR adds to the impacts, roughly doubling the exposure in 2040. However, there are locations in each of the three counties that become inaccessible, or isolated, due to storm surge and SLR.

The storm surge project demonstrates the impacts on areas with connections to open water. The most vulnerable areas are those with hydrological connections to the coast, such as inlets and areas near the Miami River, Middle River, and Loxahatchee River. More inland areas are at risk of storm surge with and without SLR in the proximity of potential breaches to the informal dikes formed from roadways such as I-95. If not already part of transportation related emergency management preparations, operational strategies to protect hydrologically vulnerable areas and to reduce storm surge impacts should be identified. For example, some agencies close roads ahead of King Tide events to prevent travelers from being stranded and to protect wet, more fragile transportation infrastructure from the weight of heavy vehicles that can promote pavement failures (potholes and washouts). Similar strategies are deployed for storm events and tools to help plan for and detour traffic are needed.

Simulated storms are predicted to reduce daily VMT in the transportation network. When coupled with sea level rise, these storms will reduce system-wide daily VMT by five to 11 percent. These reductions are due to trips that cannot be complete due to isolated origination or destination areas. Simulated storm and storm plus SLR events are predicted to increase total daily VHT in all three counties. The increase of VHT (as compared to baseline 2040 conditions) varies in the three counties and by storm track, and increases range from 19 percent to more than 300 percent. The additional hours of delay results in $49 million to more than $700 million in the value of drivers’ time spent traveling. These ranges show that while addressing storm surge and SLR is a regional challenge, different parts of the region may be more affected for any given circumstance.

Potential impacts are not limited to roadways. Several Tri-Rail, Tri-Rail Coastal Link, Metrorail, and fixed route bus segments are vulnerable to storm surge and storm surge plus sea level rise. Transit trips in the three counties is predicted to be reduced up to 16 percent with storm surge only and up to 22 percent with storm surge plus SLR. In the worst case scenarios, Miami-Dade County and Broward County may see up to 32 percent and 31 percent of transit trips lost, respectively[9]. Future transit focused studies could evaluate the impacts more closely and better incorporate adaptive capacity routing.

[9] As noted in Section 4.3.2, transit trips on Tri-Rail Coastal Link are not part of the total.

Small areas of Miami International Airport and Fort Lauderdale/Hollywood International Airport are predicted to be inundated in various scenarios. The areas most affect are the lower lying areas surrounding the runways. Access to these airports also is impacted. As to be expected, given the proximity to the coasts, PortMiami, Port Everglades, and Port of Palm Beach each have areas inundated due to storm surge and storm surge plus SLR. The facilities are critical economic engines for the region and provide important access. Acknowledging low lying areas and providing strategies to address potential risks to transportation and services should be included in master planning studies.

Based on the findings above and suggestions offered by planning partners, the following recommendation are made for future transportation planning, operations, and tools/resources:

- FDOT or other agencies should consider applying a similar (or enhanced) storm surge and SLR scenario approach to evaluating transportation implications to other areas of the state. The Treasure Coast region would be a next logical phase. In partnership with the regional council, performing a more thorough economic analysis (using REMI) would provide more detailed information to support benefit cost discussions.

- More robust assessment of airport and seaport impacts, including impacts on access to these facilities and estimations of economic cost, are appropriate, especially given the very long life span of these facilities. Airport and seaport master planning processes should consider storm surge and SLR climate stressors as part of future planning. Similarly, transit agencies plans should consider potential disruptions noted here and incorporate rerouting plans and alternate staging/maintenance areas as part of continuity of operations plans.

- Regional partners should continue to address recommendations from ongoing initiatives (e.g., FHWA Pilot and Regional Compact). These recommendations concentrate on identifying adaptation strategies and implementing projects. Storm surge risks and mitigation strategies in areas identified by this and similar projects should also be considered.

- As an ad hoc working group, a sub committee of the Regional Climate Change Compact, under the auspices of the regional councils' emergency management tasks, or via another mechanism, regional partners should continue to collaborate on transportation related storm surge and storm surge plus SLR related emergency management data, planning, operations, maintenance, and response activities. The coordination can be broadened for the protection of transportation infrastructure and operations to include water management and drainage districts, and public works officials. Emergency management and public works and maintenance personnel have information about problematic locations and also have seen the impacts past storm surge and flooding events. Their knowledge is important to prioritize areas or ways to focus resources, or recommendations to identify strategies to mitigate the impacts of flooding or surge. Also, the partners should encourage the creation of a guideline/handbook which summarizes methods, findings, and applications of various storm surge and sea level rise projects, including this project, the South Florida FHWA Pilot Project, and the Florida Sea Level Scenario Sketch Planning Tool.

- This project reiterates some vulnerabilities identified by the FHWA Pilot Project, and focuses attention on areas particularly vulnerable to storm surge. Planning partners should prioritize resiliency and emergency management considerations for highly vulnerable areas, namely those areas impacted by all three storm tracks.

- Parties are encouraged to enhance tools that support planning and operational decision making. The Pilot results and this project provide tools that can be used immediately to identify projects that may require additional vulnerability review. Adaptation modifications should be included as part of planning, engineering, design, maintenance, and operations processes and procedures. For example, FDOT could take steps to improve the geospatial accuracy of the travel demand forecasting model for use in future studies and to support asset management. It is also recommended that these projects to be incorporated in the FDOT Efficient Transportation Decision Making (ETDM) process initially for internal use. Another recommendation is to create a sketch level resource to identify potential transportation facilities in the path of an impending storm. Such a tool could be used for evacuation purposes or road closure/detour planning of at-risk areas to protect people and infrastructure.

- For future projects, using the best data and tools available at the time is recommended. With the increasing amounts of research and data, revisiting planning studies periodically (every five to ten years) is appropriate. For example, as SLR projections evolve, and new groundwater modeling results are known, it will be important to reassess vulnerabilities. For example, a next step in transportation/transit planning would be to repeat this analysis utilizing the 6 SMART Plan Corridors and the BERT express Bus Routes inclusive of their terminals in order to better plan for adaptation strategies for these projects.

- The Fixing America's Transportation Act (FAST) requires the planning process to consider projects/strategies to: improve the resilience and reliability of the transportation system, stormwater mitigation, and enhance travel and tourism. The region is ahead on the issues given the work of the FHWA Pilot Project and the Climate Compact. However, given the regions susceptibility to storm surge and SLR, incorporating resiliency in all stages of project planning, programming, engineering, construction, and maintenance should be considered. One first step would be to incorporate objectives and evaluation criteria in decision making. One suggestion is to mainstream adaptation strategies in the next round of long range transportation plans or set aside funding to allow adaptation strategies to be included in projects. Local governments are encouraged to incorporate considerations of storm surge and sea level rise in the Comprehensive Plans, Capital Improvement Plans, and Emergency Management Plans. Local transit agencies and traffic/transit operation offices should be debriefed on the findings revealed in this study. This information may help refine their Hurricane Preparation Manuals and procedures during major weather events.

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Appendices

Contents

Summary of Data Sources

The four categories of data sources below are described further in Appendices A-D

	Title	Description	Latest Revision Date	Date Accessed	Source	
LIDAR	2007-08 Palm Beach East 10-ft DEM, v1	Lidar collected July-Dec 2007 and processed at SFWMD	2009	2/15/16	my.sfwmd.gov/gisapps/sfwmdxwebdc/dataview.asp	
	2007 Broward 10-ft DEM, v1	Lidar collected July-Dec 2007 and processed at SFWMD	2009	2/15/16	my.sfwmd.gov/gisapps/sfwmdxwebdc/dataview.asp	
	Miami Dade 2015 Lidar 5-ft DEM	Classified Lidar producing a bare-earth DEM	2/2015	4/5/16	Marcia Steelman, CFM, Engineer 3 Stormwater Utility Planning Division http://www.miamidade.gov/development/flooding-protection.asp 701 NW 1st Court, 5th Floor, Miami, Florida, 33136 (305) 372-6691 (305) 372-6425 fax	
Historic Observations	SURGEDAT & U-Surge http://www.u-surge.net/	Database of documented surge heights	2/2016	2/2016	Documented surge heights for each storm are quantified based on the number of SURGEDAT data points for each storm, within each county, as well as the reliability of the data source, whether it is a tide gauge or other measurement methods, including debris lines and still water marks. The sources are cited.	

	Title	Description	Latest Revision Date	Date Accessed	Source	
SLOSH & Storm Tracks	Historical North Atlantic Hurricane Tracks - Major Storms with Landfall in the United States, 1851-2004	Documents major storms (classified on the Saffir-Simpson Hurricane Scale as Category 3, 4, or 5 at the time of landfall) with landfall center locations and intensities for all northern Atlantic major storms from 1851 through 2004.	9/2005	2/2016	http://www.nhc.noaa.gov/data/#hurdat	
Shoreline	FLORIDA COASTLINE	This GIS data set represents the Florida shoreline as lines. Initially digitized in 1990 by USFWS under FWRI contract, the data set was created from the most current National Oceanic and Atmospheric Administration (NOAA) Nautical Charts available at the time.	2/2004	2/2016	http://www.fgdl.org/metadataexplorer/explorer.jsp	

Appendix A Metadata for LiDAR

Palm Beach County Lidar Metadata

Please see baseline specifications (http://www.floridadisaster.org/GIS/specifications/Documents/BaselineSpecifications_1.2.pdf) for further detail on deliverables and specifications. Although the datum is specified as NAD83/HARN, the South Florida Water Management District (SFWMD) converted it to NGVD29 when it was decorrugating and processing the data to produce the best available digital elevation model from it. The data was retrieved from the SFWMD data catalog (http://my.sfwmd.gov/gisapps/sfwmdxwebdc/dataview.asp)

Title: 2007-08 Palm Beach East 10-ft DEM, v1

Description: This raster dataset is a 10-ft digital elevation model (DEM) of bare earth that covers most of eastern and urban Palm Beach County and a relatively small area of southern Martin County. A portion of southeast Palm Beach (by Boca Raton) is not included in this DEM, but it can be found in the Broward (block 6) DEM. Elevation values are in feet, NAVD 1988 (GEOID03). The DEM was created using data from the 2007 Florida Division of Emergency Management (FDEM) Statewide Coastal LiDAR project (Delivery Block 7, flown between Nov 2007 and Jan 2008). It was prepared to support business functions that benefit from terrain elevation surfaces for which the accuracy and other characteristics of this dataset are deemed appropriate by the DEM end user. DEMs are commonly used in the District for modeling, visualization and analysis.

Theme Keywords: topography, topographic, digital elevation model, DEM, digital terrain model, DTM, LiDAR, elevation, terrain, bare earth surface, altitude, height, hypsography, elevation, imageryBaseMapsEarthCover

Place Name Keyword: Florida, South Florida, Gold Coast Region, Palm Beach County, Martin County, West Palm Beach, Jupiter, Boca Raton, Lake Worth, Palm Beach Gardens, Boynton Beach, Delray Beach, Loxahatchee River, Lake Worth Creek Aquatic Preserve, Intracoastal Waterway, Lake Worth Lagoon

Source Organization: South Florida Water Management District (SFWMD)

Data Type: GRID

Projection: NAD_1983_HARN_StatePlane_Florida_East_FIPS_0901_Feet

2007-08 Palm Beach East 5-ft DEM in NAVD 1988, Release Version 1. This is a raster dataset, representing a 5-ft digital elevation model (DEM) of bare earth that covers most of eastern and urban Palm Beach County and a relatively small area of southern Martin County. A portion of southeast Palm Beach (by Boca Raton) is not included in this DEM, but it can be found in the Broward (block 6) DEM. Elevation values are in feet, NAVD 1988 (GEOID03). The DEM was created using deliverables from the 2007 Florida Division of Emergency Management (FDEM) Statewide Coastal LiDAR project, authorized by the Florida House Bill (HB) 7121 - Disaster Preparedness Response and Recovery. For this specific DEM, SFWMD used the last known set of accepted vendor deliverables from FDEM's delivery block 7, composed of 343 tiles. Each tile is sized 5000-ft by 5000-ft, in accordance with FDEM's tiling system. The project area is ~ 308 sq mi.

Broward County Lidar Metadata

Title: 2007 Broward 10-ft DEM, v1
Description: This raster dataset is a 10-ft digital elevation model (DEM) of bare earth for eastern portions of Broward County, as well as relatively small portions of southern Palm Beach County and northern Miami-Dade County. Elevation values are in feet, NAVD 1988. The DEM was created using data from the 2007 Florida Division of Emergency Management (FDEM) Statewide Coastal LiDAR project (Delivery Block 6, flown between Jul and Dec 2007). It was prepared to support business functions that benefit from terrain elevation surfaces for which the accuracy and other characteristics of this dataset are deemed appropriate by the DEM end user. DEMs are commonly used in the District for modeling, visualization and analysis.
Theme Keywords: topography, topographic, digital elevation model, DEM, digital terrain model, DTM, LiDAR, elevation, terrain, bare earth surface, altitude, height, hypsography
Place Name Keyword: elevation, imageryBaseMapsEarthCover
Source Organization: South Florida Water Management District (SFWMD)
Data Type: GRID

Miami Dade 2015 Lidar Metadata:

Bare-earth 5-foot DEM as 32-bit floating point raster format in ARCGIS GRID Raster format in compliance with USGS LIDAR Base
Specifications such as: georeferencing information, delivered without overlap and with no edge artifacts or mismatched, “NODATA” value for void areas, bridges removed from the surface, etc
This is a Digital Elevation Model (DEM) as a raster mosaic in ESRI float format 32bit representation on a 5ft grid created from the LiDAR
collected for the 2015_ITD_LiDAR project for the Miami-Dade County Information Technology Department (ITD).
The DEM extent is Miami-Dade County as provided by ITD
users should be aware that temporal changes may have occurred since this dataset was collected and that some parts of the data may no longer represent actual surface conditions. Users should not use the data for critical applications without a full awareness of the limitations of the data.
The data was collected under the supervision of a Florida licensed Surveyor and Mapper in compliance with Florida Statute 472.000 This control is adequate to support the accuracy specifications identified for this project.
The surveyor’s report documents and certify the procedures and accuracies of the horizontal and vertical control, aircraft positioning systems, and system calibration procedures used in this LiDAR mapping project. The horizontal
and vertical control is based on direct ties to National Geodetic Survey (NGS) control stations, National Spatial Reference System (NSRS). The horizontal control references the North American Datum of 1983/NSRS current published
datum (NAD_1983_HARN_StatePlane_Florida_East_FIPS_0901_Feet). The vertical control references the NAVD88 using Geoid 12A to perform computations from
ellipsoidal heights to orthometric heights. The vertical accuracy of the newly-established ground control is within one third of the specified LiDAR Fundamental Vertical Accuracy. All surveying & mapping performed for this project meets or exceeds FEMA Flood Hazard Mapping Program, Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A, Section A.5 Ground Control, and Section A.6 Ground Surveys and as superseded by Procedure Memorandum No.61 – Standards for LiDAR and

Other High Quality Digital Topography, 27 September 2010.
ACA collected the data at 8 points per square meter providing a spacing of 0.35m spacing at nadirThis product meets or exceeds the stated specifications for the state of Florida.
Horizontal accuracy was tested to meet or exceed a 3.8 foot horizontal accuracy (2.2 foot RMSE) at 95 percent confidence level using RMSE(r) x 1.7308 as defined by the Federal Geographic Data Committee's (FGDC) Geospatial Positioning Accuracy Standards, Part 3: NSSDA.

Projected Coordinate System:
NAD_1983_HARN_StatePlane_Florida_East_FIPS_0901_Feet</horizpar></horizpa><vertacc><vertaccr>This product meets or exceeds the stated specifications for the state of Florida.
The Fundamental Vertical Accuracy for LiDAR data over well-defined surfaces was tested to meet or exceed a 0.60 foot fundamental vertical accuracy in open well defined terrain at 95 percent confidence level using RMSE(z) x 1.9600
as set forth in the FGDC Geospatial Positioning Accuracy Standards, Part 3: NSSDA. For the purpose of this document, open terrain is defined as unobscured, consolidated surfaces, with minimal slope (< 5%) and may contain low-lying grasses through which LiDAR pulses can penetrate; LiDAR errors in these areas will have a statistically normal distribution with a mean = 0 and variance = 1. Vertical accuracies will meet the 95 percent confidence level for open terrain, assuming all systematic errors have been eliminated to the greatest extent possible and the errors are normally distributed. A minimum of thirty (30) check points per each land cover were be distributed throughout the project area and collected for each of the following land cover categories and reported in the FVA report: ⍰ Urban; ⍰ Bare ground/short grass; and ⍰ Brush (i.e. low lying vegetation). Check points are distributed so that points are spaced at intervals of at least ten (10) percent of the diagonal distance across the dataset and at least twenty (20) percent of the points are located in each quadrant of the dataset per 500 square mile block. See vendor's report. North American Vertical Datum of 1988 (NAVD88 The project was divided in two phases: Collection and classification of LiDAR data; and building height extraction.
The LiDAR data was collected utilizing a Riegl LMS-Q680i in a Cessna 206 from an approximate altitude of 1,800 feet above ground level, an approximate ground speed of 110 knots at a pulse rate repetition of 400kH, resulting in a minimum of 8.2 points per square meter. The sensor used a 60 degree field of view. The project was flown to have 50 percent overlap between swaths. The Global Positioning System (GPS) data were processed using Applanix POSPac Mapping Suite version 7.8 using Smart Base method and single base methods. A fixed bias carrier phase solution was computed in forward and reverse directions. The LiDAR collection took place when Positional Dilution of Precision (PDOP) was at or below 3. Occasionally, the PDOP rose slightly above 3. This had no effect on the data. The GPS trajectory was combined with the IMU data using the Applanix POSPac software. The resulting Smoothed Best Estimate of Trajectory (SBET) was exported and used in Riegl RiProcess software to compute the laser mass point positions in Northing, Easting, and Elevations coordinates. The raw laser data were merged with the SBET using Riegl RiProcess software. The data set was processed using RiProcess, RiAnalyze, and RiWorld software where each flight line was processed to a point cloud.
The data was adjusted flight line to flight line using Riegl's Scan Data Adjustment tool to ensure a proper relative calibration match between flight lines. Each flight was checked for project coverage, data gaps between overlapping flight lines, point density and then exported in LAS 1.3 format. The entire project was collected without gaps.
The LAS files were projected to the NAD_1983_HARN_StatePlane_Florida_East_FIPS_0901_Feet and North American Vertical Datum of 1988 (NAVD88). Ellipsoidal heights were converted to orthometric heights using the current Geiod12A. The LAS files were imported to TerraSolid, LTD TerraScan software to be classified to bare earth ground and later feature coded to USGS specifications. The LAS files contain 8 classifications: 1 = unclassified; 2 = ground; 7 = noise points; 9 = water; 10 = buffered ground

points surrounding breaklines; 12 = overlap; 15 = overpass and bridges.
The tiles dataset was imported to Digital Transfer Solutions EarthShaper® software to collect breaklines from LiDAR data. The single and double line linear hydrographic features were hydro-enforced with downhill constraints to model correct flow patterns. Water bodies were hydro-flattened to ensure uniform elevation across the feature.
The data were adjusted flight line to flight line using Riegl's Scan Data Adjustment tool to ensure a proper relative calibration match between flight lines. Each flight was checked for project coverage, data gaps between overlapping flight lines, point density and then exported in LAS 1.3 format.
The LAS files were imported to TerraSolid, LTD TerraScan software to be classified to bare earth ground and later feature coded to USGS specifications. The LAS files contain 8 classifications: 1 = unclassified; 2 = ground; 7 = noise points; 9 = water; 10 = buffered ground points surrounding breaklines; 12 = overlap; 15 = overpass and bridges.
DEMs were created using QCoherent LP360 software. The bare-earth LAS data was loaded into the software along with the tile layout and hydro shapefile collected from the LAS data set. DEMS were produced at a 5ft cell size and hydro-flattened. To QC the DEMs Global Mapper was used to check for completeness of the tiles and that the hydro features were flattened and represented correct elevations. Once the QC was complete the files were exported out of ArcGIS to create Arc DEMS.
The LiDAR data was ran through an automated ground and building classification using terrascan software. A manual check of the building classification was done in LP360 and terrascan. The provided building shapefile was loaded and data cross sections were taking to check the classification of the outlined buildings. Once the manual check was completed the building LAS points were loaded into LP360 along with the building polygon shapefile supplied by ITD. In LP360 a confliction was ran to drape each building polygon to the max Z value of LAS data found in each polygon. To QC the auto process the building polygon shapefile was brought into ArcGIS using LP360 to take cross sections of the data to check the building polygon Z value.
After all the building data was quality controlled and assured we joined the field height to complete the geodatabase BuildingPlanimetrics_from PSDE3.gdb provided by the county. Any building with a height value of 0 represents a building that did not exist in the LiDAR dataset.
The building geodatabase remained as ITD provided it projected horizontally to the NAD_1983_ StatePlane_Florida_East_FIPS_0901_Feet, and vertically to the North American Vertical Datum of 1988 (NAVD88).
COLLECTION DATES: 2/15/15, 2/17/15, 2/18/15, 2/19/15, 2/20/15, 2/21/15, 4/2/15, 4/3/15, 4/11/15/, 4/12/15, 4/13/15.
366 flight lines of data were collected
DEM raster dataset for Miami-Dade County
* Pixel depth   32
* Compression type   None
* Number of bands   1
* Raster format   GRID
* Source type   continuous
* Pixel type   floating point

Appendix B Metadata for Historic Observations

Observation points used for Hurricane Andrew:

Storm Tide (Ft)	Datum	Observation Type	Location	Lat	Lon
4.92	NGVD	Debris Line	Homestead	25.437	-80.329
6.56	NGVD	Debris Line	Biscayne National Park/Homestead	25.4525	-80.195
6.56	NGVD	Still Water Mark	Homestead	25.4633	-80.335
7.55	NGVD	Water Gage Max	Homestead	25.4705	-80.347
7.87	NGVD	Water Gage Max	Homestead	25.4895	-80.347
7.87	NGVD	Water Gage Max	Homestead	25.5112	-80.347
12.47	NGVD	Still Water Mark	Homestead	25.5194	-80.346
6.89	NGVD	Still Water Mark	Biscayne National Park/Homestead	25.5253	-80.174
17.06	NGVD	Still Water Mark	Palmetto Bay	25.6028	-80.309
17.06	NGVD		East Perrine	25.6035	-80.31
16.73	NGVD	Still Water Mark	Palmetto Bay	25.6106	-80.31
14.76	NGVD	Still Water Mark	Coral Gables	25.6377	-80.289
11.81	NGVD	Still Water Mark	Coral Gables	25.6526	-80.278
8.86	NGVD	Still Water Mark	Key Biscayne	25.6665	-80.156
7.55	NGVD	Still Water Mark	Key Biscayne	25.6814	-80.17
6.89	NGVD	Water Gage Max	Coral Gables	25.6889	-80.273
9.51	NGVD	Still Water Mark	Coral Gables	25.7005	-80.257
9.19	NGVD	Still Water Mark	Miami	25.7106	-80.251
7.55	NGVD	Still Water Mark	Key Biscayne	25.7234	-80.155
9.84	NGVD	Still Water Mark	Miami	25.7353	-80.225
9.19	NGVD	Still Water Mark	Miami	25.7412	-80.211
16.90	NGVD	Still Water Mark	Biscayne Bay	25.7453	-80.205
5.91	NGVD	Debris Line	Miami	25.748	-80.143
7.55	NGVD	Still Water Mark	Miami	25.758	-80.189
5.58	NGVD	Debris Line	Miami Beach	25.7794	-80.149
5.25	NGVD	Water Gage Max	Allapattah	25.8062	-80.259
4.92	NGVD	Water Gage Max	Miami Springs	25.8102	-80.264
3.94	NGVD	Water Gage Max	North Miami	25.8465	-80.185
3.94	NGVD	Water Gage Max	Biscayne Park	25.8816	-80.162
4.59	NGVD	Water Gage Max	Bal Harbour	25.8998	-80.125

2.95	NGVD	Water Gage Max	Maule Lake	25.9386	-80.14
6.10	NGVD	Water Gage Max	Bakers Haulover Inlet, Pier	25.901	-80.121

Sources: Mayfield, Avila, & Rappaport, 1994; Schmidt, Taplin, & Clark, 1993; Rappaport, 1993

Observation points used for Delray Beach Hurricane (1949):

Storm Tide (Ft)	Datum	Location	Lat	Lon
7.00	MSL	Palm Beach	26.7054	-80.0328

Sources:
Barnes, J., 1998: Florida's hurricane history. University of North Carolina Press
Richmond T. Zoch (December 1949). North Atlantic Hurricanes and Tropical Disturbances of 1949 (PDF) (Report). United States Weather Bureau.

Observation points used for Ft Lauderdale Hurricane (1947) (Hurricane George)

Storm Tide (Ft)	Datum	Location	Lat	Lon
3.20	MSL		25.3926	-80.3266
3.60	MSL		25.6875	-80.1566
4.20	MSL	Near Key Biscayne	25.6935	-80.1566
6.30	MSL		25.8765	-80.1198
4.20	MSL	Near Fort Lauderdale	26.1190	-80.1041
9.80	MSL	Near Pompano Beach	26.2551	-80.0837
11.00	Mean Low Tide	Hillsboro Lighthouse	26.2589	-80.0808
11.00	Normal Astronomical Tide	Boynton Beach	26.5225	-80.0482
11.00	Normal Astronomical Tide	Palm Beach	26.6972	-80.0339
8.80	MSL	Near Fort Pierce	27.4504	-80.3230
1.50	MSL	Near Wabasso	27.7512	-80.4320
4.50	MSL	Near Melbourne	28.0928	-80.5659

Sources:
https://coast.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf?redirect=301ocm
Barnes, J., 1998: Florida's hurricane history. University of North Carolina Press

Appendix C Metadata for Storm Tracks and SLOSH Grid

For Information on SLOSH Basin Development, see Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Basin Development Handbook v2.0

Reference: Conver, Andrea, Julie Sepanik, Bobby Louangsaysongkham, and S. Miller. "Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Basin Development Handbook v2. 0." (2008).
Available at http://www.nist.gov/itl/math/hpcvg/upload/BasinDevelopmentHandbook20081211.pdf

The SLOSH Display Program's (SDP) can be downloaded at https://slosh.nws.noaa.gov/sdp/register.php?L=6

SDP's primary purpose is to display the results of the SLOSH model. Dowloading the program provides access to the REX files for running historic storms. SLOSH output is available for two types of storms: Hypothetical and Historical Hypothetical SLOSH runs are described above. Historical SLOSH runs are based on the best post-storm estimates of track, intensity, and size for the historical hurricane. These runs are used to educate people about the timing and impact of a historical storm and to validate the SLOSH model.

The output of each historical storm can come in any of four file formats: A Rex File, an envelope file, an animated GIF file, and a GIS compatible shapefile. The animated GIF file and GIS compatible shapefile are derived from the Rex file. A Rex file (named after Arthur's dog Rex), contains snapshots of surge elevations at a fixed time interval (usually 10-15 minutes) and contains all of the information necessary to regenerate the wind field at that instant in time. The last frame of the animation shows the Envelope of High Water (EOHW) which is the maximum surge level for this single storm. The last frame of the Rex file should match the envelope file. The advantage of the Rex file is that it stores data rather than images. This allows the SDP to probe the Rex file at a specific point, and animate it at user specified resolutions.

Source: https://slosh.nws.noaa.gov/sdp/

Historical North Atlantic Hurricane Tracks - Major Storms with Landfall in the United States, 1851-2004

Citation_Information:
Originator:
National Oceanic and Atmospheric Administration, Tropical Prediction Center/National Hurricane Center
Publication_Date: September 2005
Title:
Historical North Atlantic Hurricane Tracks - Major Storms with Landfall in the United States, 1851-2004

Publication_Information:
Publication_Place: Reston, VA
Publisher: National Atlas of the United States
Online_Linkage:
<http://nationalatlas.gov/atlasftp.html?openChapters=chpclim#chpclim>
Description:
Abstract:
This Historical North Atlantic Hurricane Tracks file of major storms with landfall in the United States contains the six-hourly (0000, 0600, 1200, 1800 UTC) center locations and intensities for all northern Atlantic major storms from 1851 through 2004. Major storms are those that made landfall in the United States and that were classified on the Saffir-Simpson Hurricane Scale as Category 3, 4, or 5 at the time of landfall. Landfalling storms are defined as those storms whose center is reported to have either crossed or passed directly adjacent to the United States coastline, and which came ashore with tropical storm intensity or greater (sustained surface winds of 34 knots or 39 miles per hour or greater). In 2000, 2001, 2002, and 2003 there were no major landfalling hurricanes. This a replacement for the January 2005 map layer distributed as Historical North Atlantic Hurricane Tracks - Major Storms with Landfall in the United States, 1851-2003.
Purpose:
These data are intended for geographic display and analysis at the national level, and for large regional areas. The data should be displayed and analyzed at scales appropriate for 1:2,000,000-scale data. No responsibility is assumed by the National Oceanic and Atmospheric Administration or the National Atlas of the United States in the use of these data.
Supplemental_Information:
An ASCII format version of the Historical Atlantic Tropical Cyclone Tracks file is available at <http://www.nhc.noaa.gov/tracks1851to2004_atl.txt>. The ASCII file contains the source information from which the file of major landfalling storms was drawn.

For more information on the Saffir-Simpson Hurricane Scale, please see <http://www.nhc.noaa.gov/aboutsshs.shtml>.

For more information on tropical cyclone advisories, please see <http://www.nhc.noaa.gov/HAW2/english/forecast/forecast_products.shtml>.

General information on subtropical and tropical cyclones is available from the National Oceanic and Atmospheric Administration, Atlantic 0 Oceanographic and Meteorological Laboratory, Hurricane Research Division FAQ page at <http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html>, and from the National Hurricane Center Hurricane Basics page at <http://www.nhc.noaa.gov/HAW2/english/basics.shtml>.

Attribute_Accuracy_Report:
Specific accuracy information can be found in Neumann, C.J., B.R. Jarvinen, C.J. McAdie and G.R. Hammer, 1999: Tropical Cyclones of the North Atlantic Ocean, 1871-1999 (fifth revision). NCDC/NHC Historical Climatology Series 6-2, pp.11-14. Similar standards and techniques were applied to the post-1999 data.
Logical_Consistency_Report:
Over-water portions of storm tracks before 1944 are subject to considerable uncertainties. Aircraft reconnaissance of storms near critical areas was introduced in 1944, and continuous weather satellite surveillance was introduced in the mid-1960s. These two developments mean that more recent storm records have a higher degree of accuracy than those prior to 1944. No tests for logical consistency have been performed on this

map layer.

Completeness_Report:

This map layer contains all known Atlantic Basin (Gulf of Mexico, Caribbean Sea, and North Atlantic Ocean) major hurricanes that made landfall in the United States and that occurred between 1851 and 2004. Major landfalling hurricanes are those that were classified on the Saffir-Simpson Hurricane Scale as Category 3, 4, or 5 at the time of landfall. In 2000, 2001, 2002, and 2003 there were no major landfalling hurricanes.

Process_Description:

To create Atlas-hurall04 from ATL_2004, historical track information was downloaded from the National Hurricane Center's Web site. The ASCII text file was formatted into an Arc/INFO table using AML. The INFO table was then processed into a generate file and an attribute table that were converted into an attributed cover.

Location points are recorded every six hours. Each recorded point was associated with a unique line that extends from that point to the next recorded point. Small line segments, approximately 0.0001 degree long, were added to the end of each storm track to retain the final collection point's information. In the source data, tracks that crossed the 0-degree longitude line had negative longitude values even in the eastern hemisphere. These longitude values were converted to the corresponding positive longitude values.

A limit in the processing software will not allow duplicate points, so where a storm stood still longer than the six-hour collection interval, the next location point was offset approximately 0.0001 degrees to retain relevant information.

During the process of creating Atlas-hurall04, information on landfalling storms was extracted to an INFO table. This information was joined to Atlas-hurall04 and used to extract landfalling major hurricanes, which are those that made landfall as category 3 or higher.

The cover was converted into a shapefile and an SDTS-formatted file.

Entity_Type_Definition:

The path followed by the center of a major landfalling hurricane. A major landfalling hurricane is one that made landfall in the United States and that was classified on the Saffir-Simpson Hurricane Scale as a Category 3, 4, or 5 hurricane at the time of landfall. A hurricane is a warm-core tropical cyclone in which the maximum sustained surface wind is 64 knots/74 mph or more. A landfalling storm is defined as a storm whose center is reported to have either crossed or passed directly adjacent to the United States coastline, and which came ashore with tropical storm intensity or greater.

Date Attribute_Definition:

The Month/year/Day of the storm advisory. Advisories are issued for storms that have attained at least tropical depression status, and are issued every six hours, at 0000, 0600, 1200, and 1800 hours. Tropical Prediction Center/National Hurricane Center advisories are discontinued once a storm makes landfall and all storm warnings are dropped, or when the wind speed drops below 30 knots or 35 mph. The records for each date are listed in order.

There is no given name for the storm. Prior to 1950 storms were not named. Later storms that were not recognized as tropical storms or hurricanes at the time of their occurrence are also not named.

Enumerated_Domain_Value_Definition:HI

The storm was classified as a Category 1 hurricane at the time of the advisory. A Category 1 hurricane is a tropical cyclone with maximum sustained surface (10 meter) winds of 64 knots/74 mph to 82 knots/95 mph, inclusive.

