Broward MPO
Metropolitan Planning Organization


Tidal flooding along Las Olas Boulevard in Fort Lauderdale. Source: Floydphoto / Wikimedia Commons.

Resilience Analysis Methodology Technical Memo

June 2022

CONTENTS

Introduction

This memo summarizes the recommendations related to adopting and carrying out the resilience analysis methodology developed for the Broward MPO (MPO). This is part of the Transportation Resiliency Framework Study (Framework Study), the MPO's larger efforts to assess and respond to the long-term risks to transportation infrastructure from climate change. The study effort was conducted to provide a framework that the Broward MPO could apply to systematically identify, assess, and respond to risks to transportation-related infrastructure.

This study effort builds upon the 2015 FHWA South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project (Pilot Project)[1] and the 2016 Extreme Weather and Climate Change Risk to the Transportation System in Broward County Florida (Second Phase Study)[2]. The Pilot Project examined approaches to conduct climate change and extreme weather vulnerability assessments of transportation infrastructure from sea level rise, storm surge and heavy precipitation-induced flooding, and to analyze options for adapting and improving resiliency. The Second Phase Study performed more detailed analysis on the initial stressors and included the effects of climate change on temperature and how changes in temperature affect transportation infrastructure.

Expanding on the findings of these two studies, the MPO is conducting this study to further enhance its Transportation Resiliency Framework to identify and address network vulnerabilities from climate change, and to support incorporation of preparedness into project planning, design, and construction. Prior to this study, the Framework primarily focused on physical transportation infrastructure. This study expands on prior efforts and applies a system-level approach that considers surrounding area and communities. This approach considers how these surrounding communities can have an impact on potential risks and resilience improvements. In addition to considering the identified stressors (i.e., sea level rise, storm surge, precipitation, and temperature), this study also addresses programmatic concerns. Programmatic considerations describe project sponsors' institutional capabilities and data availability in areas such as methodologies, policies, procedures, data availability and quality, and resource capacity.

As part of the overall Transportation Resiliency Framework, this study establishes a nine-step iterative methodology that goes from stressor selection in the first step through to the development of program-ready projects in the last step. In addition, this study establishes a Resiliency Toolbox (Toolbox) that contains a listing of potential adaptation strategies based on identified stressors (i.e., precipitation, temperature, storm surge, sea level rise and programmatic), potential risks (e.g., inundation / flooding, erosion, extreme heat, high

[1] Dorney et al. South Florida Climate Change Vulnerability Assessment and Adaptation Pilot. Broward MPO and FHWA. 2015.
[2] WSP | Parsons Brinckerhoff. Extreme Weather and Climate Change Risk to the Transportation System in Broward County Florida. Broward MPO. 2016.

water table,) and hazard / infrastructure impacts (e.g., slope failure, closures, asset degradation). Outputs of this study intend to inform and enhance the Transportation Resiliency Framework, support the incorporation of resiliency into the MPO's 2050 Metropolitan Transportation Plan, and set a foundation for future efforts to identify problem areas and incorporate resilience into decision making.

Glossary

Resilience-related terms can have many meanings depending on their context. For purpose of this study, common definitions for key terms are provided below.

- **Adaptation**: Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.
- **Climate Change**: Any significant change in the measures of climate lasting for an extended period such as major variations in temperature, precipitation, wind patterns, sea level or increased frequency and magnitude of extreme weather events.
- **Climate/Weather Risk**: The potential for negative consequences where something of value is at stake. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard (e.g., inundation/flooding, higher stream volumes)
- **Coastal Flooding and Erosion**: Coastal flooding refers to any type of flooding that is generated from the ocean or other tidally connected waterbodies, as opposed to inland flooding caused by rain or coming from rivers. The most severe form of coastal flooding is storm surge, which is the rise in water levels caused by a storm's strong winds and low atmospheric pressure. With increased flooding and storm surge, this can erode shorelines and damage associated infrastructure assets.
- **Community Resilience**: The ability of a community to prepare for anticipated natural hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions.
- **Criticality:** The FHWA states that defining criticality of an asset depends both on its physical characteristics (e.g., replacement value) and on its function in multiple systems (e.g., emergency evacuation route, key commercial route, level of activity, value of freight carried). One of the challenges that agencies face during the criticality assessment is defining assets and determining which auxiliary systems to include in the analysis.
- **Environmental Justice**: The fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the

development, implementation, and enforcement of environmental laws, regulations, and policies.

- **Hazards/Infrastructure Impacts**: An event or condition that may cause injury, illness, or death to people or damage to assets (e.g., roadway slope failures, washouts)
- **Inland Flooding**: Also known as "urban flooding" or "flash flooding," can be caused by intense, short-term rain or by moderate rainfall over several days that can overwhelm existing drainage infrastructure.
- **Programmatic Considerations**: Describe project sponsors' institutional capabilities and data availability in areas such as methodologies, policies, procedures, data availability and quality, and resource capacity. Necessary inputs, processes, and resources are required to properly carry out the standard resilience analysis methodology.
- **Proxy indicators**: A location or collection of locations that has experienced frequent, negative weather-related impacts and / or is projected to experience negative climate change-related impacts. Provides a data-driven method to identify locations susceptible to the negative impacts of climate and weather-related risks.
- **Resilience**: Defined by FHWA as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.
- **Social Vulnerability**: Broadly defined as the susceptibility of social groups to the adverse impacts of natural hazards, including disproportionate death, injury, loss, or disruption of livelihood. Considers the social, economic, demographic, and housing characteristics of a community that influence its ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards.
- **Stressor:** A condition, event, or trend related to climate variability and change that can exacerbate hazards (e.g., precipitation).

Standard Resilience Analysis Methodology

The focus of this study effort is limited to four stressors (i.e., precipitation, temperature, storm surge, and sea level rise) that build upon work completed in the 2015 Pilot Project, and the 2016 Second Phase Study. This study provides a multi-step, iterative resilience analysis methodology that ultimately supports the identification of program-ready projects. While the Pilot Project and Second Phase Study focused primarily on sea level rise and storm surge, this study provides further analysis of temperature and precipitation, and also addresses programmatic concerns. Over time, additional stressors can be considered for inclusion as part of this analysis methodology.

The developed resilience analysis methodology is flexible and repeatable. A graphic representing the methodology is depicted in Figure 1 below. It can be applied to any geographic area and subset of infrastructure, considering physical transportation infrastructure, as well as social and community infrastructure. For purposes of this study, the resilience analysis methodology was applied to the eight (8) Priority Corridors previously identified in the 2045 MTP. A map of the corridors is shown in Figure 2.Figure 1 Figure 2That said, the resilience analysis methodology is intended to support the planning process for the 2050 MTP, and is therefore envisioned to analyze additional study areas at that time.

Figure 1 presents the 9-step methodology for conducting a resilience assessment methodology. As depicted in Figure 1, stakeholder engagement (e.g., agency staff from different areas, municipalities, state and local agencies, asset owners both public and private, advocacy and interest groups, etc.) and communication and collaboration is a component through all the 9 steps in the process.

Figure 1 – Standard Resilience Analysis Methodology

Figure 2 – Priority Corridors Identified in 2045 MTP

Step 1. Selection of Stressors

In this step, the most applicable of the four stressors are identified and selected. Selection of stressors can be based on historical events and trends, as well as future climate change projections for particular areas, or locations that might affect the agency or community infrastructure and/or operations. In addition, stakeholder engagement and collaboration are key to identify and prioritize stressors that need to be addressed in the analysis.

Due to its geographical location, Southeast Florida is one of the most vulnerable areas of the country to extreme weather conditions and climate change. In addition, its low elevation makes it susceptible to inundation and flooding from heavy rain events, storm surge, and sea level rise. Moreover, the region also experiences high temperatures that are projected to increase in the future with climate change.

Southeast Florida has been the focus of multiple studies related to extreme weather and climate change. The Second Phase Study identified four stressors that the MPO should focus its efforts on to better understand the impacts, and respond to climate / weather risks ("risks") and hazards. Those four stressors include precipitation, temperature, storm surge, and sea level rise; however, given that our understanding of climate change science is constantly evolving, the list of stressors may expand in the future, as the state of climate change science evolves.

A brief description of each of the four stressors as addressed in the current state of the resilience analysis methodology is provided below.

- **Precipitation**: In the context of climate change precipitation is generally understood to be a *substantial deviation in average precipitation levels*. However, significant precipitation events (e.g., individual storms) are another form of the precipitation stressor.
    - Scenarios related to this stressor can communicate these deviations as “a change in the annual maximum precipitation to X” but the same can be quantified by a specific season or period of the year. Alternatively, or often in concert, scenarios can communicate a change in the “number of dry days” either over a full year or other period.
    - In the context of Broward County, the precipitation stressor can result in risks associated with greater than average seasonal precipitation and / or greater precipitation in individual weather systems (including large precipitation events in typically drier seasons).
- **Temperature**: In the context of climate change temperature is generally understood to be an *increase in average temperatures*. However, significant temperature swings in a short period of time are another form of the temperature stressor.
    - Scenarios related to this stressor can communicate these increases as “an increase in average temperatures of X to Y degrees” by a certain year or within a specified period as “an additional X 95+ degree days” by a certain year or within a specified period, or more simply as “summer temperatures will be X degrees on average (or X% higher than current averages)” by a certain year or within a specified period.
    - For Broward County the temperature stressors can result in risk associated with higher maximum temperatures, higher seasonal temperatures, or longer and/or hotter heat waves. There may also be an increased range between short-term (i.e., daily) min and max temperatures.
- **Storm Surge**: In the context of climate change storm surge is generally understood to be a *flooding event associated with a weather system*. Furthermore, this stressor is heavily related to sea level rise and other stressors such as changing weather patterns.
    - Data related to this stressor typically rely on advanced modeling performed by agencies such as the National Oceanic and Atmospheric Administration

(NOAA). These models, and their underlying data, are constantly evolving. There is a strong relationship with future sea level rise and changing weather patterns in order to determine future storm surge probabilities.

  - Potential risks from storm surge include water rising over barriers or beyond prior expected limits, water not draining due to elevated tidal events, water present due to lack of general barriers / drainage infrastructure, and wave battering.
  - In comparison to the other stressors, Broward has the most consistent and specific data related to storm surge and sea level rise.

- **Sea Level Rise (SLR)**: In the context of climate change sea level rise is generally understood to be an *increase in the rise of sea water levels* either on or offshore, which can take the form of higher mean high-water marks and rising water tables, as well as the tidal effects associated with both.
  - Scenarios related to this stressor can communicate these increases as “an increase in sea levels of X to Y inches” by a certain year or over a specified period.
  - Rising sea levels may present risks due to inundation, erosion, and a higher water table, including increased salinity of the water table. Over time sea level rise raises the height of tidal systems, worsening the impacts of high tide flooding, which also referred to as nuisance flooding, sunny-day flooding, or king tide flooding. High tide flooding brings unusually high water levels and can result in localized tidal flooding.
  - In comparison to the other stressors, Broward has the most consistent and specific data related to storm surge and sea level rise.

At this stage one or more, or all, of the four stressors could be selected. Once the stressors are identified, it is important to collect the most up to date climate, or other stressor-related data from reliable sources. This data helps to identify particular areas of concern (e.g., SLR and storm surge maps) for more detailed studies, and identification of potential risks.

Based on previous studies, the most consistent and specific stressor data and maps available for Broward County are related to SLR and storm surge. Other data sources and data, as well as mapping of these stressors, are being gathered and developed as needed.

Step 2. Identification of Climate / Weather Risks

This step identifies potential risks that are attributable to the stressor(s) selected in the first step. Based on a review of relevant literature, namely the Pilot Project and Second Phase Study, eight (8) key risks were identified, some of which are associated with more than one stressor. The risks include erosion, extreme heat, temperature swings, high water table, increased water flow, inundation / flooding, overtopping, and tidal effects. In certain instances, a risk that may be associated with more than one stressor may arise from different sources; for example, erosion can arise from inundation / flooding events or tidal effects in addition to general contributors to erosion.

The Resiliency Toolbox developed as part of this study categorizes potential adaptation strategies according to particular stressor(s), risk types and sources, potential hazards / impacts to physical infrastructure, and potential asset types (e.g., roadways, drainage systems, bridges, culverts, railway infrastructure, etc.). Thus, it is important to identify potential risk types, sources, and their associated hazards / infrastructure impacts since these parameters will inform the potential adaptation strategies. A brief description of each of the eight climate / weather risks is provided below.

- **Erosion**: Describes the geological process in which earthen materials are worn away and transported by natural forces such as wind or water. Erosion can have multiple causes. The three primary sources of erosion considered in this analysis include water erosion over land, coastal erosion due to the wind and water effects of sea level rise and changing storm paths, and tidal effects that may transport physical materials in sediments that erode coasts with the ebb and flow of ocean water.
- **Environmental Justice**: Describes the fair treatment and meaningful involvement of all people with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.
- **Environmental Justice Community**: A community that is most harmed or impacted by environmental harms and risks, and thus merits greater attention during the assessment of project impacts.
- **Extreme Heat**: Weather that is much hotter than average for a particular time and place, and potentially more humid too. Thresholds to define extreme heat vary based on location and time of year. Extreme heat can melt asphalt on roads and airport tarmacs, and lead to rail track buckling, overhead line sag, and speed restrictions.
- **Temperature Swings**: Increased ranges between maximum high and low temperatures that can occur over various temporal scales from daily (diurnal), to monthly, seasonally, or annually. Greater diurnal temperature ranges are a particular concern as they can result in exceedances of material design tolerances.
- **High Water Table**: The water table is the boundary between the unsaturated zone and the saturated zone underground. Below the water table groundwater fills any spaces between sediments and within rock. Water tables become elevated, or high, when they receive more water than they drain off. This phenomenon can have causes such as unusually high amounts of rainfall, seasonal changes, and landward intrusions of seawater due to sea level rise in coastal areas.

- **Increased Water Flow**: Increases in water flow velocity and / or volume due to the effects of acute events (i.e., flash floods and other high-volume, short-duration precipitation events).
- **Inundation / Flooding**: Occurs when water inundates land that is normally dry. This can occur to due to a number of factors such as excessive rain or a ruptured dam, levee, seawall, or other protective barrier.
- **Overtopping**: In coastal areas this occurs when an extreme coastal water level exceeds the maximum coast elevation of protective infrastructure such as dunes, dykes, cliffs, levees, seawalls, etc. This can result in protection failure.
- **Tidal Effects**: Refers to the effects of high tide flooding due to factors such as sea level rise, land subsidence, and the loss of natural barriers. Over time the height of tidal systems can increase, resulting in high tides reaching higher and extending further inland.

Since climate change science is constantly evolving, it is expected that the list of risks will expand further, as well as their relationship to the stressors. It is recommended that the list of potential risks is discussed and revised as needed.

Step 3. Establishment of Impacts

This step describes a holistic approach to establishing a broader, influence area where impacts to not only affected transportation facilities, but also impacts to social and community infrastructure are established. The Florida Division of Emergency Management has prepared detailed grid maps that are utilized by the National Guard, US Coast Guard, and the military when they are deployed in the State for emergency, search and rescue, and other activities[3]. These maps capture emergency operations centers, emergency services, correctional facilities, educational facilities, community resources, hospitals, healthcare facilities, communications infrastructure, mobile home / recreational vehicle parks, energy infrastructure, dams, water / wastewater facilities, shelters, transportation infrastructure, logistics muster points, and military facilities.

Climate and weather risks rarely impact a study area in isolation, therefore impacts to nearby physical infrastructure assets should also be considered. The aforementioned Division of Emergency Management grid maps are prepared at the county level and can serve as a starting point when establishing the influence area. Performing geospatial analysis and preparing maps for the selected stressor(s) and associated risks supports the identification of a broader influence area of study. In addition to transportation facilities that are directly impacted, this approach helps to identify risks to other types of infrastructure that serve the community (e.g., golf courses, parks, recreational facilities, trailways, etc.) that might also be vulnerable to the identified stressors and risks.

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[3] Florida Division of Emergency Management. US National Grid (USNG) Map Books. https://maps.floridadisaster.org/mapbooks/

This system-level analysis provides a more comprehensive view of impacts to a various types of physical infrastructure assets. Key hazards / impacts are identified, many of which are associated with more than one climate / weather risk. Climate stressors and their related risks can result in a multitude of negative impacts on physical infrastructure. These include, but are not limited to:

- **Temporary Asset Failure**: Refers to an asset that fails for a short period of time but can later return to service.
- **Asset Loss or Permanent Failure**: Instances where an asset is catastrophically damaged or fails such that it can no longer function as intended.
- **Accelerated Asset Deterioration**: Climate and weather risks can result in rates of deterioration of assets that are greater than the original design assumptions. Results of accelerated asset deterioration vary by asset class but can include pavement rutting, cracking, or potholes; foundation erosion or scour in structures; and reduced asset life due to extreme temperatures.
- **Mobility Impacts**: Temporary or permanent system disruptions or closure may result from climate or weather-related risks. Detours and / or evacuations may also occur.
- **Safety Impacts**: Weather conditions may cause hazardous travel conditions (e.g., reduced visibility, inundated roadways, high winds, etc.) that result in increased crashes.

