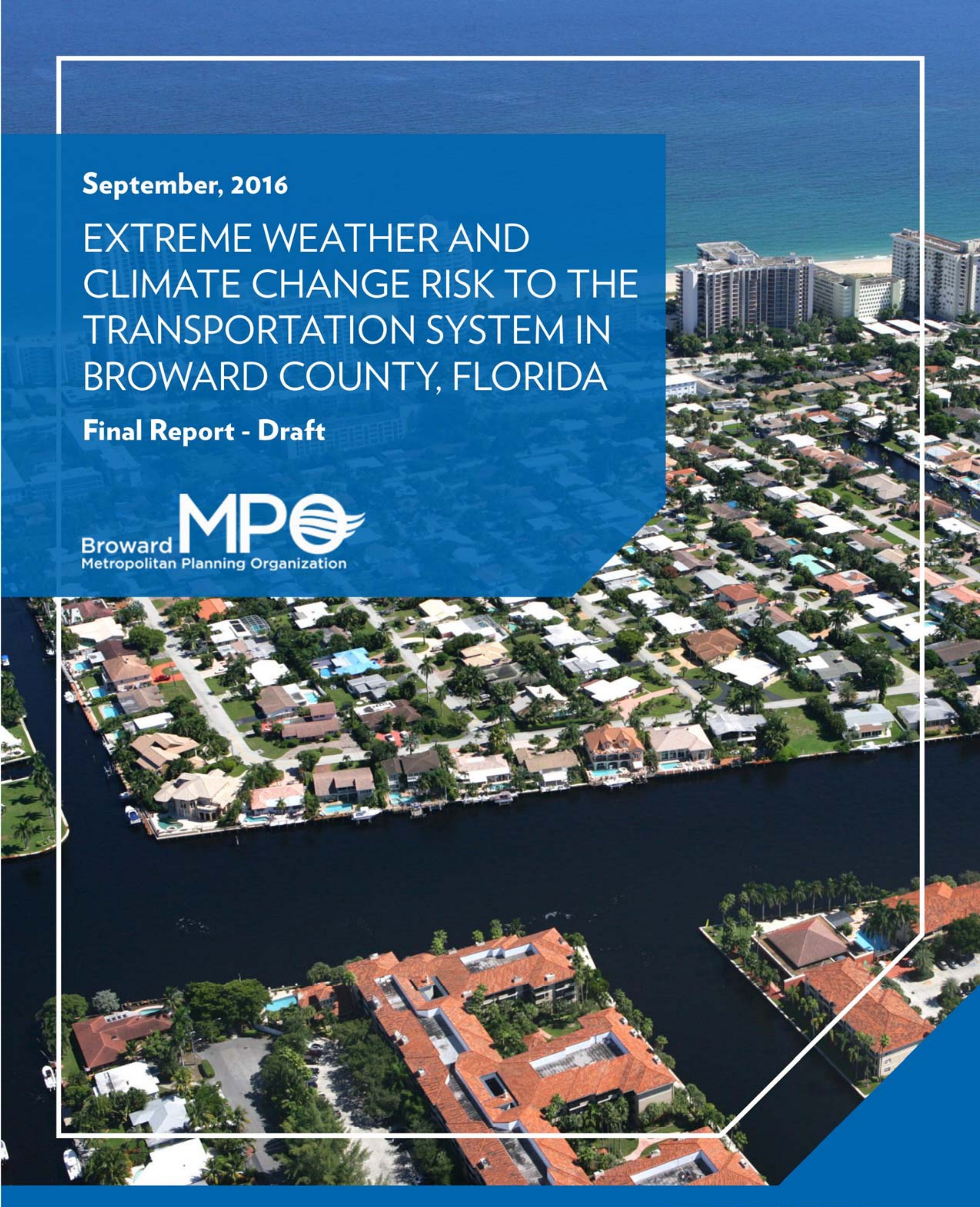
September, 2016

EXTREME WEATHER AND CLIMATE CHANGE RISK TO THE TRANSPORTATION SYSTEM IN BROWARD COUNTY, FLORIDA

Final Report - Draft

Broward MPO
Metropolitan Planning Organization



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1 Introduction

1.1 PROJECT OVERVIEW

This report summarizes the draft results of a study conducted by the Broward MPO to determine the long term risks to transportation infrastructure from climate change. The study, *Extreme Weather and Climate Change Risk to The Transportation System in Broward County, Florida,* was conducted to capitalize on existing and developing climate data to determine the risks to transportation infrastructure in the county, as well as to identify a set of potential projects to improve the long term resiliency of the transportation system.

This study is the second effort led by the Broward MPO to define the parameters of climate change and the potential effects on the regional transportation system. The first study = the *South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project* – was completed in 2015 and defined potential climate change concerns for the four county southeast Florida region. That study applied a vulnerability framework developed by the Federal Highway Administration (FHWA) to define generalized areas of concern for the regional transportation system. An outcome of that study was an interest in better defining the areas of concern within Broward County and what actions may need to be taken to address those areas to ensure a viable transportation system.

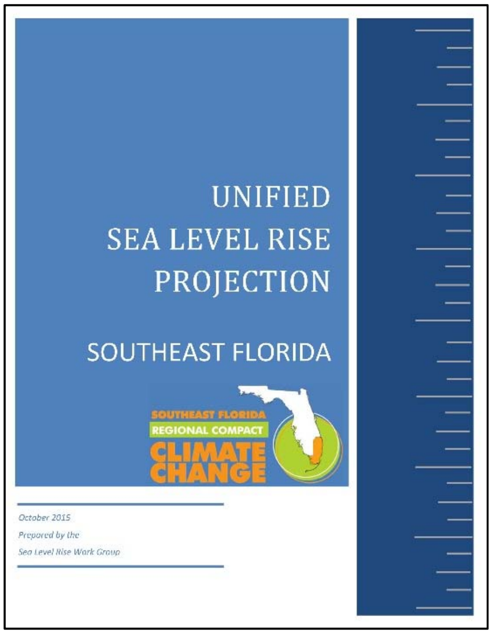
One of the primary focus areas and benefits of this project is to define at a finer level of detail the long term effects of climate change and what it may mean to the system. Climate change is, in large part, still a developing field, with refinements often occurring through ongoing studies by numerous research institutions. The original definition of climate change – a general increase in global temperatures – has evolved to a much more expansive understanding of precipitation change, rising sea levels (a phenomenon comprised of multiple actions, each a subject of additional study), and changing storm patterns associated with increased energy in the atmosphere.

Defining a future climate condition (and identifying the uncertainty inherent in the data that helps define this future) is a significant challenge of incorporating climate change considerations into agency decision-making. The science underlying projected future conditions is still developing, and it is likely that it will be several years before a consistent and agreed upon set of projected future conditions is produced by the scientific community. Given the varying forecasts for temperature change, sea level rise, precipitation change, etc. developed by various research agencies or academic institutions, developing a climate change-sensitive decision-making process for engineering-based decisions (e.g., decisions based on civil engineering concepts where well defined and historically-based parameters are the norm), will be a challenge. In such circumstances, exploring possible future conditions and understanding how they might affect the performance of the transportation system becomes an important capability of the technical support for decision making.

Southeast Florida has been the focus of several studies and articles in national news media that have sought to define likely climate change and the resulting implications to the communities in the region. Many of the region's economic and everyday activities occur near the coast, and therefore the implications of climate change are most notable in this part of the region. The Southeast Florida Climate Compact, established in part to help define a consistent framework for decision making and to limit the broad range of uncertainties of future conditions as identified above, issued guidance in 2015 on how to incorporate sea level rise into decision-making. This guidance recommended using higher level projections for sea level rise, which reflected a growing understanding that emission scenarios that assumed a lower rate of greenhouse gas emissions entering the atmosphere did not match with the reality as evidenced through atmospheric data collection. The guidance enabled better decisions by establishing the most likely parameters of change and by establishing a baseline to identify the benefits of adaptation actions.

This project looked at the potential consequences of climate change to today's transportation system, an approach that looks at the current time period and does not reflect broader investments expected to be made in the region in coming decades. Although the spatial location of the future transportation network is assumed to be the same as today, it may vary in width, capacity or technology (autonomous vehicles, etc.).

Figure 1 - Southeast Florida Climate Compact SLR Guidance Document



UNIFIED
SEA LEVEL RISE
PROJECTION

SOUTHEAST FLORIDA

SOUTHEAST FLORIDA
REGIONAL COMPACT
CLIMATE
CHANGE

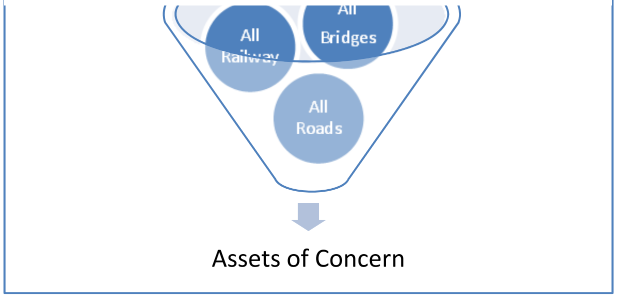
October 2015
Prepared by the
Sea Level Rise Work Group

The overall approach of this study is to apply available information towards an effort to refine the understanding of future risks to a level where decisions can be made on long term investments with an understanding of the risks. In general, the effort can be thought of as an exercise of identifying the subset of links in the transportation system that will require additional consideration given the expected extent and timing of future conditions that may affect the operation of the system.

The study conclusions are defined from the perspective of long-term transportation investment decisions within Broward County, which is consistent with the roles and responsibilities of the Broward MPO. The data developed for this study, as well as future data collection to support the continuing consideration of climate change risks, will enable the county to assess recommended projects based on the following key questions:

- How might projects in existing capital investment programs be reconsidered given the potential risks inherent from climate change?
- How should projects be developed and implemented to increase system resiliency to climate change?
- How might transportation investments be affected by long term climatic changes in ways that may reduce their lifetimes due to changing environmental conditions?

Figure 2 - Reducing the Set of Transportation Assets for Action



The information needs for the decision-making framework adopted for this study include: understanding the nature of the transportation system, obtaining forecasts for the key climate change factors in the county, determining the impacts on the system of these expected conditions, and identifying the next steps toward adapting the system to be more resilient. These four information needs also provide the organization of this report. Chapter 2 provides background on the transportation system and characterizes the respective modal networks in terms of importance to the state, region and local communities. Chapter 3 describes likely climate change effects that may impact Broward's transportation system and identifies existing and developing climate data that will enable decision-making. Chapter 4 identifies those actions that should happen next to further refine the understanding of risks to the system and help define the specific set of projects recommended to assess those long term risks.

Transportation System Resiliency - ensuring that long term change and future extreme weather events result in limited or no disruptions to the transportation system

As a final note, the term resiliency has multiple definitions as applied in extreme weather and long-term climate change risks. This perspective is often part of emergency management and focuses on the viability of evacuation routes. This study has focused on ensuring the viability of the transportation system in response to longer term climate change trends, as well as for extreme weather events. The study's intent is to ensure that long term climate change and future extreme weather events result in limited or no disruptions to the transportation system and to the communities it serves on a day to day basis. It is a measure of community viability, made more pertinent by events in other regions of the country where extreme weather-related system disruptions have resulted in serious impacts on communities.