Enumerated_Domain_Value_Definition: H2
The storm was classified as a Category 2 hurricane at the time of the advisory. A Category 2 hurricane is a tropical cyclone with maximum sustained surface (10 meter) winds of 83 knots/96 mph to 95 knots/110 mph, inclusive.

Enumerated_Domain_Value_Definition: H3
The storm was classified as a Category 3 hurricane at the time of the advisory. A Category 3 hurricane is a tropical cyclone with maximum sustained surface (10 meter) winds of 96 knots/111 mph to 113 knots/130 mph, inclusive.

Enumerated_Domain_Value_Definition: H4
The storm was classified as a Category 4 hurricane at the time of the advisory. A Category 4 hurricane is a tropical cyclone with maximum sustained surface (10 meter) winds of 114 knots/131 mph to 135 knots/155 mph, inclusive.

Enumerated_Domain_Value_Definition: H5
The storm was classified as a Category 5 hurricane at the time of the advisory. A Category 5 hurricane is a tropical cyclone with maximum sustained surface (10 meter) winds greater than 135 knots/155 mph.

Appendix D Metadata for Shoreline Layer

Source: http://www.fgdl.org/metadata/fgdc_html/coast_feb04.fgdc.htm

Originator:
FWC - Fish and Wildlife Research Institute, Center for Spatial Analysis
Publication_Date: 200402
Title: FLORIDA COASTLINE
Geospatial_Data_Presentation_Form: vector digital data
Publication_Information:
Publication_Place: St. Petersburg, Florida
Publisher:
FWC - Fish and Wildlife Research Institute, Center for Spatial Analysis
Other_Citation_Details: State of Florida
Online_Linkage: <http://research.myfwc.com/features/category_main.asp?id=1153>
Description:
Abstract:
This GIS data set represents the Florida shoreline as lines. Initially digitized in 1990 by USFWS under FWRI contract, the data set was created from the most current National Oceanic and Atmospheric Administration (NOAA) Nautical Charts available at the time. The scale of the source charts varied from 1:10,000 in some harbors to 1:80,000 in the Big Bend area. However, most of the source scale is 1:40,000.

The current data set is the result of revisions to the 1990 version. Some areas, including inland areas where there is no chart coverage and areas that have needed more accuracy for individual projects, have been digitized from USGS 7.5-minute Quadrangles and Digital Orthophoto Quarter Quadrangles (DOQQs).

Purpose:
FWRI created this for visual reference in maps at about 1:40k scale, or the largest scale available for an area.

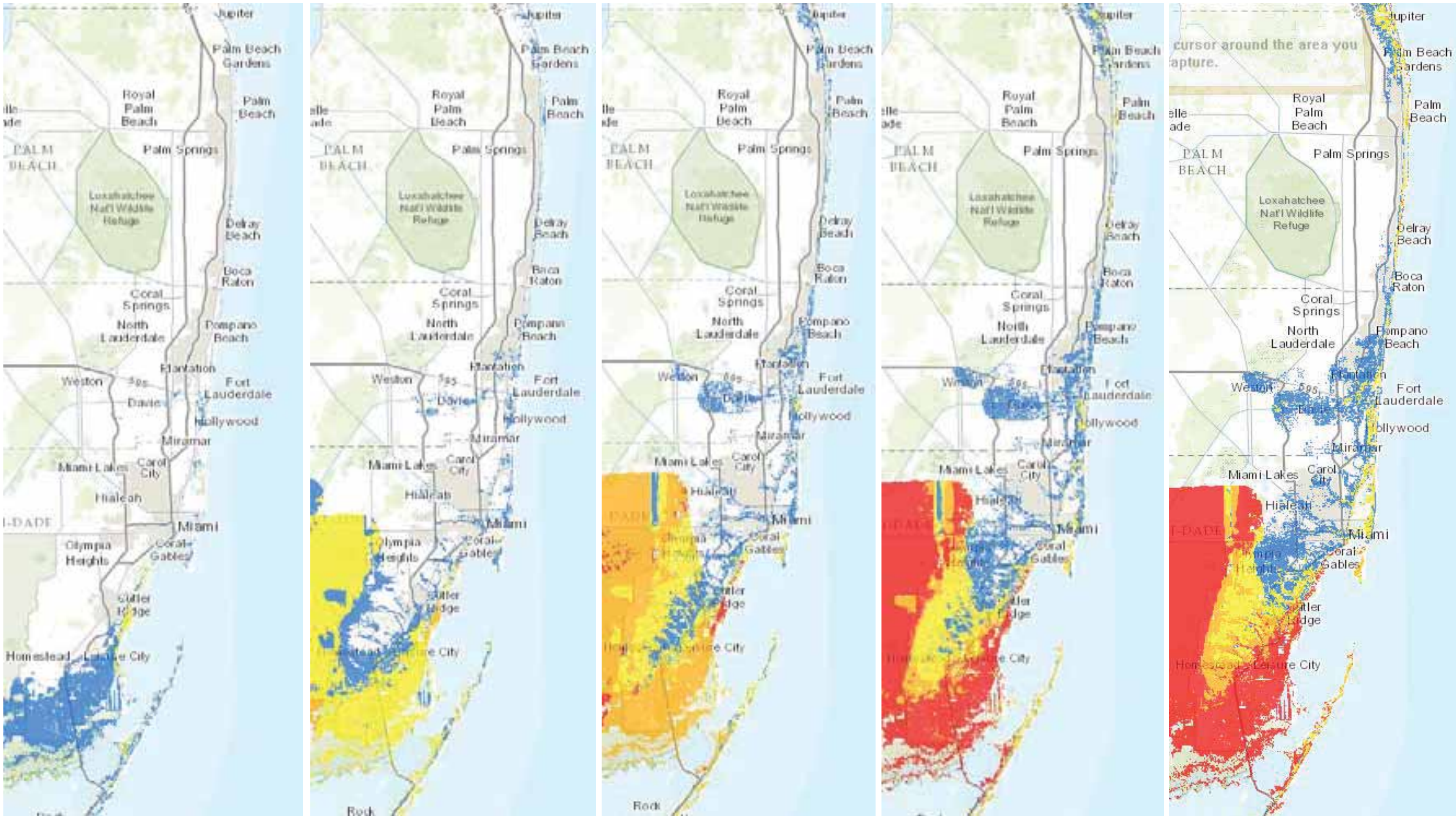
The source scale varies from 1:10,000 to 1:80,000.

Bounding_Coordinates:
West_Bounding_Coordinate: -87.429040
East_Bounding_Coordinate: -79.872251
North_Bounding_Coordinate: 30.983191

South_Bounding_Coordinate: 24.492815
Use_Constraints:
Originator:
US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS)
Publication_Date: Unknown
Title:
National Oceanic and Atmospheric Administration, 1:40,000 scale Nautical charts
Process_Description:
This Florida shoreline was originally digitized in 1990 by USFWS under FWRI contract. In all cases, USFWS used the most detailed NOAA navigational charts available at the time (i.e. harbor areas were taken from 1:10000 and the Big Bend was taken from 1:80000). In some areas, nautical charts were insufficient and 1:24000 USGS quadrangles or DOQQs were used instead of the nautical charts. This is especially true along rivers.
Contact_Organization:
FWC-FWRI (Florida Fish and Wildlife Conservation Commission-Fish and Wildlife Research Institute)
Contact_Position: GIS Data Librarian
Contact_Address:
Address_Type: mailing and physical address
Address:
Fish and Wildlife Research Institute 100 Eighth Avenue Southeast
City: St. Petersburg
State_or_Province: Florida
Postal_Code: 33701
Country: USA
Contact_Voice_Telephone: 727-896-8626
Contact_Facsimile_Telephone: 727-893-1679
Contact_Electronic_Mail_Address: GISLibrarian@MyFWC.com
Hours_of_Service: 8:00 a.m.-5:00 p.m. Eastern time
Process_Step:
Process_Description:
FWRI staff updated the line work in Miami-Dade County to include line work digitized in-house for manatee speed zones and another project. Only major shoreline line work was edited, as well as some interior canal work that was important for the manatee speed zones. The revised line work was edge matched to the 1:40,000 shoreline line work, so that no interior canals were

lost. The new line work and polygon attributes have been verified against 1999 DOQQs.
Process_Date: February 2004
Postal_Code: 33701
Country: USA
Contact_Voice_Telephone: 727-896-8626
Contact_Facsimile_Telephone: 727-893-1679
Contact_Electronic_Mail_Address: GISLibrarian@MyFWC.com
Hours_of_Service: 8:00 a.m.-5:00 p.m. Eastern time

Appendix E SLOSH MOM Depths of Inundation for Storm Categories 1 – 5 from NOAA



Category 1 Category 2 Category 3 Category 4 Category 5

Inundation Depth

- Up to 3 feet above ground
- Greater than 3 feet above ground
- Greater than 6 feet above ground
- Greater than 9 feet above ground

Source: http://noaa.maps.arcgis.com/apps/StorytellingTextLegend/index.html?appid=b1a20ab5eec149058bafc059635a82ee

How these map were created:

The SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model is a numerical model used by NWS to compute storm surge. Storm surge is defined as the abnormal rise of water generated by a storm, over and above the predicted astronomical tides. Flooding from storm surge depends on many factors, such as the track, intensity, size, and forward speed of the hurricane and the characteristics of the coastline where it comes ashore or passes nearby.

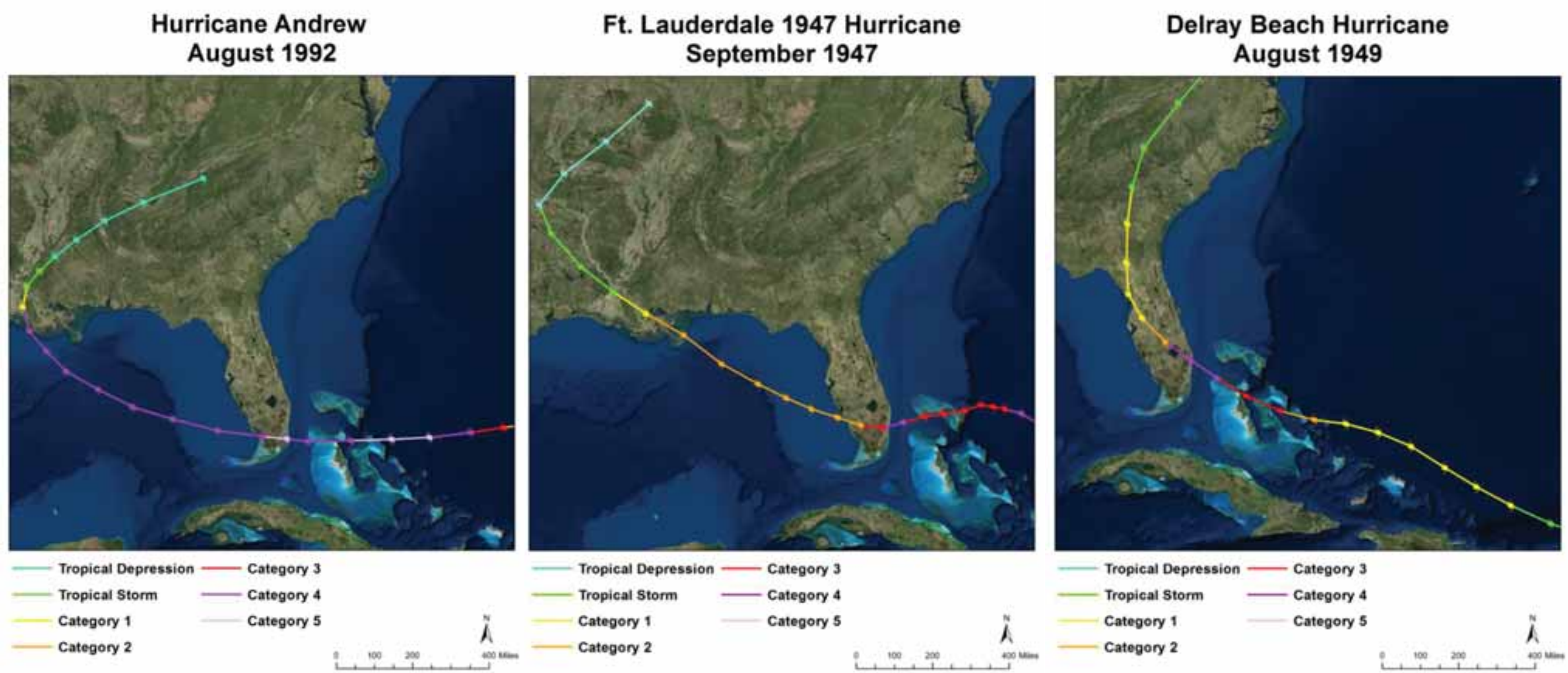
SLOSH employs curvilinear polar, elliptical, or hyperbolic telescoping mesh grids to simulate the storm surge hazard along the continental U.S. Gulf and East Coasts. The spatial coverage for each SLOSH grid ranges from an area the size of a few counties to a few states. The resolution of individual grid cells within each basin ranges from tens to hundreds of meters to a kilometer or more. Sub-grid scale water features and topographic obstructions such as channels, rivers, and cuts and levees, barriers, and roads, respectively are parameterized to improve the modeled water levels. At present, there are 33 operational SLOSH grids. Each SLOSH grid has a set of near worst case planning scenarios associated with it.

NHC provides two near worst case scenario planning products based on hypothetical storm tracks: Maximum Envelopes of Water (MEOWs) and Maximum of Maximums (MOMs). MEOWs are created by computing the maximum storm surge resulting from roughly 10,000 to 60,000 hypothetical storms simulated through each SLOSH grid of varying forward speed, radius of maximum wind, intensity (Categories 1-5), landfall location, initial water level, and storm direction. A MEOW product is created for each combination of category, forward speed, storm direction, and initial water level. SLOSH products do not include Category 5 storms north of the NC/VA border. For each storm combination, parallel storms make landfall in 5 to 10 mile increments along the coast within the SLOSH grid, and the maximum storm surge footprint from each simulation is composited, retaining the maximum height of storm surge in a given basin grid cell. No single hurricane will produce the regional flooding depicted in the MEOWs. SLOSH model MOMs are an ensemble product of maximum storm surge heights. MOMs are created for each SLOSH basin by compositing all the MEOWs, separated by category and initial water level, and selecting maximum storm surge value for each grid cell regardless of the forward speed, storm trajectory, or landfall location. MOMs represent the worst case scenario for a given category of storm and initial water level under ideal storm conditions. Here, a high tide initial water level is used in the analysis.

This product uses the expertise of the NHC Storm Surge Unit to merge 27 of the operational SLOSH grids to build a seamless national map of storm surge hazard scenarios using the MOM product. Each grid for the Category 1-5 SLOSH MOMs are merged into one national grid. The national grid is then resampled, interpolated, and processed with a DEM (Digital Elevation Model, i.e. topography) to compute the storm surge hazard above ground for each hurricane category.

The diagonal hatched areas represent certain levee areas, such as the Hurricane and Storm Damage Risk Reduction System in Louisiana. These areas are highly complex and this product should not be used to assess the storm surge hazard within these areas. Please consult local emergency management officials for information on the risk of storm surge flooding within these areas. Not all levee areas are included in this analysis – in particular, local features such as construction walls, levees, berms, pumping systems, or other mitigation systems found at the local level may not be included in this analysis. Additionally, some marshy or low lying areas are not mapped in this analysis.

Appendix F Storm Tracks with Category



Source: The National Hurricane Centers HURricane DATabases (HURDAT) and the revised Atlantic hurricane database (HURDAT2) - Chris Landsea, James Franklin, and Jack Beven – May 2015 (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html)

Appendix G Precursor Investigations

Technical Memorandum

TO: Lois Bush, Florida Department of Transportation

FROM: Josh DeFlorio, Cambridge Systematics
Karen Kiselewski, Cambridge Systematics

DATE: November 16, 2015

RE: Storm Surge and Transportation Network Disruption Task Work Order: Precursor Investigations

---

The proposed Storm Surge and Transportation Network Disruption Task Work Order (TWO) is intended to supplement the Federal Highway Administration-funded South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project (South Florida pilot project) completed in April 2015. This memorandum presents the results of two precursor investigations which will inform the proposed TWO:

1. The first task ("Inventory") entailed an inventory of storm surge modeling information and tools relevant to the Southeast (SE) Florida region. For each relevant initiative, Cambridge Systematics (CS) reviewed public documentation, contacted the project principal(s) for brief informational interviews, and summarized the findings in this memorandum.

2. CS performed a preliminary comparison of the 2040 travel demand model network (SERPM 7.0) vs. the 2035 SE Florida regional transportation network for the South Florida pilot project[1], applied a corrected bridges layer provided by the University of Florida GeoPlan Center (GeoPlan)[2], and attempted to reconcile the resulting spatial misalignments (the "Network Preparation").

---

[1] The South Florida pilot project utilized road and rail components of the 2035 SE Florida regional transportation network designated by the Southeast Florida Transportation Council (SEFTC) (see Attachment A). That network was updated as part of the development of SEFTC's 2040 Regional Transportation Plan adopted in October 2015.

[2] The underlying topographical layer (the Florida Digital Elevation Model), which was used to establish the approximate elevations of transportation facilities for the South Florida pilot, stripped out all bridges. As a result, during the assessment of potential inundation using Geographic Information System software, all facilities crossing bodies of water were—often falsely—deemed to be flooded. GeoPlan assisted the South Florida pilot project team by obtaining bridge elevations from the original, unprocessed elevation data and providing them as a separate layer, which corrected this issue for bridges on roads in the 2035 SE Florida regional transportation network only.

38 East 32nd Street, 7th Floor
New York, NY 10016
tel 212-209-6640 www.camsys.com fax 212-209-6641

Inventory

Florida DOT requested a summary-level overview and comparison of selected initiatives to simulate and map the potential impacts of Sea Level Rise (SLR) and storm surge in Southeast Florida, with the aim of ensuring that the work proposed for the Storm Surge and Transportation Network Disruption TWO adds value for the region. CS interviewed representatives of The Nature Conservancy (TNC), the University of Florida, the South Florida Water Management District (SFWMD), and the South Florida Regional Council (SFRC). The comparison revealed that the SLR and storm surge approach outlined in the TWO is, at present, unique in Southeast Florida, yet complementary to existing output[3]. The coastal inundation layers to be developed as part of the TWO are anticipated to be useful for multidisciplinary, planning-level assessments of potential future coastal flooding hazards.

The primary Inventory activity was outreach to three agency representatives, suggested by the Department with the assistance of Dr. Jennifer Jurado, Director of Environmental Planning and Community Resilience, Broward County. They were Jayantha Obeysekera, Chief Modeler at the SFWMD; Y. Peter Sheng, Professor of Coastal and Oceanic Engineering, University of Florida, and; Chris Bergh, South Florida Conservation Director of TNC. CS also interviewed Manny Cela, Deputy Director of the SFRC. The results of these interviews are summarized below, and the technical specifications of applicable storm surge and SLR modelling are compared in Table 1, below. Documentation, where available, is included in the "Sources and References" section.

- **South Florida Water Management District** (Jayantha Obeysekera). The Southeast Florida Climate Compact hopes to perform future storm surge modeling (with SLR) for the entire region using ADCIRC (which stands for ADvanced CIRCulation Model). ADCIRC is considered a more robust modelling platform than the Sea, Lakes, and Overland Surges from Hurricanes (SLOSH) model developed by NOAA (and the basis of surge estimates to be developed in the TWO), but is also significantly more resource intensive. Dr. Obeysekera anticipates that completion of ADCIRC modeling is at least 3-4 years away, meaning that, in the interim, SLOSH is likely the best available platform for regional storm surge simulations.

- **University of Florida** (Y. Peter Sheng). Dr. Sheng echoed the sentiment that SLOSH is a coarse tool (1km resolution), potentially leading to significant inaccuracies on a local scale. Dr. Sheng reported that he and his colleagues are able to perform probabilistic future coastal inundation modeling at 30-meter horizontal resolution. However, existing output is not available for the region, with the exception of a limited number of pilot sites in Miami-Dade and Broward Counties, meaning that new modeling would be required. The time frame and financial requirements entailed are dependent on the parameters requested (SLR and storm recurrence intervals) and the number of model runs performed.

[3] The Sea Level Scenario Sketch Planning Tool (Tool) developed by GeoPlan currently does not include storm surge. The Tool presents three projections of sea level change (developed by the United States Army Corps of Engineers) applied to five tidal datums.

- **The Nature Conservancy** (Chris Bergh). TNC has developed an online mapping platform called Coastal Resilience (http://maps.coastalresilience.org/network), which covers Southeast Florida (among a limited number of coastal geographies). Although the mapper allows the user to dynamically visualize inundation associated with 1-3 feet of SLR in the counties of Palm Beach, Broward, and Miami-Dade, there is no surge information for Southeast Florida with the exception of Monroe County (for which the user can visualize the flooding associated with Hurricane Wilma with 0-4 feet of SLR). The Coastal Resilience tool includes several complementary layers, including information on habitats, shoreline resilience, and social and economic layers (including a basic transportation network).

- **South Florida Regional Council** (Manny Cela). Legislation passed in response to active hurricane years in 2004 and 2005 resulted in the Regional Planning Councils preparing all-hazards evacuation studies using statewide LIDAR and SLOSH model updates. Subsequent to the 2010 study, the SFRC developed the Depth Analysis Atlas, which includes data for each storm category showing the extent and the depth of potential flooding from surge. A second project developed the Storm Tide Directional Atlas, which maps the extent of surge expected for each category of storm for storms from each of five directional storm clusters. The final project, completed in September 2015, is an update to the regional evacuation transportation analysis.

Because higher resolution future storm surge model output for the region is still potentially years away (and the parameters of such output are yet unknown), the approach proposed for the TWO is recommended. The TWO approach is both appropriate to the planning-level network analysis proposed and consistent with the TNC approach to modeling surge in Monroe County (it could, in fact, be used to supplement the TNC tool).

Table 1. Comparison of Potential Sources of Future Storm Surge Simulations

	Surge/Disruption TWO	SE Florida Climate Compact (SFWMD)	University of Florida	The Nature Conservancy	South Florida Regional Council
Surge Approach	Historical storms modeled with SLR, using SLOSH	ADCIRC (parameters unknown) with Unified SLR projection	CH3D-SSMS model using ensemble storms from climate models	SLR only, no surge*	Historical storms, directional atlas of storm surge for each category storm
Status	Available	Proposed (3-4 years from now)	Not Commissioned	Available	Available
Potential Pros	Easily obtainable, cost-effective, uses NOAA's SLOSH platform, appropriate resolution for planning assessments	High resolution, state-of-the-art model, produces locally robust results	High resolution model, probabilistic (uses storm ensembles)	Available online, free, layers downloadable	Available from SFRC, consistent with evacuation modeling
Potential Cons	Lower resolution, less accurate at local scale	Long lead time (not currently available), resource intensive	Not yet available, would require commission from State organization or regional partners, significant period of performance, cost unknown	Does not contain surge output for the study area	Does not reflect SLR

**the sole available surge output is the historical storm Wilma (2005) modeled with increments of SLR from 0-4 feet for Monroe County only, consistent with the TWO approach.*

Network Preparation

In preparation for the travel demand model runs contemplated in the TWO, CS performed a spatial comparison of the 2040 travel demand network (SERPM 7.0) versus the roads on the 2035 SE Florida regional transportation network. The resulting overlay is shown in Figure 1, with the roads on the regional transportation network shown in dark red and the SERPM network shown in green. Only a fraction of the travel demand model network is covered by the regional roads layer. The lack of spatially coincident coverage is potentially problematic because the corrected bridge elevation layer provided by GeoPlan only covers bridges for roads on the regional transportation network (meaning that bridges not part of roads on the regional transportation network may be incorrectly identified as inundated).

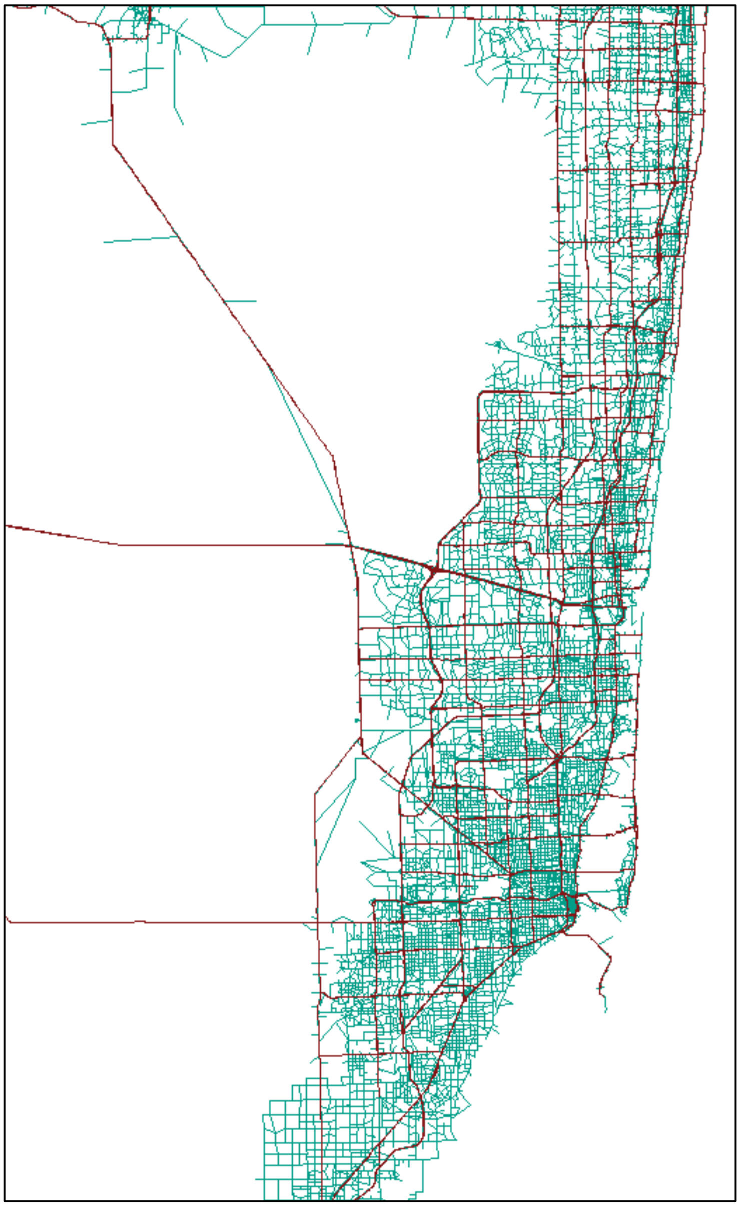


Figure 1. Roads on 2035 SE Florida Regional Transportation Network overlaid on SERPM 7.0 network

This task included spot checks on the spatial alignment of the model network versus the actual roadway network (as shown in quality controlled GIS layers and aerial imagery) and a check on the coverage and accuracy of the corrected regional bridge elevation layer (provided by GeoPlan). A typical extent, shown as Figure 2, reveals that 1) the SERPM 7.0 network is neither complete (some local streets are omitted) or entirely geospatially accurate—although the alignment is likely sufficiently accurate for this planning level assessment, especially given the coarseness of the SLOSH surge output. Of greater concern is the lack of spatial alignment between the corrected bridge elevation polygons (shown in pale yellow, misalignment indicated with orange arrows) and the network (represented by red lines). Note that centroid connectors—"false roads" used to connect Traffic Analysis Zones to the network—are included in both Figures 2 and 3.

Figure 2. Alignment of GeoPlan corrected bridge elevation layer and SERPM network

Because there were significant and widespread misalignments between these layers (due solely to the spatial inaccuracy of the SERPM roadway network—the corrected bridge polygons are accurate), CS explored geospatial methods for addressing the spatial mismatches. The approach focused on developing a geoprocessing technique to automatically identify and correct mismatches using a series of buffering operations. Figure 3 depicts an example of this technique, with the corrected bridge polygons shown in reddish-orange and the SERPM network segments and centroid connectors in teal. Segments in black were identified using a buffer applied to the bridge polygons and then assigned the minimum elevation value of the associated bridge (as provided by GeoPlan). In selecting the buffer width, the principal challenge is to establish a buffer that enables the identification of all SERPM segments that require correction, but which avoids falsely adjusting adjacent segments, to the extent possible.

For example, as depicted within the red circle, a 50-foot buffering operation correctly projected the bridge elevation onto the east-west segment (an overpass, with corrected segment in black), but incorrectly projected it onto the north-south segment (an underpass, with falsely corrected segment in dashed orange and black). After several attempts to buffer (at various widths) and then correct falsely attributed elevations, it was determined that the preferred technique is to 1) set a large buffer (greater than 100 feet) to identify all potential bridge corrections, and then 2) manually correct falsely attributed links within the surge zones (as represented by the surge polygons to be obtained from Dr. Bolter). Unfortunately, this is a more time consuming process than originally anticipated.

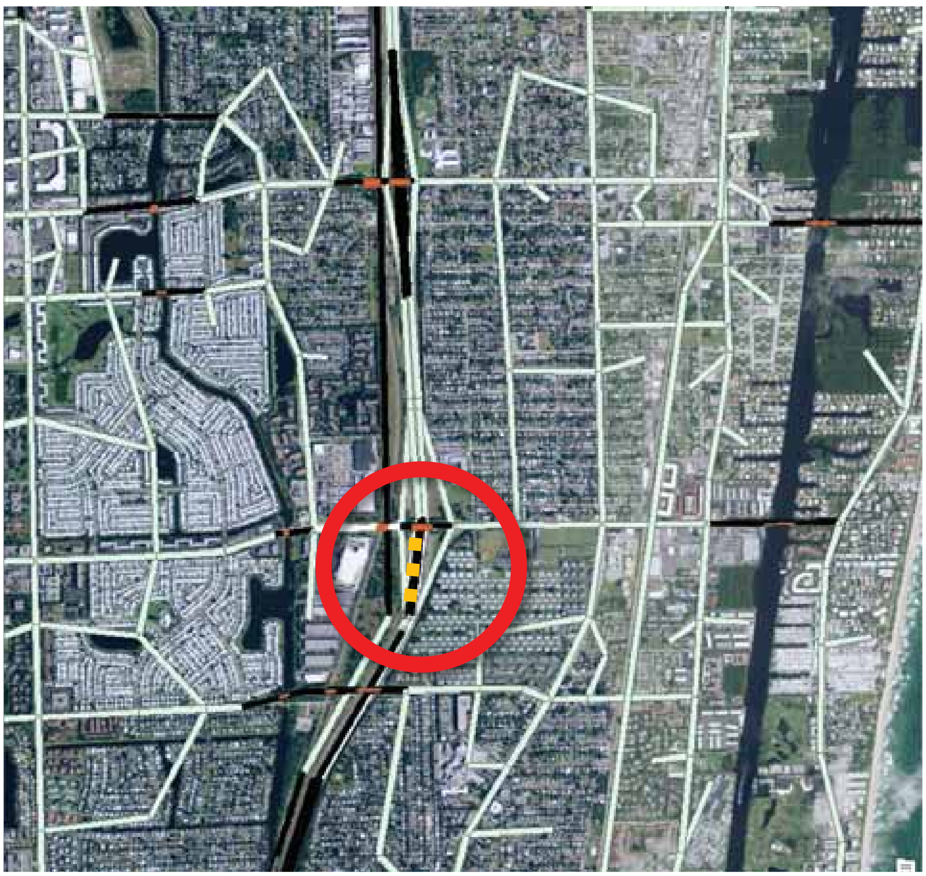


Figure 3. Corrected SERPM segment elevations by applying a 50-ft buffer to GeoPlan bridge layer

Considering that the corrected bridge elevation layer is available only for roads on the regional transportation network, and that this network represents only a portion of the more detailed SERPM network, a further complication arises. Bridges serving lower functional classification facilities (i.e., not on roads as part of the regional transportation network) were not captured by GeoPlan. Since these bridges have been removed from the underlying Florida Digital Elevation

Model, the links they serve will fail whenever they are intersected by a storm surge polygon—whether or not the bridge is sufficiently elevated in reality. Because the traffic volumes carried by these bridges can be expected to be significantly less than the volumes accommodated by bridges on roads on the regional transportation network, this deficiency may not be critical given the planning-level objectives of this analysis (although it should be documented). If the project stakeholders regard this deficiency as a fatal flaw, it could be addressed (with the help of GeoPlan) by significantly expanding the corrected bridges layer. This step may be more resource intensive than warranted at this scale of analysis.

Sources and References

Condon A, Sheng YP. 2012. *Evaluation of coastal inundation hazard for present and future climates*. Natural Hazards 62(2): 345-373.

The Nature Conservancy. 2015. *Florida Keys Flood Scenarios*. Downloaded from http://coastalresilience.org. 2 pp.

Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact). 2015. *Unified Sea Level Rise Projection for Southeast Florida*. A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee. 35 pp.