In addition to impacts to physical infrastructure, climate and weather-related risks can affect social vulnerability and community resilience. A screening of social vulnerability and community resilience should be performed for the identified influence area. The influence area Leading state-of-the-practice tools to support this type of analysis include the Federal Emergency Management Agency (FEMA) National Risk Index (NRI)[4]. The NRI utilizes the Social Vulnerability Index (SoVI), and the Community Resilience Index (BRIC) along with Expected Annual Losses to the community from multiple threats. The SoVI was developed by the University of South Carolina's (USC) Hazards Vulnerability and Resilience Institute[5] (HVRI). SoVI provides a location-specific assessment of social vulnerability that utilizes 29 socioeconomic variables deemed to contribute to a community's reduced ability to prepare for, respond to, and recover from hazards.

A screening of community resilience should also be performed to assess the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to the impacts of climate change. The NRI calculates community resilience, which ranges from very low to very high, based on USC's HVRI Baseline Resilience Indicators for

[4] FEMA National Risk Index. https://hazards.fema.gov/nri/ National Risk Index Technical Documentation. November 2021.

[5] HVRI. https://artsandsciences.sc.edu/geog/hvri/sovi-data

Communities (BRIC). BRIC is based on dataset that includes 49 indicators representing six types of resilience: social, economic, community capital, institutional capacity, housing / infrastructure, and environmental. Community engagement and consultation with stakeholder groups can be part of the process to validate the potential impacts to social infrastructure, and to review community resilience. The FEMA website for the National Risk Index Natural Hazards provides guidance on the use of the NRI online mapping application. Figure 3 provides and overview of the SoVI and Community Resilience (BRIC) Indices from the FEMA NRI site for Southeast Florida.

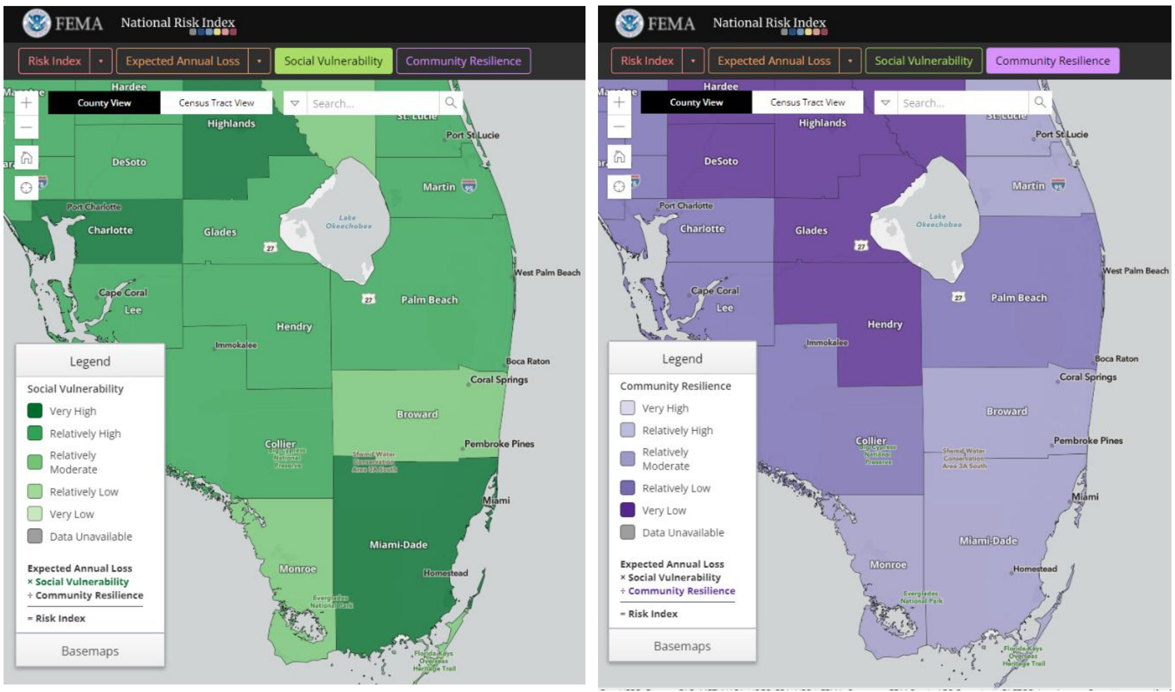

Figure 3- SoVI and Community Resilience Indices for Southeast Florida from FEMA NRI Website

The use of these type of social vulnerability and community resilience indices can help to identify assets located in underserved communities, or communities with a low capacity to recover from hazards or catastrophic events. Some agencies have used these indices as part of a criteria to estimate the criticality of their assets or corridors. Colorado DOT[6] developed a criticality model using SoVI as one of their criteria as shown in Figure 4.

[6] CDOT Risk and Resilience Analysis Procedure. https://www.codot.gov/programs/planning/assets/cdot-rnr-analysis-procedure-8-4-2020-v6.pdf

Criteria	1 Very Low	2 Low	3 Moderate	4 High	5 Very High
AADT	≤ 720	721 - 1,900	1,901 - 4,600	4,601 - 15,000	≥ 15,000
AASHTO Functional Class	Minor Collectors	Major Collectors	Minor Arterial	Principal Arterial	Interstate Freeway Expressway
Freight ($ Millions)	≤ 4,422	6,423 - 6,513	6,514 - 6,685	6,686, - 8,806	≥ 8,806
Tourism ($ Millions)	≤ 152	153 - 479	480 - 1,050	1,051 - 3,414	≥ 3,414
SoVI®	≤ (-2.93)	(-2.92) - (-1.24)	(-1.23) - 0.67	0.68 - 2.51	≥ 2.52
Redundancy	≥ 4.5	3.01 - 4.5	2.01 - 3	1.51 - 2.0	≤ 1.0

Figure 4- Use of SoVI as criteria for CDOT Roadway Criticality Model

Collectively, there are numerous, interrelated direct and indirect impacts on infrastructure that may result from climate and weather risks. As depicted in Figure 5Figure 5, a singular climate or weather-related risk may result in a multitude of hazards, a number of impacts, and ultimately, increased direct and indirect social and economic costs. Figure 5 is illustrative in nature and intends to convey that the hazards, impacts, and costs that downstream from one or more climate / weather risks are numerous. As part of a Benefit Cost Analysis (BCA), determination of costs, such as the illustrative costs in Figure 5, often need to be derived from and linked to the source(s) of the risk(s) associated with the impact. Ultimately, these types of negative impacts can have adverse effects on safety and economic development. A better understanding of the negative impacts associated with climate and weather-related risks can allow for the identification, prioritization, and development of strategies and actions to increase the resilience of infrastructure.

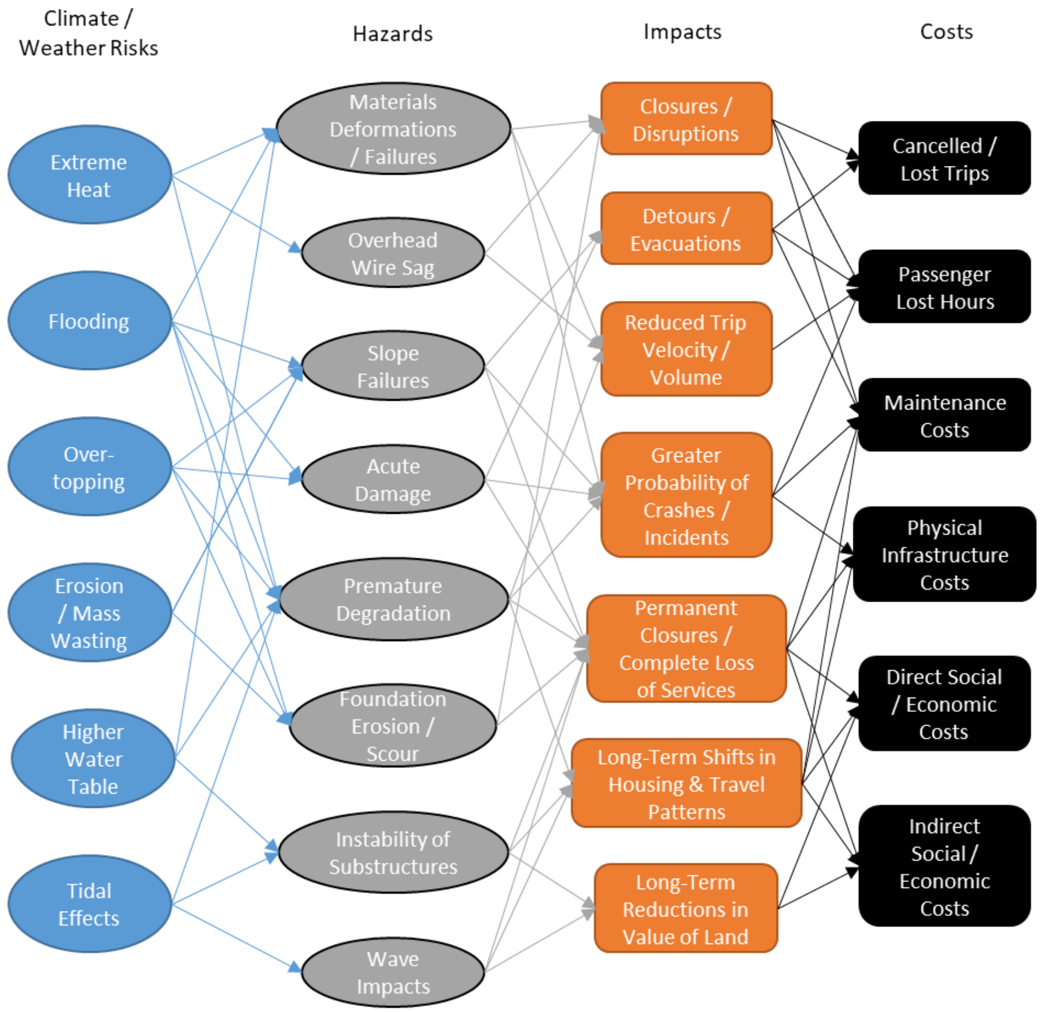

Figure 5 – Illustrative Aggregation of Impacts of Climate / Weather Risks on Infrastructure

Step 4. Identification of Proxy Indicators

Step four provides important foundational data that supports linking climate stressors and their risks, to hazards and through to potential negative impacts. Historical climate and weather-related impact data at a location or collection of locations is required to provide a data-driven means of identifying locations susceptible to the negative impacts of climate and weather-related risks, e.g., repeated flooding or drainage issues, repeated materials deformation due to heat stress, repeated overtopping of flood protection, etc. Proxy indicators can serve as possible root causes of negative impacts to systems and assets. This requires an understanding of the relationship between climate stressors, risks, hazards, and impacts. It is also contingent on the availability of historical weather-related incident data in addition to climate change projection data.

Oftentimes, geospatial analysis is an effective tool in the identification of locations that experience frequent weather-related impacts, and that may be susceptible to projected future climate change impacts. Over time, proxy indicator data should be collated in a geodatabase to identify, and catalogue locations that experience repeated weather-related incidents. Available geospatial datasets can be leveraged to support the identification of:

- Locations within known flood / surge / hazard zones
- Low crossings / links in transportation network
- Projected temperature and / or precipitation change by 2050 and beyond
- Locations with known previous incidents
- Historical flooding, overtopping, erosion, embankment / slope failure, power loss to critical systems, etc.
- Soil hydrology considering water table / tidal effects in 2050 and beyond

A number of datasets can be used to identify proxy indicators. Communication and coordination with the identified stakeholder group can enable the identification of relevant datasets.

Step 5. Identification of Physical Assets at Risk

Building upon the influence area established in step three, impacts to a broader set of assets beyond transportation facilities should be considered. This should also include infrastructure that serves the community (e.g., golf courses, parks, recreational facilities, trailways, etc.) as part of a broader influence area. For the geographic area that comprises the influence area, physical assets at risk can be identified based on the selected stressor(s), hazard(s), potential negative impact(s), and identified proxy indicators. The focus of this study effort is the identification of transportation assets at risk. These assets may include but are not limited to:

- Bridges
- Culverts
- ITS Infrastructure (e.g., cameras, variable message signs, detection devices / sensors; network backbone – hubs and nodes, fiber, cabinets; etc.)
- Traffic Control Devices (e.g., traffic boxes, light poles, signals, signs, etc.)
- Pavements
- Rail
- Others (e.g., bike / ped and transit infrastructure, tunnels, seawalls, parks and rec infrastructure, signs, traffic barriers, etc.)

Beyond transportation infrastructure assets at risk, additional, non-infrastructure types of assets should also be identified within the study area. For example, residential and commercial properties that are near a vulnerable facility may face impacts form the climate stressors or by enhancements. In contrast, parks, golf courses, and other permeable greenspaces face different challenges and could serve as temporary locations for excess water. The identified stakeholder group should be consulted when identifying assets at risk and those non-infrastructure assets that could also be considered in the analysis.

Step 6. Performance of Root Cause Analysis

Root cause analysis describes the evaluation of a system or asset's lifecycle stages to determine the factors directly contributing to the negative impact to the system or asset, i.e., identifying what the true cause of the negative impact is and why the negative impact is occurring. For example, flooding may not be caused by sea level rise in a particular geographic area, but rather by local low points and / or other drainage issues; increases in precipitation may not lead to decreases in embankment / slope stability in all cases. Root cause analysis builds upon the identification of proxy indicators, which can serve as possible root causes of negative impacts to systems and assets. Thus, the root cause analysis validates a potential linkage from climate stressors and their risks to hazards and potential negative impacts.

Root cause analysis should consider different stages of the asset lifecycle from planning and design / engineering to maintenance and operations. Working backwards from the negative impact to the system and / or asset can help identify the problems within particular systems / assets, allowing for the identification of specific mitigation strategies to address the problem. For example, frequent flooding at a particular location may be a result of inadequate maintenance and insufficient cleaning of catch basins / inlets / outlets. It could also be the case that the original design's hydraulic capacity is no longer sufficient for current conditions. The flooding may also be caused by upstream discharges that are new and / or have increased in volume from the original design. Root cause analysis may require detailed engineering studies and / or further research. In certain instances, a probabilistic analysis and risk-based engineering effort may be required to determine the most cost effective, performance-based design alternative.

Traditional engineering design is performed according to deterministic assessments and standard general codes. Deterministic design approaches are generally based on a fixed value, e.g., loading condition, according to historical conditions and / or safety factors, e.g., one and a half times typical static load, required in traditional design approaches. While quick and efficient, use of standard general codes can be costly when considering strengthening or rehabilitation projects of existing structures. A probabilistic approach entails statistical modeling of load and resistance parameters obtained through on-site measurements, as-built drawings, and structural health monitoring information where available. A specific probabilistic assessment will result in the determination of a formal probability of failure, which can then be compared to code and legal requirements to demonstrate that the calculated probability of failure exceeds the requirements. The application of probabilistic methods has been shown to provide significant cost savings in both direct and indirect costs associated with structural rehabilitation and replacement[7].

Probabilistic design approaches are typically betters suited to longer-lived assets, i.e., those with a design life of 75 years or more, such as a bridge. As long-life infrastructure assets continue to age and environmental and loading conditions (i.e., both live loading, extreme weather event-induced loading, and long-term, climate-induced loading) evolve, infrastructure owners and managers are increasingly turning to probabilistic methods. Once a deterministic assessment has resulted in a repair / rehabilitate / replace scenario, probabilistic methods can provide substantial cost savings while still fulfilling safety requirements. The probability-based assessment of the Bergeforsen Railway Bridge in Sweden provides an example of how probability-based assessment of a railway bridge can be applied to reduce maintenance costs through the avoidance of unnecessary repair / rehabilitation and / or to optimize those repairs that are deemed necessary. The principles underlying this type of optimization process for lifecycle management are depicted in Figure 6[8].

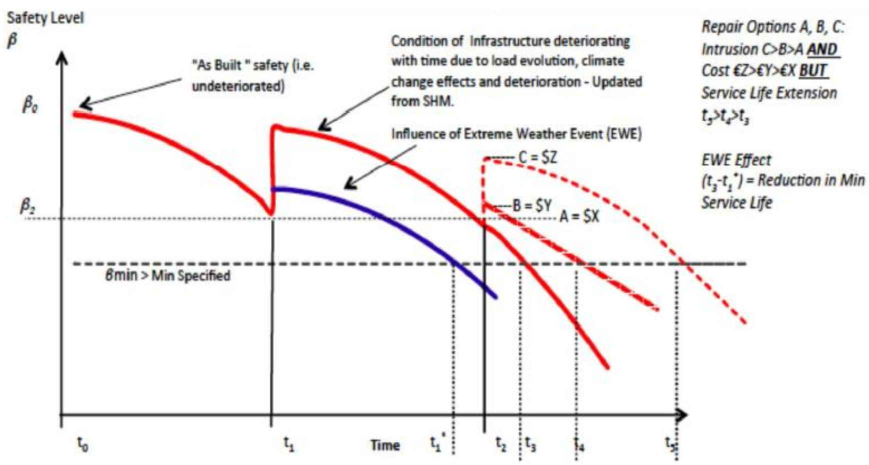

Figure 6 – Infrastructure Lifecycle Management Optimization Process Methodology

Root cause analysis will not require detailed engineering studies in all cases, nor will it result in the development of probabilistic assessments. Undertaking root cause analysis requires communication and engagement with the identified stakeholder group. Additional data and information for root cause analysis is often required and the stakeholder group can serve as a starting point for sourcing required data and information. Root cause analysis also represents an important feedback loop in the resilience analysis methodology as depicted in Figure 7. Establishing a clear link between the climate stressor, associated risks, and hazards / impacts is critical prior to selecting response

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[7] O'Connor et al. Probability-Based Assessment and Optimised Maintenance Management of a Large Riveted Truss Railway Bridge, Structural Engineering International, 2019. Vol 19:4, 375-382, DOI: 10.2749/101686609789847136

[8] Ibid.

strategies. This helps ensure that the response strategies are addressing the correct underlying problem.