1.2 CONSIDERATION OF RISK

The transportation system enables community viability, public health, and economic success, and therefore should be protected against any possible events that would disrupt this relationship. Many examples from around the country suggest that an important way of doing this is to incorporate asset protection at a level higher than currently applied in standard operating procedures. In general, the transportation system has been constructed as cost-effectively as possible based on conditions assumed at the point of design – increasing the potential for damage/disruption during extreme weather events as has been noted in South Carolina, New York, Colorado, Vermont, and California, and more broadly nationally when looking over the past two decades.

A number of factors affect the types and magnitudes of risks to transportation infrastructure as they are considered as part of the project design process. Some of these factors include:

- Applying design return periods that do not adequately recognize the lifetimes of transportation infrastructure. An example of this would be the application of a 100-year storm as a base design condition – a decision that means, statistically, that that event is more likely to be exceeded during a century, than not (an approximate 60%+ chance).
- Changing the value of a return period, where each successive severe storm can redefine the definition and value for that event. This means that facilities designed in the past to a lower

value will not be protected to the same level as those designed after a more recent storm event and an adjustment in the return period used for design. When news outlets report a 1000-year storm event, this means that this storm had very low probability based on a statistical analysis of past events – and now that event will help to redefine future return periods applied on future designs.

- Considering the conditions that contribute to flooding/damage. Saturated soils, a higher water table, development and flood control measures can all impact flood levels and damage in different areas, conditions that can change over time and increase the potential for damaging flood levels for infrastructure assets or communities.

Thus, the reliance on currently defined design storms needs to be considered carefully when setting policies for future events which include climate change. Also, assuming that infrastructure in place today is protected to the return period standard is inappropriate. More critical transportation assets that provide important access for the region and community should be considered at a higher standard for design to ensure protection and viability over the long lifetimes of transportation infrastructure.

2 Broward's Transportation Network

The study transportation system included roadways and rail lines that provide accessibility to the region as well as to economic and community centers within Broward County. The rail network is made up of two parallel rail lines, with the westernmost alignment owned by the Florida Department of Transportation (FDOT) and currently used for Tri-Rail and Amtrak service. The easternmost alignment is being examined in the region for additional regional rail service via Coastal Link, connecting business centers throughout the region.

The roadway network consists of a diverse set of roadways of varying types, from interstates to arterials, collectors and local roadways. In order to establish a level of importance for the road network in Broward County, the MPO developed three roadway classifications based on the following criteria:

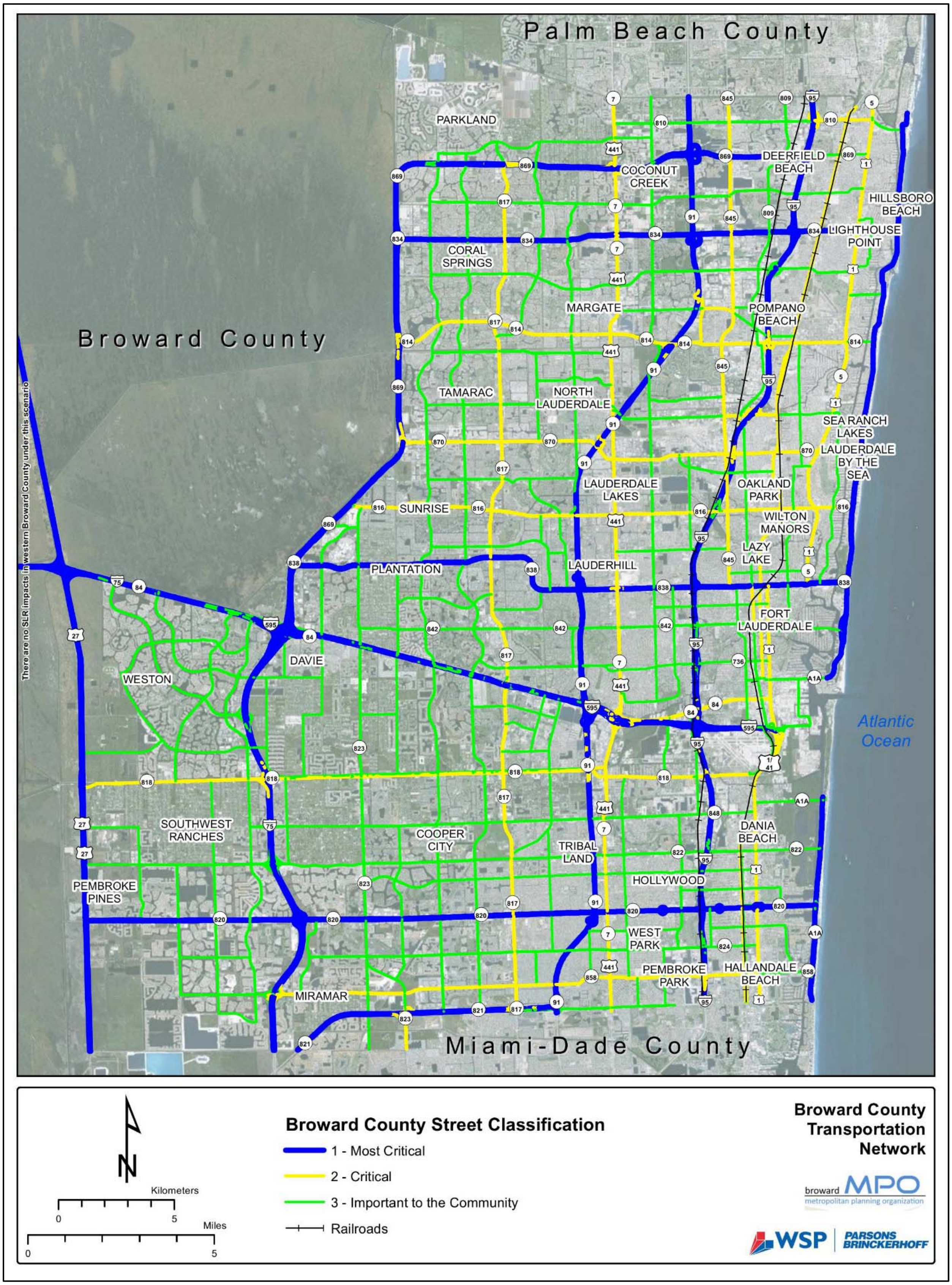
- Their position in the regional community and economy
- Their inclusion in an overall network of roads representing a connected network
- Their importance in connecting to county activity centers and economic zones

The three classes of county roads included:

- Class 1 – the most critical links in the system. Critical to regional economic viability and connectivity among regional and county business centers. This includes selected interstate and arterial roadways and the two passenger rail lines (existing and proposed) in the county. These facilities will have the lowest risk tolerance.
- Class 2 – critical to the functioning of the broader community. This network includes the core network for the county, linking activity centers and land uses and important economic centers. These facilities will have low risk tolerance.
- Class 3 – important to the community. This network makes connections to and among county communities and providing access to the county and larger regional transportation networks. These facilities will have moderate risk tolerance.

Figure 3 identifies the transportation system targeted by this study, as well as the assigned classes for county roadways developed through coordination with the Broward MPO staff. The classes noted were used for this study to identify response strategies specific to each class type, to set varying standards for various components of the Broward network based on the relative level of importance of each asset in the roadway network.

Figure 3 - Broward Roadway Transportation Network – Identified Tiers



3 Climate Change Effects by Stressor

Climate change is a term used to describe changing global and/or regional climate patterns and is a process driven primarily by increasing concentrations of greenhouse gas emissions (carbon dioxide, etc) in the earth's atmosphere. Scientists worldwide have been working to better understand how the earth will respond to this increase in these gasses, the resulting warming of the earth's atmosphere, and how that warming will result in changing conditions like sea level rise or changing weather patterns. Studies of the individual facets of the larger picture of climate change like ice melt, thermal expansion of water, or changing participation patterns are the focus of research and the conclusions of those research efforts are brought together to present an overall representation of climate change that policy-makers can use to help guide decisions.

The Intergovernmental Panel on Climate Change (IPCC) is an international body of scientists and policy leaders who have been convened to synthesize the results of numerous peer-reviewed studies ongoing worldwide into information that can be used to help guide decisions for regions like south Florida. The field is very dynamic and studies conducted by different research entities and focused on the same concern can have varying results, and therefore having an entity that provides a set of values for decision-making is a critically useful exercise.

The IPCC has identified a set of scenarios to represent possible futures for climate change. They are termed relative concentration pathways to describe scenarios for greenhouse gas emissions in the atmosphere through the end of this century. The RCPs are based on assumptions for the levels of greenhouse gas emissions that are generated worldwide and vary based on assumed timeframes at which increasing emissions may peak and may begin to decline. The four emissions scenarios and their assumptions are listed below:

- RCP 2.6 - assumes that global annual GHG emissions peak between 2010-2020, and then begin to decline substantially
- RCP 4.5 - assumes that emissions peak around 2040, then begin to decline
- RCP 6 - assumes that emissions peak around 2080, then begin to decline
- RCP 8.5 – assumes that emissions continue to rise throughout the 21st century[1]

There is a general consensus that the optimistic assumptions behind RCP 2.6 are not going to occur, there have been no international efforts put in place to reduce greenhouse emissions to those noted levels.

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[1] Meinshausen et.al – "The RCP greenhouse gas concentrations and their extensions from 1765 to 2300" – see http://link.springer.com/article/10.1007%2Fs10584-011-0156-z

3.1 Temperature Changes in Southeast Florida

3.1.1 Overview

Forecasts of future temperatures are based on assumed global emission scenarios and relationships among key variables that lead to future climatic conditions. Global climate models have been developed based on these different assumptions and varying spatial resolution to forecast key variables such as average and extreme precipitation levels, number of days exceeding 95 degrees, etc. Given this standard practice for climate forecasting, the most usual reporting of forecasted conditions includes a range in values, based on applying varying emission scenarios, and often reporting the level of certainty associated with the forecasts. The following information on future temperatures levels comes from various sources, with the results compiled and presented in the 2014 National Climate Assessment providing the most useful information.

According to the National Climate Assessment, temperatures in the southeast United States increased from 1970 to the present by an average of 2°F, with higher average temperatures during summer months. Figure 4 shows the estimates generated for the higher emissions scenario and identifies the projected number of days over 95 °F for the period 2040 to 2070, with approximately an additional 40 to 50 days over 95°F occurring by 2070 in Broward County. Projections for a region just north of Broward County indicates an average increase of 2-4°F by 2035-2045 and 5-8°F by 2075-2085.[2] The projected Increase for summer tends to be higher than winter, with summer temperatures increasing 1-2°F more, on average, than winter temperature. Another effort to forecast average summer high temperatures in 2100 for Ft. Lauderdale based on IPCC's 5th Assessment Report (based on the RCP8.5 emissions scenario) indicated that by 2100 summers in Ft. Lauderdale (currently experiencing 89°F average temperatures) will be experiencing close to 95°F as the average.[3] This forecast is consistent with a 5-8°F increase in summer temperatures forecast from other studies.