South Florida Regional Council. Statewide Regional Evacuation Study Project (SFESP). Storm Tide Atlas. Depth Analysis Atlas. Data for additional counties available from SFRC. http://sfregionalcouncil.org/portfolio-item/statewide-regional-evacuation-study-program-sresp/

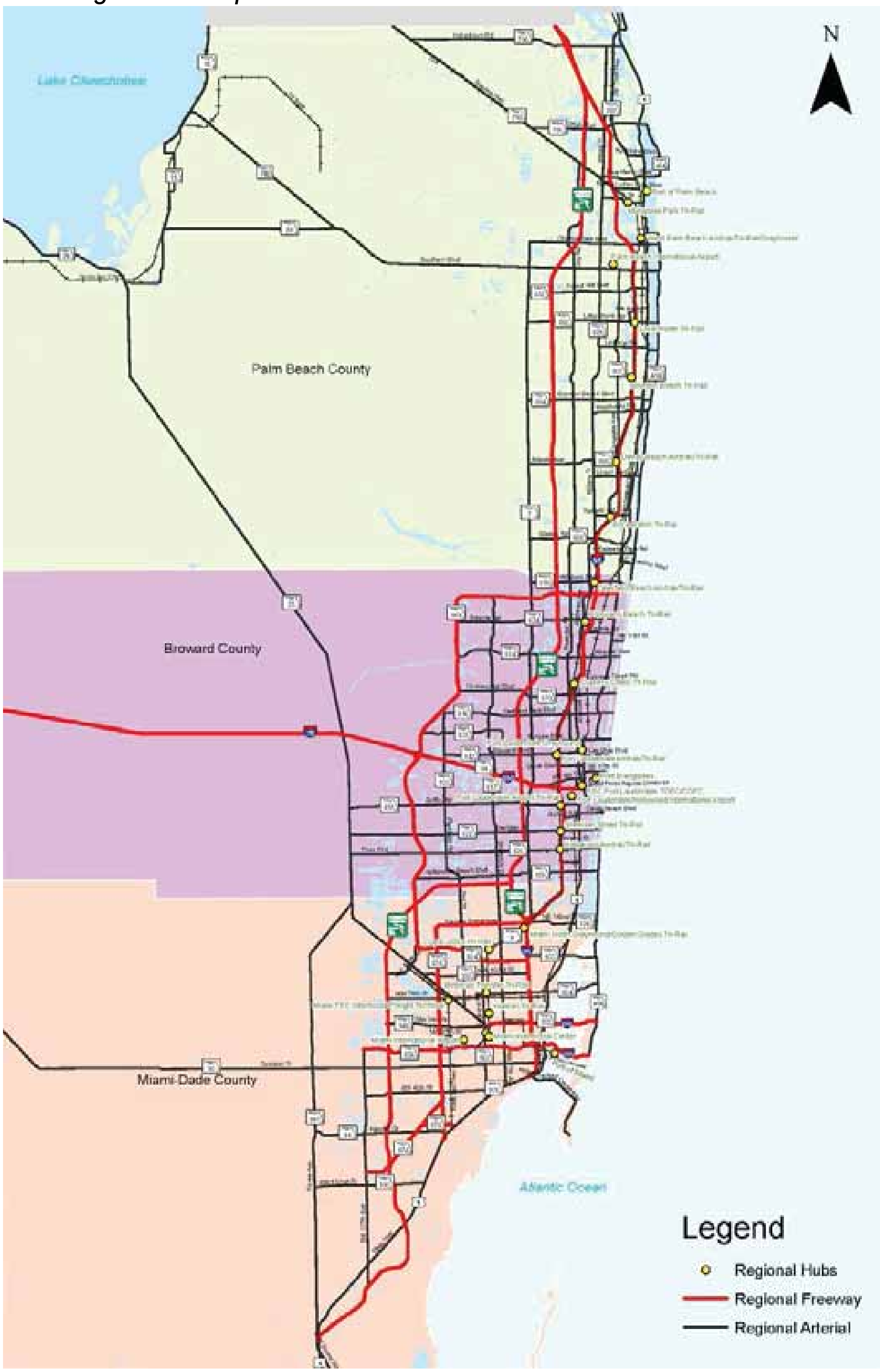
Regional Transportation Network – Southeast Florida Transportation Council

The Southeast Florida Transportation Council (SEFTC), created in 2006, is composed of members from the Miami-Dade, Broward, and Palm Beach Metropolitan Planning Organizations.

Initially, the regional (tri-county) transportation network designated by SEFTC focused on corridors of regional significance. In conjunction with development of its 2035 Regional Long Range Transportation Plan, SEFTC developed a more robust regional transportation network addressing transit, highways, and freight.

2035 Criteria for Designation of Regional Transportation Network
1. **Regional Interstate and Expressway Facilities** – Urban or Rural Principal Arterials, Interstate and Expressway Termini: Determined by Principal Arterial Classification limits. Must begin/end at another regional facility or County line.
2. **Major Regional Facilities** – Urban or Rural Principal Arterials, others that Cross County Lines Termini: Determined by Principal Arterial Classification limits. Must end at another regional facility or County line.
3. **Regional Connection Facilities** – Urban or Rural Principal Arterials, with two or more connections to any mixture of the following: Regional Interstate and Expressway Facilities, SIS Roadway Corridors, and/or SIS Hubs Termini: Determined by Principal Arterial Classification limits. Must end at another regional facility or County line.
4. **Regional Facility Designation Extensions** – Non-Principal Arterials that are a designation expansion of facilities that meet the following three criteria: (1) Regional Interstate and Expressway Facilities, (2) Major Regional Facilities, (3) Regional Connection Facilities. Extensions termini must be to/from a Principal Arterial to/from a SIS Corridor, Hub and/or a Major Regional Facility. Termini: Must begin at a Principal Arterial and end at a regional facility.
5. **SIS and Emerging SIS Hubs, Corridors and Connectors** – Facilities identified by FDOT as the Florida Strategic Intermodal System (SIS) within Southeast Florida; includes roadways, railways and waterways. *SIS Planned Drop facilities are to not be included on the Regional Transportation Network unless the facility meets one of the other criteria. Termini: Determined by FDOT.
6. **Adopted Physical Extensions of Current Regional Facilities** – Adopted LRTP Cost Feasible Plan (CFP) roadway extensions. CFP LRTP Roadway extensions designated on the Regional Transportation Network must be extensions of roadways that meet one of the other six Regional Transportation Network criteria. Termini: Begin at the LRTP roadway in question and end at a regional facility.
7. **Statewide Regional Evacuation Network Termini**: Determined by the Regional Planning Councils and the State Legislature.
Source: Technical Memorandum #8: Regional Transportation Network, Table 1. Can be viewed at http://www.seftc.org/system/datas/21/original/Tech%20Memo%208_Corridors_Final.pdf?1285175357.

2035 Regional Transportation Network



See also the Regional Transportation Network section in SEFTC's 2035 Regional Long Range Transportation Plan – Final Documentation posted on www.seftc.org.

Storm Surge, Sea Level Rise, and Transportation Network Disruption

presented to

Southeast Florida FSUTMS Users Group

prepared for

Southeast Florida Planning Partners

funded by

Florida Department of Transportation

prepared by

Cambridge Systematics, Inc.

with support from

Keren Bolter, PhD

presented by

Yingfei Huang

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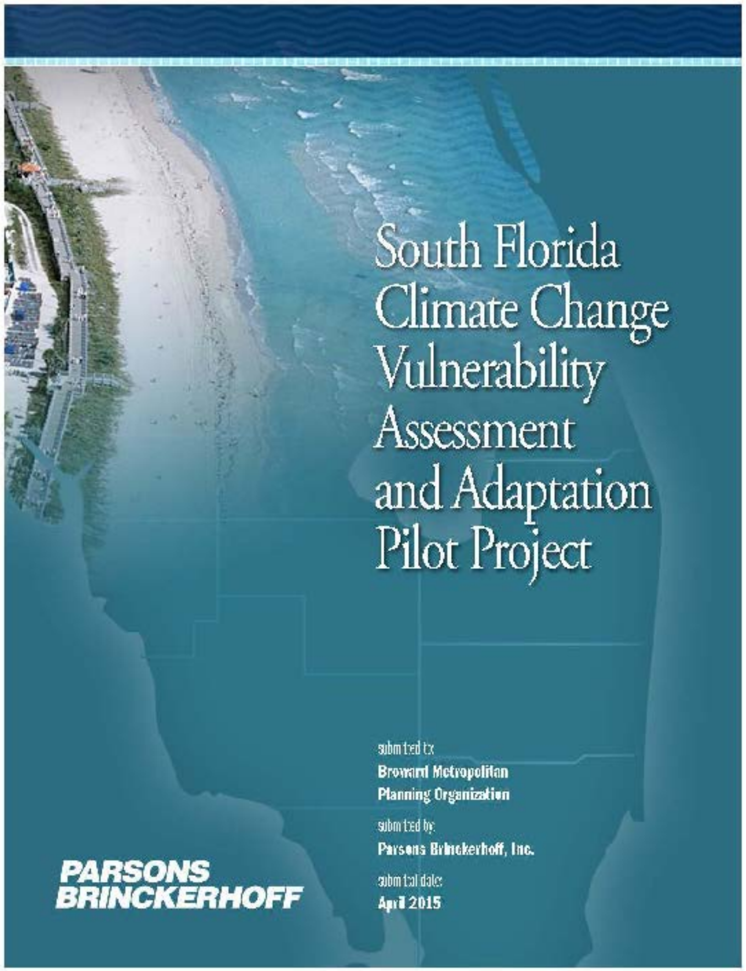
11/18/2016

Think Forward

Background



- FHWA South Florida Climate Change and Vulnerability Assessment and Adaptation Pilot Project
  - » Regional transportation network is significantly vulnerable to storm surge and sea level rise.

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Background

- FDOT Storm Surge, Sea Level Rise, and Transportation Network Disruption Project
  - Building on the Pilot Project's Work
  - Estimate impact on regional mobility using SERPM 7.0
  - Evaluate network-level risk
  - Consider the compound effect of storm surge and sea level rise

Project Overview

Storm Simulation Scenarios

- 3 historic storms tracks
- Sea level rise projection determination
- NOAA SLOSH Model

Transportation Network Inundation

- Overlay storm inundation layers on transportation network
- Identify road and rail links affected by inundation

Transportation Modeling

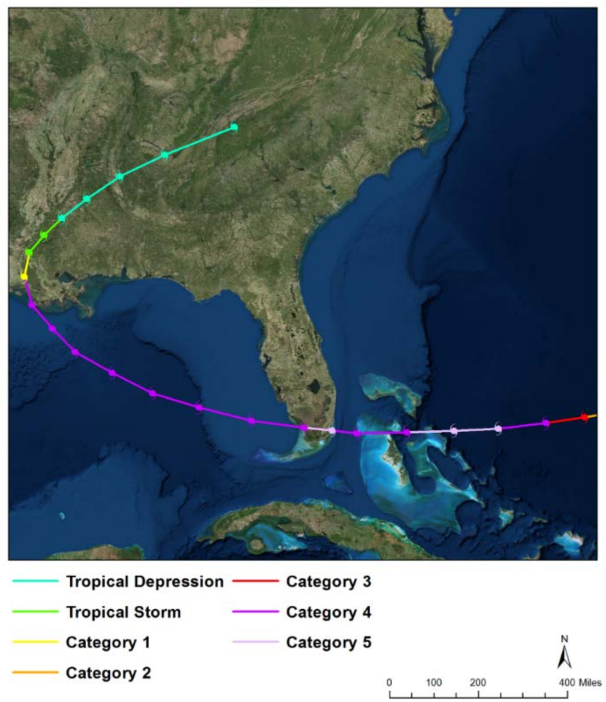
- Disable affected links from carrying trips
- Run travel demand forecasting model (SERPM 7.0) with restricted network

Compare and Evaluate Impact

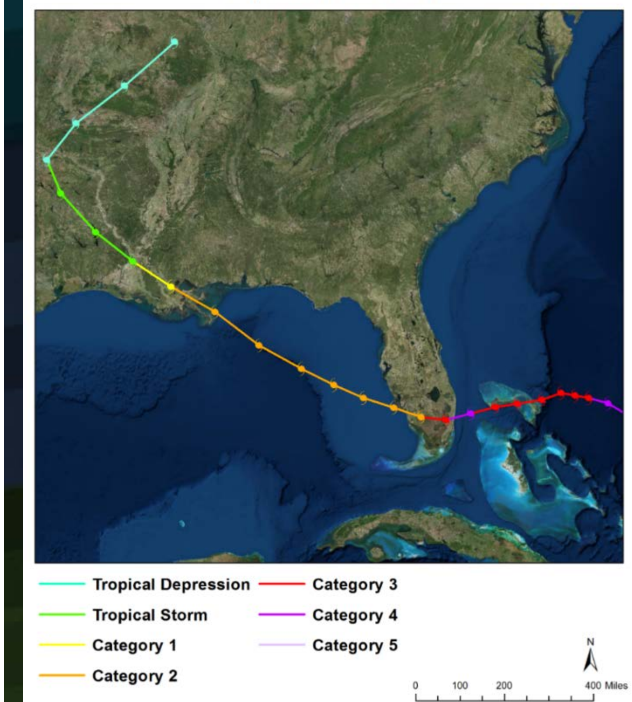
- Compare Scenarios to 2040 cost feasible baseline network
- Evaluate uncompleted trips, vehicle miles and hours, and associated economic impacts

Storm Simulation Scenarios

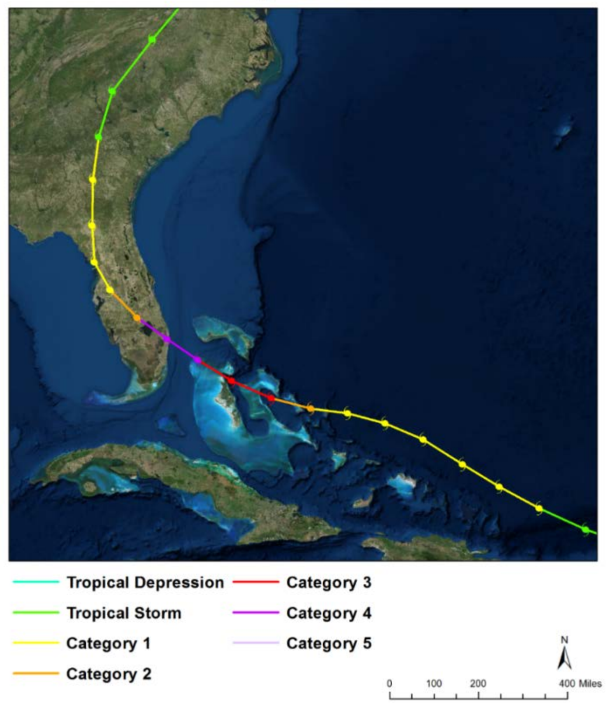
Hurricane Andrew
August 1992



Ft. Lauderdale 1947 Hurricane
September 1947



Delray Beach Hurricane
August 1949



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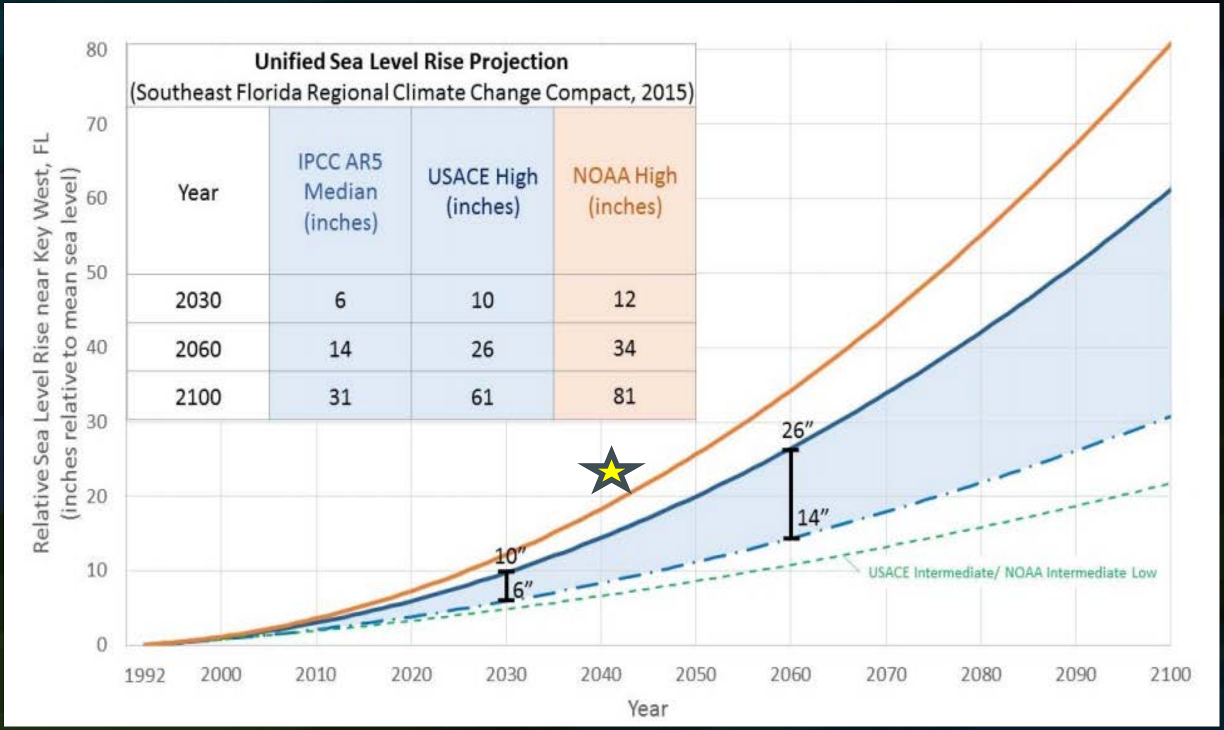
Sea Level Rise Projection

- 2040 horizon
- USACE
  - 14.52 inches
- Consistent with the 2015 Southeast Florida Regional Climate Change Compact Unified Sea Level Projection



Year	IPCC AR5 Median (inches)	USACE High (inches)	NOAA High (inches)
2030	6	10	12
2060	14	26	34
2100	31	61	81

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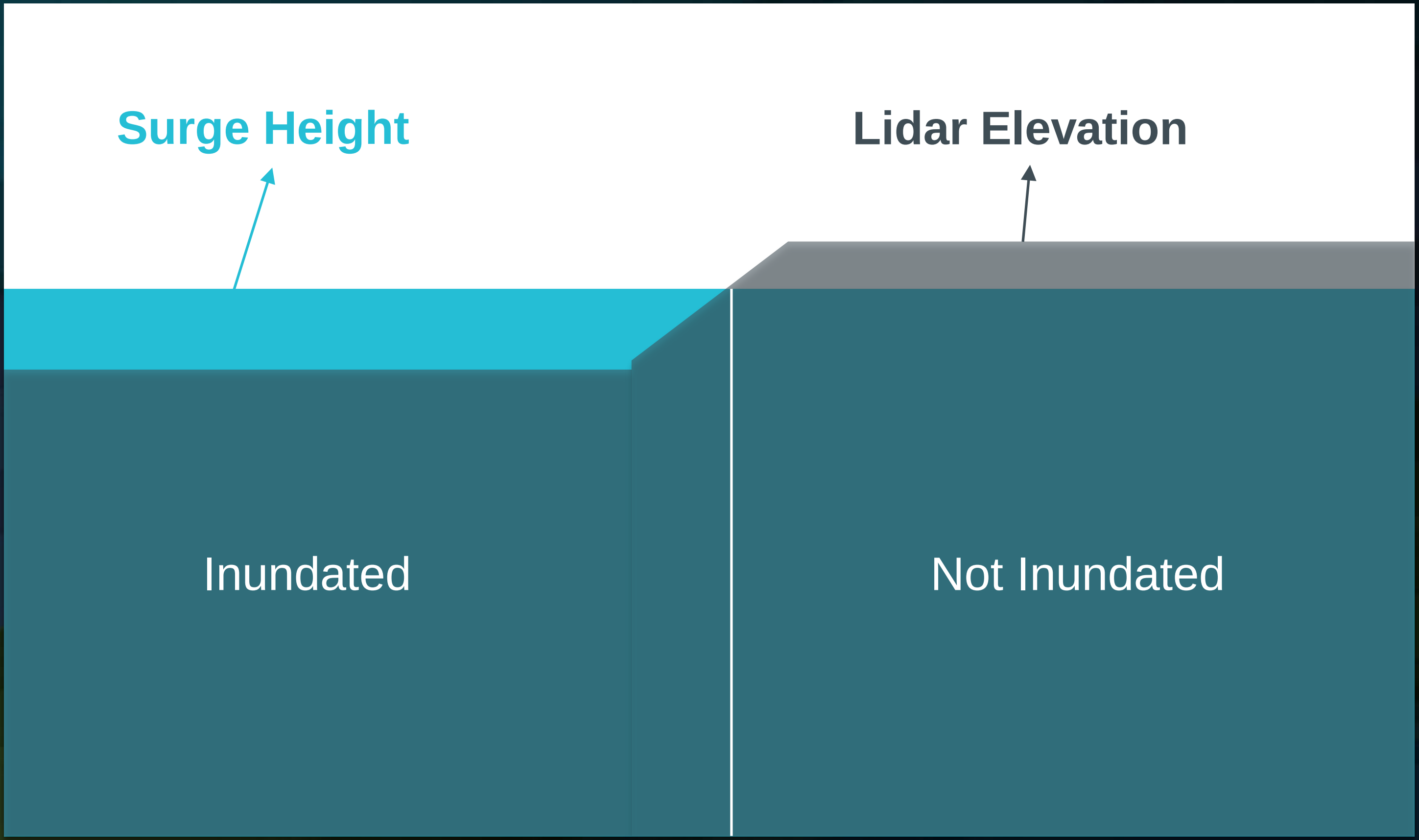
Storm Simulation Scenarios



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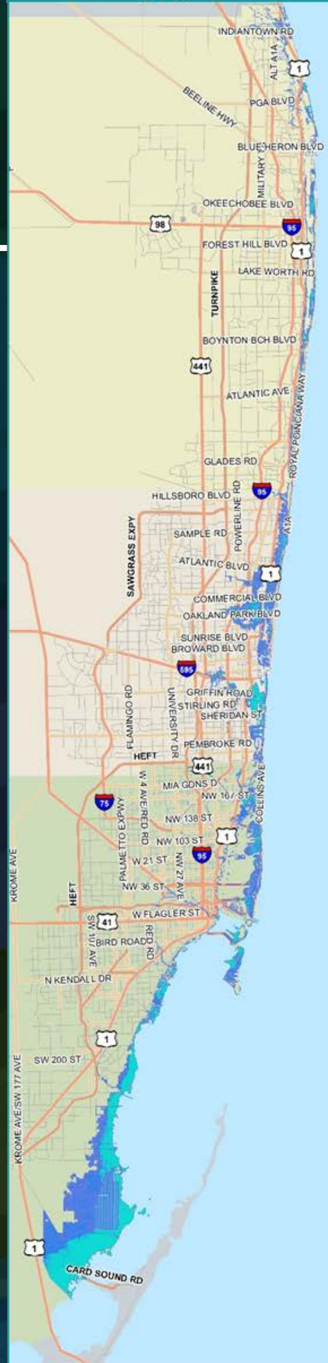
Inundated Area

Three Counties

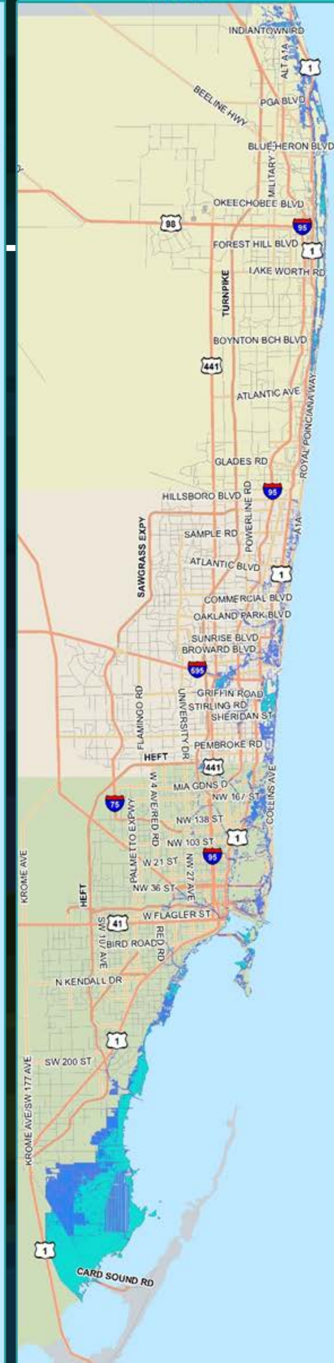
Three Storm Tracks

Hurricane Andrew 1992

Fort Lauderdale Hurricane 1947



Delray Beach Hurricane 1949



- Storm Surge
- Sea Level Rise

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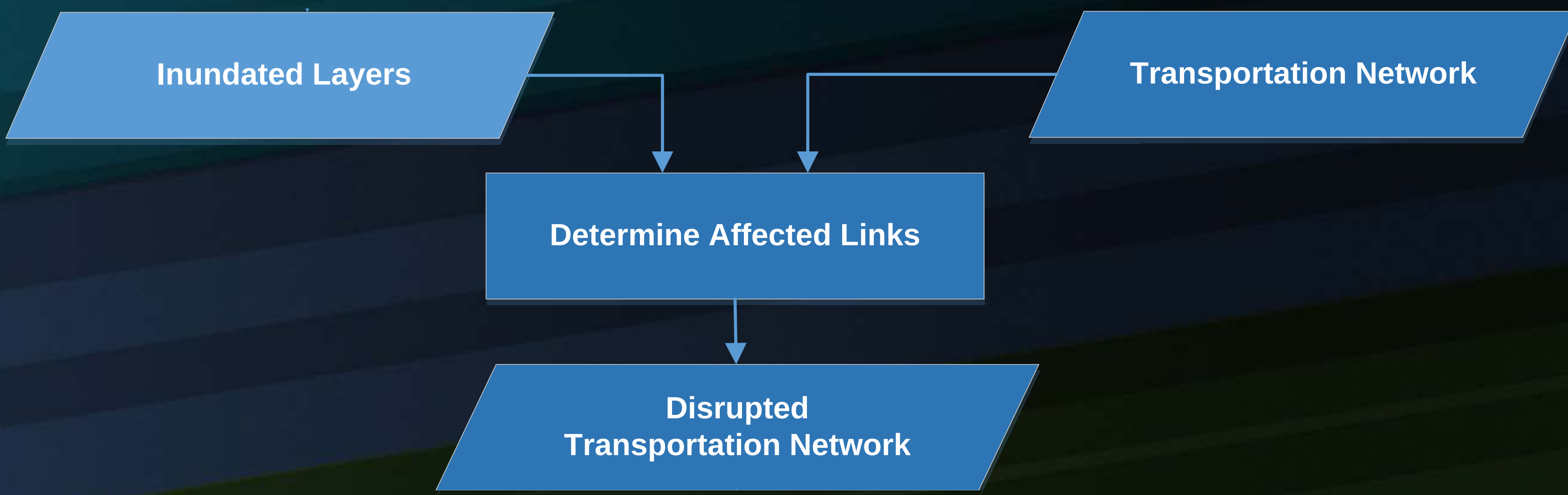
Transportation Network Disruption



Disrupted Links

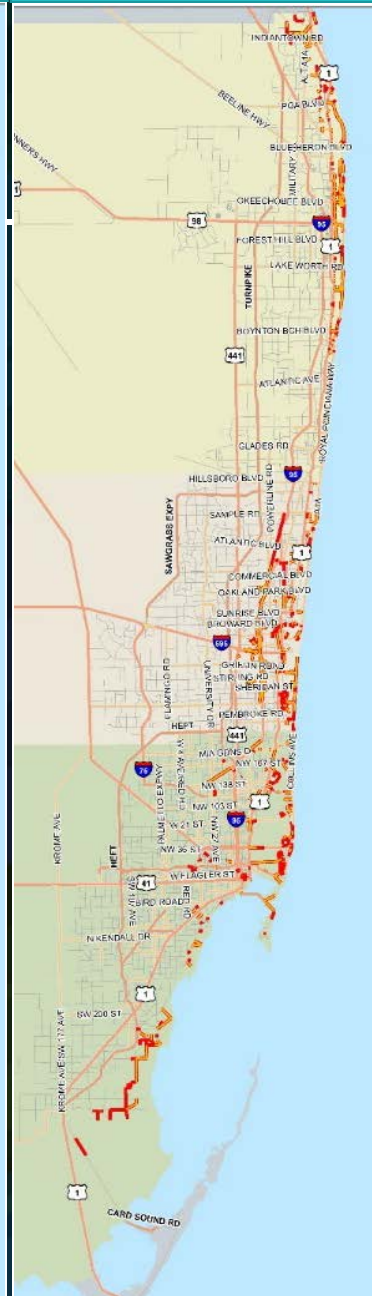
Three Counties

Three Storm Tracks

Hurricane Andrew 1992

Fort Lauderdale Hurricane 1947

Delray Beach Hurricane 1949



Storm Surge

Sea Level Rise

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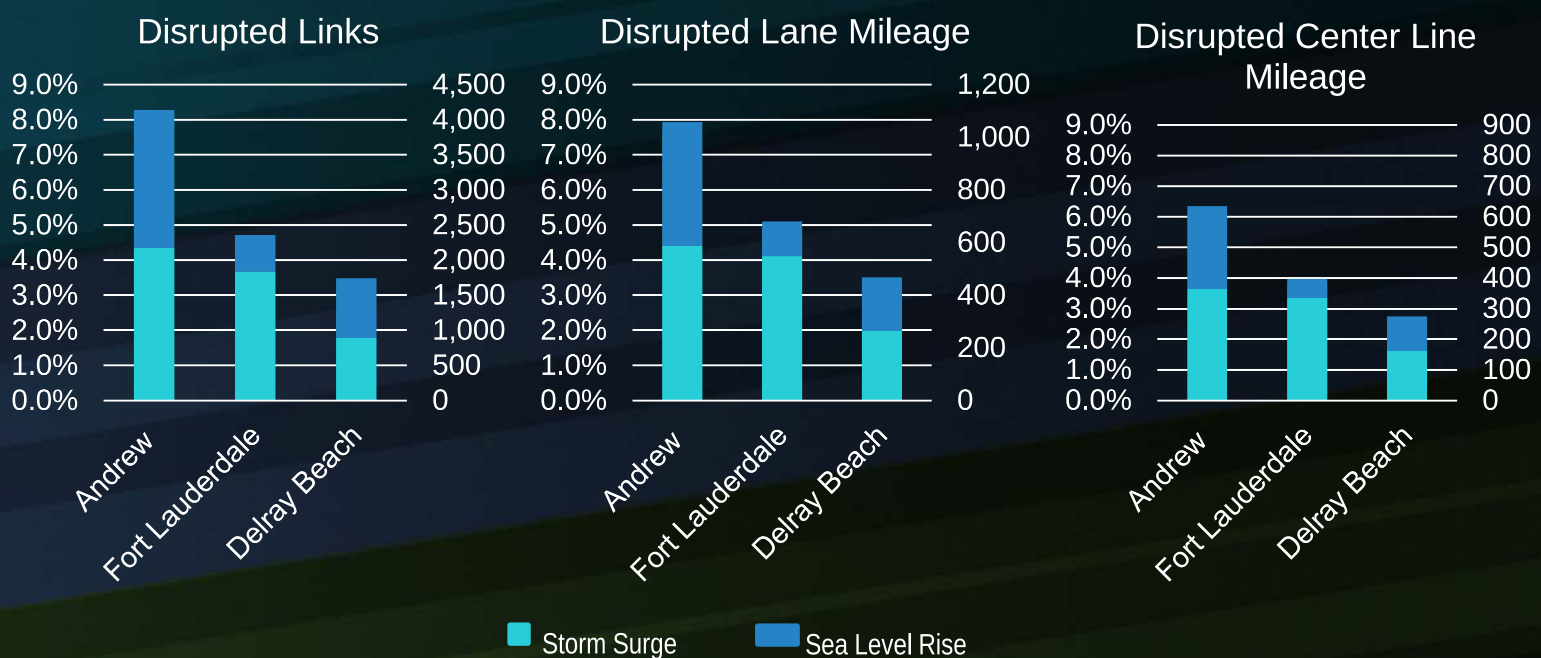
Transportation Network Disruption



Network lane mileage affected:

2% to 8% (263 to 1,057 miles)