Figure 7 – Resilience Analysis Methodology Root Cause Feedback Loop

Step 7. Identification & Selection of Response Strategies

This step describes how the Resiliency Toolbox, which is a spreadsheet-based tool that contains a listing of potential adaptation strategies based on identified stressors, potential risks, and hazard / infrastructure impacts, can facilitate the identification and selection of potential adaptation strategies. Prior steps described the selection of climate stressors, identification of risks, establishment of impacts, and identification of physical assets at risk. The Toolbox collates a listing of adaptation strategies according to stressors, risks, hazards, and assets impacted. Considering the resulting of the preceding steps in the analysis methodology, relevant adaptation strategies can be selected from the Toolbox accordingly. The climate stressors and associated climate / weather-related risks covered in the Toolbox are listed in Table 1.

Table 1 – Climate Stressors and Risks Covered in Toolbox

Stressors	Climate and Weather-Related Risks
Precipitation	Inundation / Flooding
	Increased Water Flow / Velocity and Volume
	Erosion
Temperature	Extreme Heat
	Heat Swings
Storm Surge	Overtopping
	Inundation / Flooding
	Erosion (from Inundation / Flooding)
	Tidal Effects
	Erosion (from Tidal Effects)
Seal Level Risk (SLR)	Inundation / Flooding
	Erosion (from Inundation / Flooding)
	High Water Table [Impacts]

A summary of the hazards / impacts defined previously is provided below. Each impact manifests differently depending on the climate stressor, associated risk, and ultimately, the affected physical asset(s). The list below represents a consolidation of similar hazards / impacts that are listed in greater detail in the toolbox.

- **Erosion of structural assets** due to greater precipitation levels and / or flooding associated with storms, storm surge, or sea level rise.
- **Acute damage or asset failure** due to heat, excess water exposure, temperature fluctuations, and / or ground movement.
- **Premature degradation of assets** due to heat, excess water exposure, temperature fluctuations, coastal storm effects (i.e., winds and waves), higher salinity water, changes in chemical composition of soil or water, and / or changes in moisture composition of the soil / ground movement.
- **Destabilization, subsurface erosion, subsurface expansion, or mass wasting of roadway assets** due to greater precipitation levels / flooding associated with storms, storm surge, and / or sea level rise / changes in moisture composition of the soil / ground movement.

- **Slope failures, closures, or washouts of roadway assets** due to greater precipitation levels / flooding associated with storms, storm surge, or sea level rise / changes in moisture composition of the soil / ground movement

The adaptation strategies identified in the toolbox represent the state-of-the-practice in adaptation strategies for physical infrastructure for the identified stressors, climate and weather-related risks, and hazards / infrastructure impacts as of the time of publication. The adaptation strategies identified within the toolbox should be periodically reviewed and updated. When selecting adaptation strategies, depending on the geographic area, multiple physical infrastructure assets and stressors may warrant consideration. Adaptation strategies should be selected holistically through an approach that considers:

- Estimated level of investment / rough-order-of-magnitude cost;
- Approximate implementation time horizon (i.e., time horizon until expected benefits can be attained); and
- Ability to group the selected adaptation strategy(ies) into a program, i.e., grouping of smaller projects.

The adaptation strategies in the toolbox have all been categorized according to the aforementioned considerations to facilitate the review and eventual selection of adaptation strategy(ies).

The approximate level of investment represents a rough order-of-magnitude estimate of the cost associated with the implementation of the strategy. The implementation time horizon represents an approximation of the time, according to typical programming timeframes (i.e., the work is not being "fast-tracked"), associated with attaining the desired benefits from implementation (e.g., benefits from planting vegetation may not be immediate). Lastly, the applicability for program-based implementation is an indication of the potential benefits or economies of scale / scope that may be attainable via a program-based approach (i.e., groups of smaller projects) as opposed to traditional delivery of standalone projects. Definitions for the level of investment and time horizon categories are summarized below in Table 2 and Table 3 respectively.

Table 2 – Toolbox Levels of Investment Thresholds

Levels of Investment
Low – No cost up to $500,000
Moderate – $500,001 up to $2,500,000
High – $2,500,001 and greater

Table 3 – Toolbox Implementation Time Horizons Thresholds

Implementation Time Horizons
Short – Up to 5 years
Medium – 6 to 10 years
Long – Greater than 10 years

Once a subset of adaptation strategies is identified for a particular influence area, a risk-based approach that considers the likelihood and consequence of the identified risks to the physical infrastructure assets can help balance the level of investment, implementation time horizons, and program-applicability considerations contained within the toolbox. More critical infrastructure assets (i.e., greater impact) and those assets that are older or in poorer-rated condition states may require a more expedient solution, with cost being a less important consideration. Alternatively, less critical infrastructure components may be addressed with adaptation strategies with longer implementation time horizons. An adaptation strategy can also be identified as an intermediate solution that precedes a longer-term solution offered by another adaptation strategy.

Apart from hoping that a single or small number of mitigation strategies is a silver bullet addressing all forms of hazards / risks faced by a given piece of infrastructure, the cost, time, and program-applicability considerations enable asset owners to better understand how the greatest amount of benefit, in the shortest amount of time, to varying costs, can be conferred upon the overall network.

Placing the Strategies in Context

Outputs of the root cause analysis conducted in step six should inform the ultimate selection of adaptation strategies. The root cause analysis may point to multiple potential hazards / impacts for a particular asset. Each of these potential hazards / impacts may stem from different risks and/or stressors. The results of the root cause analysis should reveal whether a specific adaptation strategy in and of itself has the ability to address multiple hazards / impacts, risks, and / or stressors. When a strategy can address multiple sources of risk simultaneously, there is likely good cause to prioritize such a strategy over others.

A clear determination of the risk(s) posed to specific physical infrastructure assets and their criticality to the overall transportation network are important to understand. As alluded to in the prior section, performing a risk analysis would result in, at a minimum, likelihood (probability) and impact (consequence) scores at an asset type level (e.g., culverts), which can then be refined for individual assets (e.g., culvert under 11th Street) based on unique conditions. The current state-of-the-practice for assigning risk impact and likelihood ratings typically recommends a five-level scoring system (seven is generally considered to be too many, and three is more appropriate in certain rating instances, but five is ideal for risk assessments).

Impact and likelihood ratings should range from Very Low to Very High. It is then up to the teams assigning the ratings to define how each level is differentiated (e.g., for impacts, they can include expressions of the effects on objectives or budgets in percentages; for likelihood, they can include estimates of the probability of an event occurring within a specified period). Following the assignment of the ratings, each rating should correspond to a score value (which may or may not be linear or equal between rating types) so that the two values can be multiplied together to obtain a risk score. The prioritization of the risks with the greater risk scores, and management of responses / mitigations to these risks provides context into the selection of response strategies to the extent that they may reduce the potential impact or likelihood ratings for assets. Alternatively, if the strategies do not have an impact on the ratings, they may still offer improved resilience in the form of the time to return to normal operations.

Additionally, assessing the criticality of asset types and individual assets is a key consideration for placing the risk likelihood and impact scores into context. FHWA defines criticality of an asset in relation to both its physical characteristics (e.g., replacement value) and on its function in multiple systems (e.g., supports emergency evacuation, key commercial, or key freight network). As far as placing the function of the asset in context, the role of an asset can typically be expressed along a continuum for greater specificity (vs. a binary on / off a network, etc.), for instance the level of commercial activity, or the value of freight carried. Two challenges that project sponsors face in performing a criticality assessment are defining discrete assets as part of the broader transportation network and determining which auxiliary systems to include in the analysis. To improve the identification of asset units and the scope of a criticality assessment, established objectives and policies should be consulted to understand how assets are related to the accomplishment of said objectives and policies. For instance, aims to improve the connectivity and reliability of infrastructure supporting freight activity would require an examination of assets as part of the key freight corridors, and subsequently the systems that support these corridors.

As asset criticality increases, as does sensitivity to higher risk impact scores – meaning the more critical the asset, then higher risk impact scores should necessitate action. It is a common practice to develop criticality ratings for key asset types and individual assets for consultation during project prioritization, which can be used as a reference point in the review of selected response strategies.

Step 8. Review of Additional Considerations

Step eight focuses on review of additional considerations once initial identification and selection of response strategies are complete. The additional considerations are organized into three areas that correspond with the subsections below: broader social impacts, benefit-cost considerations, and programmatic considerations. These considerations should be evaluated prior to final determination of adaptation strategies.

Broader Social Impact

Evaluating social infrastructure and community impacts are key activities to perform as part of confirming and ultimately progressing the selected response strategies. The evaluation of broader impacts to social infrastructure and community resilience extends beyond many traditional infrastructure project planning frameworks; however, it is key to ensuring efficient, equitable implementation of selected response strategies. Types of non-physical impacts include impacts to mobility, safety, operations, and the community. Each of these impacts can be thought of from two angles, possible impacts as a result from a failure to implement a strategy (negative risk), or possible impacts (positive or beneficial risk) as a result of the implemented strategy.

The first angle is generally easier to identify and estimate; for instance, closed roadways, flooded roadways, increased maintenance, and emergency activities, and / or inordinate impacts on a particular neighborhood. The second angle is more challenging to fully identify and estimate, in part because these impacts are based on hypotheticals of selected strategies have not been implemented and may not have been implemented in a comparable situation in the past (in contrast to impacts that have already occurred in situations without said implementation). Since climate change adaptation strategies are relatively new, there is limited data that clearly captures the impacts of implemented adaptation strategies (e.g., improvements to hydraulic capacity of drainage infrastructure resulting in reduced inundation and / or greater restoration of service, scour protection measures resulting in increased foundation asset life, novel materials that demonstrate improved head resistance, etc.). It is important to thoroughly canvas and identify broader impacts and estimate the potential negative and positive effects as they relate to a selected response strategy.

Other impacts consist of the effects of selected strategies on socioeconomic, land use, and environmental justice considerations. Environmental justice is the fair treatment and meaningful involvement of all people with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. The definition of an environmental justice community is one that is most harmed or impacted by environmental harms and risks, and thus merits greater attention during the assessment of project impacts. The ability to identify, estimate, and ultimately quantify these impacts is challenging; however, improvements in the availability of data and developments of new methodologies enable better analysis than in the past. Historically, minority populations have borne the brunt of environmental degradation and now these communities also often experience the worse negative impacts from climate change-induced risks[9].

[9] Borunda, A. “The origins of environmental justice—and why it’s finally getting the attention it deserves.” National Geographic. 24 Feb. 2021.

Environmental justice should be considered when developing an understanding of where strategies are implemented. However, it is worth noting that, while related, adverse socioeconomic impacts may occur despite the practice of environmental justice.

The impacts of selected strategies upon land use (e.g., current and future land use and associated policies) can be estimated based on either impacts to the economic value and use of adjacent land uses or alignment through prioritization of certain land uses over others. In the first instance, if strategies are implemented, they may protect and preserve adjacent properties for their intended uses, whereas if not, their value and use may be diminished. In the second instance, the prioritization of certain land uses over others may inform the prioritization of where strategies should be implemented.

Policy directives and data analysis can improve the understanding of impacts upon pursuing environmental justice and minimizing adverse socioeconomic impacts. For instance, policy directives for project selection to consult with communities (e.g., specific EJ communities, or other vulnerable communities) during project prioritization and later implementation can help ensure adverse impacts are avoided. Similarly, improved data availability combined with geospatial analysis can improve project sponsors' understanding of more equitable distribution adaptation strategies. Strategies that have already been implemented, e.g., increase in elevation of a seawall, should be accounted for when evaluating equitable distribution.

Increasingly, the ability of projects to better address and manage broader social impact considerations has improved in the face of new funding opportunities. At the federal level, the Bipartisan Infrastructure Law (BIL) significantly expands funding and eligibility for projects that will improve the resilience of infrastructure. For instance, of the 25 competitive infrastructure funding opportunities for local governments (many of which already existed and have been expanded), three stand out as possessing alignment with potential projects (i.e., mitigation strategies, and related planning efforts) in this framework, which are listed below.

- Port Infrastructure Development Program Grants
- Building Resilient Infrastructure and Communities Program
- Flood Mitigation Assistance

State and local funding opportunities will likely be created in the future with separate requirements for a project to be eligible for funding. Other state or local legislation may introduce planning requirements or considerations for project sponsors to adhere to apart from specific project funding opportunities.

Benefit-Cost Considerations

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https://www.nationalgeographic.com/environment/article/environmental-justice-origins-why-finally-getting-the-attention-it-deserves

A clear understanding of the estimated benefits and costs developed through a prescribed analysis can help project sponsors prioritize their investments to realize a more efficient use of resources and provision of the benefits. The full range of anticipated costs (i.e., beyond implementation costs) and benefits need to be estimated and analyzed as part of a benefit-cost analysis (BCA) to inform the ultimate selection of adaptation strategies. Some of these benefits and costs will have been identified as part of the review of other non-physical infrastructure impacts as noted previously. The BCA should, to the greatest extent possible, take into consideration the full lifecycle costs and the entirety of benefits conveyed to the at-risk infrastructure associated with the strategies. It should also consider second-order (i.e., indirect) economic and social benefits and costs.

Guidance on some of the key values and types of benefits that the USDOT considered as part of the BCA required within the TIGER Discretionary Grant Program are included in the TIGER Benefit-Cost Analysis (BCA) Resource Guide[10]. This BCA guidance is specifically referenced in FHWA's Vulnerability and Adaptation Framework[11]. However, the identification of benefits and costs should not be limited only to this guidance. The section below provides a more complete identification of the benefits and costs associated with selecting different adaptation strategies that can be considered when conducting a BCA.

Costs:

- **Potential Infrastructure Lifecycle Costs**
    - Costs to be "Program-Ready" (scope, estimates, identification of coordinator, resolution of support)
    - Design costs
    - Implementation costs (soft and hard)
    - Maintenance / preservation / rehabilitation costs
    - Assessment and monitoring costs
- **Potential Second-Order Economic, Environmental & Social Costs**
    - Externalities imposed by construction activities
        - Increase of ambient noise
        - Reduction of area economy due to lack of access to stores, etc. during project construction

[10] https://www.transportation.gov/sites/dot.gov/files/docs/Tiger_Benefit-Cost_Analysis_%28BCA%29_Resource_Guide_1.pdf

[11] Filosa et al. Vulnerability Assessment and Adaptation Framework. 3rd Edition. Federal Highway Administration (FHWA) Office of Planning, Environment, and Realty. 2017. https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/

        - Reduction of mobility due project construction
    - Operations and emergency response cost associated with 'no-build' alternatives
    - Safety impacts associated with 'no-build' alternatives
    - Infringement upon property via acquisition or easement, or takings
    - Reduced aesthetics or introduction of externalities due to newly installed mitigations
    - Adverse distribution of costs (or lack of equitable distribution of benefits) upon neighborhoods and land uses
    - Loss of green spaces, wetlands, or habitat

Benefits:

- **Potential Benefits Conveyed to Infrastructure**
    - Reduced maintenance / preservation / rehabilitation demands
    - Reduced / avoided down-time or periods when asset/system/location is not serviceable
    - Extended lifespan
    - Reduced risk / vulnerability, quantified as a hardening of infrastructure
- **Potential Second-Order Economic & Social Benefits**
    - Provision / protection of green and blue infrastructure
    - Reduced / avoided disruption to economic and social activities
    - Reduced / avoided operations and emergency response costs
    - Improved safety of network
    - Reduced / avoided damages to other properties as a result of infrastructure impacts
    - Equitable distribution of costs and benefits across neighborhoods and land uses

The following formulas are used in conducting the BCA analysis:

- Benefit Cost Ratio = NPV / t * $(C_t / (1 + r)^t)$
- Net Present Value[12] = t * $((B_t – C_t) / (1 + r)^t)$

[12] Note: the TIGER Benefit-Cost Analysis (BCA) Resource Guide expresses some of these variables differently, e.g., the net benefit expression of 'B_t - C_t' is "FV" for future [net] value, the discount rate of 'r' is "i".