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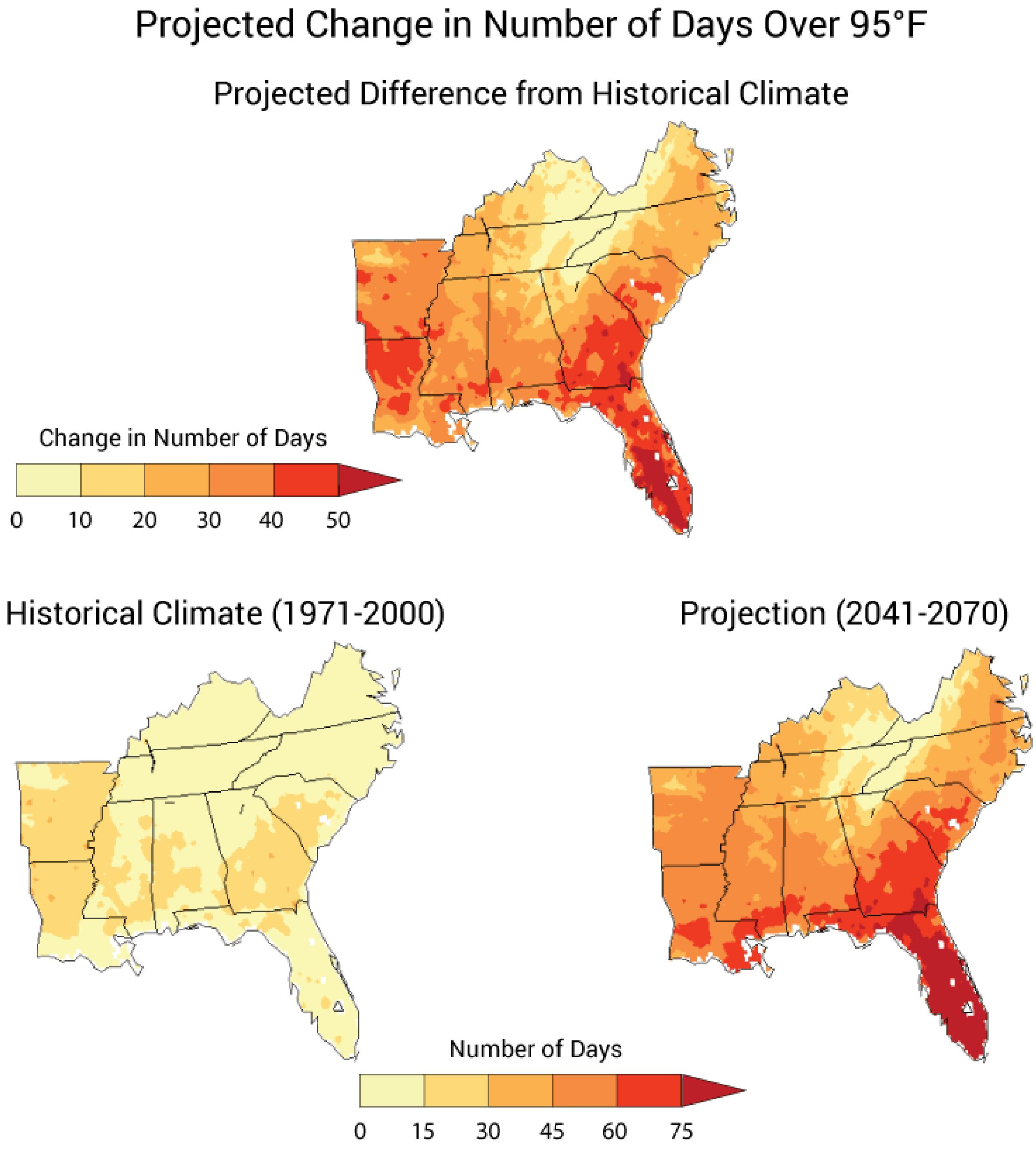
[2] ClimateWise, Future Climate Conditions in the St. Johns River Drainage Basin, Florida, Nov. 2011. Accessed from, http://climatewise.org/images/projects/saint-johns-report-projections.pdf

[3] The temperature change was calculated through that period using a downscaled multi-model ensemble approach (Downscaled CMIP5 Climate Projections archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/) and that number was added to the current temperature (from PRISM) to get the future temperature. Accessed from, *http://www.climatecentral.org/news/summer-temperatures-co2-emissions-1001-cities-16583*

Figure 4 - Projected Increases in Days over 95° F for Higher Emissions Scenario (A2)



Source: U.S. Global Change Research Program, National Climate Assessment, Southeast Region, Accessed from, *http://nca2014.globalchange.gov/report/regions/southeast*

3.1.2 Potential Impacts of Temperature Changes on Infrastructure

The impacts of increasing temperature on transportation infrastructure in an area like South Florida, where hot temperatures and moderate low temperatures are fairly normal activities, may seem somewhat limited. However, there are a few considerations specific to rail and highway infrastructure that should be considered. Table 1 summarizes some of the effects that will need to be assessed.

Table 1 - Temperature Effects on Transportation Infrastructure

Potential Impact from Temperature	Areas of Potential Exposure	Mitigation	Associated Issues
Heat Kinks/Rail Buckling	Along turns, ballasted 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 crossties as opposed to wooden ones, 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 the climate, choose joints carefully 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	Rutting, asphalt movement, slab buckling, frequent maintenance, joint failure

Potential Impact from Temperature	Areas of Potential Exposure	Mitigation	Associated Issues
		using link slabs	

3.2 Precipitation

3.2.1 Overview

Precipitation concerns in south Florida are fairly common as low areas, relatively little topographic relief, and limited drainage capacity combine to cause localized flooding during regular rainfall events. Any increase predicted in precipitation would exacerbate this issue in many areas of the county. Forecasts of future precipitation levels in south Florida have varied from models that suggest a reduction in precipitation to those predicting higher levels. Figure 5 shows the projected annual maximum precipitation and the change in consecutive number of dry days in the United States for two extremes in emissions scenarios. An interesting observation for projected annual maximum precipitation is that under both scenarios the maximum annual precipitation is expected to increase, meaning more rain for the region. The implication of the increase in the number of consecutive dry days is that although there will likely be an increase in heavy downpours, there will be longer dry periods in between. This observation is consistent with the forecasts of the South Florida Water Management District.[4]

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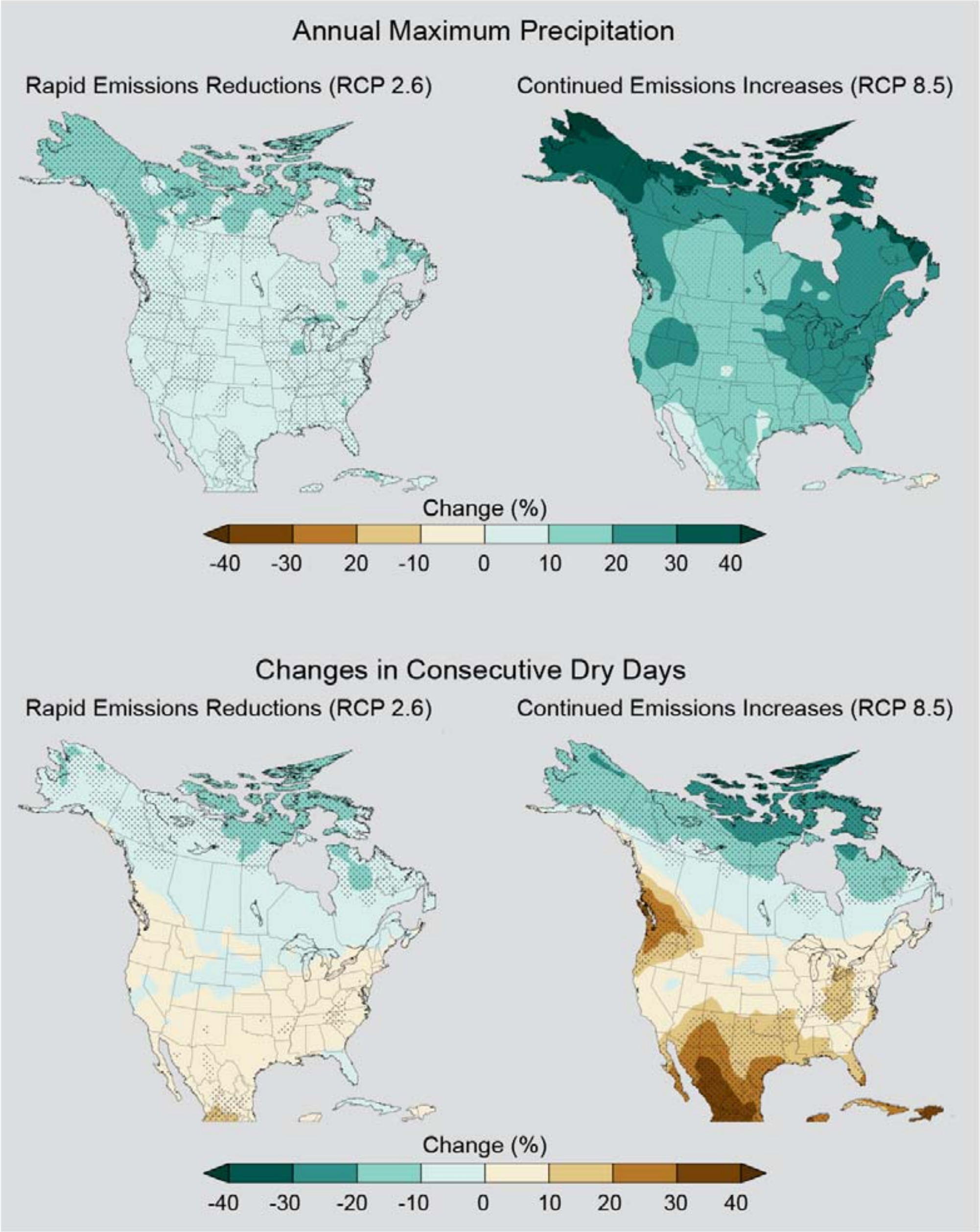
[4] See, http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/climate_change_and_water_management_in_sflorida_12nov2009.pdf

Figure 5 - Precipitation Changes Forecast for the Region



Source: U.S. Global Change Research Program, National Climate Assessment, Precipitation, Accessed from, *http://nca2014.globalchange.gov/report/our-changing-climate/precipitation-change#tab2-images*

To give some sense of the amount of rainfall these forecasts suggest, EPA's national stormwater calculator was used for the Ft. Lauderdale rain gage. Figure 6 shows the range of annual maximum daily rainfall for the near term (2020 – 2049) and Figure 7 shows the far term (2045 – 2074) forecasts for different return period events and for different emission scenarios (hot/dry, median, warm/wet and historical). As can be seen, the difference between the median and historical values is approximately 1.5 inch of additional maximum daily rainfall in the near term, and from 2 to 3 inches (depending on the scenario) for the far term.