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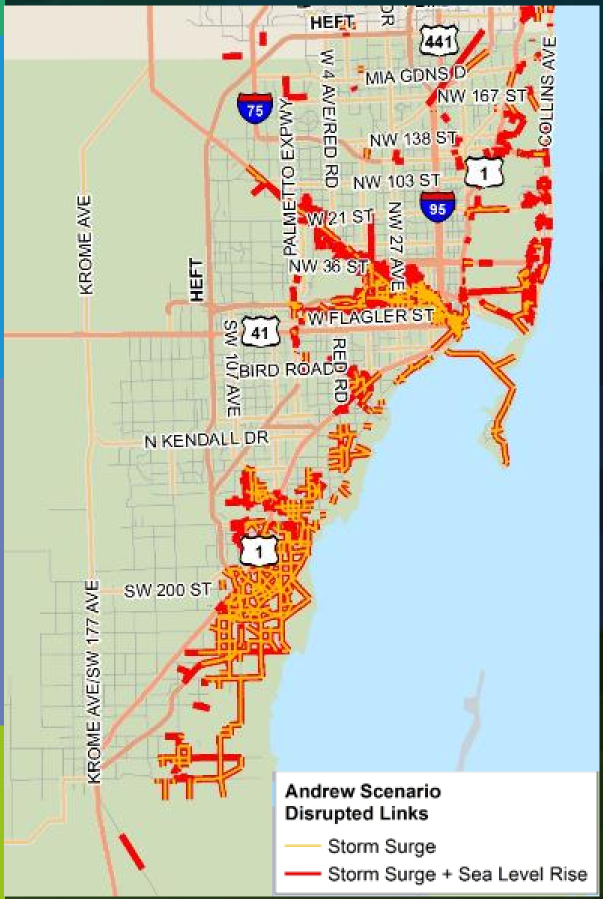
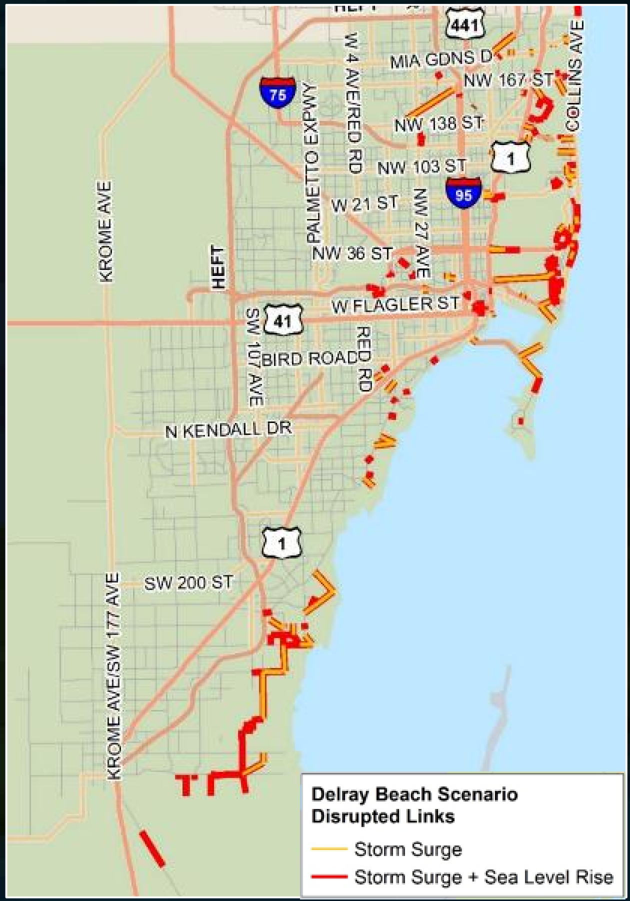
Disrupted Links – Miami-Dade County / Three Storm Tracks





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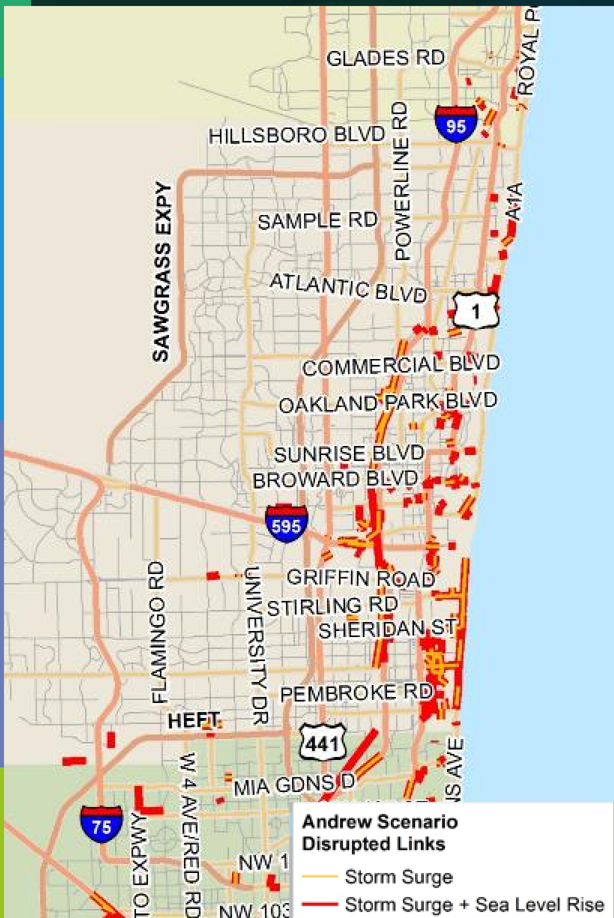
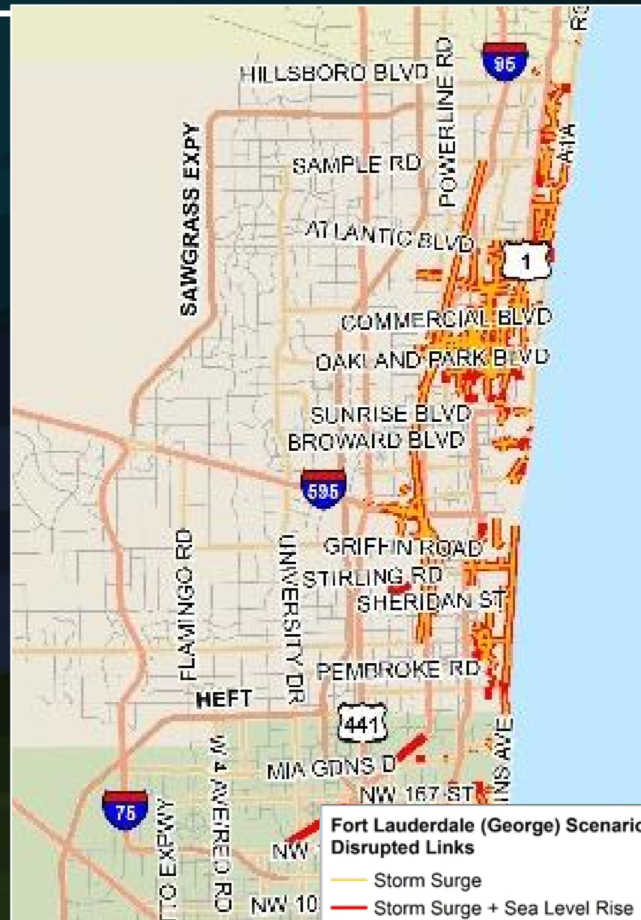
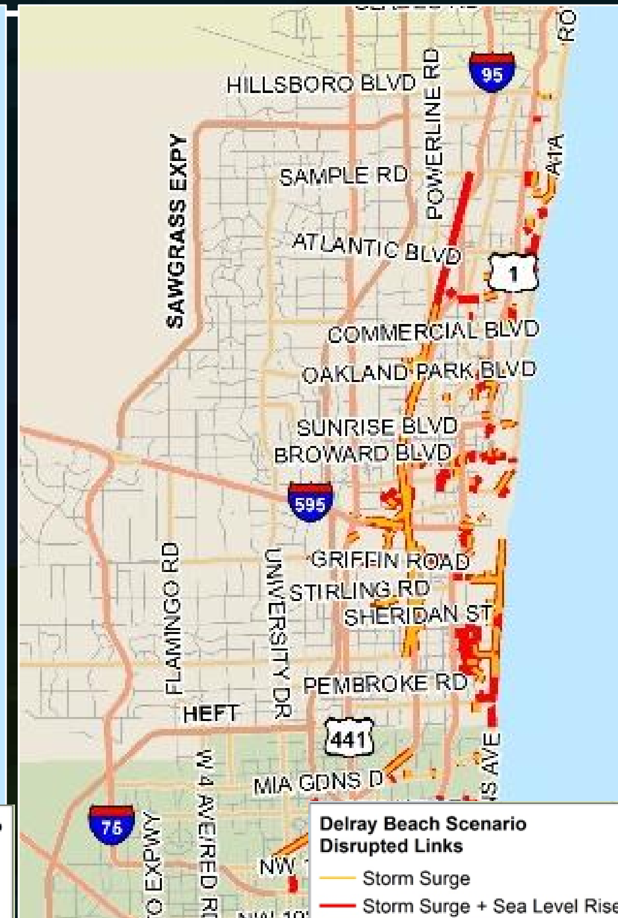
Disrupted Links – Broward County / Three Storm Tracks







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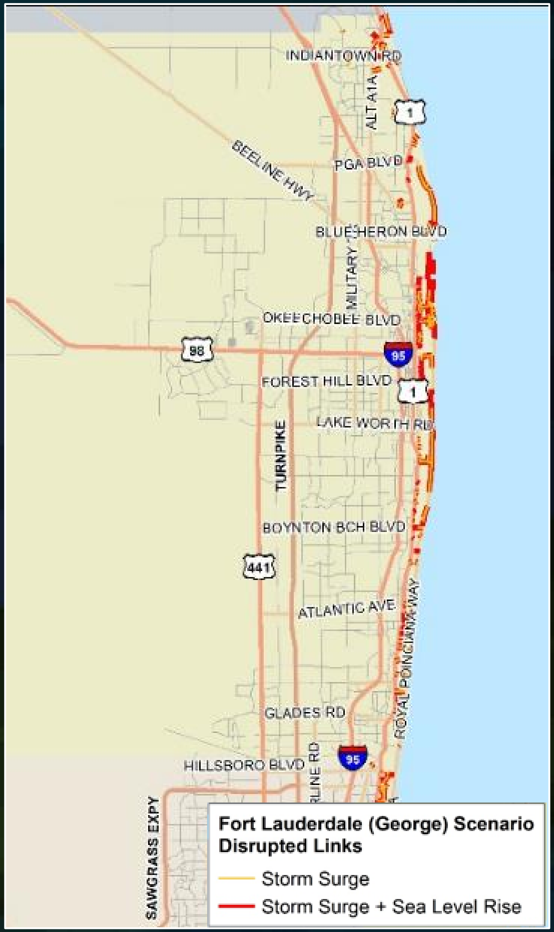
Disrupted Links – Palm Beach County / Three Storm Tracks



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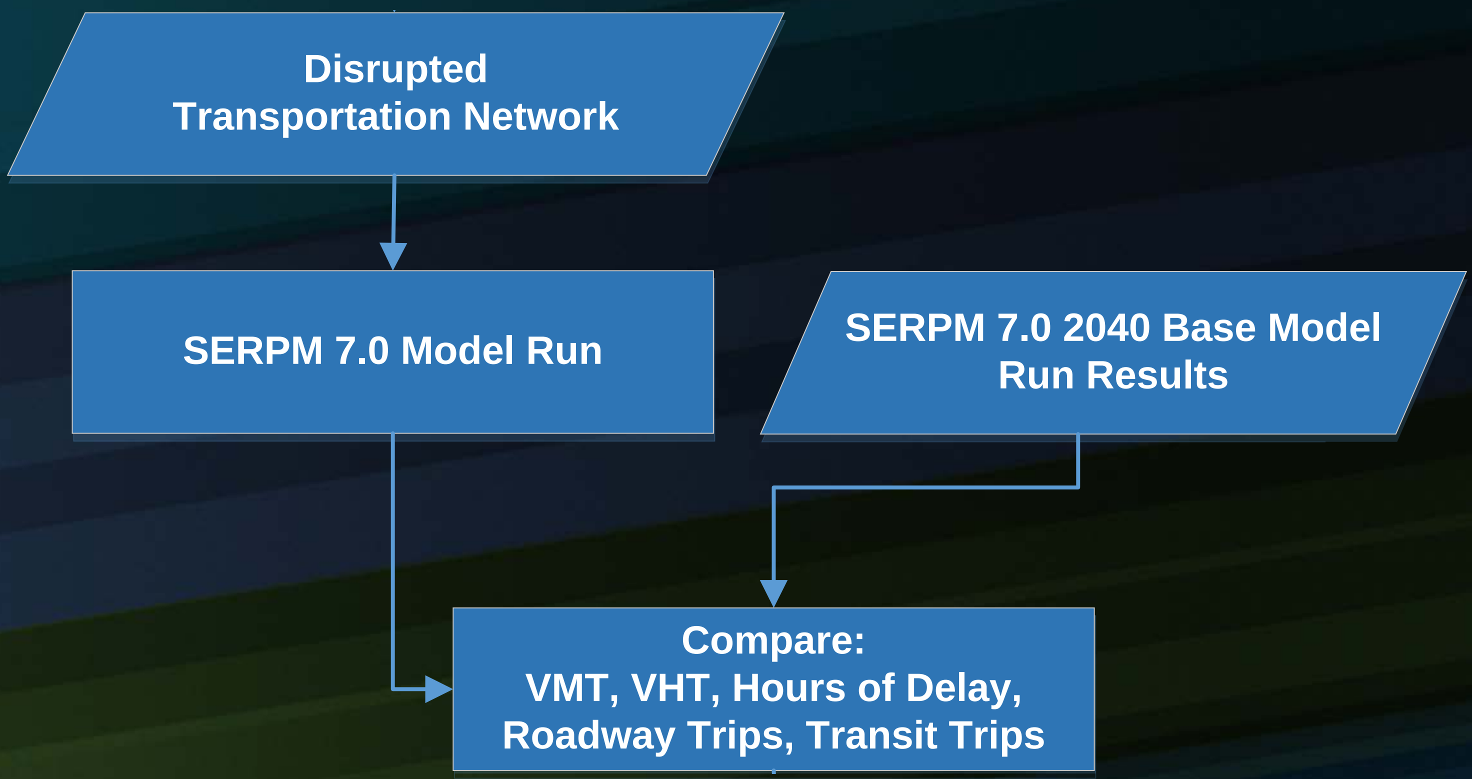
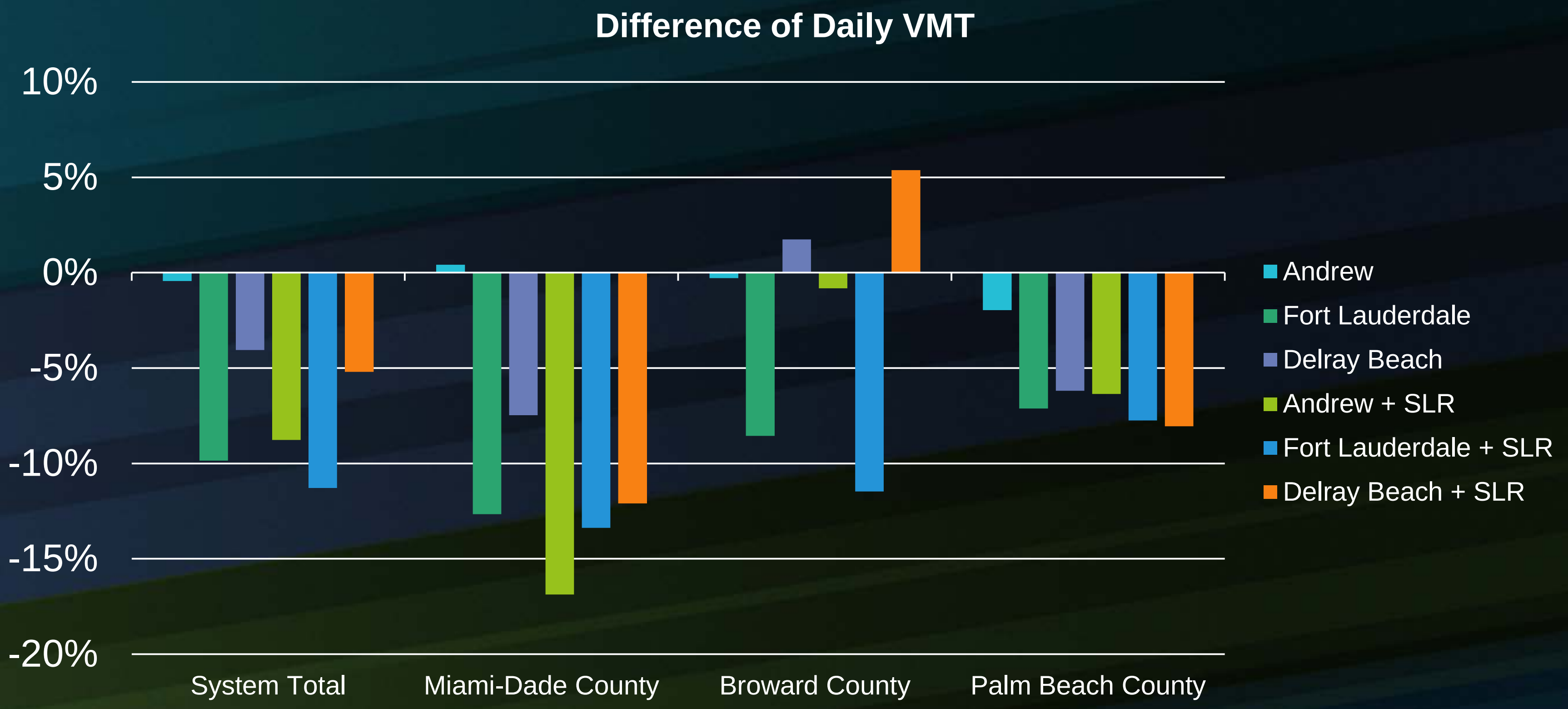
Transportation Modeling



SERPM 7.0 Model Result: Surge & Sea Level Rise Impacts – Three Counties



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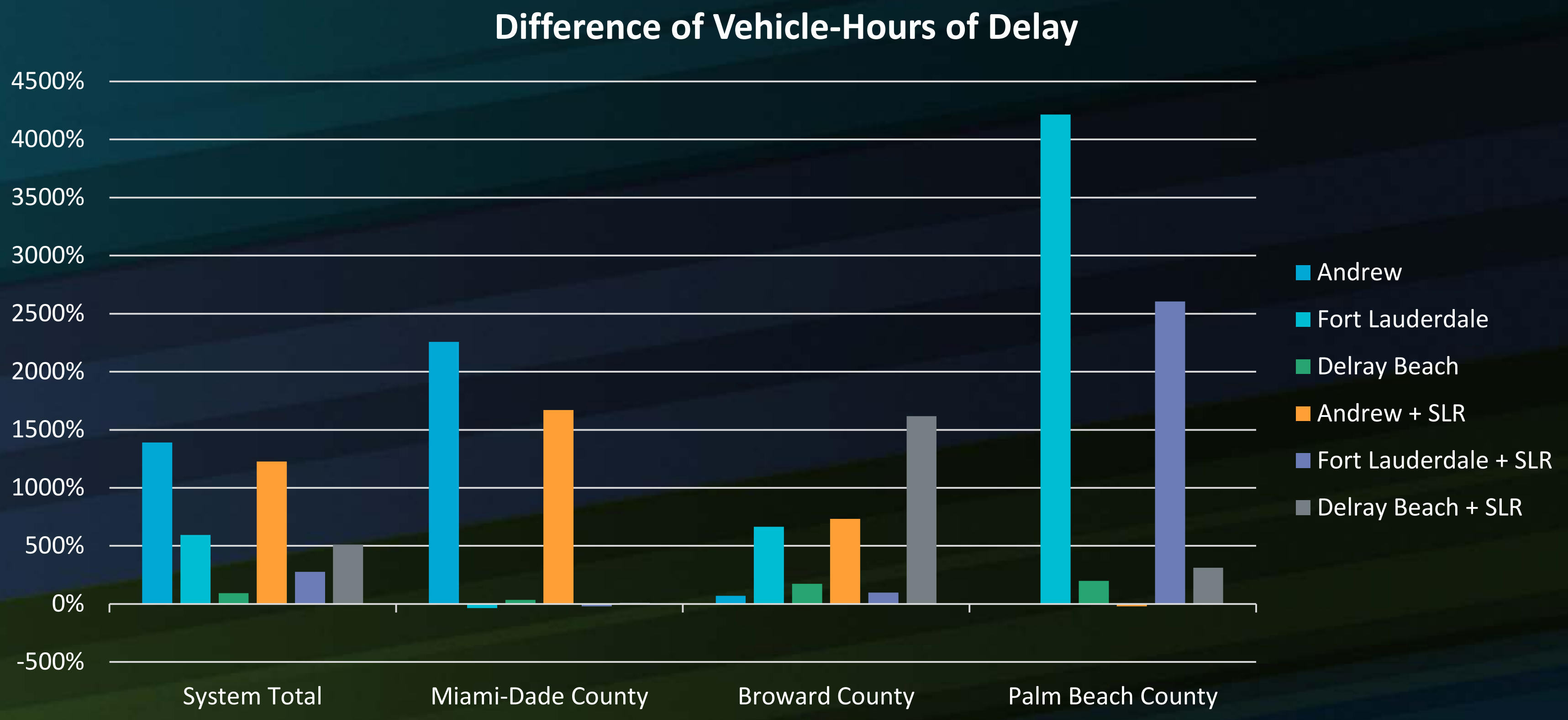
SERPM 7.0 Model Result: Surge & Sea Level Rise Impacts – Three Counties



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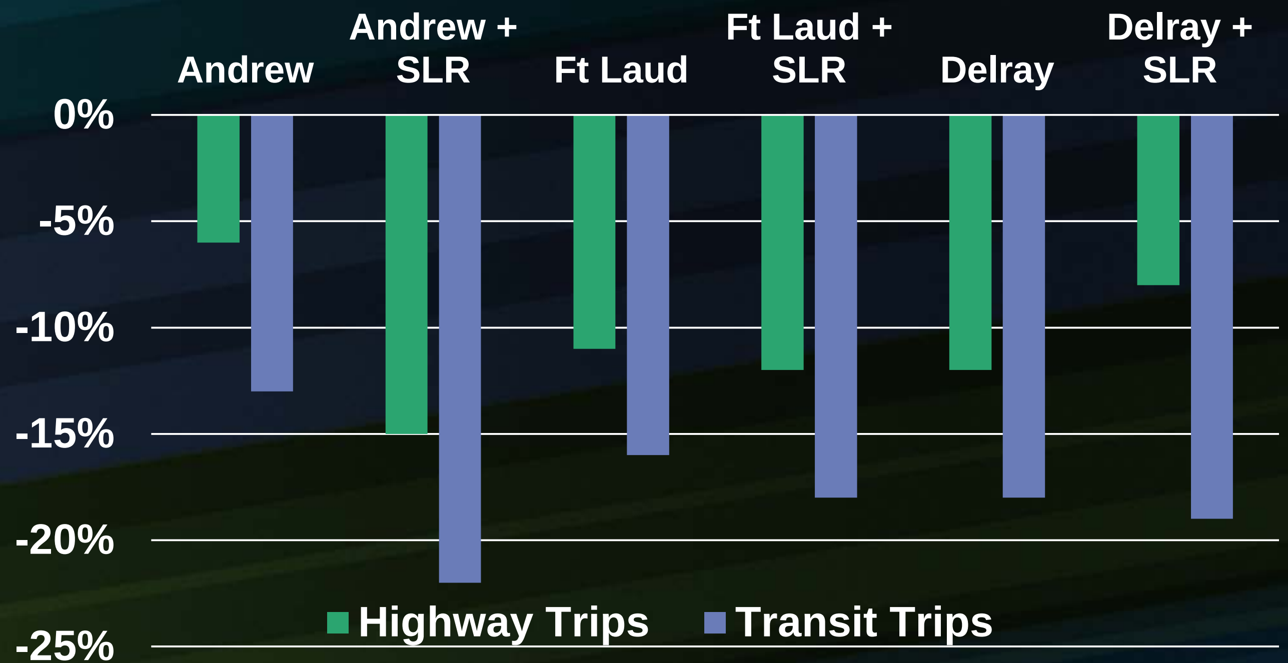
SERPM 7.0 Model Result: Surge & Sea Level Rise Impacts – Three Counties

Lost Trips:

- 6% to 15% Roadway
- 13% to 22% Transit

Trips Made:

- Longer
- More congested



Driver Related
Cost of Increased Hours of Delay

Passenger Vehicle Delay Cost

= Daily Passenger Vehicle hours of Delay x value of person time ($17/hour) x average vehicle occupancy (1.25 person/vehicle)

Truck Delay Cost

= Daily Truck hours of Delay x value of commercial time ($94/hour)

Source:
TTI's 2015 urban mobility report. *Texas A&M Transportation Institute.* Value of person time and commercial time in Miami, Florida.

Driver Related
Cost of Increased Hours of Delay

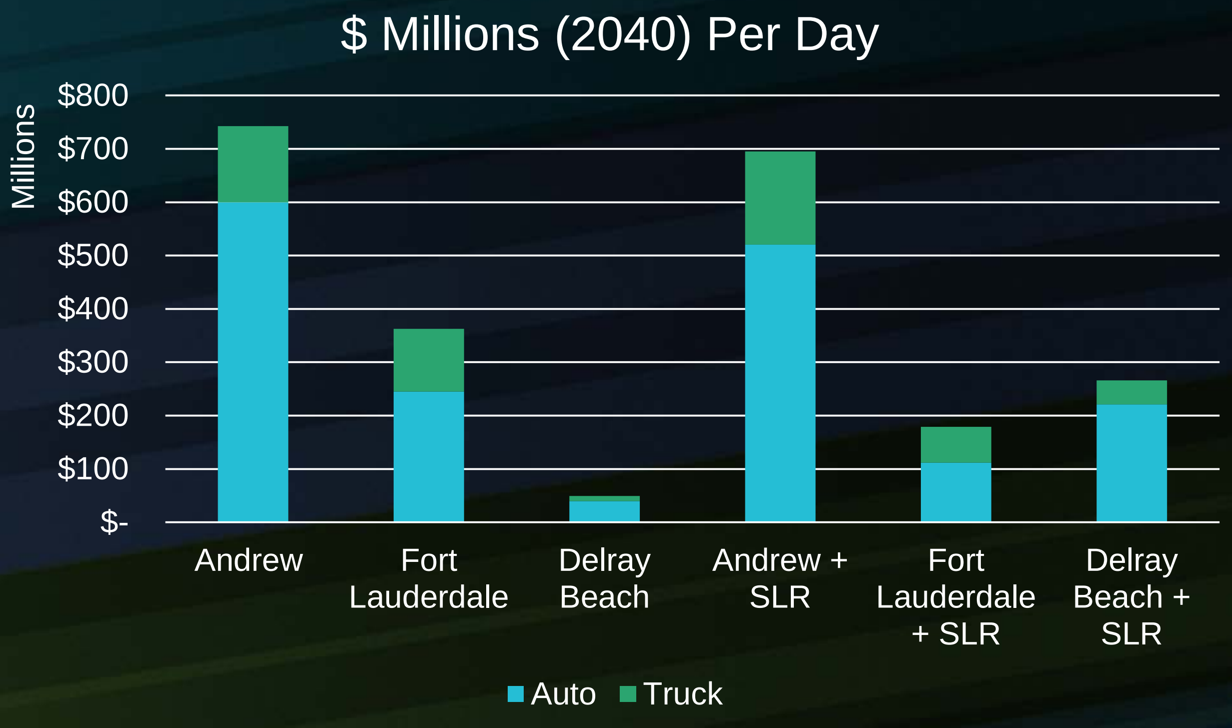
Value of drivers' time spent due to additional delay

Surge Only:

$49 to $742 million

Surge Plus SLR:

$178 to $695 million



Note: Values in 2040 dollars using FDOT 2040 Revenue Forecast Handbook inflation factors.
Does not account for "lost" trips

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Wage Related Cost of Lost Trips

Lost Highway Trips Cost

= Lost highway trips x percentage of work related highway trips (18.6%) x Median earning for workers ($13/hour) x 8 hours

Lost Transit Trips Cost

= Lost transit trips x percentage of work related transit trips (33.5%) x Median earning for workers ($13/hour) x 8 hours

Sources:
National Household Travel Survey, purposes of personal trips and transit trips in the U.S.
2014 American Community Survey, median earning for workers in Florida.

Wage Related Cost of Lost Trips

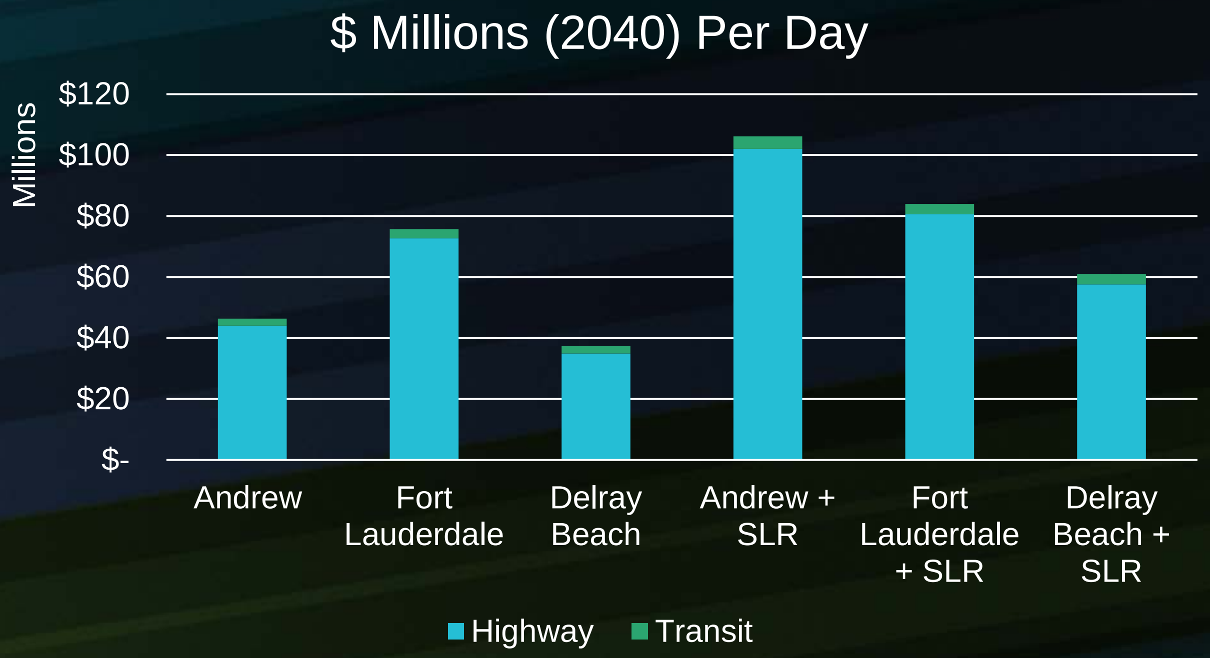
Wage impacts due to inability to get to work

Surge Only:

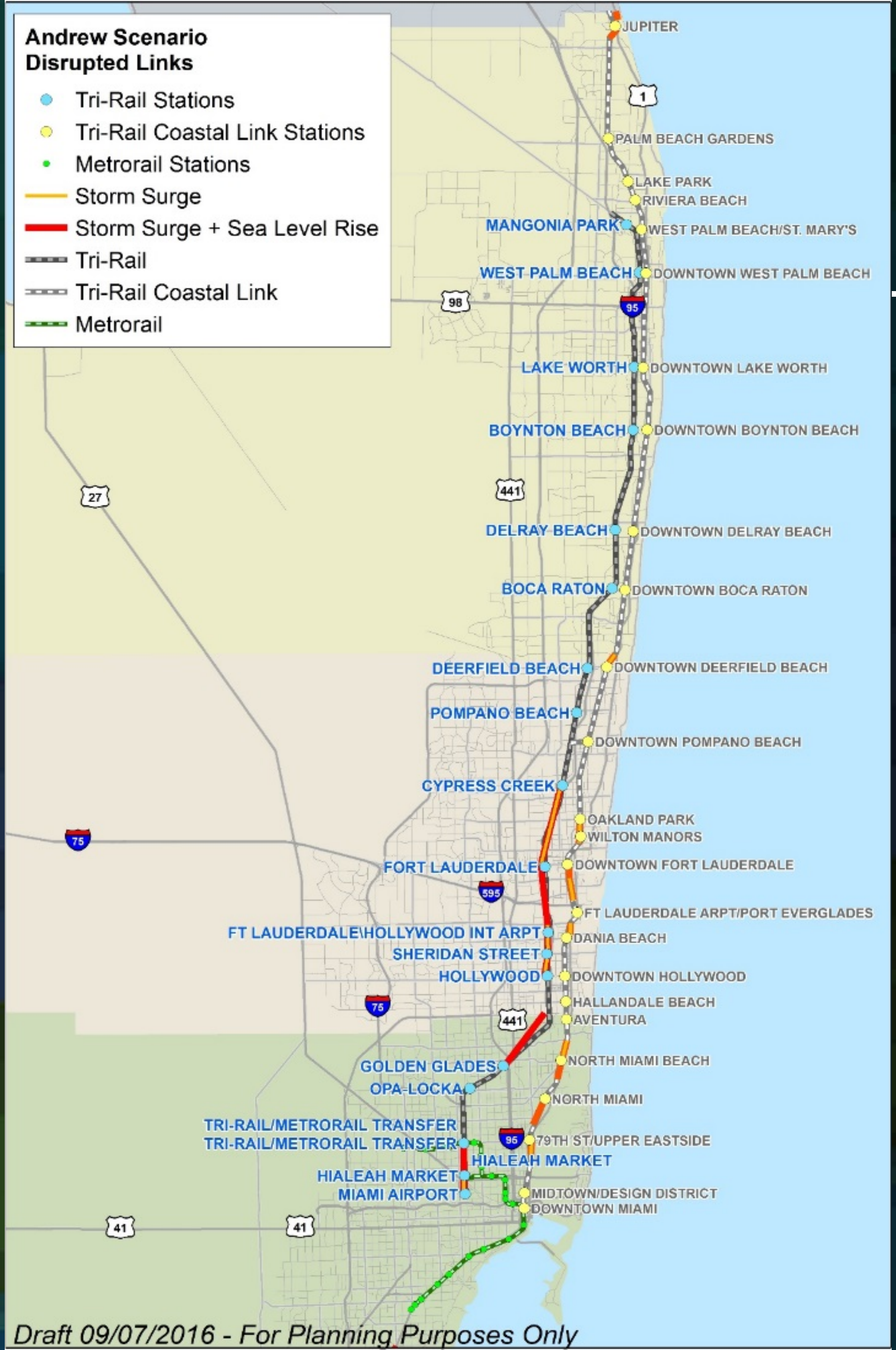
$37 to $75 million

Surge Plus SLR:

$61 to $106 million



Note: Values in 2040 dollars using FDOT 2040 Revenue Forecast Handbook inflation factors.