Following the evaluation of the additional considerations and conducting the BCA, project sponsors should have an improved understanding of how to go about programming the selected response strategies.

Stakeholder engagement can serve as a key source of input and prioritization during the evaluation of the additional considerations and conducting the BCA. Several of the potential costs and benefits can be identified or validated, and even quantified, through stakeholder collaboration. Early and regular communication with stakeholders is paramount to ensure that all positive and negative impacts of response strategies are considered and accurately estimated. Stakeholders may have a better understanding of these impacts than the project sponsors and may have any other available data used in the risk, criticality, or other analyses.

Programmatic Considerations

The capability to follow this framework and its methodologies relies on project sponsors' institutional capabilities and data availability. Without the necessary processes, inputs, or resources to leverage such, the framework and methodologies may be poorly adhered to and executed. Taken as a whole, the inherent capabilities of an organization(s) that acts a project sponsor takes to equip itself can be considered the programmatic capabilities required to support the framework and methodologies. Key programmatic stressors, which may present challenges to the execution this framework and beyond, can be categorized into five types, and are described further below.

- **Lack of Methodologies / Procedures**: When an organization does not embark upon establishing the means to execute the required methodologies. This includes processes to develop risk profiles (including likelihood and impact ratings), criticality profiles, and evaluate broader, non-physical infrastructure impacts. While processes to develop risk and criticality profiles may predate the adoption of such a resiliency framework, they will likely require modification to account for new stakeholders and data inputs. The processes to evaluate broader, non-physical infrastructure impacts may need to be created and require consultation with key stakeholders and peers / industry partners.
- **Inadequate / Non-Existent Policies**: When an organization lacks sufficient guidance for how methodologies are to be used, or when it lacks resilience considerations in its design standards or asset lifecycle plans. This includes anything from ensuring sufficient data governance for inputs and processes, to how and when risk / criticality assessments are consulted, how benefits / costs are estimated for BCA, and varying forms of updating design standards / lifecycle plans to improve resilience. For instance, design standards can be updated to be more performance-based (i.e., greater consideration of future vs. historical impacts); they can include recommendations on how to harden infrastructure and the network (i.e., for retrofits or new construction); or they can include the design of

modular features or construction techniques to improve the ease of implementation of a response strategy / performing lifecycle activity.

- **Lack of Data / Inconsistent Data**: When an organization lacks appropriate data inputs or data quality procedures such that the methodologies cannot be accurately performed. This includes ensuring availability and use of already existent internal / external data sources, identifying the means to develop initially unavailable data, properly specifying the data types / formats based on the needs of data tools, and working with partners to pool resources and converge on data standards. Additionally, this stressor may lead an organization to pursue new technologies such as specialized asset monitoring equipment or the use of LIDAR systems to capture data sufficient to inform the methodologies.
- **Inadequately / Insufficiently Implemented Policies and Procedures**: When an organization does not appropriately ensure established processes are adhered to, particularly those supporting this framework. Policies and procedures are most effective when they are followed; however, this also assumes that they are reviewed periodically to ensure they are aligned with desired objectives and performance targets for improving resilience. Organizations should also periodically review the alignment of data to support the policies and procedures, as well as interview key stakeholders to assess their efficacy and alignment.
- **Insufficient Staff Capacity**: When an organization does not adequately staff or sufficiently train staff to perform the methodologies in the framework. While the former challenge can be addressed through better resource planning, the latter will require further skills assessments, identification of training opportunities, and working with partners to ensure state-of-the-practice techniques and knowledge are acquired.

The first two types of programmatic stressor present challenges that exist whenever an organization is charting a new path in order to solve an emergent issue, such as improving resiliency. The latter three types of programmatic stressor present challenges that are not unique to resilience efforts. There are existing best practices around how to identify and procure access to data (or improve data quality), ensure adherence to established processes, as well as resourcing activities within an organization.

In summary, the review of the additional considerations provides important context about whether any set of selected response strategies is the preferred course of action, and if so, how to best implement them. A comprehensive understanding of the implementation, risk / criticality, and broader, non-physical infrastructure impact considerations can only equip project sponsors to make better-informed decisions. Additionally, through an understanding of the programmatic stressors underpinning the inputs and processes related to the framework and methodology, project sponsors can establish and maintain integrity in their analyses and decisions.

Step 9. Identification of Program-Ready Projects

Following the selection of response strategies, the project sponsor must translate the strategy into a program-ready project or set of projects. The requirements for an individual project, or a set of projects, to be considered program-ready include that they have a defined scope, preliminary cost estimates, a coordinator, and a resolution of support. Once project(s) are program-ready, they can continue in the project development process. While standalone resilience-related projects could be programmed (e.g., hardening a seawall), in many instances adaptation strategies can be delivered as part of other projects (e.g., using more heat-tolerant materials, increasing hydraulic capacity as part of drainage projects, planting more native vegetation, etc.). These groupings of smaller-scale projects could be candidates for inclusion in already-planned or programmed projects or as part of existing contracts (e.g., ditch, drain and culver cleaning and maintenance).

Later in the project development process it is recommended that project sponsors establish definitions of performance metrics to measure the success of a response strategy (e.g., reduction in surface area inundated after extreme weather events, no overtopping of flood protection during storm surge events, material deformation within tolerance during extreme heat, reduced average time to clear transportation facilities and return to operations post event, etc.), as well as defining the expected return period over which benefits will accrue. These determinations will enable the project sponsor to systematically measure and monitor if the response strategy is effective and if the benefits are accrued within the period as anticipated. The identification of the metrics and evaluation period can otherwise be thought of as the benefits-realization framework. From reviewing the findings of a project's benefits-realization framework, a project sponsor can determine how effective the response strategy was in fulfilling its specific aims as well as other established objectives and policies.

Once a project is program-ready and has a defined benefits-realization framework, the particulars of how a strategy may be best implemented are important to assess, which extend beyond understanding if a standalone versus program approach is best. The funding and contracting mechanism are just two examples of variables to consider. For instance, will the work be performed by in-house personnel or contractor crews; moreover, if external, does it require a new contract or can it be performed on existing multiple-award task orders? The contracting mechanism and funding source, to differing extents, impact the speed, budget efficiency, and quality to which the response strategy can be implemented.

Local Actions to Support Decision-Making

From Universities to local environmental groups, South Florida has a plethora of opportunities for partnering with community organizations. Collaborations between organizations offer more expertise on a project and produce better results. Leveraging local knowledge will lead to the identification and implementation of more adaptation strategies and the development of more resilient infrastructure.

The development of resilient transportation infrastructure benefits everyone. Identifying and working with implementation partners and performing outreach with external stakeholders from the start will offer a wider range of perspectives. This diversity of perspectives provides a more in-depth understanding and platform for the establishment of policies that support data requirements, process and procedure requirements, and address programmatic challenges associated with this methodology.

It is important to note that addressing climate change challenges and building more resilient infrastructure extends beyond the jurisdictional boundaries of the Broward MPO. Coordination and consultation with adjacent jurisdictions (e.g., counties and municipalities) and state and federal organizations are strong encouraged. In addition, local business groups, such as chambers of commerce, may have an interest in promoting the development of more resilient infrastructure. Outreach, communication, and early involvement of relevant stakeholders is critical.

Beyond coordination and communication, identification, consideration, and review of applicable ordinances, mandates, and regulations are imperative. In certain instances, local ordinances may exceed the minimum requirements of other design guidelines and standards such as those required at the state level. For example, the Broward County has an ordinance that sets minimum seawall and top-of-bank elevation standards. On a case-by-case basis, applicable ordinances, mandates, and regulations should be evaluated for each adaptation strategy.

Proof of Concept Summary

In support of this study effort, a proof of concept was conducted for a pair of corridors to demonstrate the nine-step resilience analysis methodology. Each step of the methodology was carried out to the extent practical for both corridors. The corridors selected for the proof of concept were Hollywood Boulevard (SR-820) from 17th Avenue to North Ocean Drive (SR-A1A) and Johnson Street from North Federal Highway (US-1) to North 14th Avenue. These two corridors were selected from the eight Priority Corridors identified in the 2045 MTP. Reasons for selecting these corridors include that one is owned by the State, Hollywood Blvd., whereas Johnson St. is owned by a municipality. The two corridors are in reasonably close geographic proximity. There is some diversity of asset types across the corridors. The Hollywood Blvd. corridor crosses the Stranahan River and includes the Hollywood Blvd. Drawbridge before terminating at North Ocean Drive (SR-A1A) and the Johnson St. corridor begins further inland and terminates at North Federal Highway (US-1), abutting the northern edge of the Hollywood Beach Golf and Country Club.

All four stressors (i.e., sea level rise, storm surge, precipitation, and temperature) were considered. The time horizons selected for climate projection data were 2050, 2060, 2070, and 2100 (precipitation and temperature forecasts were available through 2099). Readily-available climate projection data was utilized for all stressors. All the stressors except for precipitation were deemed applicable. It should be noted that storm surge effects are modeled based on data from the Florida Division of Emergency Management. This storm surge data is derived from the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, a numerical model used by the National Hurricane Center (NHC) to compute storm surge. SLOSH model outputs are provided according the five-point Saffir-Simpson Hurricane Wind Scale and not for future forecast years, i.e., not for 2050 and beyond.

Based on the applicable stressors, climate / weather-related risks were determined by stressor. To support the determination of applicable risks, percent affect threshold values were assumed for the sea level rise and storm surge stressors. The percent affected values were established based on geospatial analysis. For purposes of the proof of concept, a broad base of potential asset types affected were considered in the third step, establish impacts. Discussions with stakeholders in the community could also reveal impacts to additional assets (e.g., schools, daycares, house of worship, etc.). Without engaging stakeholders in the community, for the three applicable stressors FEMA's National Risk Index tool was utilized to establish social vulnerability and community resilience levels at the County level.

While proxy indicator data was not readily available, step four provides recommended proxy indicators by stressor (e.g., locations of known flooding / surge, areas of lower topography, areas of elevated water tables, assets known to be impact by temperature increases, etc.). Without established proxy indicators, and in the absence of site-specific, project-related engineering studies, the proof of concept assumes all assets present in each corridor are at risk in step five. Due to the lack of asset-specific data and proxy indicators / historical event data, a root cause analysis, which would validate the linkages from stressors to risks and through to hazards / negative impacts, could not be performed in task six.

The Resiliency Toolbox is utilized in step seven to identify potential response strategies for the applicable stressors, climate / weather risks, and impacts outlined in the previous steps in the methodology. For the sea level rive and storm surge stressors, and their associated risks and impacts, 24 candidate response strategies were identified. Ten candidate adaptation strategies were identified for the temperature stressor and its associated risks and impacts. Regarding additional considerations in step eight, overviews of potential impacts to mobility, safety, operations, and the community are provided. Due to a lack of specific benefit and cost elicitations, and a lack of certainty related to the organizational practices of project sponsors, benefit-cost analysis and an assessment of programmatic considerations were not performed. Without the ability to fully complete all preceding eight steps in the methodology, program-ready projects could not be identified in the ninth and final step. Nonetheless, the proof of concept proved the viability of the resilience analysis methodology and identified key data requirements and limitations associated with each step.

Conclusions and Recommendations

This study presents a nine-step, iterative resilience analysis methodology that ultimately supports the definition of resiliency-related, program-ready projects. The initial step in the methodology is the selection of stressor(s), followed by the identification of climate / weather-related risks associated with the stressor(s), the establishment of impacts to transportation facilities and social / community infrastructure across a broad influence area, and the identification of proxy indicators, which serve as possible root causes of negative impacts to systems and assets. Physical assets that are at risk are identified based on the proxy indicators through a holistic approach that accounts for adjacent assets as part of a broad influence area.

Once at-risk assets are identified, root cause analysis is performed to validate potential linkages from climate stressors and their risks to hazards and potential negative impacts. If the identified climate stressors and risks cannot be linked to hazards / impacts in the root cause analysis, there is a feedback loop in the methodology to return to third step, establish impacts. Upon completion of the root cause analysis step, potential adaptation strategies are selected from the Resiliency Toolbox, which categorizes potential adaptation strategies according to particular stressors, risk types and sources, potential hazards / impacts to physical infrastructure, and potential asset types.

A risk-based approach that considers the criticality and impact of selected risks to the physical infrastructure assets should be adopted to prioritize the adaption strategies. Broader social impacts, benefit-cost considerations, and programmatic considerations should be reviewed prior to the ultimate selection of adaptation strategies. Based on the review of additional factors, there may be a need to reprioritize the adaptation strategies. There is another feedback loop in the methodology to account for the potential need to reprioritize strategies based on the review of additional considerations. Finally, the ninth and last step of the methodology is the identification of program-ready projects based on the selected adaptation strategies.

The standard resilience analysis methodology defined in this study emphasizes the need for stakeholder identification, engagement, and communication. There are 31 municipalities in Broward County, County stakeholders, Florida Department of Transportation (FDOT), Florida Department of Environmental Protection (DEP), South Florida Water Management District (SFWMD), South Florida Regional Transportation Authority (SFRTA) / Tri-Rail, Southeast Florida Regional Climate Change Compact (Compact), civic and community groups, and other stakeholders involved in transportation planning and project delivery at the local, County, State, and Federal levels. Engagement, communication, and coordination with civic and community groups will be especially important when addressing social vulnerability, community resilience, and environmental justice considerations.

There have already been considerable prior efforts and research to identify vulnerable locations, resulting in the identification of eight (8) Priority Corridors in the 2045 MTP. The methodology presented in this study is flexible enough to be applied as a high-level screening tool to identify possible adaptation strategies for given stressors and risks / hazards and capable of supporting the definition of program-ready projects. The Resiliency Toolbox developed as part of this study can serve as a repository of potential adaptation strategies that can be applied to a variety of projects. This study and its resulting methodology can be fully integrated into the broader Framework Study.

Limitations

Additional stressors were not considered at this stage. However, the methodology developed as part of this effort offers a flexible and repeatable approach, such that other stressors can be incorporated into the resilience analysis in the future. These stressors may include storm-induced fires, sink holes / slope failures, tornadoes, high-wind events, etc. Adding stressors to the resilience analysis methodology would require definition of the additional stressor(s) in the first step as well as the definition of climate and weather-related risks associated with the stressor(s). There would be cascading effects throughout the methodology. Additional impacts from the added stressors would need to be considered in the third step and additional adaptation strategies would need to be considered in step seven.

The proof of concept for the pair of corridors, Johnson St. and Hollywood Blvd., revealed that applying the methodology without clearly-defined projects, and therefore assets, results in more of a screening-level analysis. To perform more detailed analysis, including root cause analysis and engineering analysis that informs design considerations, much more data and proposed project details are required. In addition, while the methodology as presented in this study can build upon prior efforts, additional effort would be required to apply the methodology without prior work having identified locations and assets vulnerable to climate change impacts.

Lack of data is a substantial barrier to successful implementation of this methodology as evidenced in the proof of concept. More detailed, project-specific engineering analysis requires considerable data both in terms of historical data on asset condition and impacts from prior events, as well as data related to future projected climate. While previous efforts have identified scenarios for sea level rise and storm surge, these efforts did not specify which scenario(s) should inform design considerations. The Pilot Project identified Priority Corridors and the Second Phase Study identified typologies and solutions sets based on assets and stressors. However, neither the Pilot Project nor Second Phase Study gave direction on how to prioritize addressing the stressors. Further, prior studies did not explore precipitation and temperature projections at a downscaled level (i.e., down to the County level). Precipitation and temperature projections at the County level are readily available, yet there is no clear direction on the emissions scenarios and time horizons to use.