Figure 6 – National Stormwater Forecasts, Fort Lauderdale, Near Term (2020-2049)

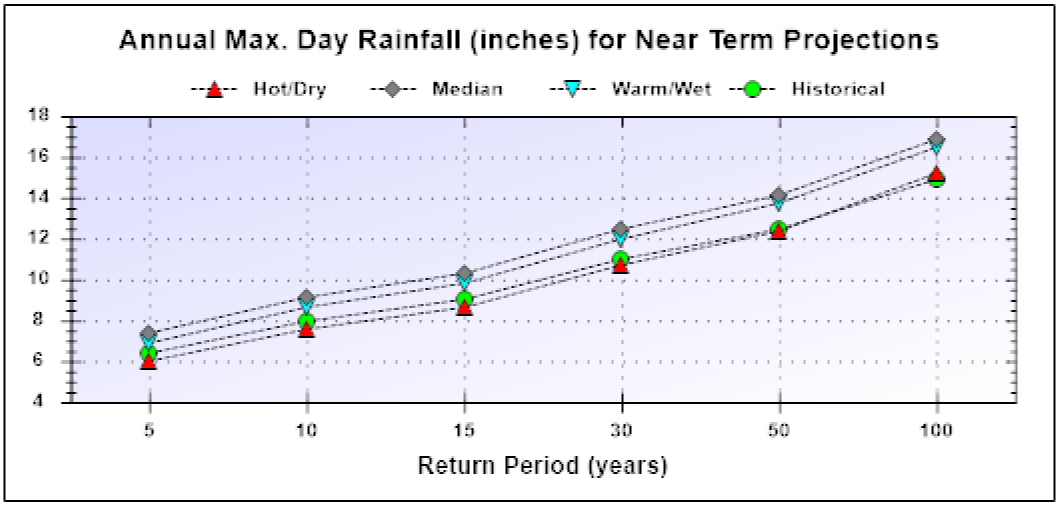
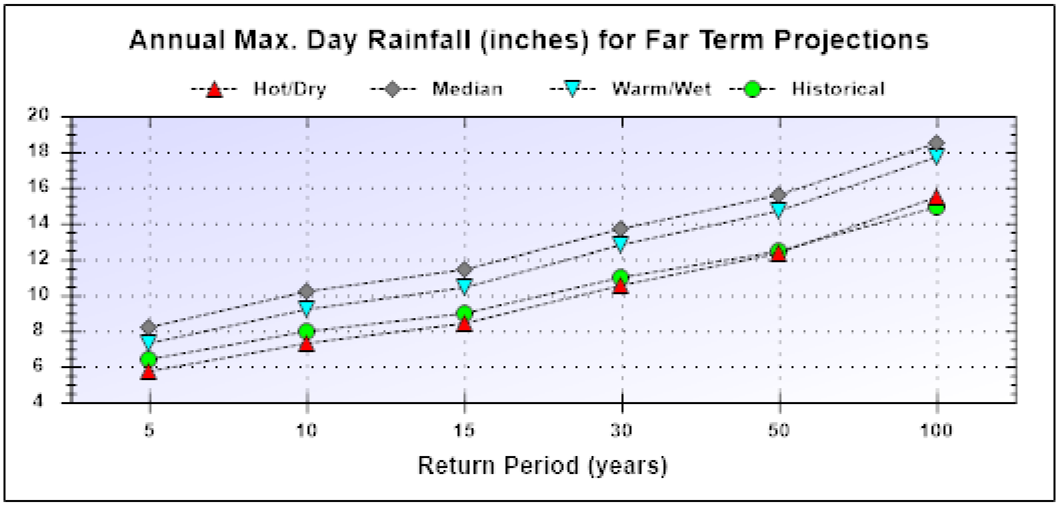


Figure 7 - National Stormwater Forecasts, Fort Lauderdale, Long Term (2045-2074)



Source: EPA, National Stormwater Calculator, Accessed from, *https://www.epa.gov/water-research/national-stormwater-calculator*

3.3 Sea Level Rise

3.3.1 Overview

A primary concern in Broward County as a coastal community is the potential long term effects of rising sea levels. This changing shoreline condition, combined with porous geology and tropical weather patterns, make south Florida unique in its exposure to long-term coastal risks. Transportation infrastructure in the region is expected to be impacted by both the slow rise of sea levels and an increasing risk from enhanced storm surge effects caused in part by these higher sea levels.

Table 2 captures the anticipated effects of climate change from the perspective of sea level rise in the Broward County area, and includes rising water levels (off-shore and in the inland water table), including tidal effects – with tidal effects being a fairly and extended recent observed condition throughout Florida in Fall, 2016. Such effects would become more impactful in the future as seas rise and a larger volume of water moves inland.

Table 2 - Expected Effects of Sea Level Rise on Transportation Infrastructure in Broward County

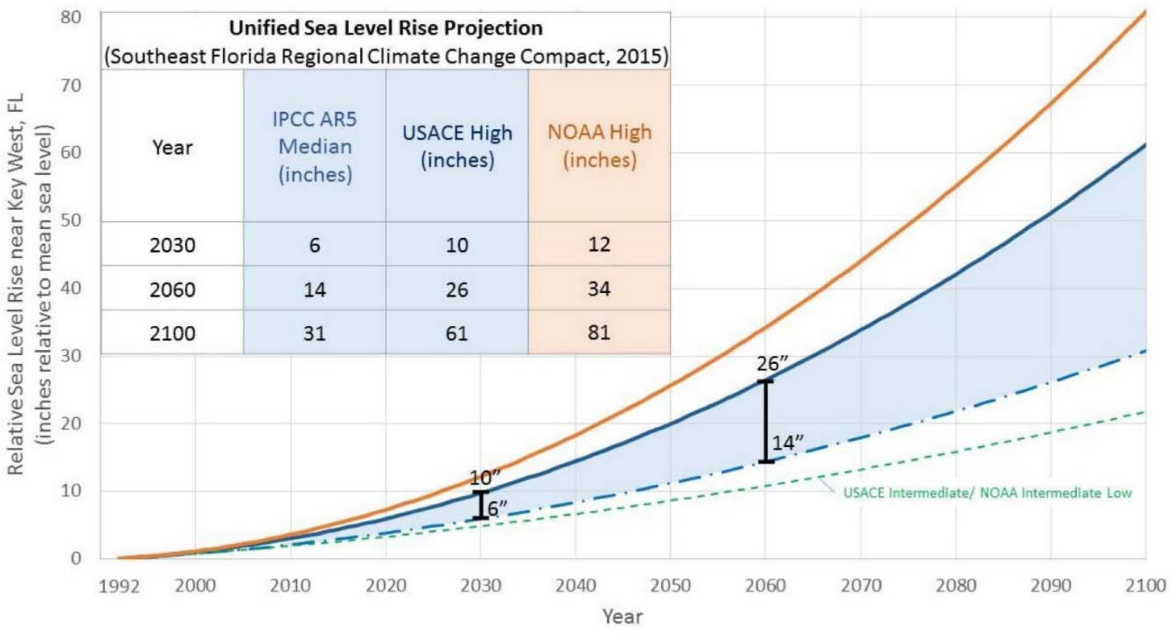
Asset	Issue	Concern	Potential Action
Roadways and Rail	Inundated Roadways	Roadways that may be inundated from sea level rise at all times, or intermittently - impacting travelers during times of peak tidal events	Raise Profile
Roadways and Rail	Higher Water Table	Reduced Drainage Capacity - Increased Effects During Precipitation Events	Raise Profile, Install Drainage Pumps
Roadways	Higher Water Table	Inundation of Pavement during tidal/storm events or at all times	Raise Profile
Roadways and Rail	Higher Water Table	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 which previously had no tidal effects and not considered in design	Add Erosion Control Measures
Bridges	Tidal Effects	Undermining of foundations (scour)	Add Scour Protection Measures
Bridges	Tidal Effects	Reduced bridge clearance	Re-Build Bridge at Replacement for Higher Clearances
Bridges	Tidal Effects	Bridge girder corrosion from salt water in areas not considered	Add Corrosion Protection Treatment
Bridges	Tidal Effects	Uplift of roadway approaches from inundation	Anchor approaches
Bridges	Tidal Effects	Additional buoyancy on bridge superstructure (timber bridges)	Add buoyancy control measures
Bridges	Tidal Effects	Mechanical system flooding	Protect/move mechanical features
Bridges	Tidal Effects	Inundation of utility connections required to operate mechanical bridges	Seal electrical systems from flooding

Sea level has already been occurring in the region, and projected increases range from 30 and 80 inches by the end of the century depending on the amount of greenhouse gases emitted into the atmosphere and the level of Earth's response to increased temperatures. A range of estimates of future conditions exist to various out years, with estimates maintained by the U.S. Army Corps of Engineers, NOAA and also local academic agencies. The intent of these estimates is to define a reasonable basis for forecasting future sea levels based on the various factors that affect the overall total.

As noted earlier, Broward County is a part of a regional compact, the Southeast Florida Climate Compact (SFCC), which acts as a single source of information to help guide policy decisions. The

SFCC released in late 2015 a document that outlined sea level rise values for three scenarios for southeast Florida[5]. Those curves are noted in Figure 8. The challenge of using three potential future conditions, particularly with regards to infrastructure, is that there is the opportunity to overspend or underspend on infrastructure protection depending on which scenario is selected. In reviewing Figure 8, one can see that building to NOAA high conditions in 2050 may be overbuilding to conditions not expected for 50 years should the IPCC AR5 Median scenario be the reality. Spending scarce resources on actions that deliver an excess of design is not something that infrastructure managers with limited funds desire,

Figure 8 - Sea Level Rise Projections - Southeast Florida Regional Climate Change Compact



Unified Sea Level Rise Projection
(Southeast Florida Regional Climate Change Compact, 2015)

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

Another primary consideration for making infrastructure decisions is the lifetime of a project, to ensure that investments consider how long an asset is expected to be in place. The point of replacement at the end of the design life would be a point at which any adjustments could be made, reducing the need to plan for longer periods of time, and larger uncertainties to each successive out year.

3.3.2 *Network Impacts*

The extent and potential timing of impacts to the network for sea level rise specific to inundated roadways was analyzed for this project. The maps prepared on the next two pages summarize the expected impacts to roadways with some level of inundation for the two recommended SLR scenarios.

The sea level rise values used to determine the noted impacts were taken from two of the curves from the Climate Compact data noted above, the IPCC AR5 median and the USACE High Curve.