Railways

Andrew Scenario

- Storm Surge
- Sea Level Rise

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Railways

Ft. Lauderdale Scenario

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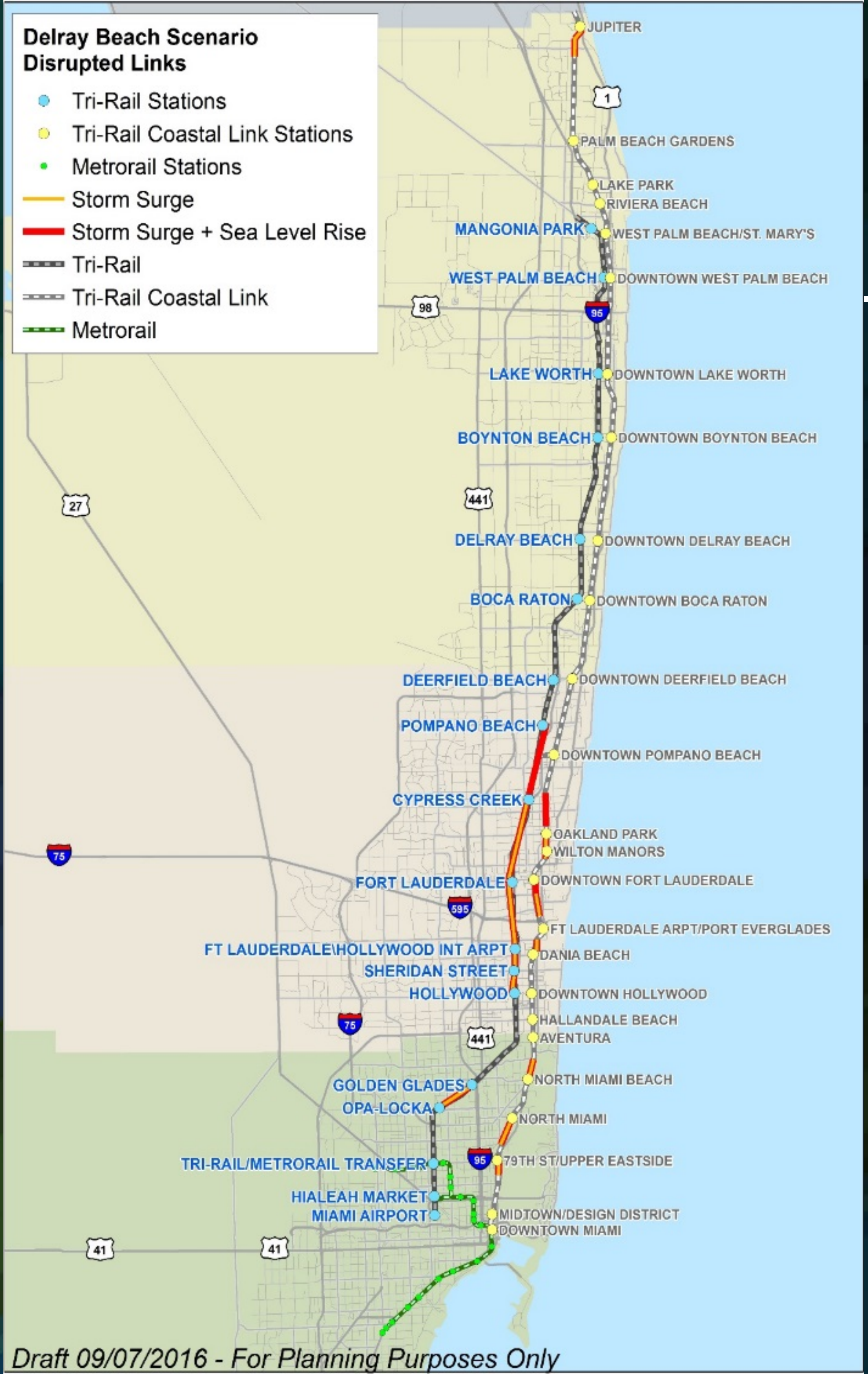
Railways

Delray Beach Scenario



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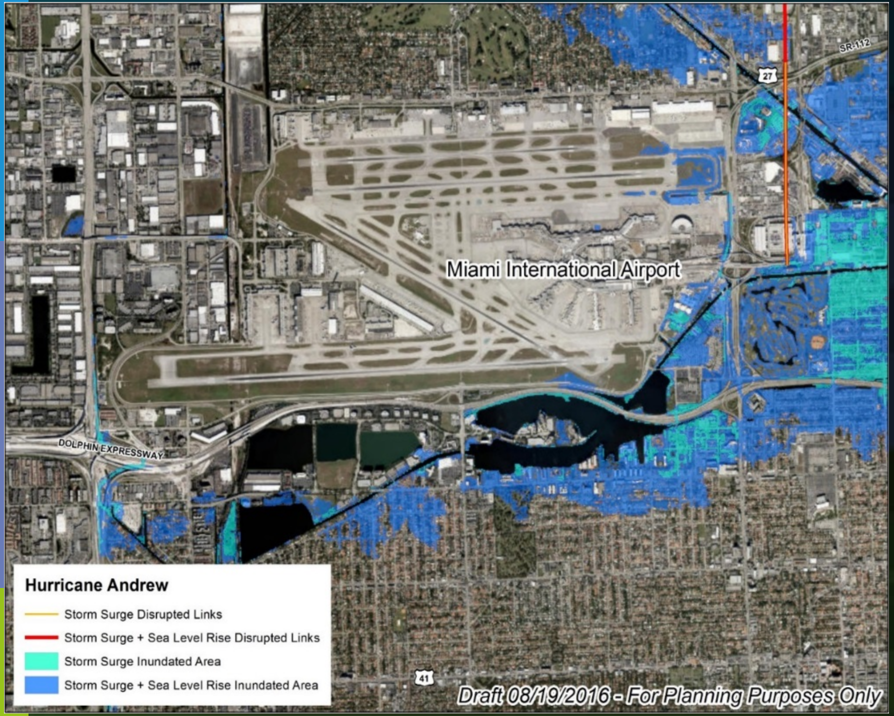
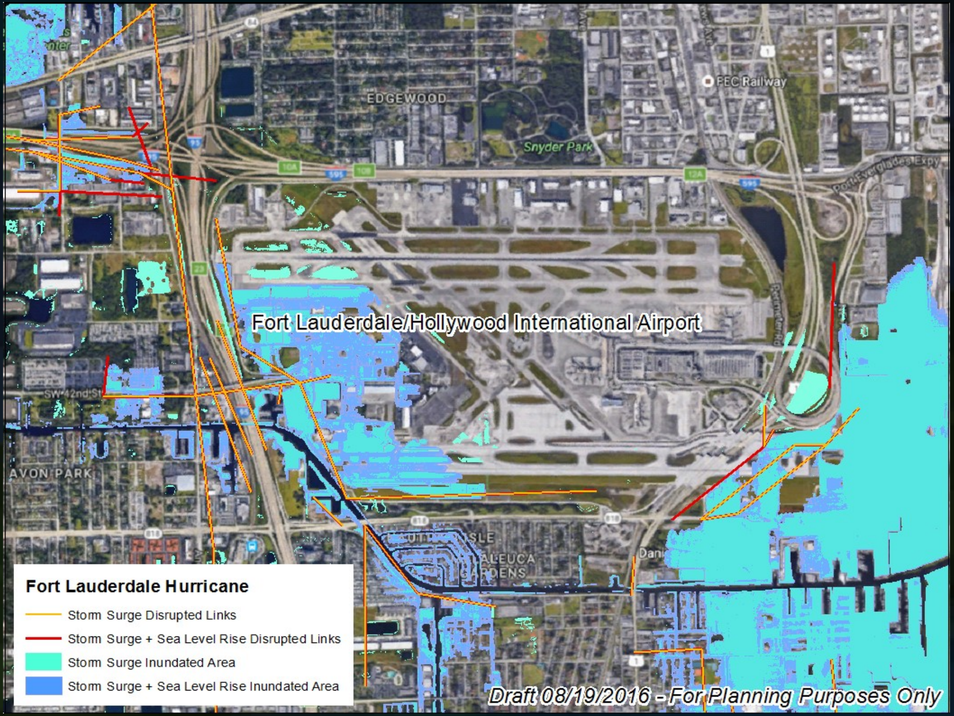
Airports





- Storm Surge
- Sea Level Rise

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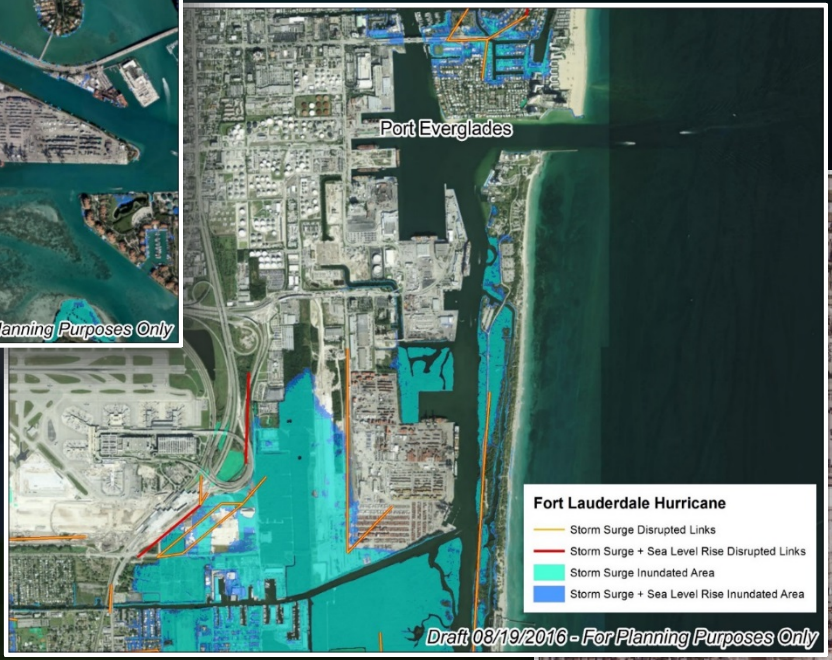
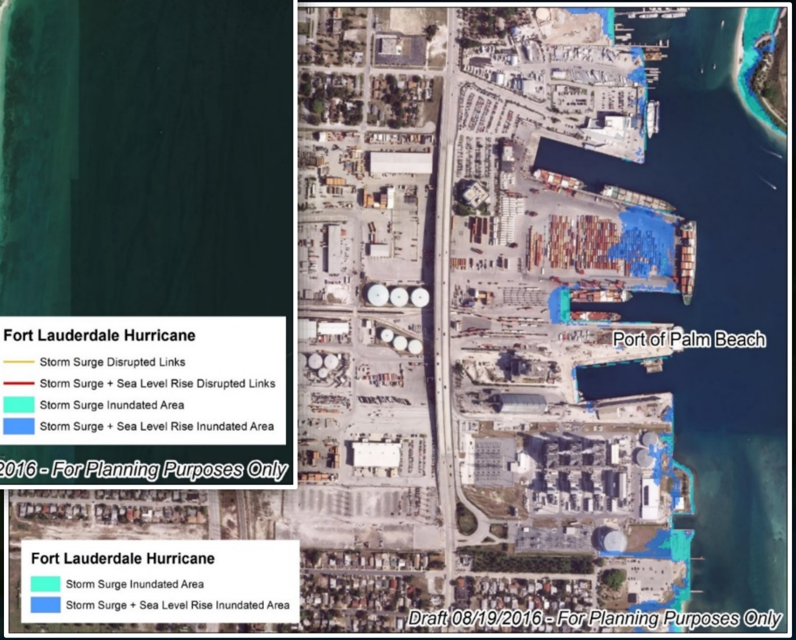
Seaports





- Storm Surge
- Sea Level Rise

Summary

- Storm Surge and Sea Level Rise affects mobility throughout the region
  - 2% to 8% Network lane mileage affected
  - 6% to 15% Roadway trips not made (1 to 2.8 million trips)
  - 13% to 22% Transit trips not made (64 to 113 thousand trips)
  - Trips made: Longer and more congested
  - Potential impacts on Tri-Rail, Airports, Seaports
- When coupled with sea level rise, these storms will reduce system-wide daily VMT by five to 11 percent.
- Most vulnerable areas are those with hydrological connections to the coast
  - Inlets and areas near the Miami River, Middle River, and Loxahatchee River.

Lesson Learned

- Using transportation models to estimate impact of storm surge & sea level rise
  - » Identify facilities/areas to be prioritized for further investigation and improvements
  - » Robust transportation network
  - » End-to-end trip perspective of adaptive capacity
- Limitations due to resources:
  - » Geospatial accuracy of infrastructure
  - » Transit Reroute
  - » Modeling in different time of a day

Recommendations

- Incorporate resiliency in all phases of transportation projects
  - Mainstream adaptation strategies in projects
- Continue and broaden collaboration on transportation resiliency
  - SFWMD and drainage districts, public works, etc.
- Update as better tools and data become available;
  - Water modeling and elevation data is rapidly improving
  - Travel Demand Model is updating
- Enhancements needed to answer questions:
  - How deep is the water?
  - How long does a facility remain inundated?
  - More robust economic impacts

Thank you!

Appendix B: Miami-Dade County's "Assessment of Available Tools to Create a More Resilient Transportation System"

Memorandum

MIAMI-DADE COUNTY

Date: November 30, 2016

To: Honorable Chairman Jean Monestime and Members, Board of County Commissioners

From: Carlos A. Gimenez
Mayor

Subject: Final Report for Assessment of Available Tools to Create a More Resilient Transportation System – Directive 160220

The following report is pursuant to Resolution No. R-235-16 adopted by the Board of County Commissioners (Board) on March 8, 2016. This resolution directed the County Mayor to analyze and implement, under certain circumstances, the methods and tools from the Federal Highway Administration and the Florida Department of Transportation that may be used to assess the vulnerability to sea level rise and extreme weather for future County transportation projects, as well as other possible applications. Resolution No. R-235-16 also directed the Mayor or the Mayor's designee to prepare a report with recommendations for the Board's consideration.

Background

The attached report first describes how sea level rise could affect transportation infrastructure in the County. Sea levels have been rising over the past century and have risen in Miami-Dade County by approximately two (2) to three (3) inches since Hurricane Andrew hit in 1992. Sea levels will continue to rise for the coming decades, and, by 2030, they are expected to be three (3) to seven (7) inches higher than current levels. Higher water levels can have multiple impacts on the transportation network. These higher water levels can reduce access to residents' property, impact evacuation networks, deteriorate roadway surfaces and substructures, and damage vehicles (including County transit vehicles) that pass through or sit in saltwater. Low-lying causeways or bridges spanning waterways can be particularly vulnerable. Even in inland areas, roadways are typically designed to be one of the lowest points in a given area. While this helps alleviate flooding risk to adjacent properties, it also means roadways may be some of the first assets affected by higher water.

The second portion of the report describes what is already known about the transportation network's vulnerability to sea level rise and storm events, including the findings from two (2) recent studies that focused on the Southeast Florida region. The report also reviews the existing tools from the federal and state governments that can help assess the vulnerability of the transportation system moving forward and discusses their potential utility for planning and other uses. These tools and previous studies offer valuable information to inform on-going planning efforts; however, their results should be considered in the context of other studies and efforts.

More detailed and tailored efforts are needed to inform any project-level decision-making process. These studies can, however, be taken into consideration as key supporting information in regular decision-making processes. In particular, these tools can help inform long-term planning efforts such as the development of the Strategic Miami Area Rapid Transit Plan and the Long-Range Transportation Plan. Moving ahead, the Office of Resilience will continue to coordinate with the Miami-Dade Metropolitan Planning Organization, Department of Transportation and Public Works, and other key stakeholders to identify opportunities to integrate risk reduction measures into on-going planning efforts. In particular, when major plans such as the Long Range Transportation Plan are updated, there will be increased scrutiny of how resiliency can be advanced alongside other goals.

In accordance with Ordinance No. 14-65, this report will be placed on the next available Board meeting agenda.

If you have questions or concerns, please contact James F. Murley, Chief Resilience Officer, Department of Regulatory and Economic Resources, at (305) 375-4811 or MurleyJ@miamidade.gov.

Attachment

c: Honorable Harvey Ruvin, Clerk of Courts, Eleventh Judicial Circuit
Abigail Price-Williams, County Attorney
Office of the Mayor Senior Staff
Department Directors
Lourdes Gomez, Deputy Director, Department of Regulatory and Economic Resources
James F. Murley, Chief Resilience Officer, Department of Regulatory and Economic Resources
Mark R. Woerner, Assistant Director for Planning, Department of Regulatory and Economic Resources
Neil Singh, Interim Commission Auditor
Eugene Love, Agenda Coordinator

ASSESSMENT OF AVAILABLE TOOLS TO CREATE A MORE RESILIENT TRANSPORTATION SYSTEM

NOVEMBER 2016

Final Report for Resolution R-235-16
in support of the Sea Level Rise Task
Force final recommendations

Table of Contents

Figure 1: Saltwater flooding on the roadway during a King Tide in 2013.

Source: Miami-Dade County, 2013

Introduction

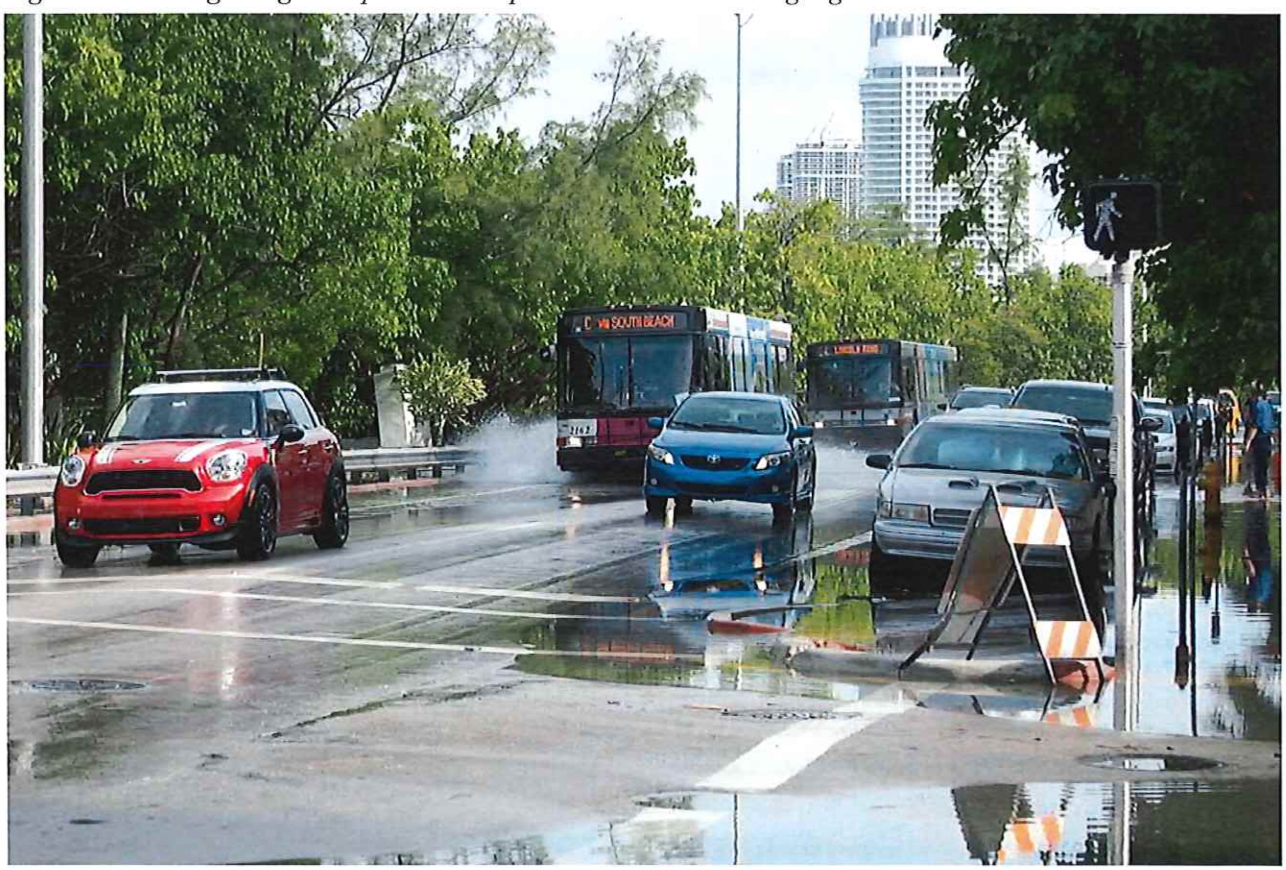
Supporting resolution & context

On March 8, 2016, the Board of County Commissioners passed Resolution R-235-16, sponsored by Commissioner Rebeca Sosa, which directed the Mayor or Mayor's designee,

> "to analyze and implement under certain circumstances the methods and tools from the Federal Highway Administration and the Florida Department of Transportation that may be used to assess the vulnerability to sea level rise and extreme weather for future County transportation projects as well as other possible applications"

This final report, provided pursuant to R-235-16, first gives a general description of how sea level rise has and could affect transportation infrastructure within the County (Figures 1 and 2). The second portion describes specific studies that have analyzed the transportation network's vulnerability to sea level rise and storm events. The report also reviews the existing tools from the federal and state governments that can help assess the vulnerability of the transportation system moving forward and discusses their potential utility for planning and other uses.

Figure 2: Flooding along an important transportation corridor during high tide in October 2014.



Source: Miami-Dade County, 2014

Why is sea level rise a concern for transportation infrastructure?

Sea levels have been rising over the past century and have risen in Miami by approximately two to three inches since Hurricane Andrew hit in 1992.[1] Sea levels will continue to rise for the coming decades and by 2030 they are expected to be three to seven inches higher than today's levels (Figure 3). While these changes appear subtle, the County's unique geology and its equally unique water management system mean that small changes can have cascading impacts across several systems. For example, higher sea levels will increase groundwater levels, which can diminish the capacity of existing drainage infrastructure. Lower lying areas, even those away from the coast, will in turn, be more prone to flooding if additional measures are not taken.

Much of the county is already vulnerable to flooding during heavy rain events and storm surges, therefore it is important to consider sea level rise in the context of these risks while planning and designing infrastructure. Considering these amplified flooding risks is particularly crucial along evacuation routes.

Figure 3: Projected sea level rise for Southeast Florida.

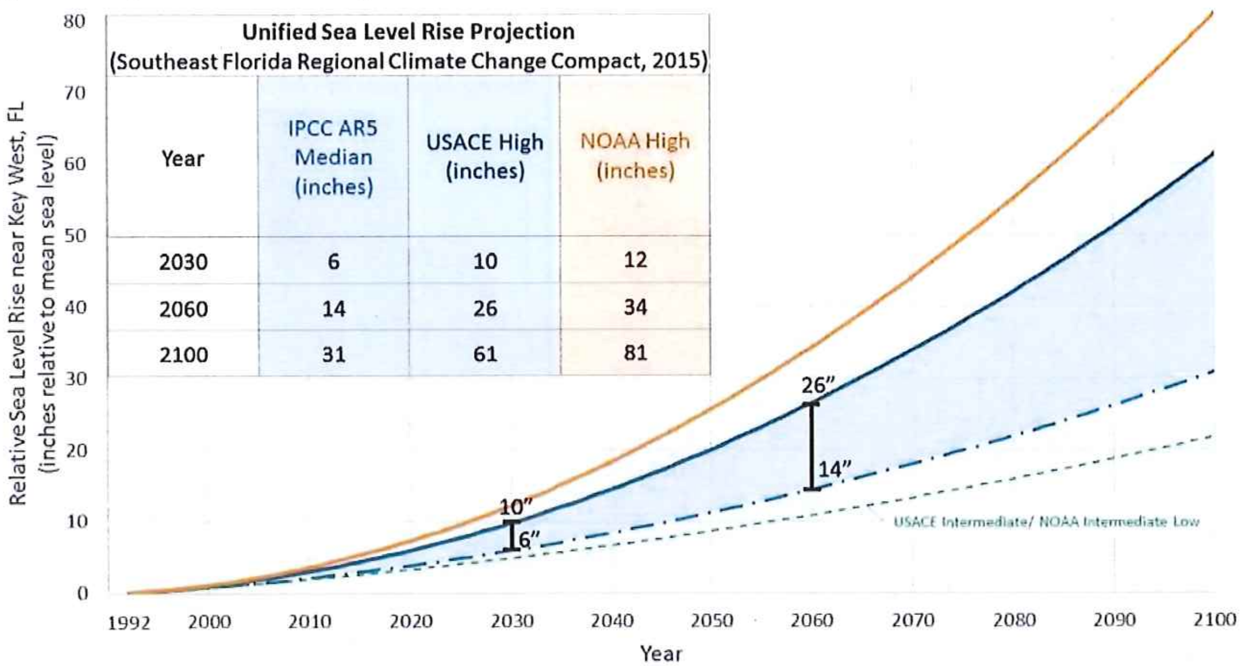


Figure 1: Unified Sea Level Rise Projection. These projections are referenced to mean sea level at the Key West tide gauge. The projection includes three global curves adapted for regional application: the median of the IPCC AR5 RCP8.5 scenario as the lowest boundary (blue dashed curve), the USACE High curve as the upper boundary for the short term for use until 2060 (solid blue line), and the NOAA High curve as the uppermost boundary for medium and long term use (orange solid curve). The incorporated table lists the projection values at years 2030, 2060 and 2100. The USACE Intermediate or NOAA Intermediate Low curve is displayed on the figure for reference (green dashed curve). This scenario would require significant reductions in greenhouse gas emissions in order to be plausible and does not reflect current emissions trends.

Source: Unified Sea Level Rise Projection for Southeast Florida, Southeast Florida Regional Climate Change Compact, 2015

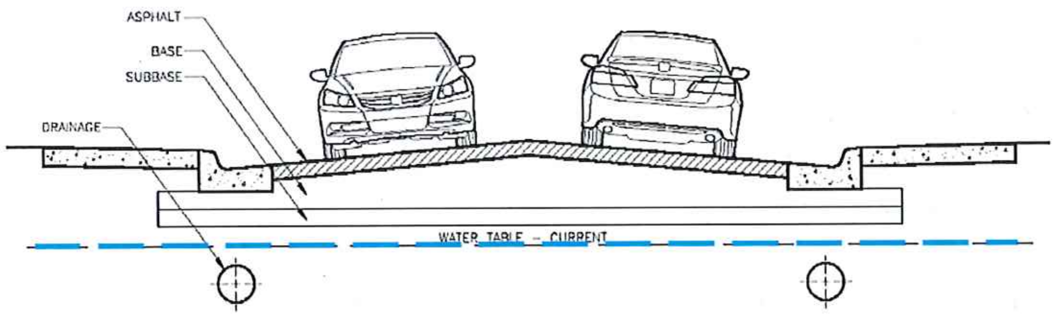
[1]Data derived from NOAA tide gauge records available at: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8723170. These data show a rise of 57.36 mm +/- 10.32 mm or 2.25" +/- 0.41". The South Florida Water Management District's S-21 tide gauge has shown a mean tailwater rise of 3.24 inches, since 1992.

Impacts on transportation infrastructure

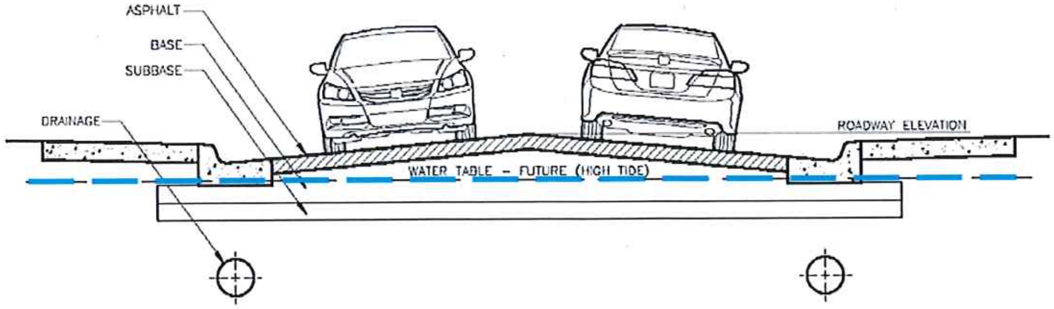
Higher water levels, which are often easiest to observe during seasonal king tides or storms, can have multiple impacts on the transportation network. These higher water levels can reduce access to residents' property, impact evacuation networks, deteriorate roadway surfaces and substructures, and damage vehicles (including County transit and emergency response vehicles) that pass through or sit in saltwater. Low-lying causeways or bridges spanning waterways can be particularly vulnerable. Even in inland areas the roadways are typically designed to be one of the lowest points in a given area. While this helps alleviate flooding risk to adjacent properties, it also means roadways may be some of the first assets affected by higher water levels. Even areas that are not directly affected by amplified flooding risks could be impacted as travel patterns shift in response to the disruption in low-lying areas.

Over the long-term, sea level rise could cause higher average groundwater levels, reduced drainage capacity, and increased inundation, which will increase wear and tear on the roadways.[2] This is particularly true if the road base becomes saturated for an extended period of time (Figure 4). Sea level rise could also have other impacts such as reducing bridge clearances for vessels, increasing erosion along coastal roadways, or increased corrosion of infrastructure.

Figure 4: Impact of rising water levels on roadways.



CURRENT BASE CONDITION FOR LOW LYING ROADS



FUTURE BASE CONDITION FOR LOW LYING ROADS

Source: Miami-Dade County, 2016

[2] Berry, L., "Development of a Methodology for the Assessment of Sea Level Rise Impacts on Florida's Transportation Modes and Infrastructure", 2012. P. 8

What have recent studies revealed about the vulnerability of the existing transportation network?

The following section provides an overview of three recent studies that explored the vulnerability of the transportation network to sea level rise and flooding. The first study was funded by the Federal Highway Administration, a second study was funded by the Florida Department of Transportation, and a final study was led by the Southeast Florida Regional Climate Change Compact. The section also reviews how the vulnerability of the system is assessed on an on-going basis by County staff.

Federal Highway Administration Climate Resilience Pilot Project for Southeast Florida

In 2013, The Federal Highway Administration launched a Climate Resilience Pilot Program, to assist state and local partners improve the resilience of their transportation systems to extreme weather events and climate change. One of the 19 pilots projects was focused on Southeast Florida and included Palm Beach, Broward, Miami-Dade, and Monroe Counties.[3] The Miami-Dade Metropolitan Planning Organization (MPO), Broward MPO, Palm Beach MPO, and the Monroe County Planning and Environmental Resources Department worked together with the Federal Highway Administration to conduct a detailed vulnerability assessment of the region's transportation infrastructure.

This completed study, *South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project*, ultilized the Federal Highway Administration's Vulnerability Assessment Framework to analyze the region's transportation network.[4] This project's five key objectives were to:

- Provide member agencies with the ability to analyze adaptation strategies
- Identify adaptation projects and strategies
- Apply a vulnerability framework and provide feedback to the planning process
- Incorporate climate change throughout agency decision-making processes
- Strengthen institutional capacity to address climate change risk within partner agencies

To determine which assets were "vulnerable", this pilot study conducted a detailed geospatial analysis to determine scores for "regionally significant" road and rail segments.[5] The assessment approach, summarized in Figure 5, defined vulnerability as a function of exposure, sensitivity, and adaptive capacity. The study explored whether assets would be affected by:

- sea level rise,
- storm surge and related flooding, and
- heavy precipitation and related flooding.