Recommendations

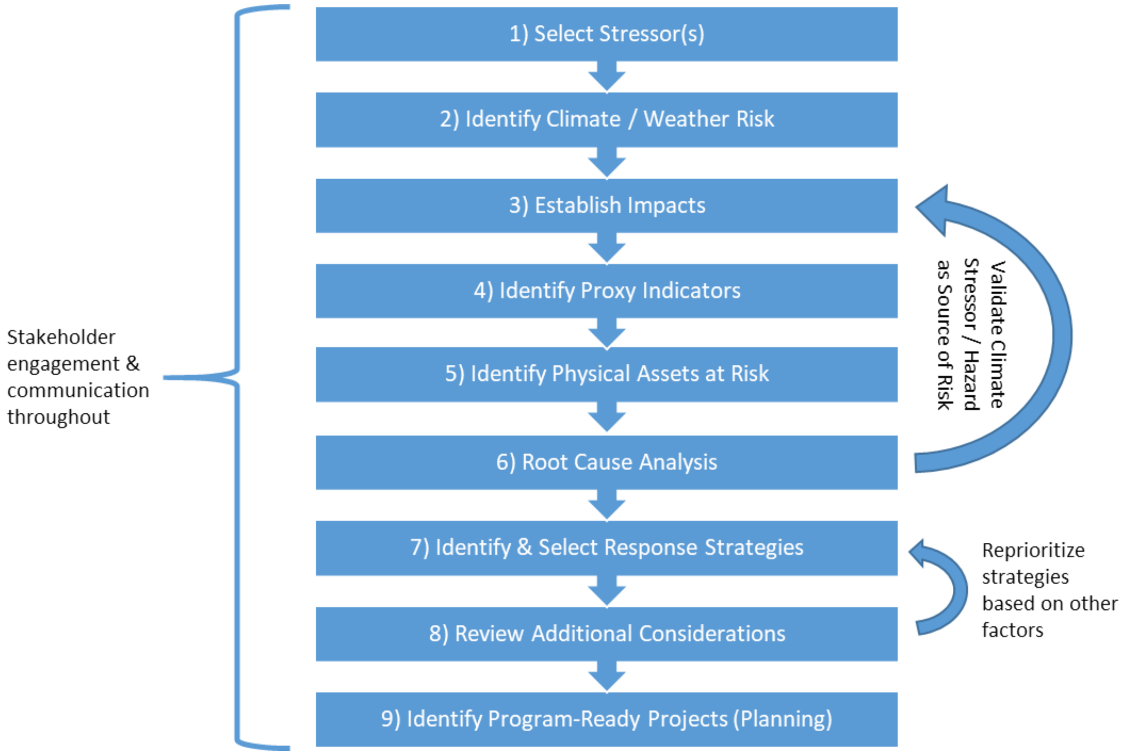
- Consider the constantly evolving research into climate change from stakeholders such as the Intergovernmental Panel on Climate Change (IPCC) and university-based and other research institutions to ensure appropriate stressors and their associated risks and hazards are addressed.
- Develop and maintain a database of stakeholders who would typically be involved in this process.
- Select preferred emission scenarios and time horizons for purposes of engineering analysis and design. Based on the selected emission scenarios and time horizons, detailed climate projections can then be used for probabilistic analysis that can recommend potential design changes.
- Updated the Resiliency Toolbox over time so it serves as a living document that captures new adaptation strategies as well as modifications to existing strategies based on lessons learned from implementations.

Appendices

Appendix A: Proof of Concept

Proof of Concept Corridors

This proof of concept demonstrates a high-level application of the nine-step standard resilience analysis methodology that is described in greater detail in the Resilience Analysis Methodology Technical Memo. The figure below depicts the steps in this methodology. A pair of corridors, Hollywood Blvd. and Johnson St., were selected for the proof of concept. To the extent practical, given readily-available data and without site-specific, project-related engineering studies, the sections below describe how to carry out each step in the methodology.



Two corridors were selected for the proof of concept for several reasons including the fact that one corridor is owned by the State (Hollywood Blvd.) whereas the other is owned by a municipality. How the adaptation strategies are ultimately implemented and become program-ready projects is likely to differ across these two corridors since they have different owners, i.e., potentially differing design guidelines / standards. Another reason these two corridors were selected relates to their relatively close geographic proximity, therefore placing the two corridors in the same influence area. The Hollywood Blvd.

corridor extends nearly to the shoreline, terminating at N Ocean Dr. (SR-A1A), providing a differing set of assets, namely the Hollywood Blvd. Drawbridge, and thus different potential adaptation strategies.

The Johnson St. corridor is unique in that a large portion of the corridor abuts a golf course, which could serve as potential area to capture excess water when drainage system capacity is insufficient. In addition, considering a pair of corridors that sit in close geographic proximity to one another presents challenges related to how potential adaptation strategies may impact surrounding assets and communities. For example, raising the profile of a roadway while most of the surrounding transportation network remains inundated does not seem like a practical adaptation strategy. This consideration of broader impacts demonstrates the importance of considering the influence area associated with the impacted assets. The extent of the corridors is captured below:

Hollywood Boulevard: Hollywood Blvd (SR-820) starting at S/N 17th Ave and terminating after the Stranahan River and the Hollywood Blvd Drawbridge before connecting with N Ocean Dr (SR-A1A).

Johnson Street: Johnson St starting at N Federal Hwy (US-1) and terminating at N 14th Ave.

Step 1. Selection of Stressors

The applicability of each stressor is described below as well as the selection of applicable stressors.

- **Sea Level Rise**: Stressor = Applicable; in context of the 2019 update of "Unified Sea Level Rise Projection Southeast Florida" that is based on projections of sea level rise developed by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014), as well as projections from the National Oceanic and Atmospheric Administration (NOAA) (Sweet et al., 2017), the consensus report uses (in descending order) the NOAA High Curve, the NOAA Intermediate High Curve, and the curve corresponding to the median of the Intergovernmental Panel on Climate Change (IPCC) AR5 RCP 8.5 scenario. The projected extent of sea level rise for the corridors is shown as part of the map series in Appendix X.

Hollywood Blvd (17th Ave to N Ocean Dr)				
	Sea Level Rise			
	2050	**2060**	**2070**	**2100**
% of Corridor Length Affected	~34%	~63%	~69%	~85%

Note: % Affected based on NOAA Intermediate High Curve (the middle curve of the three consensus curves)

Note: Total corridor length calculated as 15,000 feet (2.84 miles) based on total of each east/west direction length / centerline miles since road is largely separated by median

Johnson St (N Federal Hwy to N 14th Ave)				
	Sea Level Rise			
	2050	**2060**	**2070**	**2100**
% of Corridor Length Affected	~30%	~37%	~43%	~58%

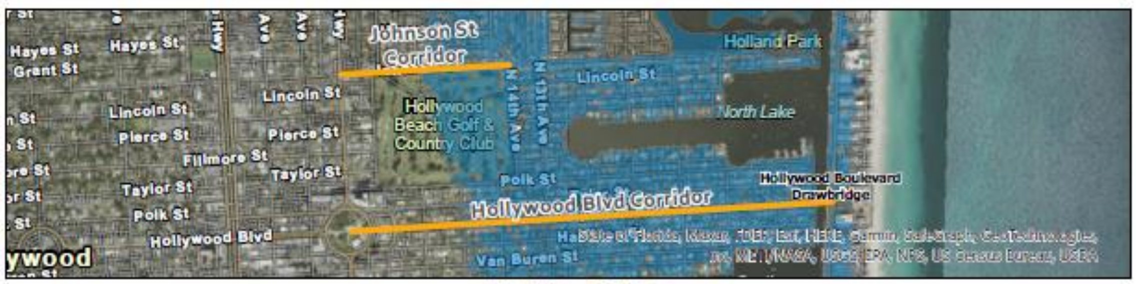
Note: % Affected based on NOAA Intermediate High Curve (the middle curve of the three consensus curves)
Note: Total corridor length calculated as 3,000 (0.568 miles) feet based on ROW length / centerline miles, not total of each east/west direction length since road is only separated by striping

- Additional context to consider in terms of projected inundation of surrounding roadways and communities
  - Degree to which connecting streets are affected by SLR, i.e., what is rationale for hardening either of these corridors if many connecting roadways are not?

Resilience Analysis Methodology Proof of Concept
SLR in 2050, 2060, 2070, 2100

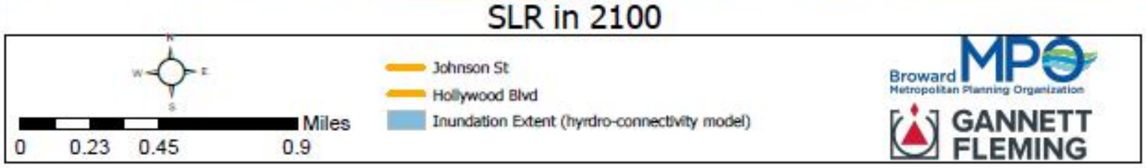
SLR in 2050

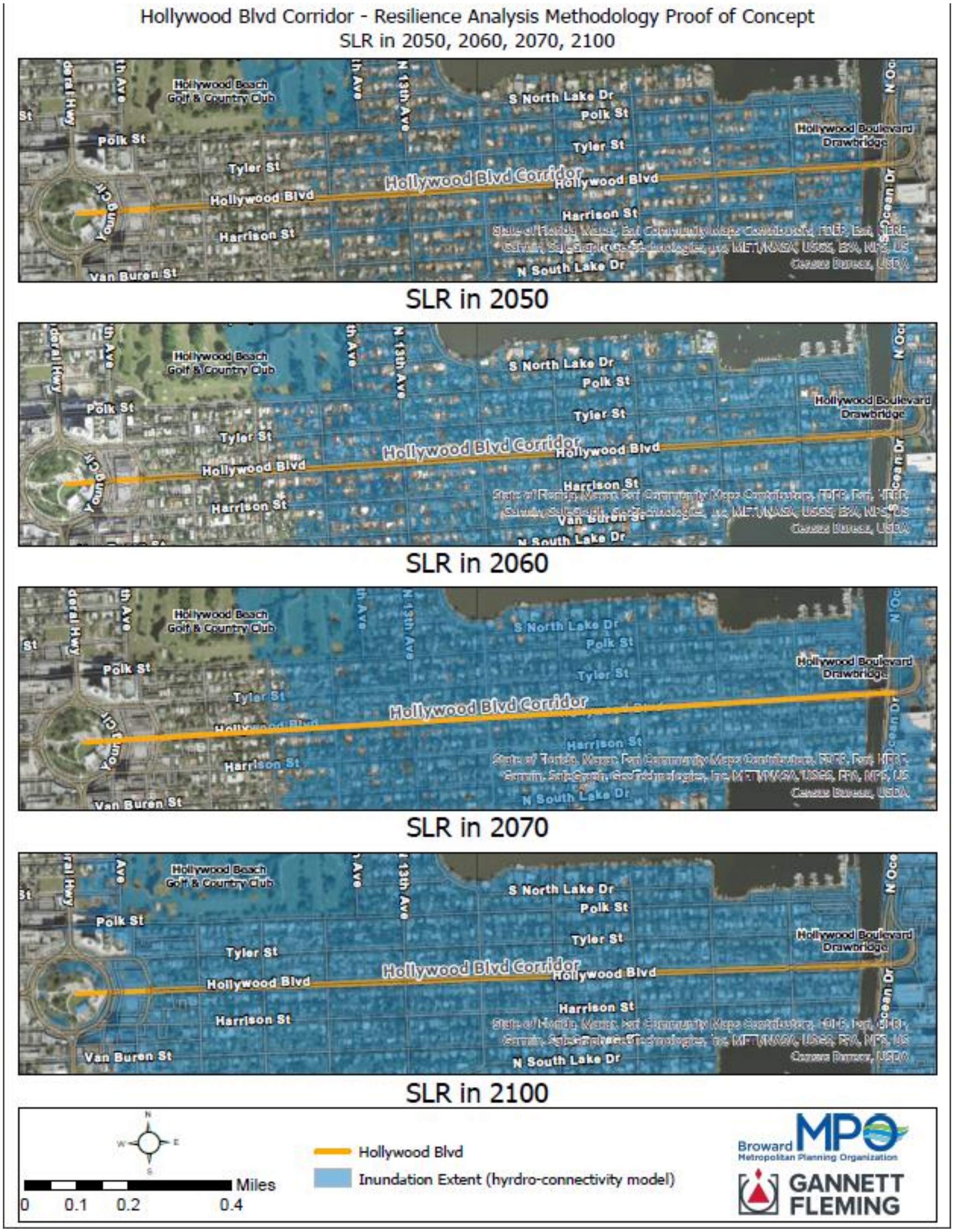
SLR in 2060



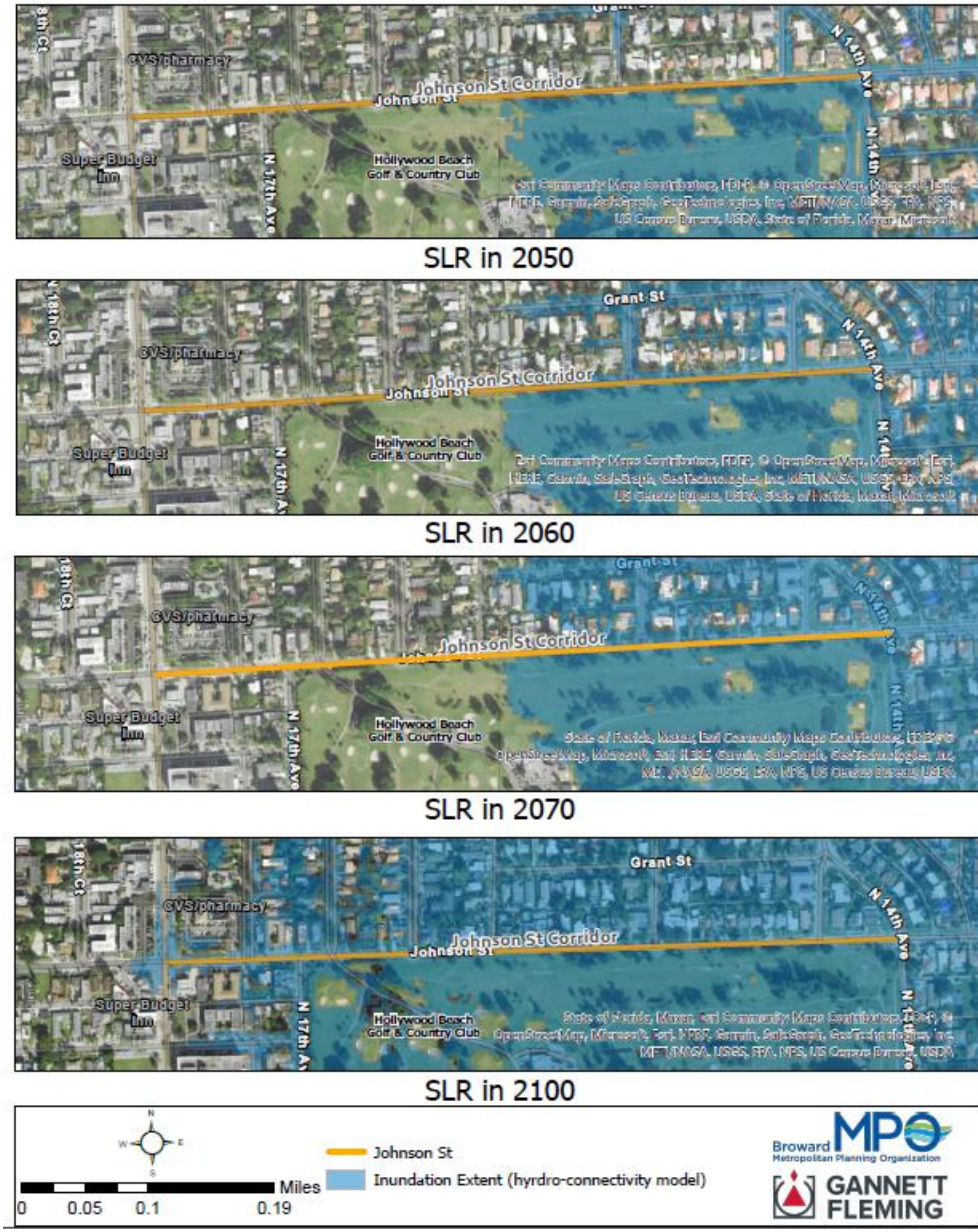
SLR in 2070

SLR in 2100




Hollywood Blvd Corridor - Resilience Analysis Methodology Proof of Concept
SLR in 2050, 2060, 2070, 2100
Hollywood Beach Golf & Country Club
S North Lake Dr
Polk St
Tyler St
Hollywood Blvd Corridor
Hollywood Blvd
Harrison St
Van Buren St
N South Lake Dr
N 13th Ave
Hollywood Boulevard Drawbridge
SLR in 2050
SLR in 2060
SLR in 2070
SLR in 2100
Miles
0
0.1
0.2
0.4
Hollywood Blvd
Inundation Extent (hyrdro-connectivity model)
Broward MPO
Metropolitan Planning Organization
GANNETT FLEMING

Johnson Corridor - Resilience Analysis Methodology Proof of Concept
SLR in 2050, 2060, 2070, 2100



- **Storm Surge:** Stressor = Applicable; in context of the 2019 Florida Division of Emergency Management Storm Surge Zones in Florida dataset[13], which is derived from the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model, a numerical model used by the National Hurricane Center (NHC) to compute storm surge. The SLOSH model is based on a composite, i.e., combination of deterministic and probabilistic, modeling approach to simulate potential hurricane impacts to SLOSH model basins. On average three to six SLOSH basins are updated annually based on factors such as changes in topography / bathymetry due to a landfalling hurricane, degree of vulnerability to storm surge, new data, coastal changes, and the addition of flood protection infrastructure. SLOSH model outputs are based on several thousand model runs of hypothetical hurricanes under different storm conditions. Outputs are in the form of Maximum Envelopes of Water (MEOWs) and Maximum of MEOWs (MOMs). MEOW provides a worst-case snapshot of a SLOSH basin for a particular storm category and the MOM provides a worst-case snapshot for "perfect" storm conditions. MEOWs and MOMs are regarded by the NHC as the best approach for determining storm surge vulnerability since they consider forecast uncertainty. Additional information on the SLOSH model and its approach is available through the NHC[14]. MOMs from the surge model were combined with elevation data from LiDAR data (converted to a Digital Elevation Model, or DEM, with 5-foot pixel resolution, and contiguous shoreline or sea polygons. The projected extent of storm surge for the corridors is shown as part of the map series in Appendix X.