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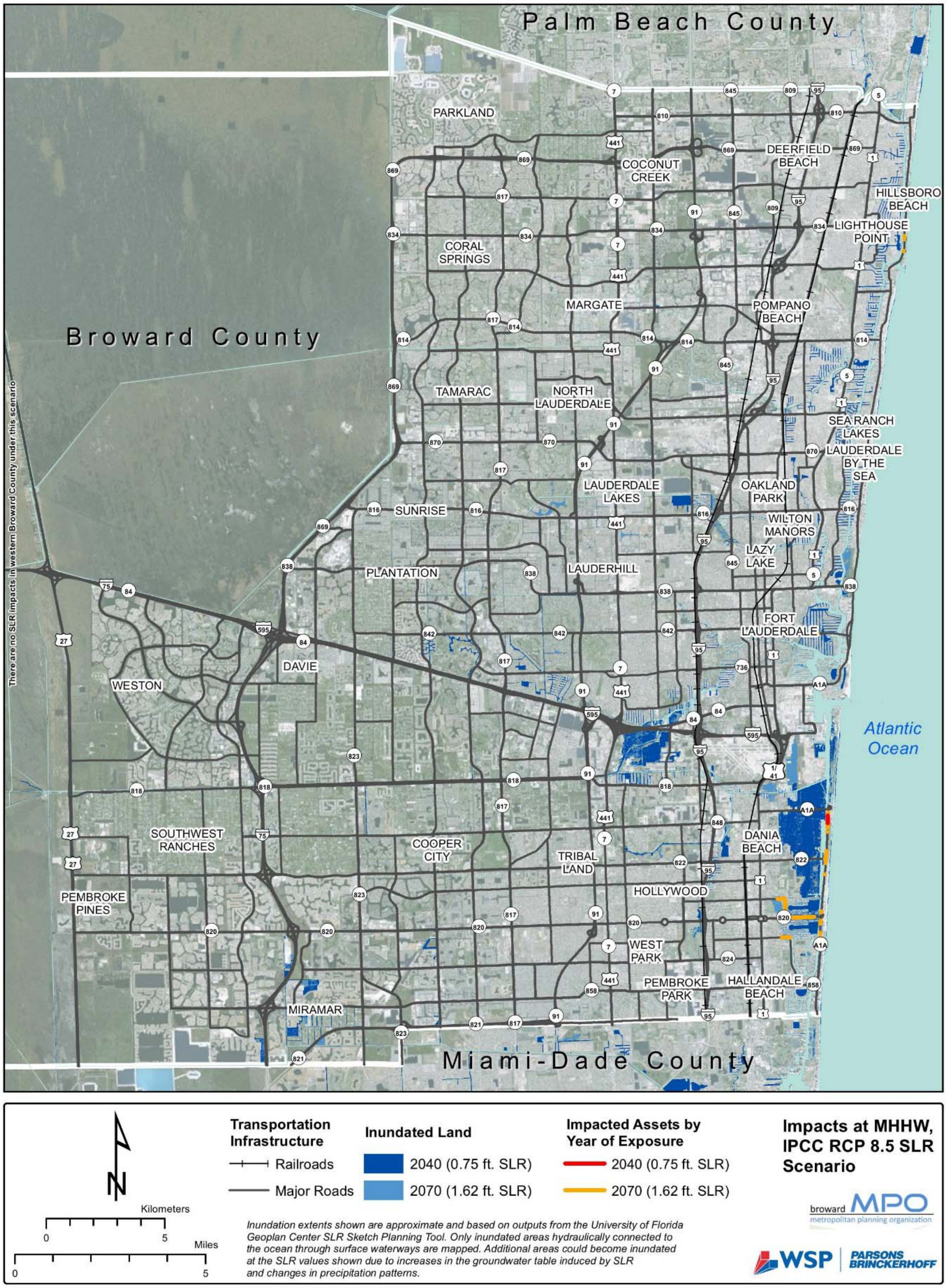
[5] Unified Sea Level Rise Projections – Southeast Florida, October 2015

These curves were used based on guidance contained in the Compact document, and were used to estimate potential inundation of roadways to the years 2040 and 2070 for the purposes of identifying those assets that may require action within the far horizon timeframe of transportation decision-making. 2040 was used as a horizon year to match a horizon year for long range transportation planning, and 2070 was used also as a value as any transportation investments made today would be expected to have a 50+ year lifetime and therefore assessing potential impacts to that out year were also considered.

The sea level rise inundation layers developed by the University of Florida Geoplan center were used for this assessment. The analysis was conducted by utilizing the Mean Higher High Water (MHHW) estimated inundation area values for future years. Mean Higher High Water can be generalized to mean the highest of the two daily high tide values, or a value at which point the roadway will become inundated at some point every day on average. This condition was used as daily inundation was seen as an impact on community travel and one which would likely trigger some action on the part of the county to address. It is likely though that in the future the community will begin to request action to address less regular flooding events, for concerns like the King Tide where access may be cut off for a few days. The point is that MHHW was while used for this study, the timing of desired change will likely occur before that condition exists.

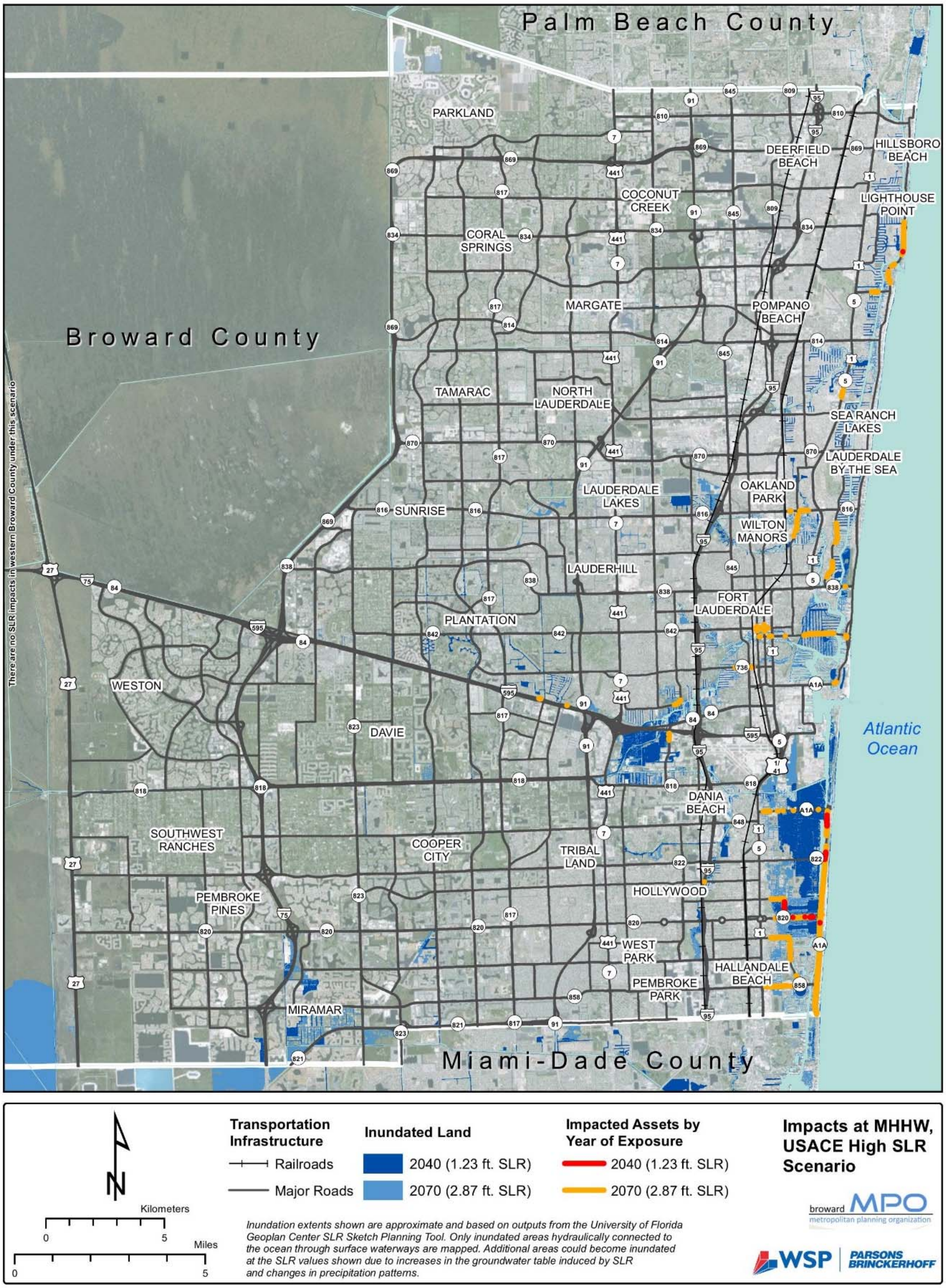
Figures 9 and 10 below show the results of the roadway inundation assessment for sea level rise. Figure 9 shows the estimated inundation areas for the IPCC Median Curve (9 inches and 19 inches of SLR for 2040 and 2070 respectively) and figure 10 shows the estimated inundation areas for the USACE high curve (15 inches of SLR in 2040 and 33 inches in 2070) It can be noted from these maps that there are certain roadways within the coastal zone that are expected to be inundated within the timeframe of transportation investments to 2070 and therefore would require action to address.

Figure 9 - County Inundated Roadways - Based on the IPCC Median Policy SLR Curve



Inundation extents shown are approximate and based on outputs from the University of Florida Geoplan Center SLR Sketch Planning Tool. Only inundated areas hydraulically connected to the ocean through surface waterways are mapped. Additional areas could become inundated at the SLR values shown due to increases in the groundwater table induced by SLR and changes in precipitation patterns.

Figure 10 - County Inundated Roadways - Based on USACE Policy Curve



Inundation extents shown are approximate and based on outputs from the University of Florida Geoplan Center SLR Sketch Planning Tool. Only inundated areas hydraulically connected to the ocean through surface waterways are mapped. Additional areas could become inundated at the SLR values shown due to increases in the groundwater table induced by SLR and changes in precipitation patterns.

The analysis of sea level rise risk has identified a need to raise roadway profiles for a number of county facilities to maintain an appropriate level of service free from regular inundation to 2040. A summary of the costs of adapting those roadways to address climate change is included in the next chapter of this report.

3.3.3 Combined Effects – Areas of Reduced Drainage Capacity

Increases in precipitation (should these predictions come true) would impact area roadways through increased and more regular localized flooding, a concern that could be potentially exacerbated by rising sea levels, which would reduce the capacity of the land and/or drainage infrastructure to process surface water effectively. Figure 11 illustrates potential flood conditions. Groundwater levels and sea levels are an interrelated system in south Florida where porous geology allows for water flow underground. An increase in sea levels would be expected to also increase groundwater levels, meaning that the surface water would have less capacity to infilltrate storm water. This would expect to increase the extent and duration of surface flooding during rain events.

Figure 11 - Conceptualized View of Drainage Capacity of the Land in Coastal Florida

The effect of sea level rise on groundwater is the subject of a study currently underway and being led by the United State Geological Survey (USGS). Draft results have been issued; however, the results have not yet been formally reviewed and/or adopted so the final results are not available for use. A recent presentation on the preliminary study results was presented to county officials.[6] The information presented by USGS is that, for various scenarios tested, the effects of sea level rise would be expected to be nearly 1:1 near the coastline in terms of sea level rise to water table rise, with the effects diminishing further inland depending on rainfall totals anticipated and also water system pumping capacity. The amount of land area with reduced drainage capacity and therefore

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[6] Decker, Potential for Increased Inundation in Flood Prone Regions of South Florida in Response to Climate and Sea-Level Changes in Broward County, FL, 2060-2069 (April, 2016)

increased anticipated local flooding of roadways during rainfall events would vary depending on the factors noted.