The project team assessed both exposures to flooding today and in the future. The team analyzed the implications of 1-, 2-, and 3-feet of sea level rise according to the methodology developed by the Army

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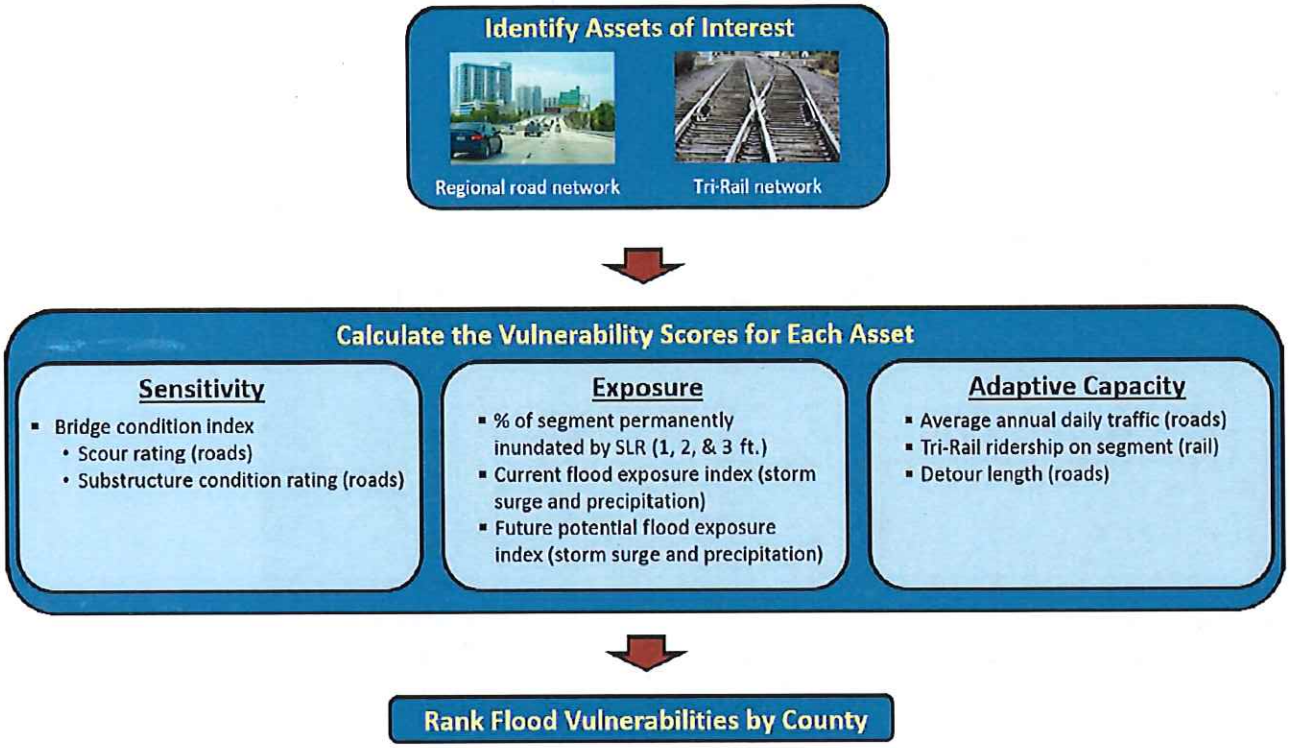
[3] For information on the other pilot projects see http://www.fhwa.dot.gov/environment/climate_change/adaptation/.
[4] *South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project*. Federal Highway Administration. 2015. Available at http://www.browardmpo.org/images/WhatWeDo/SouthFloridaClimatePilotFinalRpt.pdf
[5] as defined by the Southeast Florida Transportation Council

Corps of Engineers. This is consistent with the *Unified Sea Level Rise Projections* put forth by the Southeast Florida Regional Climate Change Compact.[6]

Figure 5: Vulnerability assessment approach used in the Federal Highway Administration Southeast Florida Study.

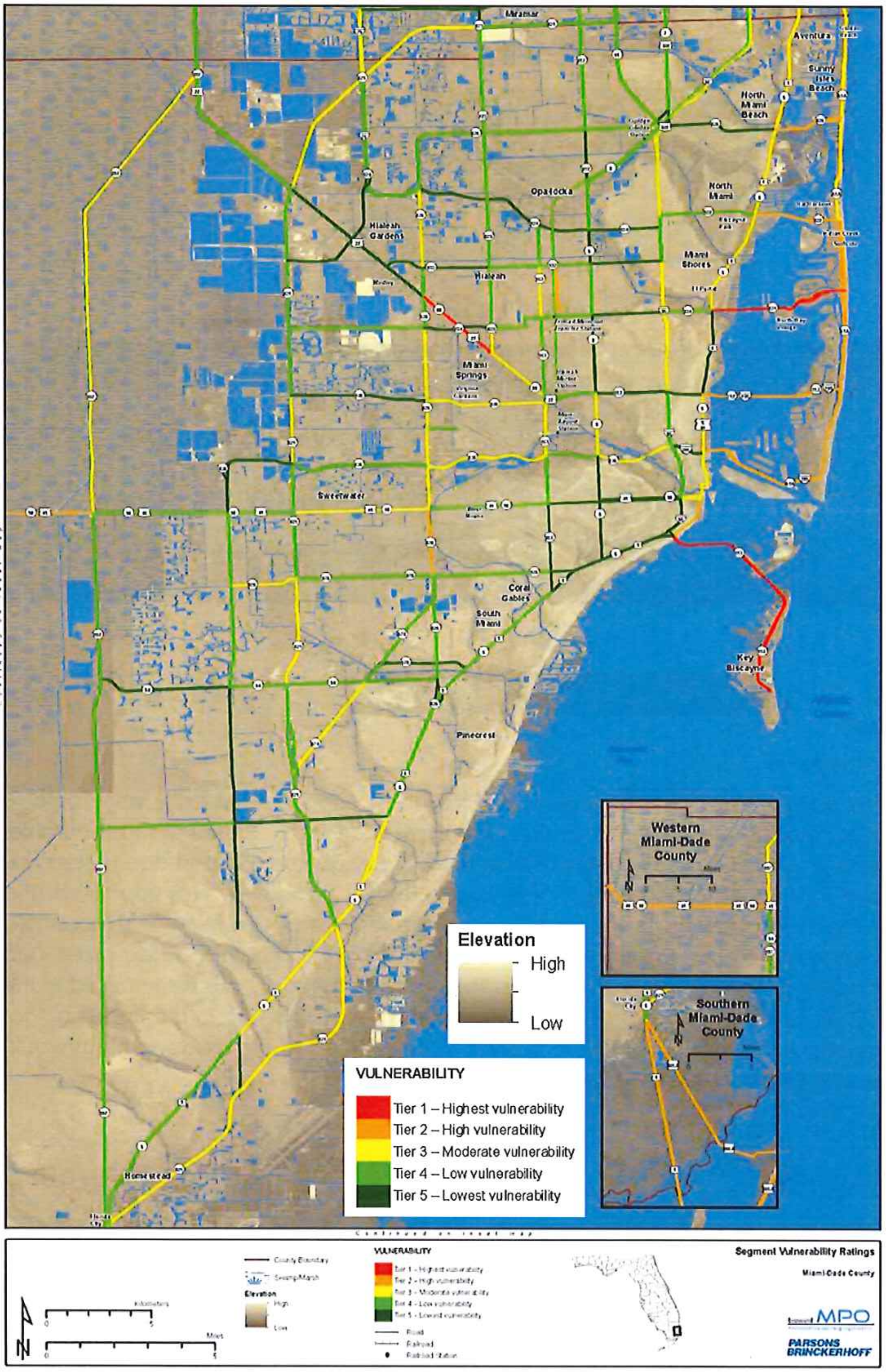


Source: Federal Highway Administration, 2016

The study revealed that several road and rail segments within the County are currently vulnerable to flooding and will become more so as sea levels rise if no measures are taken. Causeways to the barrier islands such as Key Biscayne and Miami Beach were found to be highly exposed, in part due to their low elevations and also due to the long detour lengths that would result if a roadway was impacted. The study also found that regional roadways that pass through wetlands, such as Tamiami Trail and Card Sound Road, are also highly vulnerable. This is again due to their low elevation, high flood exposure, and the long detour lengths due to limited alternative routes. The results of this study are summarized in the following figures, which show the results of the vulnerability assessment (Figure 6), future flooding "hot spots" (Figure 7), the current vulnerability to a 100-year storm (Figure 8), and where road segments would be permanently inundated following three feet of sea level rise (Figure 9).

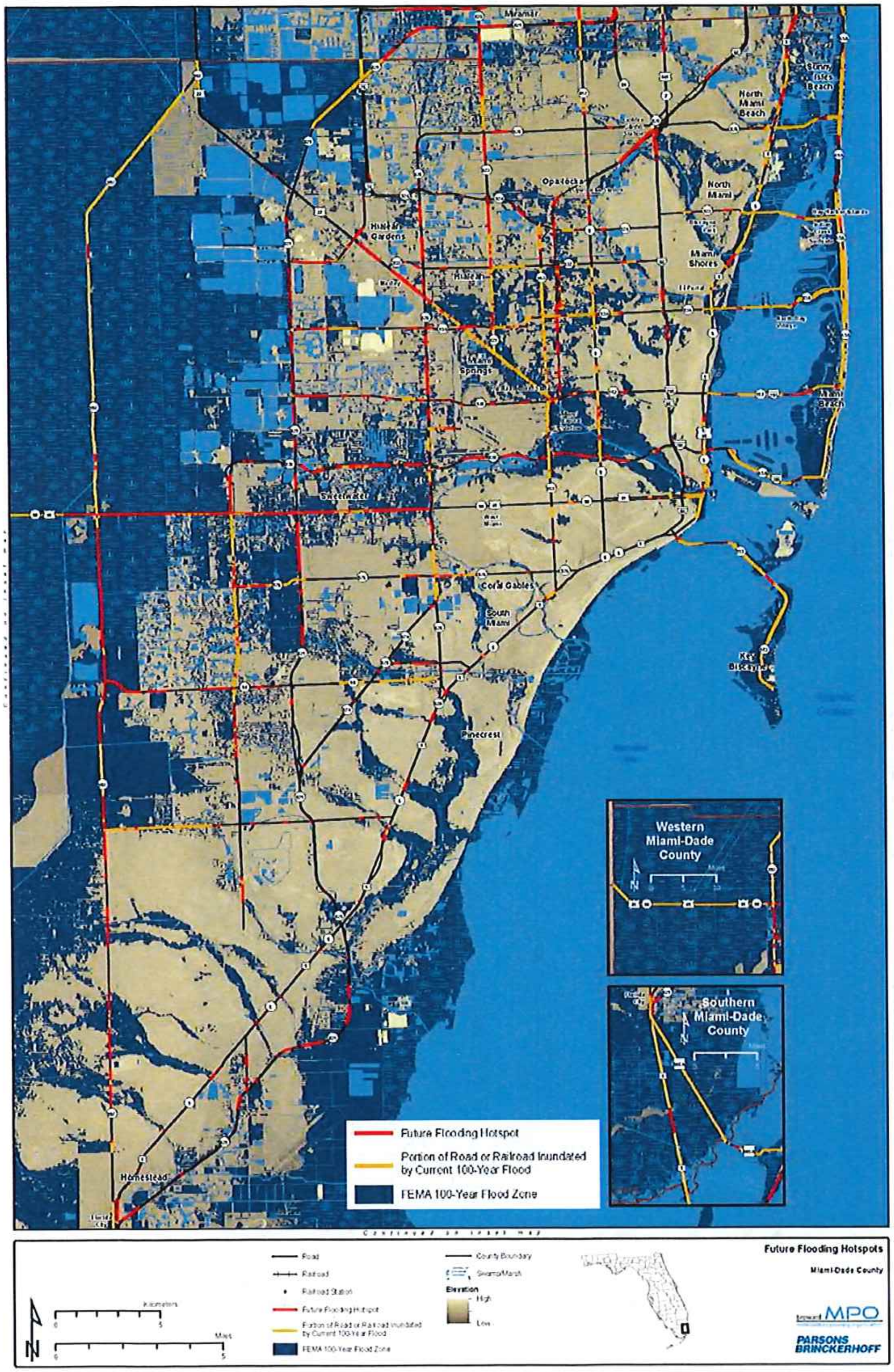
[6] The Southeast Florida Regional Climate Change Compact's "Unified Sea Level Rise Projections" are available at http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2015/10/2015-Compact-Unified-Sea-Level-Rise-Projection.pdf

Figure 6: Vulnerability assessment results for Miami-Dade County.



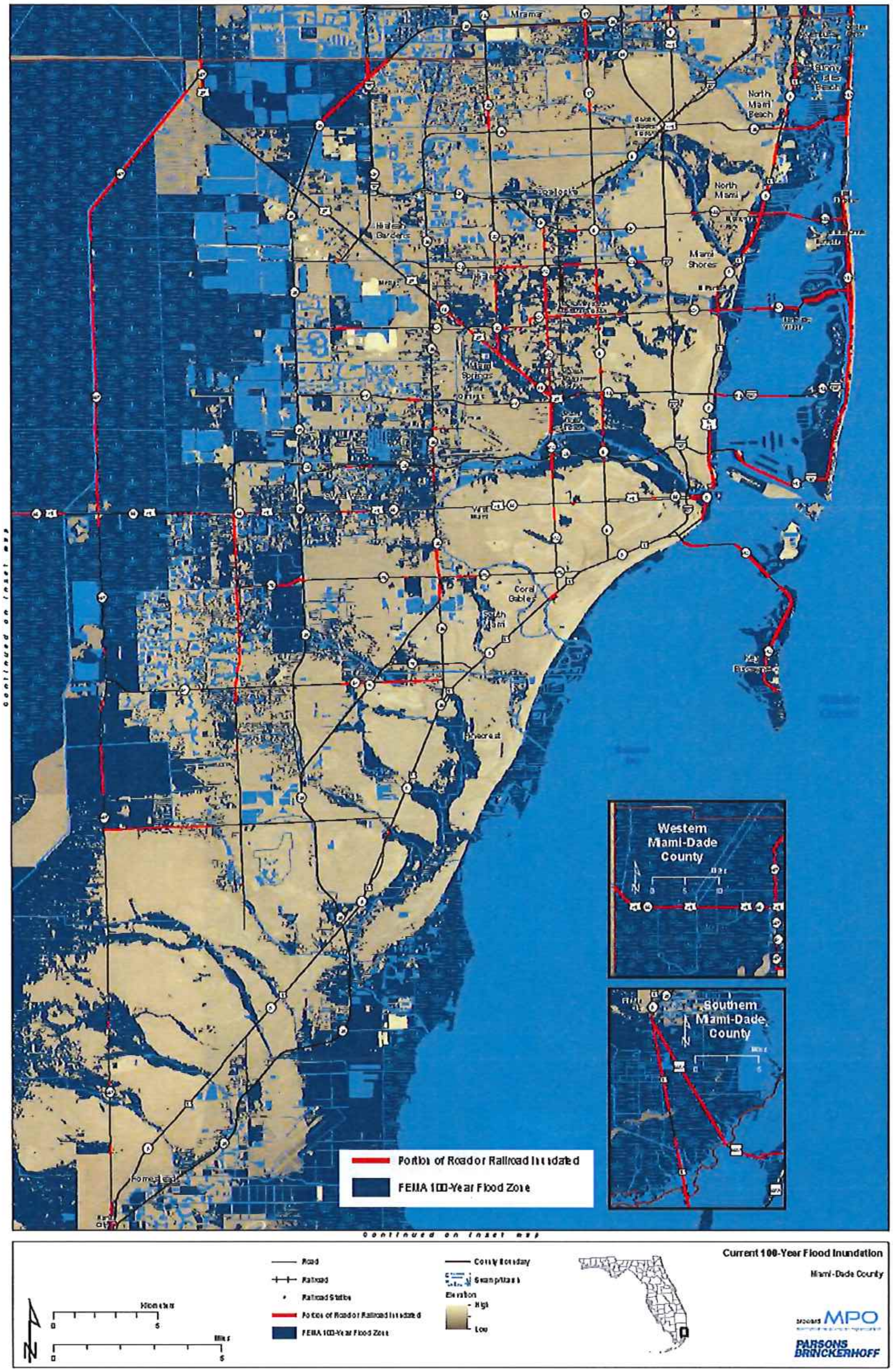
Source: Federal Highway Administration, 2015

Figure 7: Future flooding "hot spots" in Miami-Dade County.



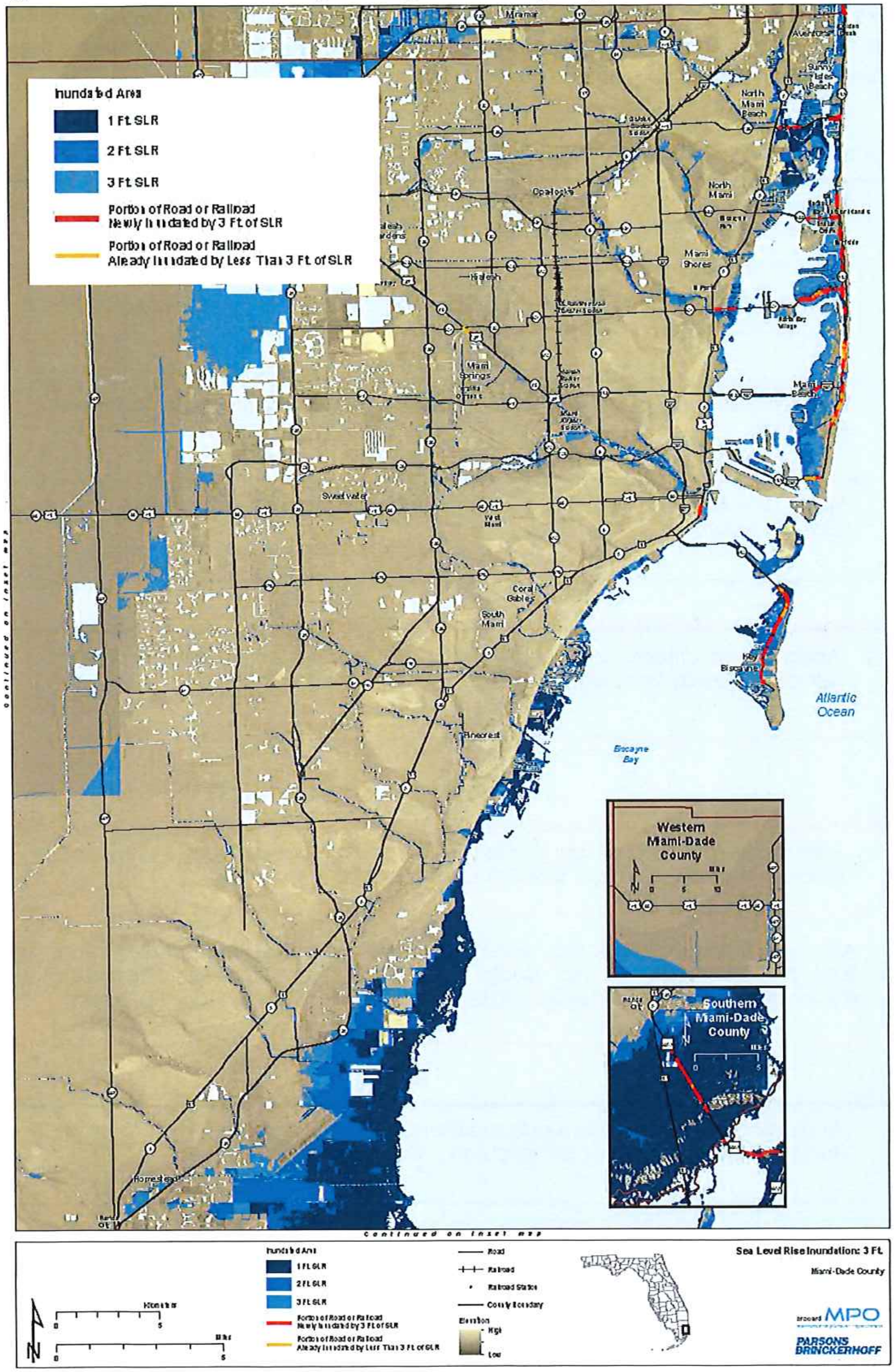
Source: Federal Highway Administration, 2015

Figure 8: Current vulnerability to a 100-year storm event.



Source: Federal Highway Administration, 2015

Figure 9: Permanent inundation of road segments with 3 feet of sea level rise.



Source: Federal Highway Administration, 2015

Another component of this study focused on identifying opportunities to better integrate climate change vulnerabilities into existing decision-making processes. The study identified five types of decision-making processes where it would be prudent to consider potential disruptions from flooding. These recommendations are summarized below (Table 1).

Table 1: Opportunities to integrate considerations of vulnerability into decision-making processes.

Transportation policy, planning & 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.
New facility or right of way 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.

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.

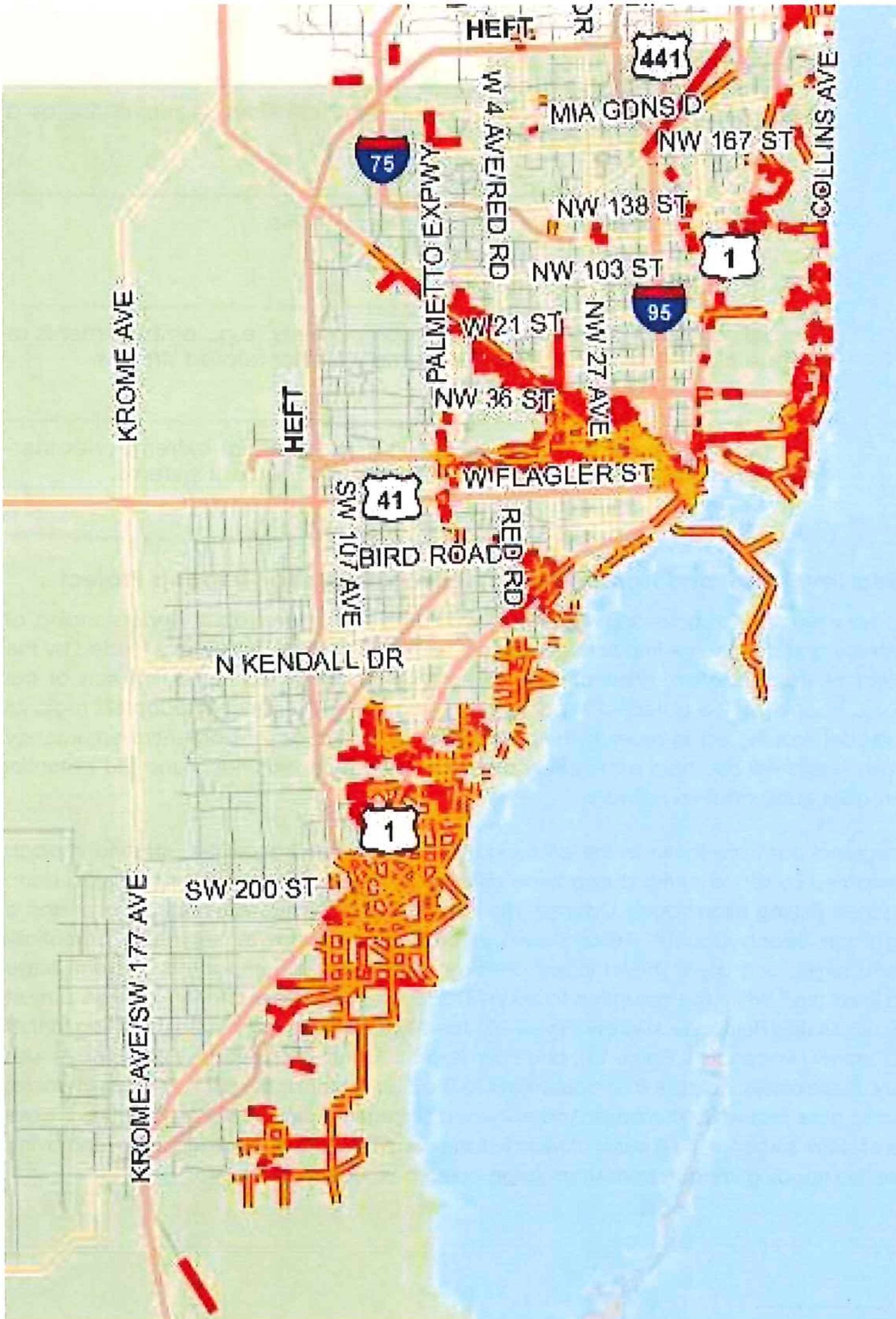
Storm Surge, Sea Level Rise, and Transportation Network Disruption Impacts Project

A second study, now nearing completion, will further contribute to a more robust understanding of potential sea level rise and storm surge impacts on regional mobility. This study, which was funded by the Florida Department of Transportation, attempted to quantify the general economic impacts of the resulting disruptions. In doing so, a potential expanded application of the recently-adopted regional travel demand model was tested in order to help understand the impact on potential emergency response. The study results will also help emergency managers and planners understand the potential impacts to the broader transportation network.

Results from this regional study are shown in the following figures. These maps show the potential impacts of storm surge amplified by sea level rise during three different historical storm events including a storm like Hurricane Andrew (hitting Miami-Dade County), Hurricane George (hitting Broward County), and a hurricane hitting Palm Beach County. Areas shown in orange are roadway segments potentially impacted by storm surge, and areas shown in red are segments potentially impacted by storm surge amplified by sea level rise.[7] While the disruption to Miami-Dade County's transportation network is most extensive during a simulated Hurricane Andrew (Figure 10), there are still impacts from storms hitting farther north in Broward County (Appendix 1, Figure 15), and Palm Beach County (Appendix 1, Figure 16). As with the previous study, these results indicate that causeways to the barrier islands are particularly vulnerable. It is also important to note that while Hurricane Andrew was a Category 5 storm it was not the worst case scenario in terms of storm surge for the County. If Miami-Dade were to be hit by a larger or slower-moving storm in the future the flooding impacts from storm surge could be much more severe.

[7] This study explored the impact of the amount of sea level rise expected by 2040 according to the U.S. Army Corps of Engineers "high" sea level rise estimate. The value used for storm surge amplified by sea level rise in 2040 for this study was 14.52 feet.

Figure 10: Disrupted links during a storm surge event similar to Hurricane Andrew amplified by sea level rise.



Source: Storm Surge, Sea Level Rise, and Transportation Network Disruption Impacts Project, 2016

Regional Vulnerability Assessment Supporting the Local Mitigation Strategy (LMS)

A third study conducted by the Southeast Florida Regional Climate Change Compact looked at the vulnerability of regional assets to sea level rise. The results of this study were subsequently incorporated into the The Local Mitigation Strategy. The strategy is a whole community initiative designed to reduce or eliminate the long-term risk to human life and property from hazards. The strategy is a multi-volume plan that documents the planning process and addresses mitigation measures in relation to the hazard risk and vulnerability assessment of Miami-Dade County. One component of that plan identifies roadways that are potentially vulnerable to sea level rise (Table 2), which was based on the preliminary vulnerability assessment to the impacts of sea level rise that was led by the Southeast Florida Regional Climate Change Compact.[8] One component of the larger study looked specifically at the roadways that would be affected by one, two, and three feet of rise. It is important to note that the method this study used to model sea level rise (known as a bathtub model) can significantly underestimate the impact of sea level rise because it does not account for rising groundwater levels and diminished drainage capacity. However, despite these limitations, the results of that study are still informative and were integrated into the last update of the Local Mitigation Strategy.[9] Based on this approach the study estimated that 72 miles of roadways would be impacted by one foot of sea level rise and 257 miles would be impacted by two feet. However, the area impacted jumped significantly to 555 miles of the network permanently inundated with three feet of sea level rise.

Table 2: Vulnerability assessment results from the Southeast Florida Regional Climate Change Compact Study.

Roads by FDOT Category
Roadways are summarized by Functional Class in miles. High volume categories include sections of roadway where bridges were removed from the LIDAR data and represented bare earth rather than the actual roadways.

1-Foot Sea Level Rise – Assumption: 50% Percent Inundation = Whole Segment Affected

Functional Class	Total Inundation (Miles)	Total Coverage (% impacted)
1 – high volume, maximum speed	3	0.08%
2 – high speed, channels traffic to FC1	4	
3 – high speed, lower mobility, connects to FC2	3	
4 – moderate speed, through neighborhoods	62	
5 – low volume, i.e. access roads, parking lanes	Not assessed	
Total	72	

2-Foot Sea Level Rise – Assumption: 50% Percent Inundation = Whole Segment Affected

Functional Class	Total Inundation (Miles)	Total Coverage (% impacted)
1 – high volume, maximum speed	6	3%
2 – high speed, channels traffic to FC1	11	
3 – high speed, lower mobility, connects to FC2	8	
4 – moderate speed, through neighborhoods	232	
5 – low volume, i.e. access roads, parking lanes	Not assessed	
Total	257	

3- Foot Sea Level Rise – Assumption: 50% Percent Inundation = Whole Segment Affected

Functional Class	Total Inundation (Miles)	Total Coverage (% segments impacted)
1 – high volume, maximum speed	12.18	6%
2 – high speed, channels traffic to FC1	26.33	
3 – high speed, lower mobility, connects to FC2	21.22	
4 – moderate speed, through neighborhoods	496.21	
5 – low volume, i.e. access roads, parking lanes	Not assessed	
Total	555.94	

Source: Miami-Dade County, Local Mitigation Strategy, 2015

On-going internal review of vulnerability

New roads are designed for a specified level of service, which are detailed in Section D-4 of the Public Works Manual and the Florida "Greenbook".[10] This section establishes the design criteria for each roadway. Transportation infrastructure must also comply with the Florida Department of Environmental Protection standards and the Florida Department of Transportation standards.[11] The County's Comprehensive Development Master Plan also includes policies that touch upon the flood level of service including Policy CON-5A and CON-5E.[12]

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[8] The full vulnerability assessment is available online at http://www.southeastfloridaclimatecompact.org/wp-content/uploads/2014/09/vulnerability-assessment.pdf

[9] Miami-Dade County's full mitigation strategy is available online at http://www.miamidade.gov/fire/mitigation.asp

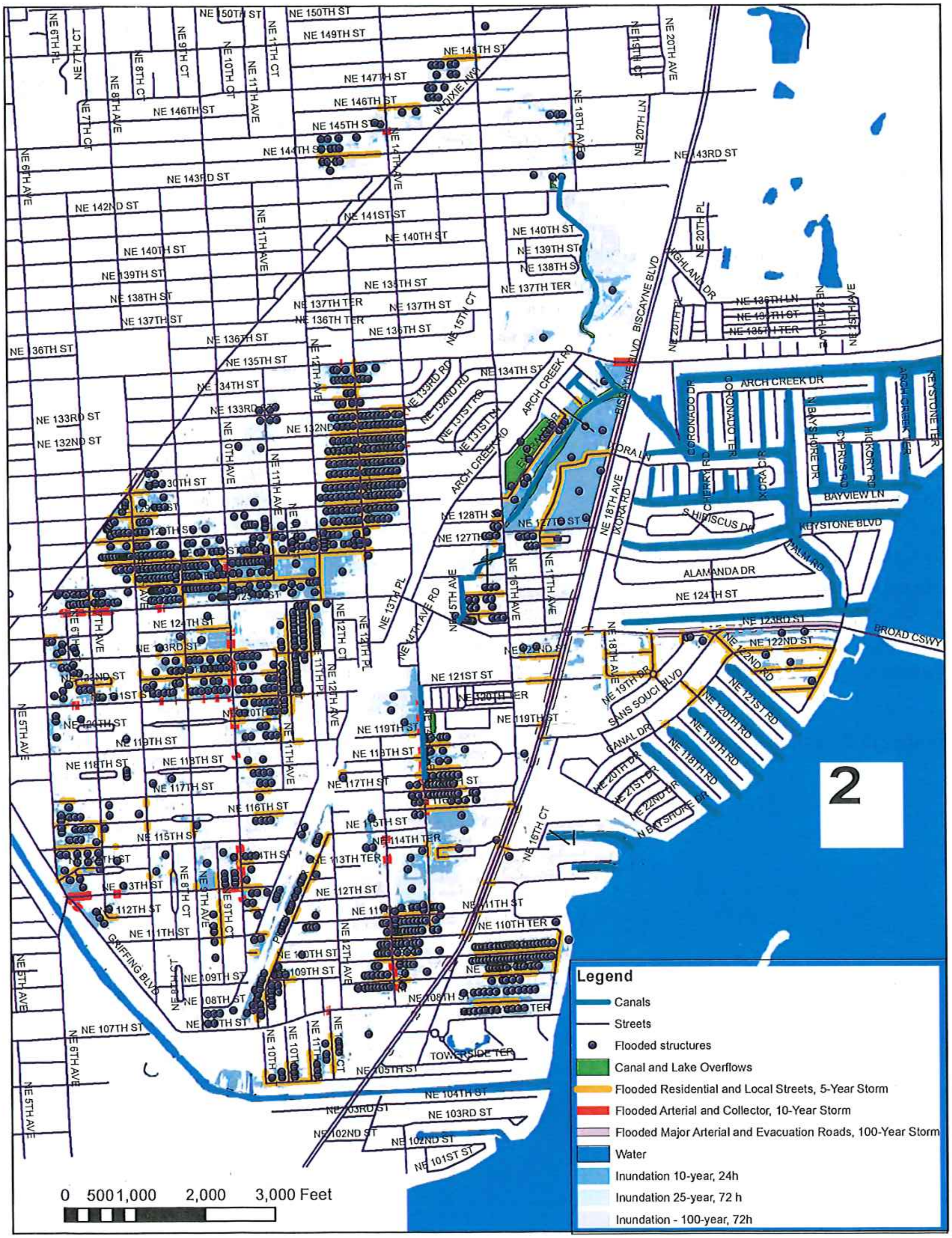
[10] The Florida Department of Transportation's "Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways" is available at http://www.dot.state.fl.us/rddesign/FloridaGreenbook/FGB.shtm

[11] The Florida Department of Transportation design manuals are available at http://www.dot.state.fl.us/rddesign/Drainage/files/DrainageManual.pdf

[12] The County's Comprehensive Development Masterplan is available at http://www.miamidade.gov/planning/cdmp.asp

Over time the level of service can diminish as additional development increases run-off, as groundwater levels rise, as sea levels rise, or as the drainage network capacity diminishes. The County therefore regularly inspects existing drainage infrastructure to determine which areas may have capacity issues and these areas are rated using a Maintenance Rating Program scale to prioritize improvements. There is a simultaneous process to systematically evaluate the vulnerability of the transportation network as part of the Stormwater Master Planning process. Through that assessment of flooding risk, by stormwater basin, County staff identify roadway segments that are no longer meeting their "designed level of service" or, in other words, are more flood-prone than they were originally designed to be. The Stormwater Master Plan has a very detailed and thorough ranking and prioritization procedure to triage necessary capital improvements. This ranking procedure is described in more detail in Appendix 2. An example of the results of this type of analysis is shown in Figure 11. This map shows areas where residential streets are flooded during a five-year storm (shown in orange), areas where arterial or collector roads are flooded in a ten year storm (shown in red), and where major arterial roads and evacuation corridors are flooded by a hundred year storm (shown in purple).