Hollywood Blvd (17th Ave to N Ocean Dr)					
	Storm Surge				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
% of Corridor Length Affected	~24%	~58%	~75%	~87%	~98%

Note: % Affected based on the Florida Division of Emergency Management Storm Surge Zones 2019 dataset, which is derived from the NHC SLOSH Model
Note: Total corridor length calculated as 15,000 feet (2.84 miles) based on total of each east/west direction length / centerline miles since road is largely separated by median

Johnson St (N Federal Hwy to N 14th Ave)					
	Storm Surge				
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
% of Corridor Length Affected	~10%	~26%	~32%	~40%	~56%

Note: % Affected based on the Florida Division of Emergency Management Storm Surge Zones 2019 dataset, which is derived from the NHC SLOSH Model

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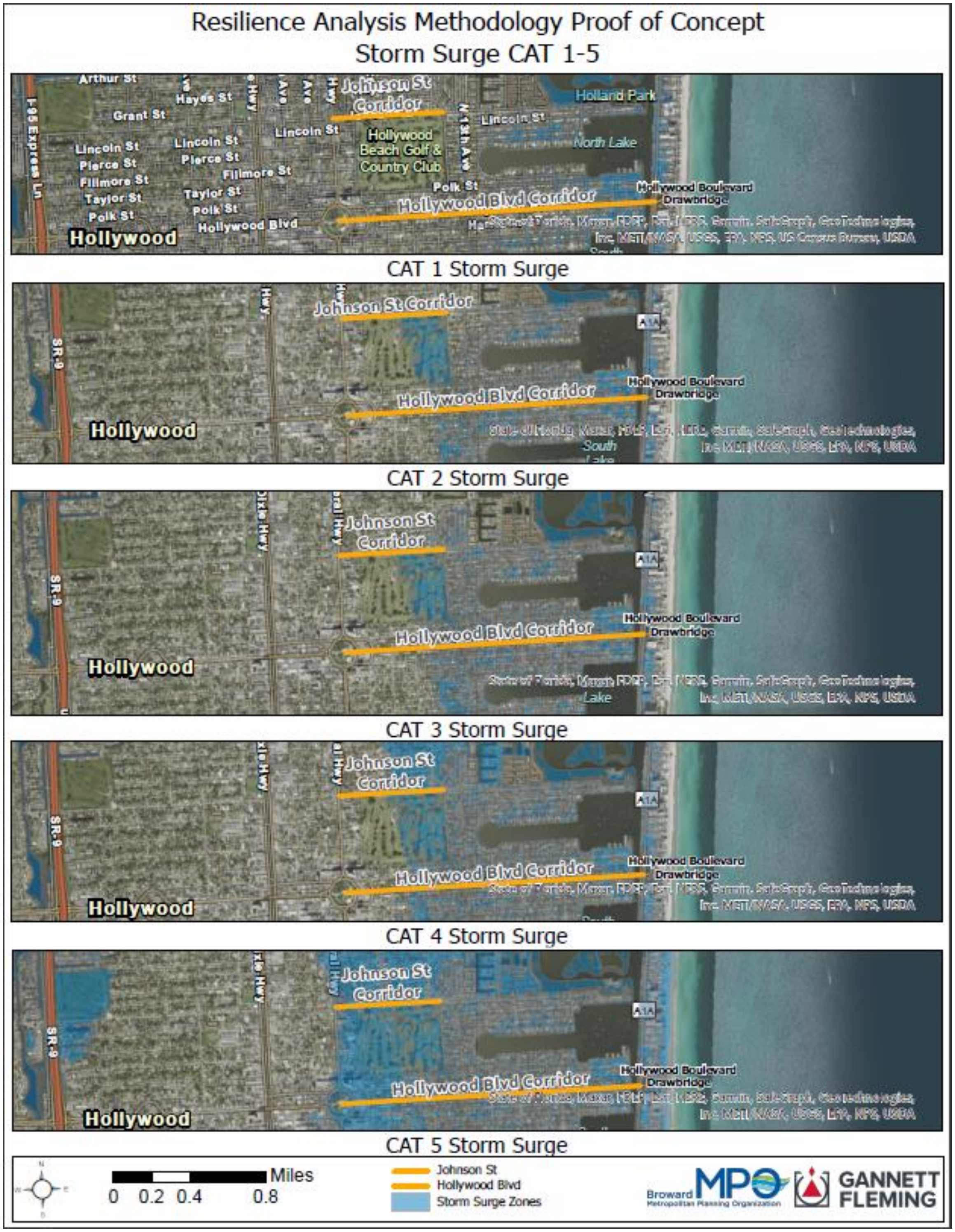
13 https://sls.geoplan.ufl.edu/pub/sls/docs/gis_metadata/Storm%20Surge%20Zones%20(FDEM%20&%20RPCs).xml

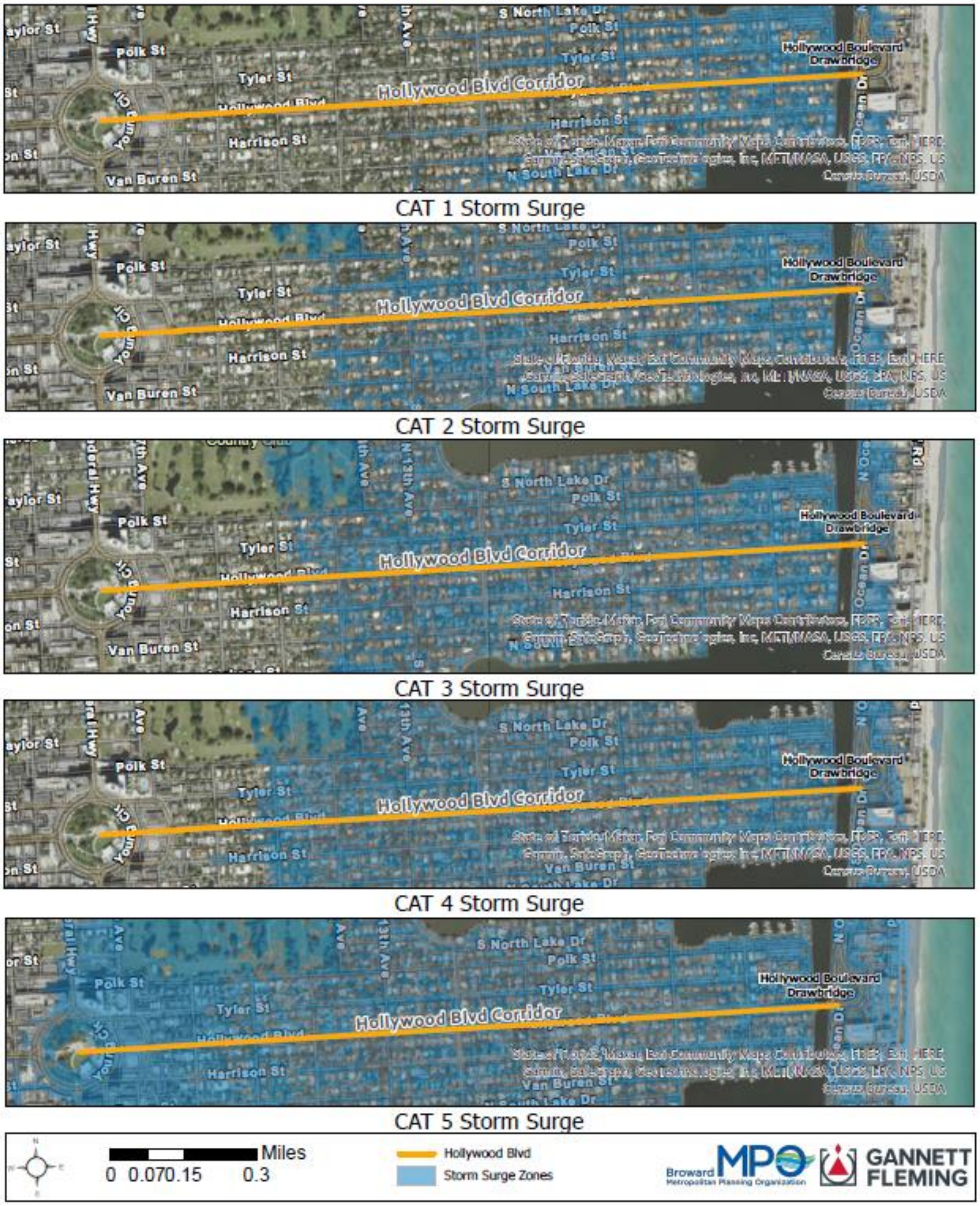
14 www.nhc.noaa.gov/surge/slosh.php

Note: Total corridor length calculated as 3,000 feet (0.568 miles) based on ROW length / centerline miles, not total of each east/west direction length since road is only separated by striping

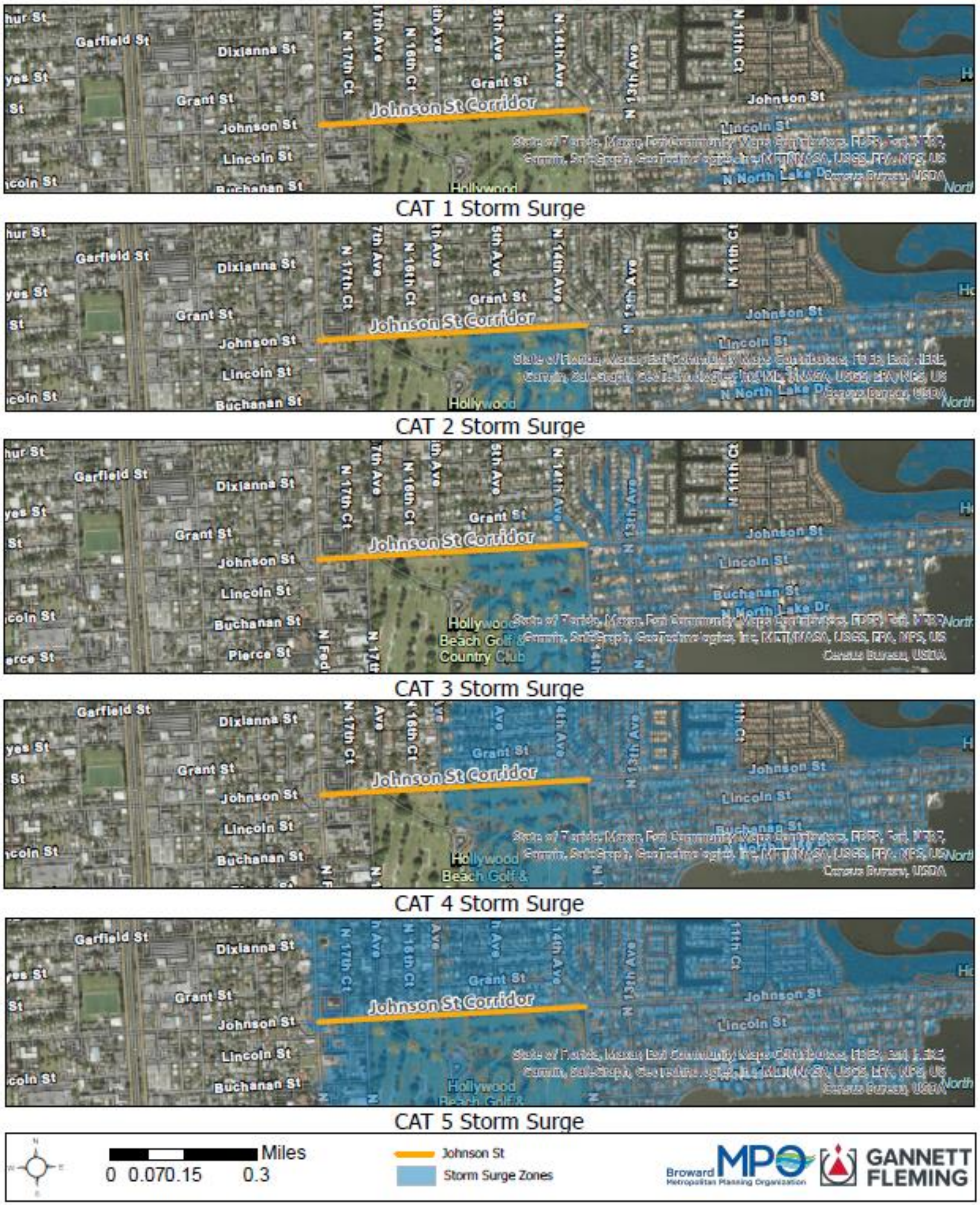
- Additional context to consider
  - While the study corridors may be impacted by the stated levels of storm surge in a given storm category, adjacent areas may be under greater impacts. For example, under a Category 4 storm scenario, there are parcels adjacent to the corridor that are projected to be under up to 6 ft of surge when the immediately adjacent corridor is only projected to be under up to 3 ft of surge (e.g., northeast corner of golf course for Johnson St corridor; select parcels on the eastern end of the Hollywood Blvd corridor).


Resilience Analysis Methodology Proof of Concept
Storm Surge CAT 1-5
Johnson St Corridor
Hollywood Blvd Corridor
Hollywood Boulevard Drawbridge
Hollywood
Hollywood Beach Golf & Country Club
Holland Park
North Lake
CAT 1 Storm Surge
CAT 2 Storm Surge
CAT 3 Storm Surge
CAT 4 Storm Surge
CAT 5 Storm Surge
Miles
0 0.2 0.4 0.8
Johnson St
Hollywood Blvd
Storm Surge Zones
Broward MPO Metropolitan Planning Organization
GANNETT FLEMING

Johnson Corridor - Resilience Analysis Methodology Proof of Concept
Storm Surge CAT 1-5



Johnson Corridor - Resilience Analysis Methodology Proof of Concept
Storm Surge CAT 1-5



- **Precipitation**: Stressor = Not applicable; in context of the NEMAC Climate Explorer[15] tool, which forecasts minimal changes in the days receiving greater than 2 inches of rain. Total annual precipitation is forecast to span a greater range, with slight potential increases in maximum total precipitation for most future years. Observed data from 1990 – 2010 was used as a baseline. It should be noted that in the baseline data the number of days receiving greater than 2 inches of rain exceeded three in only one year, 1999. The forecast data consistently shows the potential for more than three days a year with greater than 2 inches of rain; observed data should be monitored to determine if the days receiving greater than 2 inches of rain consistently increases. The data below is taken form the higher emissions scenario, aligning more closely than the lower emissions scenario with the RCP8.5 IPPC emissions scenario that is also referenced in the Unified Sea Level rise projection.

Hollywood Blvd & Johnson Street*					
	Precipitation				
	1990-2010 *(observed)*	**2040-2050**	**2051- 2060**	**2061- 2070**	**2090 - 2099***
Days Receiving Greater than 2" Rain	0 – 3.2	0 – 3.9	0 – 3.76	0 – 3.42	0 – 3.46
Total Precipitation for Year (in.)	45.1 – 66.4	34 - 72	31.9 – 69.5	31.5 – 67.7	27.1 – 66.5

Note: Data is only available at County level.
**Data only available thru 2099*

- **Temperature**: Stressor = Applicable; in context of the NEMAC Climate Explorer tool, which forecasts an increase in the days over 95 degrees Fahrenheit the increase in the average daily maximum temperature. The data below is taken form the higher emissions scenario, aligning more closely than the lower emissions scenario with the RCP8.5 IPPC emissions scenario that is also referenced in the Unified Sea Level rise projection.

Hollywood Blvd & Johnson Street*					
	Temperature				
	1990-2010 *(observed)*	**2040-2050**	**2051-2060**	**2061-2070**	**2090 - 2099***
Days Above 95 Degrees	2.86	50.0	67.1	81.0	130.0
Average Daily Max Temp (degrees F)	84.1	87.9	88.6	89.3	91.7

[15] National Environmental Modeling and Analysis Center (NEMAC) at the University of North Carolina Asheville developed a tool that provides interactive graphs and maps showing past and projected climate for counties across the United States. The Climate Explorer supports the U.S. Climate Resilience Toolkit, which operates under the United States Global Change Research Program, an inter-agency initiative. Two emissions scenarios, Lower (also known as RCP4.5) and Higher (also known as RCP8.5), are available in the Toolkit. For purposes of this analysis the Higher Emissions scenario was selected since RCP8.5 aligns to the IPCC scenario utilized in the Unified Sea Level Rise Projection Southeast Florida. https://nemac.unca.edu/

Note: Data is only available at County level.
**Data only available thru 2099*

Step 2: Identification of Climate / Weather Risks

The applicable climate / weather risks are described below by stressor:

- **Sea Level Rise**:
  - Inundation / Flooding (from Rising Sea Levels): water that inundates land that is normally dry due to generally rising sea levels or failure associated with dams, levees, seawalls, or other protective barrier designed to address rising sea levels.
  - Erosion (from Inundation / Flooding): the geological process in which earthen materials are worn away and transported by natural forces such as wind or water.
  - High Water Table: the process by which water tables become elevated when they receive more water than they drain off, which can be caused by landward intrusions of seawater due to rising sea levels.