The implications for transportation system management and roadway design when considering future heavy precipitation events is that a series of response actions will need to be explored once the final results of the USGS study are determined and areas of concern are fully identified. Low-lying roadways near the coastline would need flood mitigation strategies, including raising roadway profiles and possible stormwater pumping to eliminate problematic local flooding and ensure transportation access. Pumping as a measure would have to be assessed carefully as some of these areas may be inundated constantly, and the ability of pumps to handle flooding in these areas would be very limited.

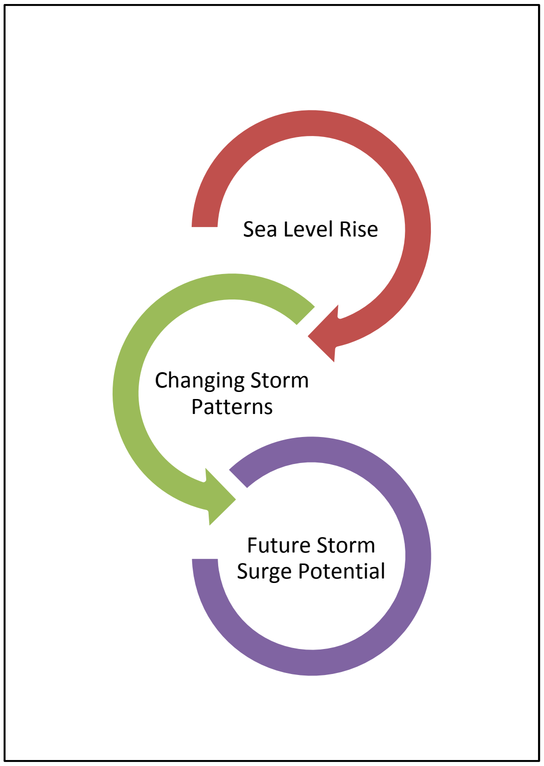
This concern will be an important consideration to include in future considerations for improving drainage and eliminating potential increases in localized flooding within the timeframe of the recommendations for this study. Later coordination on the conclusions of this study, and the potential design recommendations for transportation infrastructure are included in the strategies outlined in later project recommendations sections of this report.

3.4 STORM SURGE

3.4.1 Overview

The current risk of storm surge is traditionally defined by FEMA flood zones which help to identify areas of the county that have identified risk from storm flooding. This information is currently being updated by FEMA for the region to update the probabilities of return period events based on updated storm profiles and improved background data used in generating the understanding of risk (i.e. – more accurate elevation data, etc.). This effort is ongoing, with final results expected in 2019, but with preliminary products available starting in late 2016 and into early 2017[7]. FEMA data is, by definition, based on a statistical analysis of past storm events to define areas of relative risk for the state and is used to define the Flood Insurance Rate Map (FIRM) which affects property insurance rates in Monroe County. The development of data for that effort will include extended periods of review and comment, and there will be some interesting dialogue on the results.

Figure 12 - Climate Change and Future Storm Surge



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[7] http://www.southeastcoastalmaps.com/PublicDocs/Technical_Update_Meeting_Presentation_Monroe_3-15-16.pdf

There is an interest for the purposes of this study of determining future storm surge potential, rather than looking only at past events. Past research projects conducted in southeast Florida area have looked at historical storm events (like Hurricane Andrew) and the potential change in damage that could have resulted from higher sea levels during such events. Others have modeled multiple past events with sea level rise and determined the resulting impacts from these events on transportation infrastructure. These processes, however, are reliant on back-casted past events to predict the future, a future that has been theorized to be different on a number of fronts including variations in storm type and probability of occurrence.

Future storm surge potential should consider the implications of two changing elements of storm surge: 1) increasing sea levels, and 2) changing storm patterns. Researchers at the University of Florida (Peter Sheng and Vladimir A. Paramygin) in combination with other research institutions (Florida State and North Carolina State) have begun to develop a set of probabilistic models of future surge, which incorporate new probabilities for future storm events in the Atlantic Ocean combined with higher sea levels to generate an understanding of how the risks from surge may change over time given climate change. This approach to determining future risks – titled A Coastal Inundation and Decision Support System - is similar to work also underway in Massachusetts and the New York region among others where similar future-oriented multi-criteria models have been developed for use in identifying areas of potential concern for future conditions and to help facilitate decision-making.

The primary concern with increasing storm surge extent and water levels is the impact on the transportation system of such events. Table 3 below highlights how those transportation assets may be impacted by storm surge, enhanced through the effects of higher sea levels and changing storm patterns associated with climate change.

Table 3 - 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
Tunnels	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
Roadways / Rail	Pavement	Extended surge area inland, where pavement design would not likely have considered storm surge	Add anchoring during pavement rehabilitation cycles
Roadways / Rail	Embankments	Erosion of embankments - higher surge levels for structures where surge was considered and erosion effects in areas where surge was 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

Asset	Issue	Concern	Potential Action
Bridges	Foundation	Increase in flow and velocity undermining foundations through scour for bridges analyzed previously for scour	Add scour protection measures
Bridges	Foundation	Scour potential at bridges where surge was not previously considered, impact on erosion walls etc.	Add scour protection measures
Bridges	Approaches	Water flowing over approaches causing uplift and damaging approaches	Anchor or redesign approaches
Bridges	Approaches	Flowing water washes out approaches to bridges	Re-design approaches

Future storm surge models that are being generated through this research effort are only available in a few scenarios for consideration as the research process is ongoing. An available storm model was collected from the University of Florida researchers and the data was reviewed for the purposes of completing an initial review of the potential for increasing risks associated with climate change from this method. The storm model was developed assuming 1 foot of sea level rise to the year 2040, combined with a set of statistically analyzed storm options which reflect the changing storm patterns expected. Figure 13 below shows the initial results of that modeling effort in Broward County.

The effort conducted to determine future risks of flooding was completed using a statistical analysis technique that assessed multiple storm tracks and intensities to generate a set of probable future impacts. By applying this method - modeled storms that may start at the shoreline and cross at some point further inland would exhibit a higher probability in that inland area than in other areas where probable storm tracks did not overlap in the statistical analysis.

The model results then are not the result of one storm, but instead multiple storms analyzed to better define an understanding of future risk – with the results being identified areas of inundation and water levels associated with a future 100 year probability (1% in any given year) storm event. As this is not a single storm event the areas are not all contiguous and constant in their flooding as one would see from the outputs of running a single storm model.

The model was assessed for its applicability to Broward County and found to be a tool with good potential. The results are not yet focused enough to draw investment conclusions for individual assets but there is data coming on line that could be resolved for these purposes through additional study investment.

There are some design and policy considerations that can be assumed from the material already generated by this effort. Some of the concerns outlined include a set of risks to county assets. Considerations of bridges alone point to some of the increased risks to infrastructure from changing storm conditions. Those include:

- Bridges in coastal zones would likely be exposed to storms with higher water/wave energy than was anticipated in their original design.

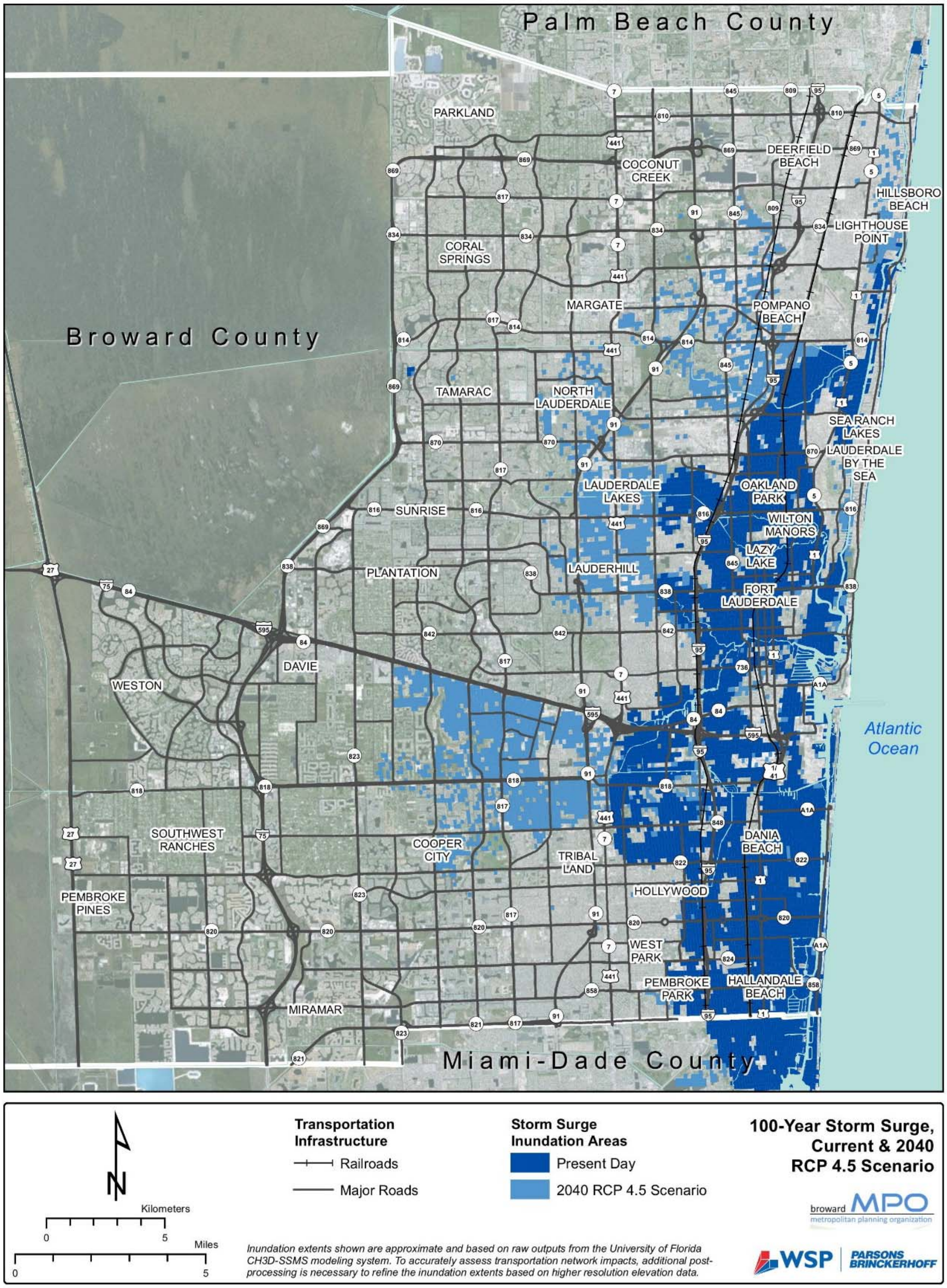
- Bridges that were built outside of currently identified FEMA zones may have been designed with potentially no assessment of surge/flooding risk and these bridges may now be in surge risk areas due to expanding future surge zones in the county.