Figure 11: Map of failed level of service within a select sub-basin.



Source: Miami-Dade County Stormwater Masterplan

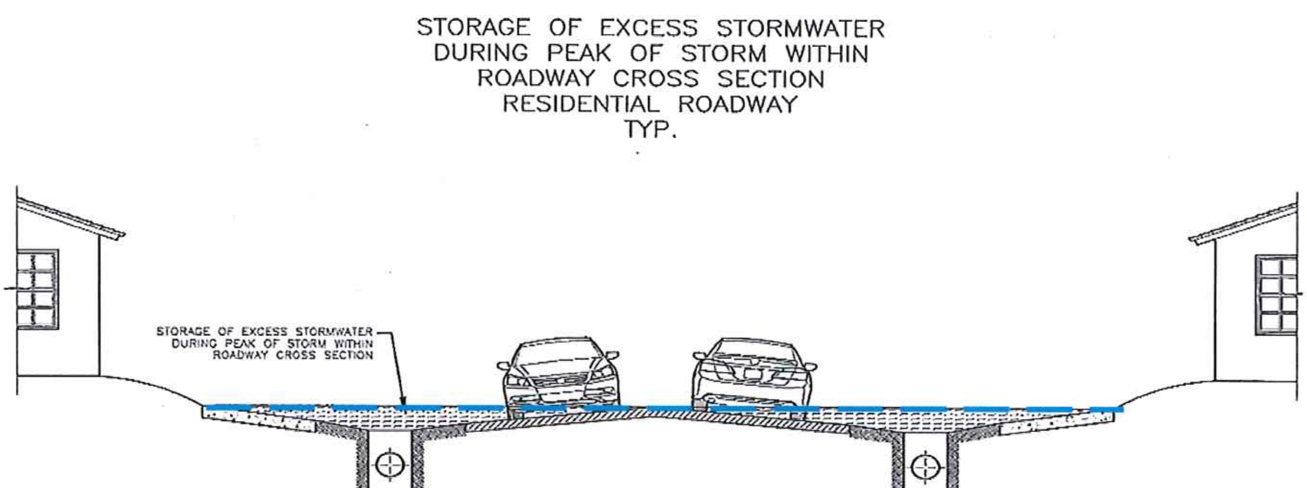
The Stormwater Master Plan is focused on assessing the vulnerability of County-owned roadways; however, it does include assessments of the vulnerability of state, municipal or privately owned roadways. According to the most recent assessment, which does not include the barrier islands, more than 2,400 miles of County-owned roadways are currently below their designed level of service. Additionally, more than 75 miles of evacuation routes are currently below their designed level of services; however, these roads are primarily state-owned and are the responsibility of the Florida Department of Transportation. Many of these areas that are vulnerable to flooding today will become more vulnerable due to rising sea levels and groundwater levels, particularly in coastal areas. Needed improvements of these roadways are typically paid for by the Stormwater Utility fee and other drainage-specific funding sources. The utility regularly analyzes its current and future needs and adjusts the fees as needed.

Figure 13: A flooded roadway stores excess run-off and protects neighboring houses.

Source: Roger Wollstadt

Once the vulnerable segments are identified this information is passed on to the Miami-Dade Department of Transportation and Public Works. The Department, in turn, goes through a prioritization process to identify opportunities to retrofit the roadway and improve the level of service. In some cases it is difficult to retrofit roadways in existing urban areas, because roadways may need to be elevated to ensure the required level of service. In some cases, raising a roadway may be impossible because it would increase the risk of flooding to adjacent areas. By design, most roadways are lower than the adjacent homes and businesses. This allows the roadway to collect and hold water during a storm and minimize the risk of flooding to the surrounding properties (Figures 12 and 13). If a roadway was raised above the neighboring

Figure 12: Roadways are designed to reduce the risk of flooding to adjacent properties by storing stormwater.



Source: Miami-Dade County, 2016

properties, the ability to store water would diminish and flood risks would increase. Therefore a roadway's elevation is constrained by the elevation of the adjacent properties.

What tools are available to assess the vulnerability of the transportation network moving forward?

Federal Highway Administration

Because climate change threatens considerable federal investment in transportation infrastructure, the Federal Highway Administration has been working extensively on advancing tools to support vulnerability assessments and adaptation measures. The Federal Highway Administration began to address the impacts of climate change early during the George W. Bush administration and initially focused publishing a series of short papers on the scope and scale of climate impacts on transportation.[13] The Federal Highway Administration then led the *Impacts of Climate Variability and Change on Transportation Systems and Infrastructure: Gulf Coast Study*, which found that many critical transportation assets were extremely vulnerable.[14] For example, the study found nineteen percent of major roads and five percent of rail lines in the central Gulf Coast region could be affected by just two feet of sea level rise. In October 2008, the Federal Highway Administration published another comprehensive report, *Potential Impacts of Global Sea Level Rise on Transportation Infrastructure - Atlantic Coast Study*.[15] This report concluded that many transportation assets along the Atlantic Coast of Florida would be impacted by various sea level rise scenarios.

In light of the magnitude of the impacts revealed by these initial projects, the agency concluded that climate impacts did threaten the Administration's key goals of safety, system reliability, asset management, and financial stewardship. The agency also determined that the existing climate projections were not well suited for making design decisions at the project-level. Therefore, the Administration initiated a series of efforts to gain experience applying climate information and to develop capacity in state departments of transportation and MPOs. In May 2010, Federal Highway Administration produced a report, *Regional Climate Change Effects: Useful Information for Transportation Agencies*, which provided projections of temperature, sea level rise and precipitation through 2100.[16] Federal Highway Administration produced a conceptual vulnerability assessment framework in 2009 to help local partners better understand risks to their systems. The Administration piloted the framework in five locations in 2010 and 2011[17] and then tested a refined framework in a second of round projects, including the Southeast Florida pilot project described earlier.[18]

Recently, the Federal Highway Administration has been focused on analyzing adaptation strategies to increase resiliency, including engineering analyses of measures such as enlarging culverts, raising bridges, or using more heat resistant materials. The *Transportation Engineering Approaches to Climate Resilience* study will develop specific recommendations and engineering approaches for improving

[13] These papers are available at http://climate.dot.gov/impacts-adaptations/forcasts.html
[14] Available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/index.cfm
[15] Available at http://climate.dot.gov/impacts-adaptations/sea_level_rise.html
[16] Available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications/climate_effects/
[17] More information is available at
http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications/vulnerability_assessment_framework/
[18] Information about the other pilot projects is available at
http://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/index.cfm

resilience.[19] Additional research will develop methods to incorporate changes in precipitation patterns in the highway design process, research climate impacts on geohazards, and conduct a watershed sensitivity study to help owners identify drainage assets at high risk. Climate resilience considerations have also been integrated into the Administration's programs, guidance, and policies, consistent with existing transportation law, including the Secretary's 2011 policy statement on climate adaptation and the President's Executive Order 13653 on climate preparedness. [20] For example, Federal Highway Administration Order 5520 commits the agency to taking action in this area.[21] The Administration also issued a memo in 2012 clarifying that climate adaptation activities are eligible for Federal Highway Administration funding. This eligibility extends to vulnerability assessments and projects to protect assets from damage associated with climate change. [22] Federal Highway Administration updated the Emergency Relief Manual to reflect concerns tied to resilience[23] and is developing a rule designed to implement the legislative requirement that state Departments of Transporation develop risk-based asset management plans. This legislation also includes requirements to consider alternatives for facilities repeatedly needing repair or replacement using federal funding. [24] The *Fixing America's Surface Transportation Act (FAST)* is an important transportation reauthorization that contains provisions for local MPOs to consider resiliency needs, reducing vulnerability to natural disasters, and mitigating stormwater impacts in their planning efforts.

Federal Highway Administration's climate change website offers publications, policies, guidance, webinar recordings, and tools for assessing vulnerabilities and building resilience (Table 3).[25]

Table 3: Tools available from the Federal Highway Administration to support building resilience.

Tools available	Description
Sensitivity Matrix	A spreadsheet tool that documents the sensitivity of roads, bridges, airports, ports, pipelines, and rail to eleven climate impacts.
Guide to Assessing Criticality in Transportation Adaptation Planning	This guide reviews challenges associated with assessing criticality, defining criticality and identifying scope, and the process of applying criteria and ranking assets.
CMIP Climate Data Processing Tool	A spreadsheet tool that processes raw climate model outputs into relevant statistics for transportation planners, including changes in the frequency of extreme precipitation events that may affect transportation infrastructure and services.
Vulnerability Assessment Scoring Tool	A spreadsheet tool that guides the user through conducting a quantitative, indicator-based vulnerability screen. Intended for agencies assessing how components of their transportation system may be vulnerable to climate stressors.
Updated Hydraulic Engineering Circular 25: Highways in the Coastal Environment	This circular includes guidance on estimating future sea levels and storm surges along with designing protection measures such as revetments, beach nourishment, and bridge deck elevation.
Updated Riverine Hydraulic Engineering Circular	The update will provide technical guidance and methodologies for incorporating floodplain management, risk, extreme events (i.e., climate change and extreme weather), resilience, and adaptation considerations when addressing highway

[19] Available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/index.cfm
[20] The policy statement is available at http://www.fhwa.dot.gov/environment/climate_change/adaptation/policy_and_guidance/usdot.cfm and the Executive Order is available at https://www.whitehouse.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change
[21] Available at http://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm
[22] Available at http://www.fhwa.dot.gov/federalaid/120924.cfm
[23] Available at http://www.fhwa.dot.gov/reports/erm/er.pdf
[24] Moving Ahead for Progress in the 21st Century (MAP-21) Section 1315b
[25] http://www.fhwa.dot.gov/environment/climate_change/adaptation/

	planning and design within the riverine environment. The reference will focus on issues related to hydrology, statistics, risk assessments, and regulatory issues associated with precipitation and stream flow in a riverine environment.
Green Infrastructure Techniques for Improving Coastal Highway Resilience	This project is investigating nature-based techniques (e.g. Living Shorelines) that could be implemented as part of highway and bridge planning, design, maintenance and construction to preserve and/or improve natural infrastructure function, thereby increasing the resilience of highways to the effects of storm surges and sea level rise.

The agency has also provided several recorded webinars which can be accessed by staff and municipal partners at any time (Table 4).

Table 4: Recorded webinars focused on resilience available from the Federal Highway Administration.

Recorded webinars
Session 1: Getting Started-Determining assets to study and climate information
Session 2: System-Level Vulnerability Assessments
Session 3: Applying the results
Session 4: Hurricane Sandy - Lessons Learned
Understanding Criticality and Sensitivity
Developing Scenarios of Future Temperature and Precipitation Conditions
Engineering Roads and Other Transportation Assets to be Resilient to Climate Change
Developing Future Sea Level Rise and Storm Surge Scenarios
Assessing Vulnerability with VAST
Climate Resilience Pilots: Results from Oregon DOT, WSDOT, Caltrans, and MTC
Climate Resilience Pilots: Results from CT DOT, Maine DOT, NYSDOT, and MassDOT
Climate Resilience Pilots: Results from MnDOT, Michigan DOT, Iowa DOT, and Alaska
International Climate Resilience: Practices from Denmark, Norway, and more

Florida Department of Transportation and the University of Florida GeoPlan Center

Building off of an earlier investigation completed in 2012 by researchers at Florida Atlantic University that recommended developing a tool to visualize the potential impacts of sea level rise,[26] the Florida Department of Transportation worked with The University of Florida's GeoPlan Center to develop such a tool. The work, which utilized the the Army Corps of Engineers methodology for determining future sea level rise rates, was completed over several phases beginning in 2012.

During Phase 1, the researchers at the University of Florida began mapping where and when flooding could be expected, using the Army Corp of Engineers estimates of sea level rise. The Army Corps of Engineer's *Sea Level Change Curve Calculator* is consistent with the South East Florida Regional Climate Change Compact's *Unified Sea Level Rise Projections*. The tool they developed allows users to visualize various scenarios at different time periods in the future. They also developed a georaphic information system (GIS) planning tool to identify transportation infrastructure that is vulnerable to higher tides due to sea level rise.[27] The resulting tool became known as the *Sea Level Scenario Sketch Planning Tool*.[28] The freely available online tool is intended to assist transportation planners; however, the interface is very user-friendly and could be readily used by the general public to see areas of future inundation (Figure 14). The underpinning data and data layers for inundated areas and vulnerable assets are also downloadable

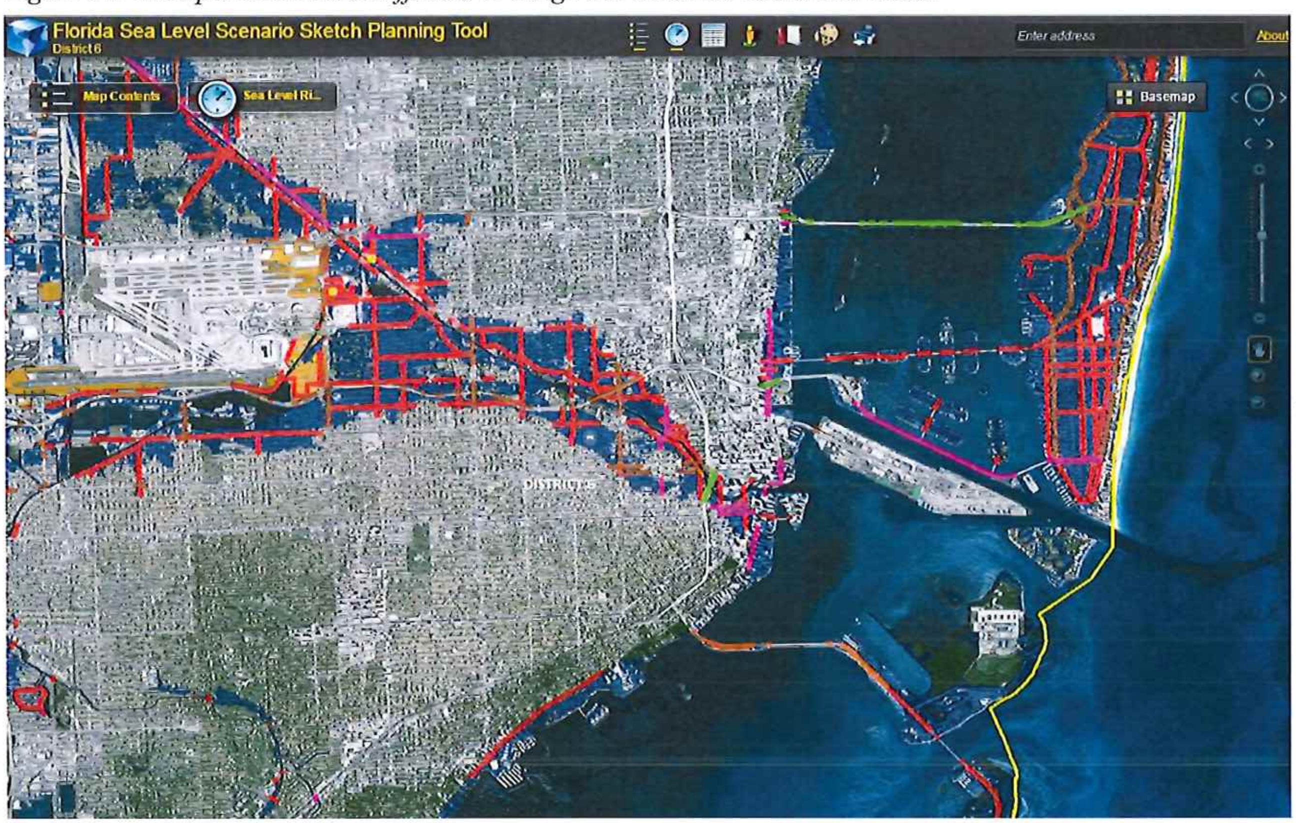
[26] research completed under Florida Department of Transportation (FDOT) contract BDK79 977-01, Development of a Methodology for the Assessment of Sea Level Rise Impacts on Florida's Transportation Modes and Infrastructure (Florida Atlantic University, 2012).
[27] For this study "transportation infrastructure" included roadways, rails, rail freight connectors, SIS airports and SIS ports.
[28] The tool can be accessed at http://sls.geoplan.ufl.edu

from the website for more detailed or refined analysis by planners or transportation departments. For example, Miami-Dade County staff could do a more accurate analysis using the County's more detailed elevation data. The tool can also generate reports summarizing the road miles impacted and other key statistics within a given area of interest.

In the second phase of the project, the tool was further tested and refined through coordination with the Federal Highway Administration Climate Resiliency Adaptation pilots to test and gather feedback on the tool. This included coordinating with the project members from the pilot project that included Miami-Dade County. Phase 3 work is currently underway to enhance the tool by re-running the inundation model results and affected infrastructure using updated data and methods. This work involves correcting bridge elevation data, updating and modernizing the web viewer and calculator tool, and adding flood risk and storm surge layers.

One important distinction to note is that the "Sketch" Tool currently models only areas that are vulnerable to direct inundation from sea level rise, as modeled by a "bathtub" model. Therefore the tool will not represent infrastructure that might be vulnerable to the indirect consequences of higher sea levels. For example, assets may be vulnerable to elevated groundwater levels away from the coast, flooding during rain events due to reduced drainage capacity, or vulnerable to storm surge enhanced by sea level rise. These secondary vulnerabilities are not shown in the Sketch Tool, as it is designed today, but should be part of the County's analysis as that information becomes available. Phase 3 enhancements of the Sketch Tool will involve the addition of analyses of future flood risk (100-year storm surges amplified by various sea level rise scenarios), but will not include groundwater analyses.

Figure 14: Transportation assets affected in a high sea level rise scenario in 2100.



Source: University of Florida, Florida Sea Level Scenario Sketch Planning Tool, 2016

There are many advantages to the tool including the fact that the online interactive maps can be used by anyone for free. Very little experience or expertise is required to use the online mapping tool. Those with more familiarity with mapping techniques can download the data as GIS layers or use the Sea Level Rise Inundation Surface Calculator Ad-in for ArcGIS to customize the outputs and incorporate additional information. Additionally, their website provides user guides and tutorials including those listed in Table 5.

Table 5: Tools available from the University of Florida.

Resource	Description
Quick Start Guide for the SLR Sketch Planning Tool	This short document is an introduction to the data and tools available in the Sketch Planning Tool. It is intended to guide users on how the tool can be used for assessing transportation infrastructure at risk to sea level rise.
Map Viewer User Guide	This is a detailed guide to step users through how to use the Map Viewers.
SLR Inundation Surface Calculator User Guide	This is a detailed guide on how to install and run the SLR Inundation Surface Calculator for ArcMap.
Webinar Recordings	Recordings are available from SustainableComm on Vimeo.

How useful are the available tools for improving the resiliency of the transportation network?

Applicability for transportation planning

These tools are applicable to Miami-Dade County's infrastructure network and can be used to inform decision-making moving forward. The results of these projects have already been reviewed by the Miami-Dade Metropolitan Planning Organization and the County's Department of Transportation and Public Works; however, there are plans to share these resources more widely with staff to ensure they are being integrated into future planning efforts. The Sketch Tool was intended to serve as a regional level planning tool to help identify future vulnerabilities and was not intended to be applied to design level decisions. These tools provide additional information that can be used in the context of the many other considerations and evaluations that are on-going.

Potential for other uses

The Florida Department of Transportation "Sketch" tool is focused on transportation infrastructure and therefore is best used for that purpose. However, the inundation layers used in the tool could be downloaded and used by other departments to gain an understanding of where sea level rise impacts could be expected. However, the County currently has other inundation layers developed by County staff. The most useful feature is the easy-to-use web interface which may have value as an online viewer of sea level rise impacts. This tool, in contrast to other online viewers, provides a very good representation of elevation data which is useful for many purposes.

The Federal Highway Administration's vulnerability assessment framework offers useful general guidance on an approach to conducting a vulnerability assessment that could be used to assess other infrastructure systems. While it is feasible, the approach would need to be adapted to accurately evaluate each system, which would require expertise in those systems.

Costs

There are no immediate costs associated with using the outputs from either the Federal Highway Administration vulnerability assessment framework or the Sketch Tool beyond staff time. The outputs from both of these initiatives are accessible as GIS layers that can be integrated into on-going decision-making processes. Furthermore, because both of these tools looked at transportation infrastructure across the County and are freely-available online the results are likely to be helpful to municipalities within the County.

If the County decided to pursue a more detailed study looking at different stressors or different infrastructure (such as local roadways), it would need to be determined if additional resources were needed. At present, the results of these two tools are sufficient to inform high-level planning. No new funding requests need to be included in the next budget cycle.

The need for additional legislation

No additional legislation would be required to integrate the results of these studies of sea level rise into transportation planning. To fully consider sea level rise into all transportation planning and design work, it will be necessary to update the County Flood Criteria as well as the Public Works Manual. There is work underway currently to update these criteria to reflect today's conditions; however, additional work will be needed in the future to account for future changes in sea level and ensuring projects will maintain their designed level of service over the lifetime of that asset.

Conclusion and next steps

These tools and previous studies offer valuable insights to inform on-going planning efforts; however, their results should be considered in the context of other studies and efforts. More detailed and tailored efforts are needed to inform any project-level decision-making process. These studies can, however, be taken into consideration as key supporting information in regular decision-making processes. In particular these tools can help inform long-term planning efforts such as the development of the Strategic Miami Rapid Transit Plan ("SMART") plan and the long-range transportation plan.

Over the longer term, other steps will be needed to address the challenges of rising sea levels and to increase the resilience of the transportation network. These changes should be balanced with addressing other needs, such as maintaining reasonable costs and reducing environmental impacts. Given the complexity of the environment in existing urban areas and the heterogeneity of the risks, it will be necessary to use a suite of measures in concert. Each adaptation measure should be individually assessed and be responsive to the surrounding neighborhood and environment. For example, in neighborhoods with very low-lying structures, it may be more difficult to elevate roadways without increasing flood risk to adjacent structures. In other areas, it may be relatively easier to increase the drainage capacity or the road elevations to reduce flooding risk.

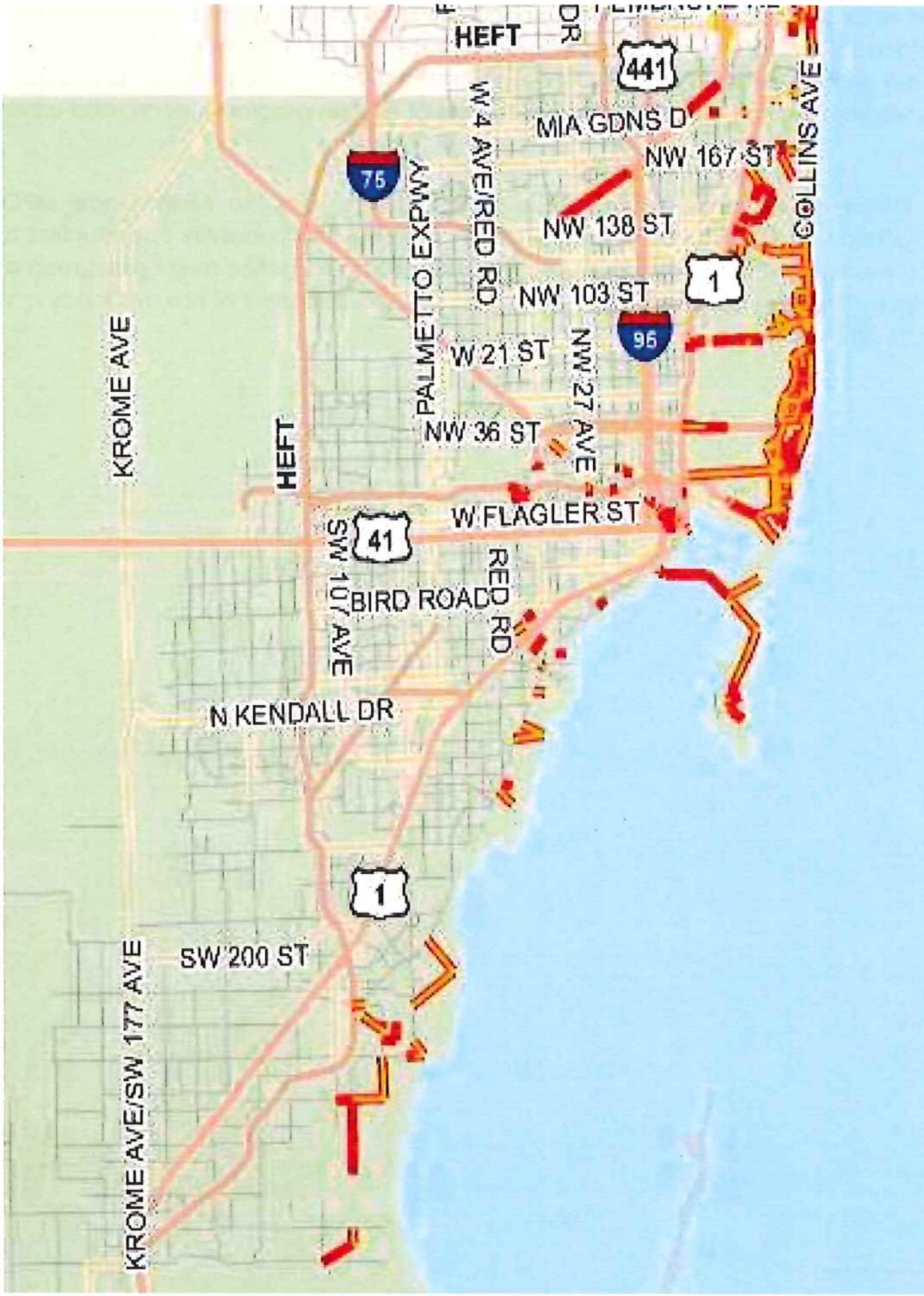
There are many potential opportunities to explore as the County looks for ways to cost-effectively and proactively adapt the transportation system incrementally. For example, the County could prioritize the assessment of key evacuation corridors and coordinate with other entities to focus on these areas first. Another avenue to explore is to review the established flood protection levels of service for roadways through the Comprehensive Development Master Plan and Public Works Manual to reassess the current design storms used. The County could also explore how to develop procedures for incorporating future levels of service into designs, including evaluating sea level rise discharge conditions. The County Flood Criteria could also be updated to account for recent changes in groundwater elevations. . There may also be benefits to improve the current USGS Water Watch website to be used as a clearing house and central database for the current groundwater table conditions as well as forecast groundwater conditions that is available to all entities designing transportation infrastructure within Miami-Dade County.[29] Similarly, there may be opportunities to make information about other current and future water levels and environmental conditions, such as changes in the Coastal Control Line, more readily available to other governments and private entities. There may be other opportunities to re-evaluate roadway design to further improve drainage or to adjust maintenance projects to incrementally gain elevation when roads are resurfaced. There are also opportunities to update design guidelines to include green infrastructure and create design standards with typical details and information on calculation procedures. All potential changes would need to be explored in the context of existing programs, goals, and urban development patterns.

Moving ahead, the Office of Resilience will continue to coordinate with the Miami-Dade MPO, Department of Transportation and Public Works, and other key stakeholders to identify opportunities to integrate risk reduction measures into on-going planning efforts. In particular, when major plans such as the Long Range Transportation Plan are updated, there will an increased scrutiny of how resiliency can be advanced alongside other goals.

[29] The Groundwater Watch database is available at http://groundwaterwatch.usgs.gov/StateMap.asp?sa=FL&sc=12 an example of data from one station can be found at http://groundwaterwatch.usgs.gov/AWLSites.asp?mt=g&S=254000080181002&ncd=awl

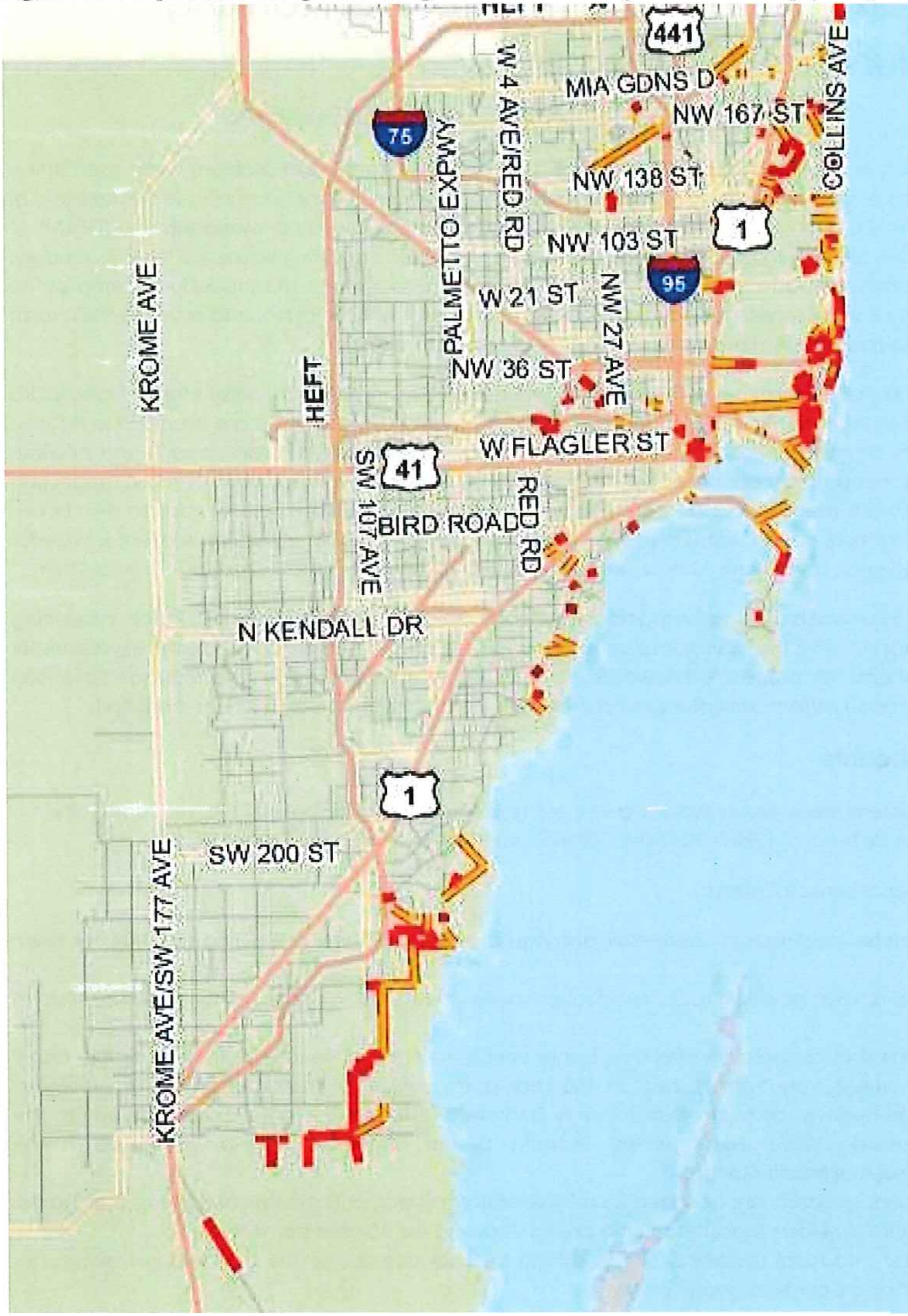
Appendix 1: Potentially disrupted transportation networks during two simulated hurricanes

Figure 15: Disrupted links during a storm surge event similar to Hurricane George amplified by sea level rise.



Source: Storm Surge, Sea Level Rise, and Transportation Network Disruption Impacts Project, 2016

Figure 16: Disrupted links during a storm surge event like the Delray Beach Storm amplified by sea level rise.



Source: Storm Surge, Sea Level Rise, and Transportation Network Disruption Impacts Project, 2016

Appendix 2: Stormwater Master Plan ranking procedures

IDENTIFICATION AND RANKING OF PROBLEM AREAS

This is a summary of the procedure for ranking and prioritizing of stormwater problem areas used in the Stormwater Master Plan. The ranking procedures were first developed by the Miami-Dade Department of Regulatory and Economic Resources' Division of Environmental Resource Management (DERM) in *Volume 3, Stormwater Planning Procedures of Part I, Planning Criteria and Procedures* (CH2M Hill, January, 1996); henceforth referred to as DERM's Planning Criteria and Procedures. The procedure estimates the flood protection level of service for stormwater areas (sub-basins) within a basin, and provides the overall estimates of the flood protection level of service for the entire basin.