Hollywood Blvd				
Climate / Weather Risk	**2050**	**2060**	**2070**	**2100**
Inundation/Flooding	No <50% affected	Yes > 50% affected	Yes > 50% affected	Yes > 50% affected
Erosion (from Inundation / Flooding)	No <50% affected	No <50% affected	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge
High Water Table	Yes, inside fresh-saltwater boundary	Yes, inside fresh-saltwater boundary	Yes, inside fresh-saltwater boundary	Yes, inside fresh-saltwater boundary

Note: The 50% threshold for yes or no was selected for this high-level analysis but can be adjusted.

Johnson St				
Climate / Weather Risk	**2050**	**2060**	**2070**	**2100**
Inundation/Flooding	No <50% affected	No <50% affected	No <50% affected	Yes > 50% affected
Erosion (from Inundation / Flooding)	No <50% affected	No <50% affected	No <50% affected	No applicable assets
High Water Table	No <50% affected	No <50% affected	No <50% affected	Yes, inside fresh-saltwater boundary

- **Storm Surge**:

  - Overtopping: water rising over barriers or beyond prior expected limits.
  - Inundation / Flooding (from elevated tidal events/storms): water than inundates land that is normally dry due to generally rising sea levels or failure associated with dams, levees, seawalls, or other protective barrier designed to address rising sea levels; or due to lack of drainage infrastructure following an event/storm.
  - Erosion (from Inundation / Flooding): the geological process in which earthen materials are worn away and transported by natural forces such as wind or water.
  - Tidal Effects: the physical impacts rendered by wave impacts from tides and high winds.
  - Erosion (from Tidal Effects): the process in which earthen materials are worn away and transported by wave impacts.

Hollywood Blvd					
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Overtopping	No <50% affected	Yes	Yes	Yes	Yes
Inundation/Flooding	No <50% affected	Yes	Yes	Yes	Yes
Erosion (from Inundation / Flooding)	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge
Tidal Effects (from wind/waves)	No <50% affected	Yes	Yes	Yes	Yes
Erosion (from Tidal Effects)	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge	Yes, related to Hollywood Blvd Bridge

Note: "Yes" because >50% affected

Johnson St					
	Cat 1	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Overtopping	No <50% affected	No <50% affected	No <50% affected	No <50% affected	Yes
Inundation/Flooding	No <50% affected	No <50% affected	No <50% affected	No <50% affected	Yes
Erosion (from Inundation / Flooding)	No applicable assets	No applicable assets	No applicable assets	No relevant assets	No applicable assets
Tidal Effects (from wind/waves)	No <50% affected	No <50% affected	No <50% affected	No <50% affected	Yes
Erosion (from Tidal Effects)	No applicable assets	No applicable assets	No applicable assets	No applicable assets	No applicable assets

Note: "Yes" because >50% affected

- **Precipitation**:

  - Inundation / Flooding (from greater than average precipitation): water than inundates land that is normally dry due to higher levels of or greater periods of intensity of precipitation.
  - Increased Water Flow / Velocity and Volume (from greater precipitation): increased water in streams and in drainage networks.
  - Erosion (from greater precipitation): increased run-off and drainage around structures.

Hollywood Blvd & Johnson Street				
	Precipitation			
	2050	2060	2070	2090
Inundation/Flooding	No	No	No	No
Increased Water Flow/Velocity and Volume	No	No	No	No
Erosion	No	No	No	No

This information on climate / weather risks for the precipitation stressor is shown for information only of the risks that are not applicable, as the stressor was determined not relevant in Step 1.

- **Temperature**

  - Extreme Heat: higher average or maximum temperatures, an increase in days above a certain temperature, or longer/hotter heat waves.
  - Heat Swings: greater differences between short-term (e.g., daily) minimum and maximum temperatures.

Hollywood Blvd & Johnson Street				
	Temperature			
	2050	2060	2070	2090
Extreme Heat	Yes	Yes	Yes	Yes
Heat Swings	N/A	N/A	N/A	N/A

Step 3: Establishment of Impacts

The possible hazards / infrastructure impacts associated with the climate / weather risks are below, and also include the typical impact type(s):

- An inventory of the assets in the study area should be compiled to obtain a better understanding of the possible hazards / infrastructure impacts. While a complete identification of the physical assets *at risk* is elicited in

Step 5 of this framework (vis-à-vis established impacts), an initial understanding of the assets within the study area is required first. Not all assets in the study area will ultimately be deemed ‘at risk’ but all assets must be inventoried in order to be assessed. For instance, a database or a GIS data layer of culverts in the study area can confirm whether there are any in the study area. An asset identification process should be performed for all possible asset types in the study area. This identification process and the establishment of impacts may be aided by a site tour of the study area. Additionally, through discussions with the community, assets may be cast in new perspectives such as realizing that a corridor is a key route for kids travelling to school, or that a community center is located along the corridor. After confirming the assets that exist in the study area, the impacts can be more comprehensively identified.

- **Sea Level Rise**:
  - Physical Impacts

Hollywood Blvd		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Inundation / Flooding (from Rising Sea Levels)	Increased risk of slope failures or closures due to prolonged flooding	Roadway; roadway bed
	Increased risk of premature degradation from water exposure	Roadway plantings; roadway lighting; roadway signage; roadway signalization and crosswalk signalization; ITS infrastructure; electrical cabinets / boxes; hand pulls / manholes, etc.; traffic control devices (bollards)
	Increased risk of premature degradation or acute damage to pedestrian and non-vehicular areas due to water exposure	Pedestrian sidewalks & amenities (pedestrian lighting, trash cans); bus shelters & amenities
Erosion (from Inundation / Flooding)	Increased risk of erosion around structural assets	Hollywood Blvd Bridge (including abutment and piers)
High Water Table	Increased risk of premature degradation due to exposure to higher salinity water	Drainage infrastructure; sewer infrastructure; public utility infrastructure;

	Increased risk of roadway embankment/subsurface destabilization and slope failures due to greater soil moisture content or ground movement	Roadway bed

Note: Bicycle and parking facilities on Hollywood Blvd are not separated from the roadway but rather they are at-grade, so are included in 'roadway' and 'roadway signage'

Johnson St		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Inundation / Flooding (from Rising Sea Levels)	Increased risk of slope failures or closures due to prolonged flooding	Roadway; roadway bed
	Increased risk of premature degradation from water exposure	Roadway plantings; roadway lighting; roadway signage; electrical cabinets / boxes; hand pulls / manholes, etc.
	Increased risk of premature degradation or acute damage to pedestrian and non-vehicular areas due to water exposure	Pedestrian sidewalks
High Water Table	Increased risk of premature degradation due to exposure to higher salinity water	Drainage infrastructure; sewer infrastructure; public utility infrastructure;
	Increased risk of roadway embankment/subsurface destabilization and slope failures due to greater soil moisture content or ground movement	Roadway bed

- **Storm Surge**:
  - Physical Impacts

Hollywood Blvd		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Overtopping	Increased risk of roadway embankment/subsurface erosion and mass wasting due to in/out-flow of water	Roadway; roadway bed
	Increased risk of premature degradation from exposure to higher salinity water	Roadway plantings; roadway lighting; roadway signage; roadway signalization and crosswalk signalization; ITS infrastructure; electrical cabinets / boxes; hand pulls / manholes, etc.; traffic control devices (bollards)

Inundation / Flooding (from elevated tidal events/storms)	Increased risk of roadway embankment/subsurface erosion and slope failures due to greater soil moisture content or ground movement	Roadway; roadway bed
	Increased risk of premature degradation from prolonged water exposure	Roadway plantings; roadway lighting; roadway signage; roadway signalization and crosswalk signalization; ITS infrastructure; electrical cabinets / boxes; hand pulls / manholes, etc.; traffic control devices (bollards)
	Increased risk of premature degradation due to exposure to higher salinity water	Roadway plantings; roadway lighting; roadway signage; roadway signalization and crosswalk signalization; ITS infrastructure; electrical cabinets / boxes; hand pulls / manholes, etc.; traffic control devices (bollards)
	Increased risk of premature degradation or acute damage to pedestrian and non-vehicular areas due to water exposure	Pedestrian sidewalks & amenities (pedestrian lighting, trash cans); bus shelters & amenities
Erosion (from Inundation / Flooding)	Increased risk of erosion around structural assets	Hollywood Blvd Bridge (including abutment and piers)
Tidal Effects	Increased risk of premature degradation due to successive wave impacts (i.e., waves in a surge and from wind gusts)	Hollywood Blvd Bridge (including abutment and piers); roadway lighting; roadway signage; roadway signalization and crosswalk signalization
	Increased risk of roadway embankment/subsurface destabilization and slope failures due to successive wave impacts	Roadway; roadway bed
Erosion (from Tidal Effects)	Increased risk of erosion around structural assets due to successive wave impacts	Hollywood Blvd Bridge (including abutment and piers)

Johnson St		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Overtopping	Increased risk of roadway embankment/subsurface erosion and mass wasting due to in/out-flow of water	Roadway; roadway bed
	Increased risk of premature degradation from exposure to higher salinity water	Roadway plantings; roadway lighting; roadway signage; electrical cabinets / boxes; hand pulls / manholes, etc.

Inundation / Flooding (from elevated tidal events/storms)	Increased risk of roadway embankment/subsurface erosion and slope failures due to greater soil moisture content or ground movement	Roadway; roadway bed
	Increased risk of premature degradation from prolonged water exposure	Roadway plantings; roadway lighting; roadway signage; electrical cabinets / boxes; hand pulls / manholes, etc.
	Increased risk of premature degradation due to exposure to higher salinity water	Roadway plantings; roadway lighting; roadway signage; electrical cabinets / boxes; hand pulls / manholes, etc.
	Increased risk of premature degradation or acute damage to pedestrian and non-vehicular areas due to water exposure	Pedestrian sidewalks
Tidal Effects	Increased risk of premature degradation due to successive wave impacts (i.e., waves in a surge and from wind gusts)	Hollywood Blvd Bridge (including abutment and piers); roadway lighting; roadway signage
	Increased risk of roadway embankment/subsurface destabilization and slope failures due to successive wave impacts	Roadway; roadway bed

- **Temperature**:
  - Physical Impacts

Hollywood Blvd		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Extreme Heat	Increased risk of premature deterioration from exposure to temperatures outside of design tolerance	Roadway; roadway plantings; bridge components; ITS infrastructure; electrical cabinets / boxes; and to a lesser extent other electrical assets
	Increased risk of acute damage to or failure of assets from exposure to temperatures or temperature durations outside of design tolerance	ITS infrastructure; electrical cabinets / boxes; and to a lesser extent other electrical assets

Johnson St		
Climate / Weather Risk	**Hazards / Infrastructure Impacts**	**Possible Assets Affected**
Extreme Heat	Increased risk of premature deterioration from exposure to temperatures outside of design tolerance	Roadway; roadway plantings; electrical cabinets / boxes; and to a lesser extent other electrical assets

	Increased risk of acute damage to or failure of assets from exposure to temperatures or temperature durations outside of design tolerance	Electrical cabinets / boxes; and to a lesser extent other electrical assets

- For All 3 Applicable Stressors - Social Impacts:
  - Based on FEMA's National Risk Index's Social Vulnerability assessment, the whole of Broward County is considered to be at a "Relatively Moderate" level of social vulnerability, the middle rating on the five-level scale. The five-level scale runs from Very Low to Very High where *lower ratings* indicate less vulnerability and are better. Based on FEMA's National Risk Index's Community Resilience assessment, the whole of Broward County is considered to be at a "Relatively Moderate" level of community resilience, the middle rating on the five-level scale. The five-level scale runs from Very Low to Very High where *higher ratings* indicate greater resilience and are better.
  - Looking at the study corridors, based on assessments at the census tract level, approximately two-thirds of the Hollywood Blvd corridor is considered to be a "Relatively Moderate" level of social vulnerability, the middle rating on the five-level scale and the remaining one-third is considered to be at a "Relatively Low" level of social vulnerability, the second-lowest rating on the five-level scale. The entirety of the Johnson St corridor is considered to be at a "Relatively Moderate" level of social vulnerability, the middle rating on the five-level scale. The entirety of both the Hollywood Blvd and Johnson St corridors are considered to be at a "Relatively Moderate" level of community resilience, the middle rating on the five-level scale.
  - Using the full FEMA formula for the National Risk Index, Broward County is considered to be at a "Relatively High" level of risk, which is calculated as: Risk Index = Expected Annual Loss × Social Vulnerability ÷ Community Resilience.
  - Looking at the study corridors, based on assessments at the census tract level, approximately two-thirds of the Hollywood Blvd corridor is considered to be at a "Relatively Moderate" level of risk, while of the remaining third, one sixth is at "Relatively Low" and another is at "Very Low". The Johnson St corridor bisects two census tracts that are at "Relatively Moderate" and "Very Low" (which are separated by the rating of "Relatively Low"); the latter of these ratings is probably depressed due to the presence of the golf course and the lower expected losses associated with damage to such.
  - As discussed further in Step 8, to more completely understand social impacts and the extent of community resilience, outreach to key stakeholders in the community should be undertaken to confirm these ratings, perform a community-level assessment (i.e., of social infrastructure located along the corridor; looking beyond transportation assets, or at least identifying the social role of the transportation assets), and to improve the understanding of potential impacts to the community.

Step 4: Identification of Proxy Indicators

Proxy indicators provide a data-driven means of identifying locations susceptible to the negative impacts of climate and weather-related risks and can serve as possible root causes of negative impacts to systems and assets. They require an understanding of the relationship between climate stressors, risks, hazards, and impacts. Geospatial analysis is an effective tool in the identification of locations that experience frequent weather-related impacts and that may be susceptible to projected future climate change impacts. Proxy indicator data can be sourced from a geodatabase that identifies and catalogues locations that experience repeated weather-related incidents.

The identification of proxy indicators is intended to aid in the identification of the specific assets (of the total candidates identified previously) that are at risk. By definition, a proxy indicator does not indicate a causal or definite relationship between the indicator and an actual risk; however, when using historical data and accurate geospatial data, proxy indicators can be reliable. Key recommended proxy indicators are listed below, by stressor (and include examples of assets that may be at risk):

- **Sea Level Rise**:
  - Locations of known flooding issues – all assets (e.g., by 2050 with approximately 2 feet of SLR at the intersection of 14th Avenue and Hollywood Blvd. 14th Ave. is nearly completely inundated and Hollywood Blvd. is partially inundated).
  - Areas of lower topography (relative to rest of corridor, as well as surrounding areas) – all assets
  - Areas of elevated water tables; Locations of underground infrastructure impacted by water intrusion – underground assets, roadway bed, structural asset foundations

- **Storm Surge**:
  - Locations of known flooding / surge issues – all assets
  - Locations of known flooding / surge issues, overtopping events, or embankment/slope failures – roadway and roadway bed
  - Locations of critical systems impacted by water intrusion – underground assets

- **Temperature:**
  - Assets with known issues of being impacted by temperature
  - Projected temperature changes within the lifecycles of installed assets

Step 5: Identification of Physical Assets at Risk

Without the availability of specific proxy indicators or understanding of what potential projects are otherwise under consideration, it is assumed that all assets present in each corridor are "at risk." The assets at risk are listed below, by corridor

- Hollywood Blvd: roadway; roadway bed; roadway plantings; roadway lighting; roadway signage; roadway signalization and crosswalk signalization; ITS infrastructure; electrical cabinets / boxes; hand pulls / manholes, etc.; traffic control devices (bollards); pedestrian sidewalks & amenities (pedestrian lighting, trash cans); bus shelters & amenities; Hollywood Blvd Bridge (including abutment and piers); Drainage infrastructure; sewer infrastructure; public utility infrastructure.
- Johnson St: roadway; roadway bed; roadway plantings; roadway lighting; roadway signage; electrical cabinets / boxes; hand pulls / manholes, etc.; pedestrian sidewalks; drainage infrastructure; sewer infrastructure; public utility infrastructure.

This step also requires the identification of physical assets and characteristics of the study area that may be relevant to the ultimate identification and selection of response strategies, for instance assets or areas that may be able to improve the ability to implement a response strategy (e.g., undeveloped land).

Step 6: Performance of Root Cause Analysis

Root cause analysis builds upon the identification of proxy indicators, which can serve as possible root causes of negative impacts to systems and assets. Thus, the root cause analysis validates a potential linkage from climate stressors and their risks to hazards and potential negative impacts. Since specific proxy indicators were not available, the root cause analysis was excluded due to lack of specific asset data or events for which to examine root causes.

One outcome of a root cause analysis is to validate the full list of climate / weather risks as a source of risk identified in Step 3. Root cause analysis would describe the evaluation of a system or asset's lifecycle stages to determine the factors directly contributing to the negative impact to the system or asset. Results of a root cause analysis may determine that flooding is not caused by sea level rise in a particular geographic area but rather by local low points and / or other drainage issues.

Step 7: Identification & Selection of Response Strategies

This step utilizes the Resilience Toolbox developed as part of the overall framework in order to identify response strategies for the applicable stressors, climate / weather risks, and impacts outlined in the prior steps.