Figure 13 below highlights the results of this storm modeling for Broward County for both current year 100 year return period exposure and 2040 1% return period exposure for the county. This map is shown for reference, as the final results would require the development of updated models to assess specific facility impacts and identify strategies that may be needed to provide required protections.

There are a few higher level conclusions that can be drawn from this analysis and the initial model results, including:

- There are potentially a larger number of transportation assets at risk currently from storm surge than may be indicated from current FEMA data
- The area exposed to a 1% probability of an event occurring potentially expands into the future, reflecting increasing water levels combined with changing assumptions for storms
- There is a dialogue that will need to occur county-wide on the implications of this potentially growing risk and how the increasing risks are incorporated into planning and design decision-making at the asset level

Figure 13 - Preliminary Data Depicting Areas of Increasing Risk from Storm Surge in Broward County



Inundation extents shown are approximate and based on raw outputs from the University of Florida CH3D-SSMS modeling system. To accurately assess transportation network impacts, additional post-processing is necessary to refine the inundation extents based on higher resolution elevation data.

4 Next Steps and Actions

Decision-making on transportation investments and climate change is a challenging exercise, one which requires consideration of uncertain future conditions and the effect of those events on the transportation system in order to make appropriate financial decisions. This section outlines the rationale and approach developed to identify the set of projects recommended at the conclusion of this report. The recommended strategies in this section are based on the followign guiding principles:

- Change is coming – the level of change is uncertain but actions need to be taken now to ensure that decisions made reflect this reality, investing now based on current practices ignores the changing conditions predicted for Broward County
- Transportation investments of today should be made to ensure viability to near the end of the century given the transporation project lifetimes
- The range of future scenarios requires consideration of what may be, how an investment may be made to address that future, and what the implications are of that decision if actions are taken to address that future
- Investments should be made to reduce potential risk over time and ensure the long term viability of the transportation system from long term change

4.1 Responding to a Changing Future

Climate change represents a different future than what has been observed in the past, a past that represents the data points on which current transportation planning and design decisions are made. South Florida is the subject of much research on the long-term implications of climate change and data is coming on-line to help define what the future may hold in the region, as well as the timeframe of change which will be important to final project decision-making.

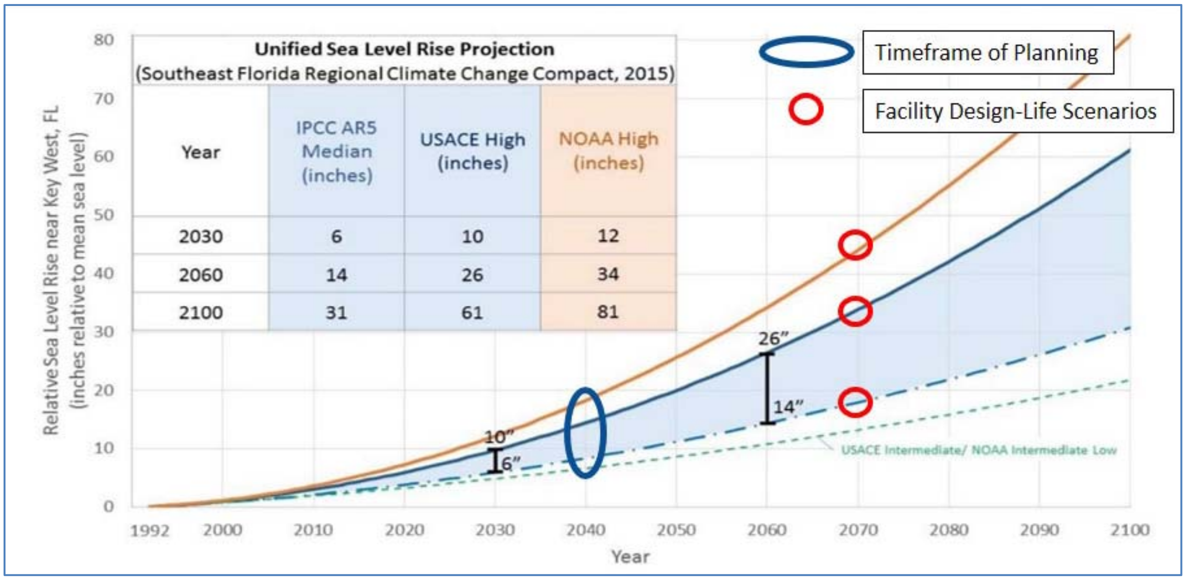
The findings of the data review outlined above and the potential areas of concern associated with changing climate conditions across the county point to the need for a perspective on investment for transportation facilities that looks at the implications of decisions through the lens of long-term change. The potential impacts are broad enough countywide and within the long timeframe of transportation investment decisions that there needs to be a programmatic shift in how facilities are planned, and designed. It is time to incorporate climate change into decision-making at all levels and for all projects.

There is work ahead to incorporate these changes into the business of transportation planning. Recommendations for how this gets implemented are in the following sections.

4.1.1 Policy Guidance on Investments

The Southeast Florida Regional Climate Change Compact has published material on incorporating sea level rise into project decision-making, identifying policies and associated sea level rise curves that are recommended for use on infrastructure projects. Figure 8 above identifies the sea level rise curves recommended for decision-making. The transition from policy to action for transportation project has fairly significant implications in terms of cost. That figure has been repeated below to highlight the challenge of making appropriate investment decisions.

Figure 14 - Facility Design Options for Sea Level Rise



Unified Sea Level Rise Projection
(Southeast Florida Regional Climate Change Compact, 2015)

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

Figure 14 above highlights some of the challenges associated with decision-making for transportation facilities. 2040 is a point 25 years into the future, and the identified timeframe of planning for the Broward MPO Commitment 2040 planning document and therefore the projects in that document will need to be assessed for climate change. There are also projects not in the plan that will need to be considered once the entirety of the universe of potential long-term exposure to the system is better defined.

Figure 14 also identifies an estimated end of a design-life for a facility designed today, approximately 50+ years into the future. So, the implications of design decisions made today will have implications depending on the sea level rise that occurs. As was outlined in sections above and clarified here, the decisions to be made need to incorporate the following:

- Projects assessed today need to consider the full lifetime of the asset, not just to a normal planning horizon.
- Planning needs to incorporate the implications of decisions as well as the rationale for the decision itself. In this case that would include:

- Designing to the NOAA high is not recommended in SFRCCC documents unless a facility will be in place beyond the end of the century, which may be the case for new bridges
- If the facility is designed to the USACE high scenario for 2070 and the IPPC median were to occur, the facility would be overbuilt to a time extending beyond the end of the century.
- Were the facility to be designed to the IPCC median scenario for 2070 and the USACE high scenario to occur, the facility would potentially be overtopped by 2050.

4.1.2 Estimating Costs for Raising Roadway Profiles to Address Sea Level Rise

To address those concerns outlined above, an exercise to develop the cost implications of addressing sea level rise in the county was completed. This method used the spatial data developed to generate Figures 9 and 10 to identify the inundation of Broward's network expected with the sea levels identified in the IPCC Median Curve and USACE High Curve to 2070. An approach to addressing these concerns was developed and applied to identify a level of funding that would be necessary to raise roadway profiles to be clear of flooding the roadway network for those roadways identified as inundated for any scenario in 2040. To accomplish this work, the following steps were taken:

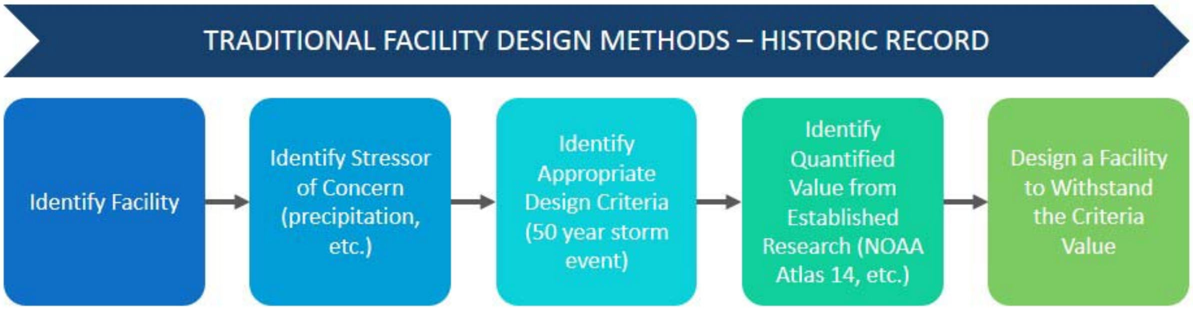
- Identify roadway areas expected to be inundated by 2040
- Raise the profile of the identified roadways, but design to 2070 IPCC curve – recognizing that roadway lifetimes will extend 50+ years into the future
- Expand horizontally along the road to a point which recognizes potential 2070 conditions, so that the total length adapted would be greater than 2040, and the heights would be suited for 2070 conditions

This method was chosen through a dialogue with roadway design engineers who indicated that it would be possible to re-construct a facility today so that it is adaptable to higher potential future water levels in the future. That future potential adaptation adds a greater level of flexibly to design by extending the life of raising the profile to the point where it may be inundated should a higher rate of sea level rise be the reality. The conclusion is that this method provides a response to sea level rise while also recognizing the decision-making needed given future uncertainties for sea level rise.