The ranking and the prioritization of the problem areas identified in the Stormwater Master Plan guides the implementation of Stormwater Capital Improvement Projects. These projects are intended to address the high-priority stormwater problem areas in each primary canal basin. In order to rank and prioritize problem areas, inundation maps are first generated with the use of a hydrology and hydraulic model (XP-SWMM), to estimate the water surface elevations and depths of inundation. The inundation depths are calculated for multiple design storms associated with the established flood protection levels of service for the 100-year, 10-year, and 5-year 24 hour storm as well as the 100-year and 25-year-year 72 hour storm.

The outputs of the models are then mapped using Geographic Information System (GIS) tools, producing inundation maps showing the maximum depths of inundation and maximum water surface elevations for each design storm. This process is followed by a Control Measure Evaluation and Management Plan Selection which evaluates stormwater control measures to address the problem areas identified.

Ranking procedure

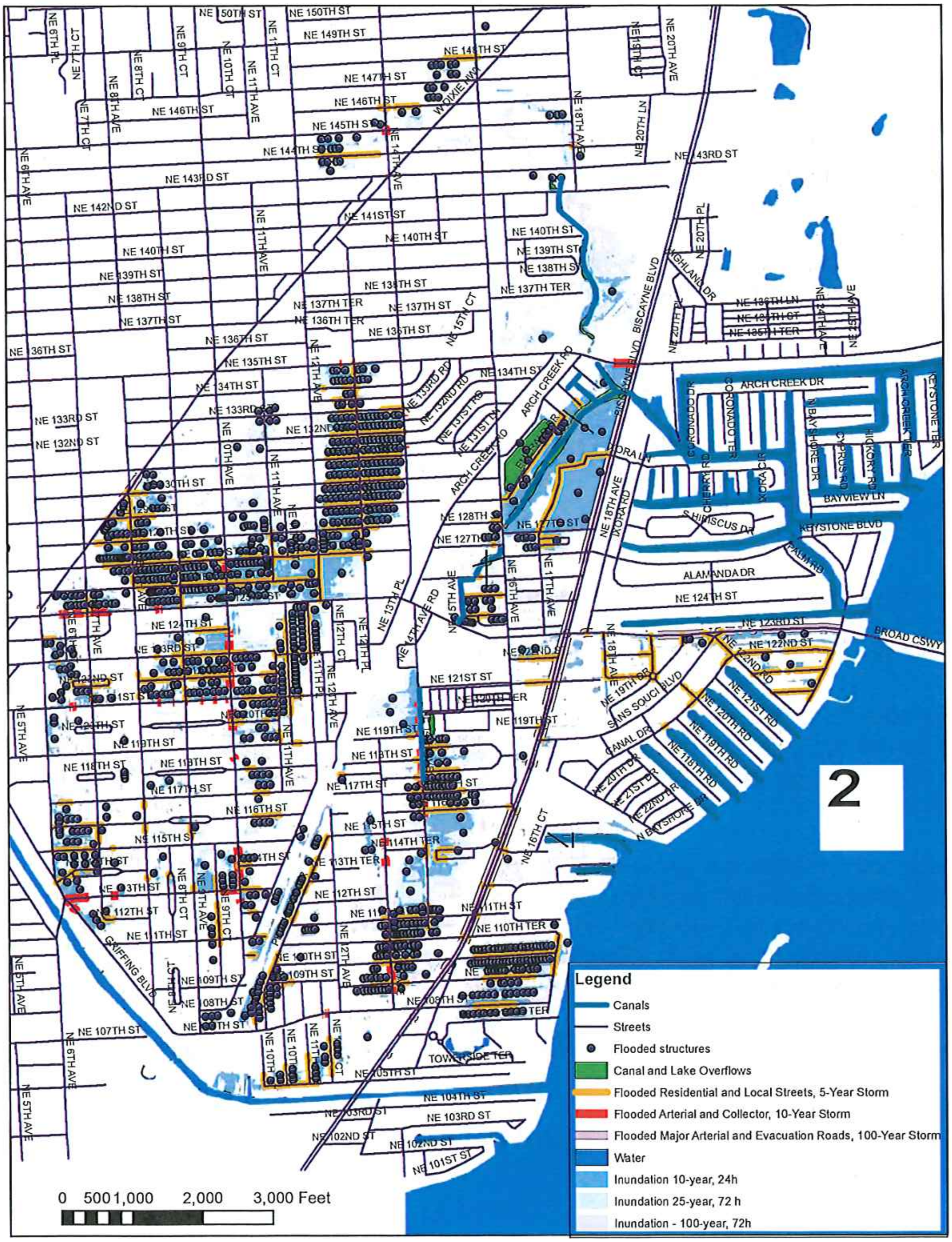
The various problem areas across Miami-Dade County are ranked on the basis of the five floodplain levels of service defined in DERM's Planning Criteria and Procedures as summarized below:

Floodplain Level of Service Criteria:

1. All structures (commercial, residential, and public) should be flood-free during the 100-year storm event.
2. Principal arterial, including major evacuation routes, should be passable during the 100-year storm event.
3. All canals should operate within their banks during their respective design floods. Primary canal design criteria vary from 10-year to 100-year storm events and are described for the major drainage basins in the Miami-Dade County Comprehensive Development Master Plan and by the South Florida Water Management District's Design Discharge Criteria, presented in the Environmental Permit Manual.
4. All secondary canals are designed for a 25-year storm event, and should not overtop their banks.
5. Minor arterial (4-lane roads) should be passable during the 10-year storm event.
6. Collector and local residential streets should be passable during the 5-year storm event, per Miami-Dade County drainage policy.

A map with the failed levels of service is prepared using the inundation limits and GIS layers for the canals, streets and relevant County infrastructure. An example of such a map for one of the sub-basins (Arch Creek) is shown below in Figure 17.

Figure 17: Failed flood protection level of service for one sub-basin.



Source: Miami-Dade County Stormwater Master Plan

The severity of flooding within each sub-basin is determined through the calculation of a flooding problem severity score (FPSS), which is a function of five "severity indicators" that are directly related to the flood protection level of service criteria described above. These "severity indicators" are defined in DERM's Planning Criteria and Procedures and are summarized below. Each of these indicators has also been assigned a "weighting factor" (WF), which is related to the relative importance of the flooding severity indicators, described below.

Sub-basin Flooding Severity Indicators

1. Number of structures flooded by the 100-year flood (NS), which can include commercial, residential, and public buildings. For the purpose of this evaluation, all structures and/or buildings are considered equivalent, regardless of their size or value. (Weighting Factor = 4).

2. Miles of principal arterial roads, including major evacuation routes, which are impassable during a 100-year flood (MER). Miami-Dade County has defined that a principal arterial road is considered impassable if the depth of flooding exceeds 8 inches above the crown of the road during the 100-year storm event. (Weighting Factor = 4).

3. Miles of canal with out-of-bank flow, expressed in bank miles (BM). The length of canal flooding shall be determined for the design storm event originally used to design the canal. A listing of recurrence intervals used to design primary canals in Miami-Dade County is provided in DERM's Planning Criteria and Procedures, which ranges from 10-year to 100-year storm events. (Weighting Factor = 3).

4. Miles of minor arterial roads impassable during the 10-year flood (MMAS). Miami-Dade County has defined that a minor arterial road is considered impassable if the flooding stage exceeds the crown of the road during the 10-year design event. (Weighting Factor = 2).

5. Miles of collector and local residential streets impassable during the 5-year flood (MCLRS). Miami-Dade County has defined that collector and local residential streets are considered impassable if the flooding stage exceeds the crown of the road during the 5-year design storm event. (Weighting Factor = 1).

The severity indicators describe the number of flooded structures, the length of impassable roads, and the length of flooded canals within each sub-basin. Another measure of flooding presented in DERM's Planning Criteria and Procedures is identified as the degree of exceedance or "exceedance factor" (E), which address the average flood depth within the sub-basin and the degree that the Flood Protection Level Of Service has been exceeded, as defined below.

Depth of Flooding Above the Flood Protection Level Of Service: E (Exceedance Factor)

- Less than or equal to 6 inches: E=1
- Greater than 6 inches and less than or equal to 12 inches: E=2
- Greater than 12 inches: E=3

Given the definitions for the flooding severity indicators (NS, ME, BM, MMAS, and MCLRS), WF and E, the flooding problem severity score (FPSS) for each sub-basin is calculated using the following formula, where E1 through E5 express the degree of exceedance for each of the five severity indicators:

$$FPSS = 4 * E_1 . NS + 4 * E_2 * MER + 3 * E_3 * BM + 2 * E_4 * MMAS + E_5 * MCLRS \quad (Eq. 1)$$

The flooding problem severity score is determined for each sub-basin using the above stated definitions and floodplain information developed during the modeling process. The flooding severity indicator scores for each sub-basin are summarized in tables, providing the flooding problem area ranking for each sub-basin. The sub-basin with the highest FPSS and poorest performance is ranked as 1 (one)

Appendix C: List of Vulnerable Facilities from Broward MPO's "Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida"

Name	Length	From Road	To Road	County	Vuln Ranking
SR-A1A (B)	3.4	South of Arizona St	SR-858	Broward	5
I-75	54.7	Collier County Line	US 27	Broward	6
SR-820	3.2	US 1/SR-5 (B)	SR-A1A (B)	Broward	9
US 1/SR-5 (C)	1.6	E Las Olas Boulevard	SR-736 Davie Boulevard	Broward	10
US 27	81.6	SR-15/SR-80	I-75	Broward	18
E Las Olas Boulevard	3.0	US 1/SR-5 (C)	SR-A1A	Broward	20
Johnson Street	0.6	US 1/SR-5 (B)	N 14th Avenue	Broward	22
US 1/SR-5 (C)	0.4	SR-842 Broward Boulevard	E Las Olas Boulevard	Broward	33
US 1/SR-5 (B)	1.5	SR-824 Pembroke Road	SR-858	Broward	35
SR-858	2.9	US 1/SR-5 (B)	SR-A1A (B)	Broward	40
SR-842 Broward Boulevard	0.8	US 1/SR-5 (C)	Andrews Avenue	Broward	43
I-95	2.0	SR-838	SR-842 Broward Boulevard	Broward	45
I-95	0.9	SR-84	I-595	Broward	50
SR-A1A (B)	7.8	SR-826	SR-858	Broward	52
SR-816	5.4	US 441/SR-7	I-95	Broward	53
SR-A1A E Dania Beach Boulevard	3.1	US 1/US 41/SR-5 (B)	SR-A1A	Broward	56
Andrews Avenue	2.1	SR-816	SR-838	Broward	57
I-95	2.7	I-595	SR-818	Broward	61
Andrews Avenue/SE 6th Avenue	2.0	SR-84	Eller Dr	Broward	62
SR-822 Sheridan Street	1.7	US 1/SR-5 (B)	SR A1A N Ocean Dr	Broward	63
I-95	3.1	SR-822 Sheridan Street	SR-820	Broward	68
SR-84	0.5	Andrews Avenue	US 1/US 41/SR-5 (B)	Broward	70
US 1/SR-5 (D)	3.9	SR-814 Atlantic	Cypress Creek Road/NE 62nd	Broward	71

Name	Length	From Road	To Road	County	Vuln Ranking
		Boulevard	Street		
SR-821 Florida's Turnpike	8.2	SR-823	I-75	Broward	76
SR-736 Davie Boulevard	1.9	Andrews Avenue	I-95	Broward	77
I-95	4.2	SR-814 Atlantic Boulevard	Cypress Creek Road/NE 62nd Street	Broward	79
NE 14th Street	1.5	US 1/SR-5 (D)	SR A1A N Ocean Boulevard	Broward	80
I-95	4.3	SR-816	SR-838	Broward	83
I-95	2.1	SR-848 Stirling Road	SR-822 Sheridan Street	Broward	85
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	2.4	SR-816	SR-870	Broward	86
SR-822 Sheridan Street	2.5	I-95	US 1/SR-5 (B)	Broward	87
I-95	2.5	SR-736 Davie Boulevard	SR-84	Broward	89
I-95	2.1	SR-842 Broward Boulevard	SR-736 Davie Boulevard	Broward	90
SR-820	0.7	SR-91 Florida's Turnpike	US 441/SR-7	Broward	92
SR-870	2.1	US 1/SR-5 (D)	SR-A1A	Broward	94
US 1/SR-5 (B)	8.4	SR-858	SR-826	Broward	95
I-75	4.1	Miramar Parkway	SR-821 Florida's Turnpike	Broward	97
US 1/SR-5/SR-838	1.7	US 1/SR-5 (C)	US 1/SR-5 (D)	Broward	99
Andrews Avenue	1.0	SR-842 Broward Boulevard	SR-736 Davie Boulevard	Broward	103
I-95	10.3	SR-858	SR-826	Broward	104
US 1/SR-5 (C)	1.0	SR-736 Davie Boulevard	SR-A1A (A)	Broward	106
SR-838	2.4	US 1/SR-5 (D)	SR-A1A	Broward	107
SW 4th Avenue	0.8	SR-84	SW 34th Street	Broward	109
I-75	10.2	I-595	SR-818	Broward	111
I-95	4.5	CR-798 Palmetto Park	SR-810 Hillsboro Boulevard	Broward	112

Name	Length	From Road	To Road	County	Vuln Ranking
		Road			
SR-91 Florida's Turnpike	6.3	SR-838	I-595	Broward	113
US 1/SR-5 (D)	4.3	US 1/SR-5/SR-838	SR-816	Broward	122
I-95	2.0	SR-820	SR-824 Pembroke Road	Broward	123
SR-818	2.7	US 1/US 41/SR-5 (B)	I-95	Broward	126
I-95	2.0	SR-818	SR-848 Stirling Road	Broward	129
I-95	2.4	Cypress Creek Road/NE 62nd Street	SR-870	Broward	133
I-75	4.5	SR-820	Miramar Parkway	Broward	134
SR-816	0.7	I-95	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	136
SR-838	1.2	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Andrews Avenue	Broward	140
Sheridan Street	5.0	SR-817	US 441/SR-7	Broward	142
US 1/US 41/SR-5 (B)	1.1	SR-84	SR-A1A (A)	Broward	144
I-95	1.5	SR-824 Pembroke Road	SR-858	Broward	145
I-595	4.3	US 441/SR-7	I-95	Broward	148
SR-858	5.2	SR-817	US 441/SR-7	Broward	149
SR-814 Atlantic Boulevard	5.5	SR-817	SR-869	Broward	151
I-95	2.3	SR-834 Sample Road	Copans Road	Broward	153
SR-817	4.0	SR-838	SR-842 Broward Boulevard	Broward	154
SR-870	4.0	US 1/SR-5 (D)	Andrews Avenue	Broward	155
I-95	3.3	SR-870	SR-816	Broward	158
SR-842 Broward Boulevard	3.1	Andrews Avenue	I-95	Broward	159
I-95	4.1	Copans Road	SR-814 Atlantic Boulevard	Broward	160

Name	Length	From Road	To Road	County	Vuln Ranking
I-95	1.9	SR-810 Hillsboro Boulevard	SR-869	Broward	161
I-95	4.2	SR-869	SR-834 Sample Road	Broward	162
SR-817	6.4	SR-814 Atlantic Boulevard	SR-870	Broward	164
SR-821 Florida's Turnpike	2.9	SR-817	SR-91 Florida's Turnpike	Broward	168
SR-822 Sheridan Street	5.5	I-95	US 441/SR-7	Broward	171
US 441/SR-7	3.0	SR-870	SR-816	Broward	172
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	6.2	SR-814 Atlantic Boulevard	SR-834 Sample Road	Broward	175
SR-91 Florida's Turnpike	7.9	SR-814 Atlantic Boulevard	SR-870	Broward	176
SR-820	3.8	US 441/SR-7	I-95	Broward	177
I-75	4.6	SR-818	Sheridan Street	Broward	178
SR-823	6.3	SR-821 Florida's Turnpike	SR-826	Broward	179
SR-848 Stirling Road	1.5	I-95	US 1/SR-5 (B)	Broward	180
SR-870	0.4	I-95	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	186
SR-817	4.5	SR-834 Sample Road	SR-814 Atlantic Boulevard	Broward	190
SR-814 Atlantic Boulevard	3.5	SR-91 Florida's Turnpike	US 441/SR-7	Broward	193
I-75	3.3	Sheridan Street	SR-820	Broward	196
SR-821 Florida's Turnpike	6.0	SR-817	SR-823	Broward	198
SR-814 Atlantic Boulevard	6.3	US 441/SR-7	SR-817	Broward	200
SR-824 Pembroke Road	1.6	I-95	US 1/SR-5 (B)	Broward	202
Copans Road	3.9	I-95	US 1/SR-5 (D)	Broward	204
SR-91 Florida's Turnpike	8.0	SR-870	SR-838	Broward	205

Name	Length	From Road	To Road	County	Vuln Ranking
SR-814 Atlantic Boulevard	0.6	I-95	Andrews Avenue	Broward	206
SR-870	0.6	Andrews Avenue	I-95	Broward	212
SR-817	3.2	SR-842 Broward Boulevard	SR-84	Broward	215
Andrews Avenue	1.0	SR-838	SR-842 Broward Boulevard	Broward	216
SR-870	1.2	US 441/SR-7	SR-91 Florida's Turnpike	Broward	217
SR-91 Florida's Turnpike	7.6	SR-821 Florida's Turnpike	NW 7th Avenue Extension	Broward	220
Flamingo Road	1.0	SR-842 Broward Boulevard	I-595	Broward	221
I-595	1.9	SR-91 Florida's Turnpike	US 441/SR-7	Broward	224
US 27	11.8	I-75	SR-818	Broward	226
I-595	4.4	SR-817	SR-91 Florida's Turnpike	Broward	227
SR-817	6.4	SR-821 Florida's Turnpike	SR-826	Broward	228
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	5.9	SR-870	SR-814 Atlantic Boulevard	Broward	229
SR-842 Broward Boulevard	7.7	SR-817	Flamingo Road	Broward	230
SR-817	1.3	SR-858	SR-821 Florida's Turnpike	Broward	232
SR-816	3.7	US 1/SR-5 (D)	Andrews Avenue	Broward	235
SR-814 Atlantic Boulevard	1.2	US 1/SR-5 (D)	SR A1A N Ocean Boulevard	Broward	237
SR-91 Florida's Turnpike	3.5	SR-818	I-595	Broward	240
SR-869	2.4	I-95	US 1/SR-5 (D)	Broward	242
SR-817	2.5	SR-816	SR-838	Broward	243
SR-870	6.0	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	US 441/SR-7	Broward	245

Name	Length	From Road	To Road	County	Vuln Ranking
SR-838	6.0	SR-817	SR-91 Florida's Turnpike	Broward	246
SR-842 Broward Boulevard	4.1	I-95	US 441/SR-7	Broward	247
SR-816	1.5	US 1/SR-5 (D)	SR-A1A	Broward	248
US 441/SR-7	5.0	SR-842 Broward Boulevard	I-595	Broward	249
US 441/SR-7	6.9	SR-808 Glades Road	SR-810 Hillsboro Boulevard	Broward	252
SR-810 Hillsboro Boulevard	3.0	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	SR-809 Military Trail	Broward	259
Andrews Avenue	1.7	SR-870	SR-816	Broward	260
US 1/SR-5 (D)	3.3	SR-816	SR-870	Broward	262
SR-A1A (A)	3.1	US 1/SR-5 (C)	Mayan Drive	Broward	263
SR-810 Hillsboro Boulevard	2.5	I-95	US 1/SR-5 (D)	Broward	267
US 441/SR-7	1.5	Sheridan Street	SR-820	Broward	269
SR-91 Florida's Turnpike	4.9	SR-820	SR-821 Florida's Turnpike	Broward	272
SR-91 Florida's Turnpike	8.6	SR-808 Glades Road	SR-869	Broward	276
US 1/SR-5 (D)	2.5	SR-814 Atlantic Boulevard	NE 14th Street	Broward	277
SR-809 Military Trail	4.5	SR-869	SR-834 Sample Road	Broward	279
SR-84	1.3	SR-91 Florida's Turnpike	US 441/SR-7	Broward	280
US 27	7.9	SR-820	SR-997	Broward	281
I-75	1.9	US 27	SR-84	Broward	284
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	4.0	SR-816	SR-838	Broward	285
US 1/SR-5 (D)	2.2	Cypress Creek Road/NE 62nd Street	SR-870	Broward	290

Name	Length	From Road	To Road	County	Vuln Ranking
US 441/SR-7	1.9	SR-820	SR-858	Broward	295
SR-817	4.7	SR-84	SR-818	Broward	297
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	7.4	SR-810 Hillsboro Boulevard	SR-808 Glades Road	Broward	298
SR-84	0.8	SW 4th Avenue	Andrews Avenue	Broward	300
US 441/SR-7	6.7	SR-814 Atlantic Boulevard	SR-870	Broward	301
Eller Dr	0.5	US 1/US 41/SR-5 (B)	Andrews Avenue/SE 6th Avenue	Broward	302
US 441/SR-7	6.9	SR-858	NW 7th Avenue Extension	Broward	303
US 441/SR-7	3.1	I-595	SR-818	Broward	304
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	4.1	SR-834 Sample Road	SR-869	Broward	305
SR-818	7.6	SR-823	SR-817	Broward	306
SR-838	7.2	Flamingo Road	SR-817	Broward	307
Andrews Avenue	5.1	SR-814 Atlantic Boulevard	SR-870	Broward	308
SR-823	7.0	I-595	SR-818	Broward	312
SR-817	3.8	SR-820	SR-858	Broward	313
SR-91 Florida's Turnpike	7.6	SR-820	SR-818	Broward	314
Cypress Creek Road/NE 62nd Street	3.2	I-95	US 1/SR-5 (D)	Broward	317
SR-814 Atlantic Boulevard	1.9	Andrews Avenue	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	319
US 441/SR-7	3.5	SR-818	SR-822 Sheridan Street	Broward	320
Andrews Avenue	2.1	SR-736 Davie Boulevard	SR-84	Broward	321
I-595	8.1	SR-823	SR-817	Broward	322
SR-817	3.0	SR-820	Sheridan Street	Broward	323

Name	Length	From Road	To Road	County	Vuln Ranking
SR-84	4.4	US 441/SR-7	I-95	Broward	326
US 441/SR-7	2.1	SR-838	SR-842 Broward Boulevard	Broward	328
US 1/US 41/SR-5 (B)	1.7	SR-84	I-595	Broward	329
SR-838	1.0	Andrews Avenue	US 1/SR-5 (C)	Broward	330
SR-834 Sample Road	2.0	Andrews Avenue	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	333
US 1/US 41/SR-5 (B)	1.1	SR-818	SR-A1A E Dania Beach Boulevard	Broward	335
SR-838	1.9	I-95	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	336
SR-869	5.5	SR-838	I-75	Broward	340
SR-91 Florida's Turnpike	6.3	SR-834 Sample Road	SR-814 Atlantic Boulevard	Broward	343
SR-838	2.1	SR-91 Florida's Turnpike	US 441/SR-7	Broward	344
SR-816	7.1	SR-817	Flamingo Road	Broward	347
SR-816	6.7	US 441/SR-7	SR-817	Broward	348
SR-869	5.5	SR-814 Atlantic Boulevard	SR-870	Broward	351
SR-816	0.6	SR-869	Flamingo Road	Broward	352
US 1/SR-5 (D)	1.2	Copans Road	NE 14th Street	Broward	354
SR-817	4.7	SR-818	Sheridan Street	Broward	355
SR-869	9.4	SR-817	SR-834 Sample Road	Broward	357
SR-869	4.3	SR-870	SR-816	Broward	359
SR-817	3.9	SR-870	SR-816	Broward	360
US 1/SR-5 (D)	1.8	SR-810 Hillsboro Boulevard	SR-869	Broward	363
US 27	4.1	Sheridan Street	SR-818	Broward	364
SR-869	5.5	SR-834 Sample Road	SR-814 Atlantic Boulevard	Broward	366

Name	Length	From Road	To Road	County	Vuln Ranking
SR-842 Broward Boulevard	6.3	US 441/SR-7	SR-817	Broward	368
SR-84	10.6	I-75	I-595	Broward	369
SR-820	3.5	I-75	SR-823	Broward	370
SR-84	4.1	SR-817	SR-91 Florida's Turnpike	Broward	372
SR-814 Atlantic Boulevard	2.6	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	SR-91 Florida's Turnpike	Broward	373
SR-91 Florida's Turnpike	4.3	SR-869	SR-834 Sample Road	Broward	375
SR-810 Hillsboro Boulevard	1.5	SR-809 Military Trail	I-95	Broward	377
SR-818	1.1	US 441/SR-7	SR-91 Florida's Turnpike	Broward	381
SR-823	3.0	Sheridan Street	SR-820	Broward	382
SR-834 Sample Road	3.4	US 1/SR-5 (D)	I-95	Broward	383
SR-823	4.7	SR-818	Sheridan Street	Broward	388
US 1/SR-5 (C)	2.1	US 1/SR-5/SR-838	SR-842 Broward Boulevard	Broward	389
SR-870	5.2	SR-91 Florida's Turnpike	SR-817	Broward	390
SR-870	5.4	SR-869	SR-817	Broward	392
US 27	3.0	Sheridan Street	SR-820	Broward	394
SR-869	2.9	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	SR-809 Military Trail	Broward	395
SR-818	5.4	I-95	US 441/SR-7	Broward	396
SR-869	6.0	US 441/SR-7	SR-817	Broward	397
US 1/US 41/SR-5 (B)	2.8	I-595	SR-818	Broward	400
US 441/SR-7	4.0	SR-816	SR-838	Broward	406
SR-834 Sample Road	1.3	I-95	Andrews Avenue	Broward	408

Name	Length	From Road	To Road	County	Vuln Ranking
SR-869	2.2	SR-91 Florida's Turnpike	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	409
SR-858	5.1	US 441/SR-7	I-95	Broward	410
SR-817	4.1	SR-869	SR-834 Sample Road	Broward	413
SR-823	5.1	SR-820	Miramar Parkway	Broward	414
SR-816	1.0	Andrews Avenue	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	415
SR-820	4.3	SR-817	SR-91 Florida's Turnpike	Broward	416
SR-818	5.0	I-75	SR-823	Broward	417
SR-810 Hillsboro Boulevard	1.4	US 1/SR-5 (D)	SR-A1A	Broward	419
Flamingo Road	3.4	SR-838	SR-842 Broward Boulevard	Broward	420
SR-820	2.9	I-95	US 1/SR-5 (B)	Broward	422
SR-84	2.8	I-95	SW 4th Avenue	Broward	424
US 441/SR-7	2.4	SR-810 Hillsboro Boulevard	SR-869	Broward	429
SR-818	4.6	SR-817	SR-91 Florida's Turnpike	Broward	430
SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	1.9	SR-869	SR-810 Hillsboro Boulevard	Broward	431
Miramar Parkway	7.0	SR-823	I-75	Broward	434
US 1/SR-5 (B)	1.9	SR-820	SR-824 Pembroke Road	Broward	435
SR-858	2.9	I-95	US 1/SR-5 (B)	Broward	436
US 1/SR-5 (D)	4.1	SR-869	SR-834 Sample Road	Broward	438
SR-834 Sample Road	2.1	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	SR-91 Florida's Turnpike	Broward	439
SR-84	4.0	I-595	SR-823	Broward	440
SR-818	8.2	US 27	I-75	Broward	443

Name	Length	From Road	To Road	County	Vuln Ranking
SR-838	4.1	US 441/SR-7	I-95	Broward	445
Flamingo Road	3.1	SR-816	SR-838	Broward	448
I-595	6.2	I-75	SR-823	Broward	449
SR-809 Military Trail	2.0	SR-810 Hillsboro Boulevard	SR-869	Broward	451
Andrews Avenue	5.5	SR-834 Sample Road	SR-814 Atlantic Boulevard	Broward	454
SR-814 Atlantic Boulevard	4.2	US 1/SR-5 (D)	I-95	Broward	455
SR-838	3.6	SR-869	Flamingo Road	Broward	458
I-595	4.3	I-95	US 1/US 41/SR-5 (B)	Broward	463
US 441/SR-7	5.5	SR-834 Sample Road	SR-814 Atlantic Boulevard	Broward	465
US 1/SR-5 (D)	2.3	SR-834 Sample Road	Copans Road	Broward	466
Sheridan Street	8.7	US 27	I-75	Broward	467
SR-736 Davie Boulevard	0.4	US 1/SR-5 (C)	Andrews Avenue	Broward	468
Sheridan Street	4.9	I-75	SR-823	Broward	469
SR-869	4.9	US 441/SR-7	SR-91 Florida's Turnpike	Broward	470
Johnson Street	1.5	N 29th Avenue	US 1/SR-5 (B)	Broward	472
SR-84	8.1	SR-823	SR-817	Broward	474
US 1/SR-5 (B)	1.0	SR-822 Sheridan Street	Johnson Street	Broward	475
SR-834 Sample Road	5.7	SR-869	SR-817	Broward	478
SR-834 Sample Road	6.0	US 441/SR-7	SR-817	Broward	479
SR-A1A Ocean Boulevard	1.2	E Camino Real	NE 2nd Street	Broward	481
SR-823	1.1	Miramar Parkway	SR-821 Florida's Turnpike	Broward	487
SR-834 Sample Road	4.1	SR-91 Florida's Turnpike	US 441/SR-7	Broward	488
US 441/SR-7	3.6	SR-869	SR-834 Sample Road	Broward	490
SR-820	7.9	SR-823	SR-817	Broward	493

Name	Length	From Road	To Road	County	Vuln Ranking
US 1/SR-5 (B)	0.2	SR-A1A E Dania Beach Boulevard	SR-848 Stirling Road	Broward	494
SR-810 Hillsboro Boulevard	6.2	US 441/SR-7	SR-845 Jog Rd/Powerline Rd/S Pompano Pkwy	Broward	496
US 1/SR-5 (B)	1.0	SR-848 Stirling Road	SR-822 Sheridan Street	Broward	497
SR-869	5.1	SR-816	SR-838	Broward	499
Miramar Parkway	6.0	SR-817	SR-823	Broward	502
Sheridan Street	7.9	SR-823	SR-817	Broward	503
SR-820	11.5	US 27	I-75	Broward	504
US 1/SR-5 (B)	0.5	Johnson Street	SR-820	Broward	515
SR-869	1.2	SR-809 Military Trail	I-95	Broward	526
US 1/SR-5 (D)	3.3	E Camino Real	SR-810 Hillsboro Boulevard	Broward	534
SR-809 Military Trail	7.3	SR-808 Glades Road	SR-810 Hillsboro Boulevard	Broward	561
I-75	8.4	SR-84	I-595	Broward	582

Source: Broward MPO, Appendix B – Jurisdiction Ranking,
http://www.browardmpo.org/images/WhatWeDo/Appendix_B-Jurisdiction_Ranking.pdf

Appendix D: Partner Agency Comments Received Regarding Resiliency

City of Fort Lauderdale Comments

Page #	Paragraph/ Table/ Figure or Map #	Comment
3-11		Resiliency - it is stated that the recommendations were used in the development of the MTP. Are there specific projects that were identified in the Plan that will implement improvements to vulnerable roadways to make them less vulnerable? Could you share those projects?
5-10	Table 5-3	Could you provide more information on project #22? It is within the city of Fort Lauderdale; however, it was not one that was presented to the City during the coordination meetings and was not a part of the previous resolution of support.
5-11	Table 5-3	Could you provide more information on project #23? It is within the city of Fort Lauderdale; however, it was not one that was presented to the City during the coordination meetings and was not a part of the previous resolution of support.
5-11	Table 5-3	Could you provide more information on project #24? It is within the city of Fort Lauderdale; however, it was not one that was presented to the City during the coordination meetings and was not a part of the previous resolution of support.

FDOT Comments

Page #	Paragraph/ Table/ Figure or Map #	Comment
3 4	10, 11, 5-7	The section on Resiliency on pp. 3-10 and 3-11 covers the South Florida Climate Change Vulnerability and Adaptation Pilot Project (Pilot Project) and the Extreme Weather and Climate Change Risk to the Transportation System in Broward County, Florida project. Regarding the Resiliency Scenario description on pp. 3-11 and 4-5, it is unclear why only the Extreme Weather and Climate Change Risk study was used to identify vulnerable facilities. Among the studies and tools covered in Miami-Dade County's Final Report for Assessment of Available Tools to Create a More Resilient Transportation System are the Pilot Project; the Storm Surge, Sea Level Rise, and Transportation Network Disruption project completed to supplement the Pilot Project, and the UF GeoPlan Center Sea Level Scenario Sketch Planning Tool. The Miami-Dade report is posted at https://www.miamidade.gov/mayor/library/memos-and-reports/2016/11/11.30.16-Final-Report-for-Assessment-of-Available-Tools-to-Create-a-More-Resilient-Transportation-System-Directive-160220.pdf. A presentation summarizing results of the Storm Surge, Sea Level Rise, and Transportation Network Disruption project is posted at http://www.fsutmsonline.net/images/uploads/southeastfloridafsutms/FSUTMS_Storm_Surge_2nd_Transportation_Network_Disruption_YH.pdf). The project report is being sent with the comments.
3 4	11 5 & 7	The Resiliency =Scenario is described as seeking to prohibit future investment to roadways identified as vulnerable. Suggest clarifying how this approach relates to efforts by local governments and others to increase the resiliency of transportation and other infrastructure in vulnerable areas (e.g., through designation of Adaptation Action Areas in comprehensive plans) and the plan's provision for studies of resiliency improvements for vulnerable transportation facilities (e.g., SR-A1A from South of Arizona St to Hallandale Beach Blvd).

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