4.1.3 Risk-Based Design

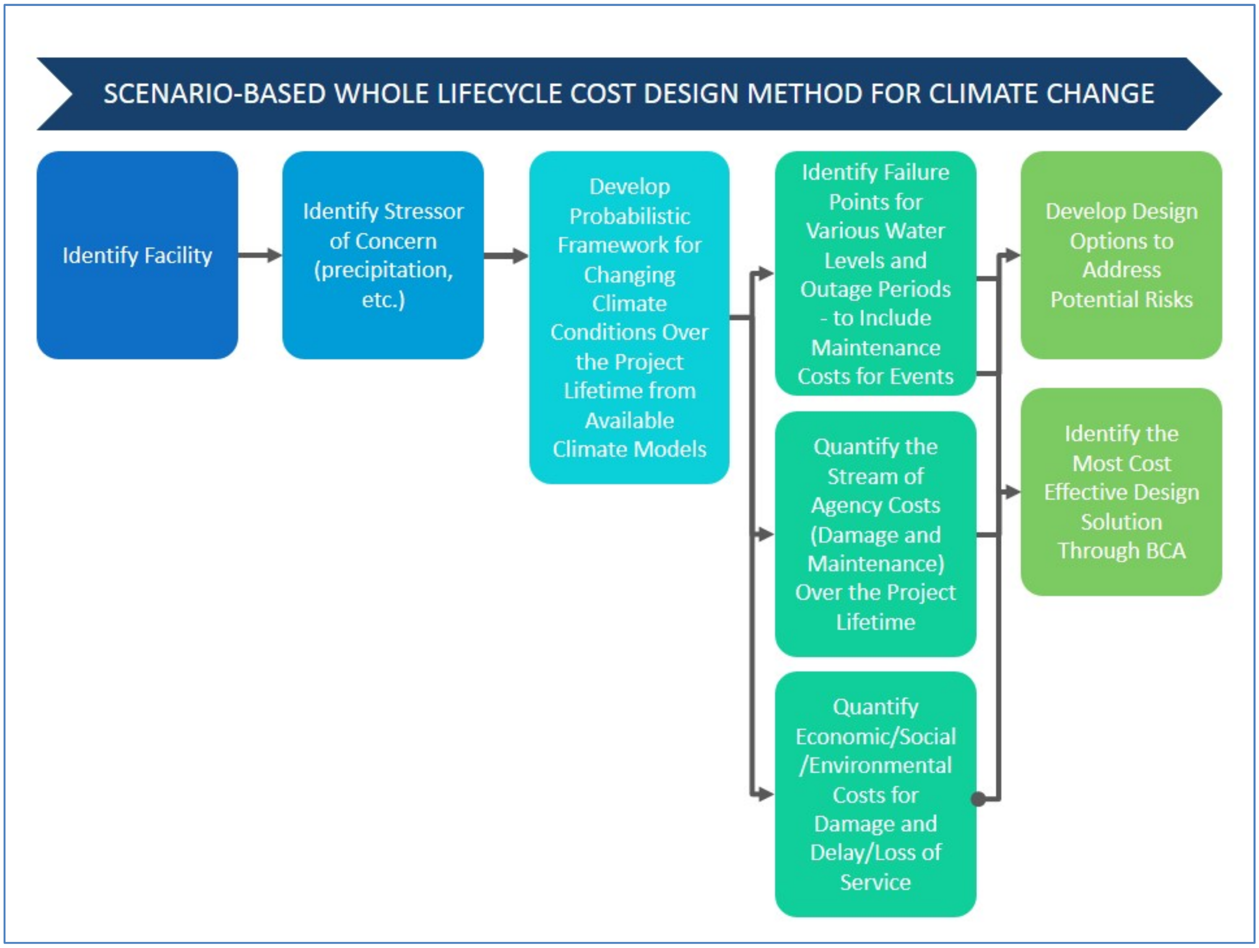
The policy based decisions outlined in the section above are one approach to determining the actions required to address climate change. There are also others which help quantify the implications of climate change for events (storm surge, etc) that may impact transportation infrastructure. Uncertainties in future climate data have resulted in the development of risk-based methods for facility design. These methods incorporate a design focus that moves away from traditional criteria-based design methods applied today and instead assess the long-term implications of climate change in terms of the implications of change over time and what implications those changes may have on transportation facilities and the customers that utilize them. Figure 15 below shows how designs are approached currently, while Figure 16 identifies how this method can be altered to incorporate climate change data and also risk-based design methods to facilitate a dialogue on how climate change may impact a facility over its lifetime. This method is a powerful tool to help guide decisions for facility design and is forwarded for implementation as a strong recommendation of this effort.

Figure 15 - Generalized Approach to Design - Current


TRADITIONAL FACILITY DESIGN METHODS – HISTORIC RECORD

Identify Facility → Identify Stressor of Concern (precipitation, etc.) → Identify Appropriate Design Criteria (50 year storm event) → Identify Quantified Value from Established Research (NOAA Atlas 14, etc.) → Design a Facility to Withstand the Criteria Value

Figure 16 - Recommended Risk-Based Decision Framework for Incorporating Climate Change into Facility Design



SCENARIO-BASED WHOLE LIFECYCLE COST DESIGN METHOD FOR CLIMATE CHANGE

Identify Facility

Identify Stressor of Concern (precipitation, etc.)

Develop Probabilistic Framework for Changing Climate Conditions Over the Project Lifetime from Available Climate Models

Identify Failure Points for Various Water Levels and Outage Periods - to Include Maintenance Costs for Events

Quantify the Stream of Agency Costs (Damage and Maintenance) Over the Project Lifetime

Quantify Economic/Social /Environmental Costs for Damage and Delay/Loss of Service

Develop Design Options to Address Potential Risks

Identify the Most Cost Effective Design Solution Through BCA

This method has the advantages of incorporating many of the guiding principles of good design by assessing the implications of damage and/or failure of an asset due to climate change and also the timing and possibility of the recurrence of the event that may trigger that damage or event. It also includes an assessment of the social/economic benefits of transportation facilities and includes those potential impacts as a part of the decision-making quantification. FHWA has been working for a few years in developing methods that incorporate long-term risks for transportation assets and can be incorporated into asset level decision-making in Broward[8].

4.2 Actions to Plan and Design for a Changing Future

The following recommnedations were developed from the work concluded for this study to higlight the set of actions that should be taken by the Broward MPO to incorporate climate change into system wide decision making in a way that is forward focused.

Response Actions:

Temperature

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[8] https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/teacr/

- Conduct a study of transit assets along the Tri-Rail system to define localized heat reducing strategies (plantings, etc) or a potential need for air conditioned facilities at stations given the expectation for increases in high heat days. Add air conditioned waiting areas in high use stations in the near term and lower use stations in the longer term.

- Assess transit infrastructure to determine rail neutral temperature applied and determine if rail kink risks may exist moving forward. Apply the new rail neutral temperature on all future rail installations.

- Assess potentially expanding needs for electrical suppies for the system and identify whether existing sources will be sufficient and/or resilient to increasing risks and plan accordingly if not. Develop a system for electrical service to address any system defficiences during high heat days or after storms to potentially include microgrids or other independent and redundant services

Precipitation

- Obtain FEMA analysis when completed and determine potentially expanding precipitation flooding damage on the system and any protection strategies and determine if any models developed would be available for planning and design

- Develop a precipitation based method for facility design that includes climate change and follows the outlined noted in Section 4.1.3 above.

- Re-size all culverts and bridges to accommodate higher potential water flows during regular maintenance and replacment activities.

Storm Surge

- Fund a more complete study of long-term combined surge potential of the system to determine risks using models which incorporate sea level rise and also future storm scenarios. Identify a set of actions to take immediately for Tier 1 assets to ensure long term resiliency and develop a set of prioritized strategies for Tier 2 assets. The set of improvements for Tier 1 and 2 assets should be included in the next update to the LRTP.

- Retrofit Bridges, the New River tunnel, and roadways in wave zones to withstand increasing surge potential and protect critical infrastructure

- Design all new facilities to a new future surge standard.

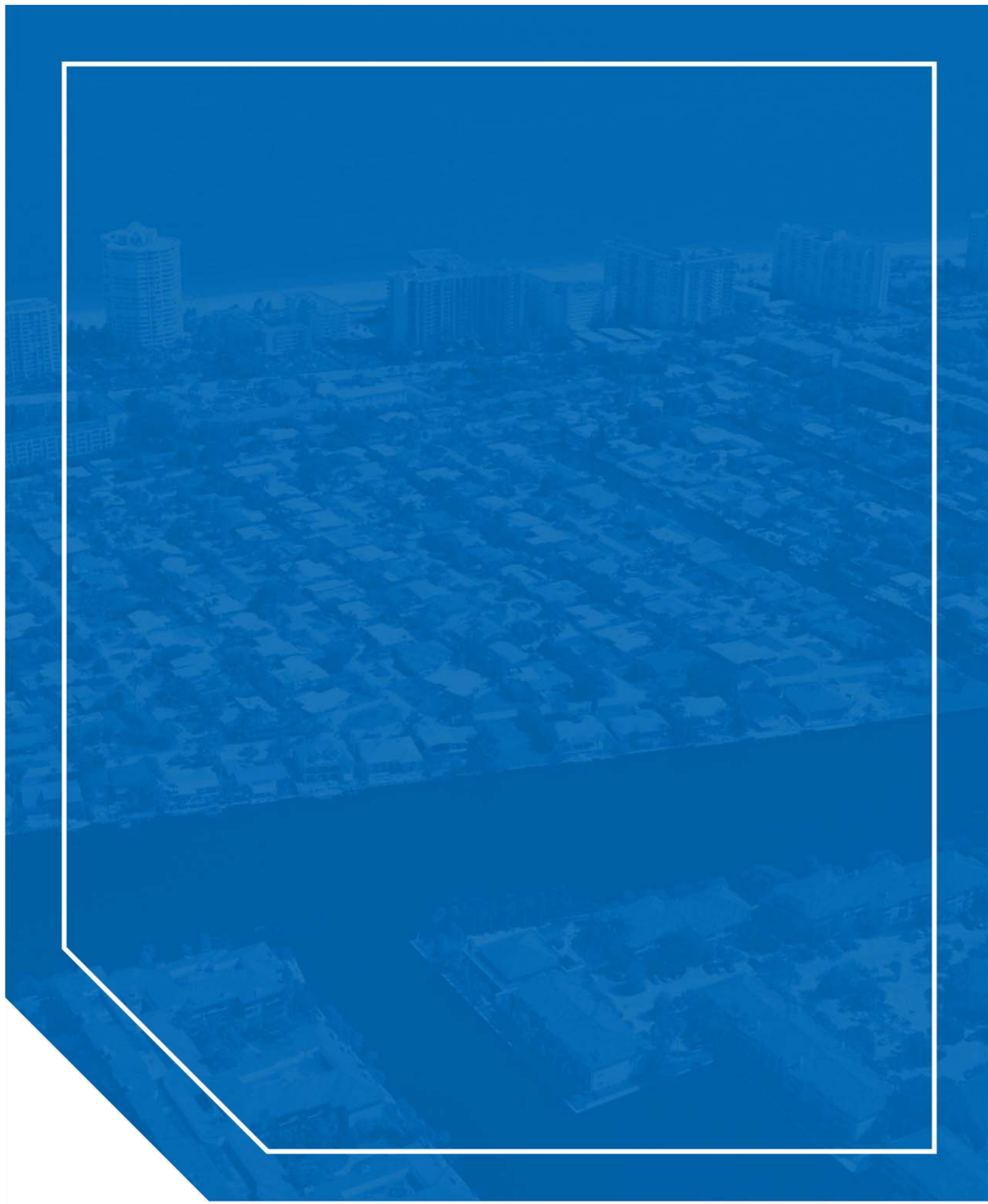
Sea Level Rise

- Raise the roadway profile for approximately 2+ miles of roadway expected to be innundated by sea level rise to 2040 and identified in Figure 10. Elevated these roadways to raise them above the future innundation areas identified for 2070. Elevate to the 2070 IPCC curve to provide long-term viabilty for the system while also providng a change to adapt, and not to overbuild. The cost estimate for this work is between $43 and $48 miillon dollars.

- At the conclusion of the USGS study on water table effects - conduct a study in the area to the east of the county to assess raising the roadway profiles to ensure an appropriate level of service during heavy rain events, particularly for Tier 1 and 2 roadways lower than approximately 3 feet in elevation (NAVD 88) east of the flood control structures. Raise all Tier 1 and 2 roadways in the identified effected areas to limit localized precipitation induced flooding and maintain a travel level of service

Programmatic

- Utilize a risk-based design method as outline in 4.1.3 above for all infrastructure projects moving forward, which utilizes an assessment of future risk (flood levels, SLR) as a measure of transportation investment effectiveness.
- Apply a risk-based design method on all master planned projects identified in at various risk areas from the analysis above
- Establish a county-wide design policy which requires future climate change considerations as a part of all system design and maintenance activities.



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