- **Seal Level Risk & Storm Surge**: In consideration of the full listing of assets at risk, as well as the identified climate / weather risks and impacts, 23 response strategies were identified for further analysis. The response strategies often address more than one impact and ultimately stressor. For the purposes of the proof of concept, the strategies have been placed into seven groupings and are listed below. Given the data available for this application of the framework, all identified strategies are applicable to both corridors with the exception of Proof of Concept ID (POC) ID#'s A, B, and C, which are only applicable to the Hollywood Blvd corridor (Note: the POC ID#'s are only applicable within this report, and not related to strategy numbers in the full toolbox). Additionally, while applicable to both corridors, POC ID#'s P through U are particularly relevant for Johnson St due to the proximity of the golf course and its ability to serve as a means of water uptake/retention.

POC ID#	Adaptation Strategies
Flood Walls *(only applicable to Hollywood Blvd.)*	
A	-Design armoring / flood walls that can be heightened in the future with minimum additional expense
Bridge Modifications *(only applicable to Hollywood Blvd.)*	
B	-Increase bridge heights and / or increase hydraulic openings for waterways, and to improve conveyance to reduce scour
C	-Modify bridges to tie decks more securely to substructures and strengthen foundations
Elevation/Relocation	
D	-Realignment and / or raising the road out of the floodplain
E	-Relocate or elevate ancillary assets / equipment for structural facilities (i.e., that is NOT co-located)
F	-Relocate or elevate structures / co-located infrastructure, especially if flood prone
Overtopping, Scour, and Erosion Prevention	
G	-Install roadway overtopping scour protection: for example, one or more of reinforced vegetation, geotextiles, roller-compacted concrete, soil cement, cast-in-place concrete, articulating block concrete sublayers, 'rip-rap', etc.
H	-Articulated concrete block revetment system to protect against storm surge
I	-Use 'rip-rap' (placing large blocks at the base of the bridge piers) to protect the foundation footings and piers from 'bridge scour' (the direct impact of water flow)
J	-Use native vegetation for outfall protection
K	-Utilize and replace outfall scour protection measures (e.g., fill material, geotextile fabric)
Drainage System Improvements	
L	-Upgrading of stormwater drainage system
M	-Install additional drainage inlets
N	-Install debris guards / racks
O	-Maintenance of stormwater drainage system

P	-Install backflow preventers and/or stronger pumps to prevent wastewater backflow
Improved Water Uptake Abilities *(particularly relevant for Johnson St.)*	
Q	-Install / construct parks and waterfront areas adjacent to roadways to accommodate flooding
R	-Install / construct parks and waterfront areas to accommodate flooding
S	-Install / construct walkways to be able to flood
T	-Increase permeable surface acreage or incorporate green infrastructure to support distributed take-up of moisture
U	-Construction of storm retention basins for short, high intensity storms, i.e., flash flooding
V	-Install riparian buffers along corridors, or restore natural streams
Improved Material Capabilities	
W	-Reconsider material composition and resistance to new environmental conditions (e.g., salinity) during preservation, rehab, and reconstruction work
X	-Reconsider material composition and resistance to new environmental conditions (e.g., salinity, acidification, etc.), including liners and coatings, during preservation, rehab, and reconstruction work

Another summary of the possible response strategies is shown below by the stressor and climate / weather risk, demonstrating how a strategy may address multiple impacts as part of the identified risks/stressors. For instance, the "3" in row L (i.e., Upgrading of stormwater drainage system) for the "Inundation / Flooding" risk addresses impacts from: 1) premature degradation due to prolonged water exposure, 2) premature degradation due to exposure to higher salinity water, and 3) roadway subsurface erosion/slope failures as a result of prolonged soil moisture content.

	Storm Surge (# of impacts addressed by adaptation strategy)					Sea Level Rise (# of impacts addressed by adaptation strategy)			Grand Total
POC ID#	**Erosion (from Inundation / Flooding)**	**Erosion (from Tidal Effects)**	**Inundation / Flooding**	**Overtopping**	**Tidal Effects**	**Erosion (from Inundation / Flooding)**	**High Water Table**	**Inundation / Flooding**	
A		1		1					2
B	1		2			1	1	1	6
C		1			1				2
D			3				2	2	7
E			2		1		1	1	5
F	1	1	2		1	1	1	1	8
G			1	2	1				4
H	1			1					2
I						1			1
J	1	1	1	1	1	1			6
K	1			1	1	1			4
L			3	1			1	1	6
M			2						2
N			1			1			2
O			3	1			1	1	6
P	1		1			1			3
Q							1	1	2
R			2					1	3
S			1					1	2
T			1				1	1	3
U			2						2
V						1	1	1	3
W				1					1
X			1				1		2
Grand Total	**6**	**4**	**28**	**9**	**6**	**8**	**11**	**12**	**84**

- **Temperature**: In consideration of the full listing of assets at risk, as well as the identified climate / weather risks and impacts, 10 response strategies were identified for further analysis. Two of the response strategies address both impacts (T1 and T2), meaning the strategies address the potential impacts of premature deterioration and temporary / permanent asset failure, both resulting from exposure to temperatures beyond design tolerances. For the purposes of the proof of concept, the strategies are listed below. Given the data available for this application of the framework, all identified strategies are applicable to both corridors

POC ID#	Adaptation Strategies
Improved Heat Tolerance	
T1	-Reconsider material composition and resistance to higher heat during preservation, rehab, and reconstruction work
T2	-Install bridge expansion joints that can withstand higher levels of heat
T3	-Proactive replacement of highway and bridge expansion joints
T4	-Overlay roads with “rut-resistant” asphalt to combat softening
T5	-Install concrete pads in roadway (e.g., at locations with repeat acceleration / deceleration such as intersections, bus stops, loading / unloading zones) to prevent rutting on hot days
T6	-Upgrade asphalt performance for new, warmer conditions
T7	-When repaving occurs, adjust paving mix as needed. Consider utilizing cooler pavements (e.g., light-colored aggregate) to reduce surface temperatures
T8	-Install high-reflectivity hardscape when resurfacing roads and parking lots
T9	-Install a biodiverse array of native street trees on sidewalks and medians, whose canopies will shade and cool down the area
T10	-Add redundancy to reduce impacts to the system

A key consideration associated with evaluating response strategies is the relative implementation cost and time horizon until the benefits of a response strategy can be realized. Understanding the immediacy of a need for a response strategy will help balance the selection of response strategies based on the time horizons until benefits are realized. The preliminary assessments of cost and time are summarized below by response strategy; however, these will need to be revisited once closer to a program-ready project.

POC ID#	Adaptation Strategies
Flood Walls	
A	Low Cost, Medium Horizon
Bridge Modifications	
B	High Cost, Long Horizon
C	High Cost, Long Horizon
Elevation/Relocation	
D	High Cost, Long Horizon
E	Low Cost, Short Horizon
F	High Cost, Long Horizon
Overtopping, Scour, and Erosion Prevention	
G	Moderate Cost, Medium Horizon
H	Low Cost, Short Horizon
I	Moderate Cost, Short Horizon

J	Low Cost, Medium Horizon
K	Moderate Cost, Short Horizon
Drainage System Improvements	
L	Moderate Cost, Medium Horizon
M	Moderate Cost, Medium Horizon
N	Low Cost, Short Horizon
O	Low Cost, Short Horizon
Improved Water Uptake Abilities	
P	Moderate Cost, Medium Horizon
Q	Moderate Cost, Medium Horizon
R	Low Cost, Medium Horizon
S	Low Cost, Short Horizon
Z	Moderate Cost, Medium Horizon
U	Moderate Cost, Medium Horizon
Improved Material Capabilities	
V	Low Cost, Medium Horizon
W	Low Cost, Medium Horizon

POC ID#	Adaptation Strategies
Improved Heat Tolerance	
T1	Low Cost, Medium Horizon
T2	Low Cost, Short Horizon
T3	Low Cost, Short Horizon
T4	Moderate Cost, Medium Horizon
T5	Moderate Cost, Short Horizon
T6	Low Cost, Medium Horizon
T7	Low Cost, Medium Horizon
T8	Low Cost, Short Horizon
T9	Low Cost, Medium Horizon
T10	Moderate Cost, Medium Horizon

Step 8: Review of Additional Considerations

Key areas of additional consideration, which are discussed further below, include the following impacts to: mobility, safety, operations, and the community. Maps of current and future land use for the influence area of the proof of concept corridors are provided below for further context related to the key areas of additional consideration.

- **Mobility**:

  - Hollywood Blvd: The corridor is a key east-west arterial in southern Broward County, connecting Young Circle and the beach areas. The corridor is also served by Broward County Transit bus route #4, which at Young Circle connects with several other bus routes (e.g., 1, 7, 8, 9, and the U.S. 1 Breeze). Furthermore, this corridor is identified as a hurricane evacuation route. Finally, the AADT along the corridor ranges from 9,400 vehicles on the western end (i.e., Young Circle to 14th St) up to 15,252 on the eastern end, which is only exceeded in east-west vehicle volume by SR 822 and SR 858, 1,5 miles and 1.8 miles to the north and south, respectively. The north-south connections along the corridor consist of minor connectors / local roads. Beyond the role that this corridor serves within the broader transportation network, in the context of the identified climate / weather risks and impacts, it is worth noting that many of the north-south connector roads are projected to be impacted prior to or more severely than the Hollywood Blvd corridor itself. Thus, implementing response strategies along the corridor may be best served by also implementing them on at some of the connectors / local roads. A broader evaluation is required to determine if investments solely on the Hollywood Blvd. corridor are worthwhile if many (or all) connections, and possibly beach destinations, are impacted to a similar or greater extent than Hollywood Blvd. itself.
  - Johnson St.: The corridor is a minor east-west arterial in southern Broward County, connecting U.S. 1 and the neighborhoods to the east. The AADT along the corridor is estimated to be 6,300 vehicles. The north-south connections along the corridor consist of minor connectors / local roads. Beyond the role that this corridor serves within the broader transportation network, in the context of the identified climate / weather risks and impacts, it is worth noting that many of the north-south connector roads are projected to be impacted prior to or more severely than the Johnson St. corridor itself. Thus, implementing response strategies solely along the Johnson St. corridor may be best served by also implementing them on some of the connectors / local roads. A broader evaluation is required to determine if investments in solely on the Johnson St. corridor are worthwhile if many (or all) connections, and possibly beach destinations, are impacted to a similar or greater extent than Johnson St. itself.

- **Safety**:

  - Hollywood Blvd: As indicated previously, the corridor is a hurricane evacuation route, thus, until a time when there may be no residents to the east, it serves an important role in ensuring public safety during extreme weather events. In the context of the identified climate / weather risks and impacts, any potential response strategy should improve (or not diminish) the level of safe travel through the corridor. For instance, the need to improve drainage at a low point along the corridor (e.g., before the Hollywood Blvd Bridge) may be prioritized over other response strategies in importance if repeat flooding events and / or crashes occur as a result of such flooding. The safety of non-automobile travelers such as pedestrians, transit riders, or cyclists will also need to be considered during the prioritization of response strategies.

- Johnson St.: In the context of the identified climate / weather risks and impacts, any potential response strategy should improve (or not diminish) the level of safe travel through the corridor. For instance, the need to install overtopping / scour protection along the corridor may compete with right-of-way dedications for pedestrian or cycling uses. The safety of non-automobile travelers such as pedestrians, transit riders, or cyclists will also need to be considered during the prioritization of response strategies.

- **Operations**:

  - For both corridors, the extent to which a response strategy can reduce the burdens placed upon operational crews to respond to possible impacts is important. For instance, if maintenance crews find they are cleaning out the storm grates on either corridor much more frequently, then installing debris guards can free up the crews to address other issues. Similarly, if low-area flooding occurs frequently, the effort associated with closing lanes or the entire corridor (and then supporting a detour) would also be required; therefore, addressing the source of flooding could alleviate this need.

- **Community**:

  - For both corridors, the three main veins of community impacts can be categorized under economic / land use impacts and social infrastructure / environmental justice considerations. For the first, the prioritization of a response strategy must consider the potential impacts upon land values and uses that it may impact. Typically, the absence of a response strategy can be expected to have negative impacts; however, certain response strategies may require easements, or other takings (i.e., infringements upon the best use of the land). For the second, engagement with the community is an important step to establishing the role of the corridor as a connection and / or destination (e.g., location of a church, community center, or child services). For instance, First Presbyterian Church, which also houses a preschool and early learning center is located on Hollywood Blvd; moreover, the corridor serves as a connector to other neighborhood churches via north-south local roads. From an environmental justice perspective, the economic, land use, and social infrastructure impacts should ideally not be borne (or provided) unevenly to communities facing the same risks and impacts.

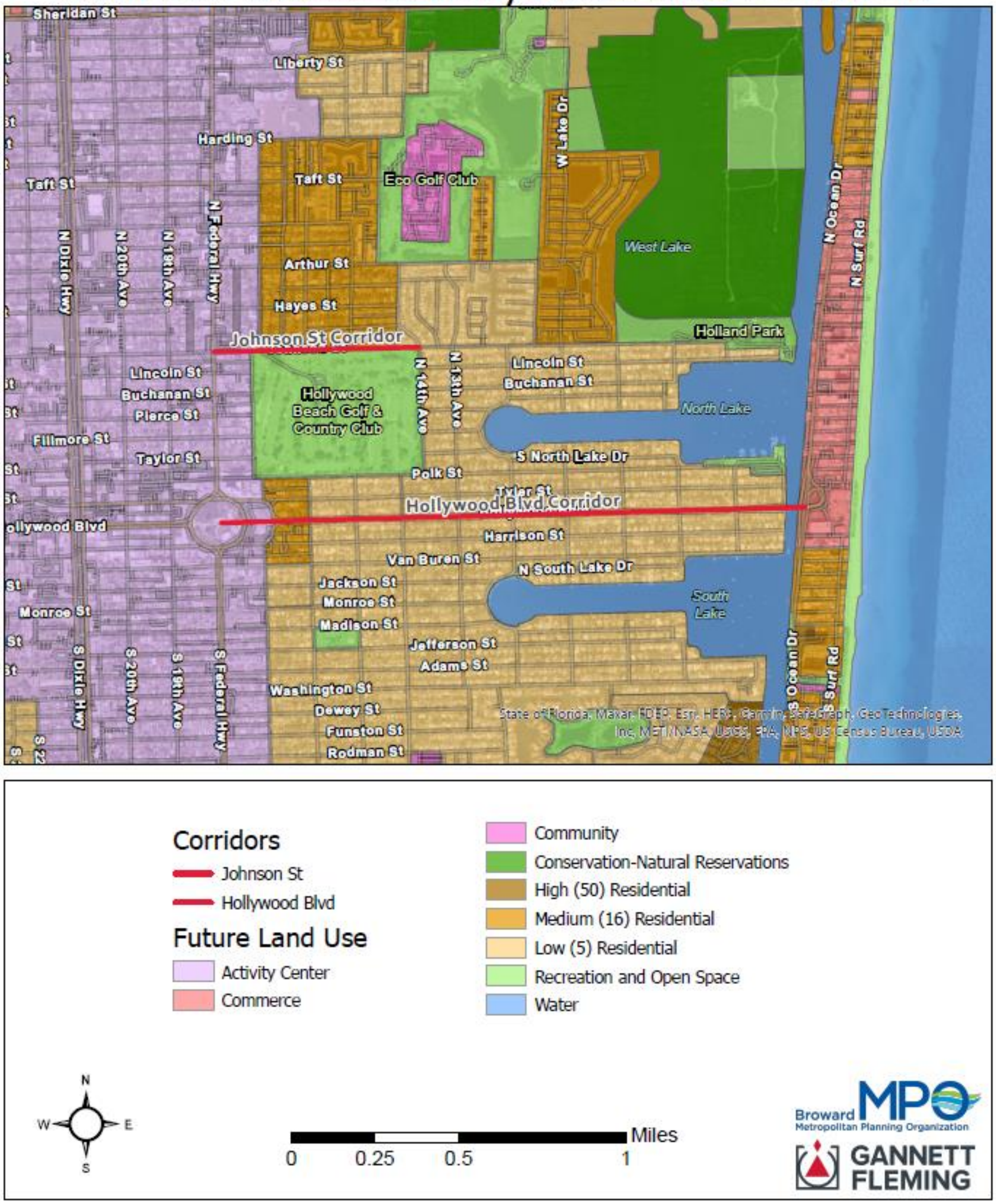
- Benefit-Cost Analysis (BCA) and assessment of Programmatic Considerations – not reviewed as part of proof of concept due to lack of specific benefit and cost elicitation and determination of MPO (or other project sponsor) organizational practices for performing BCA. Generally, a good starting point for a BCA is the USDOT guidance for the TIGER Discretionary Grant Program contained in the TIGER Benefit-Cost Analysis (BCA) Resource Guide. Additional benefits and costs beyond those specified in the TIGER BCA Resource Guide should also be considered and will vary based on the influence area, adaptation strategies, assets, risks, and impacts.

Step 9: Identification of Program-Ready Projects

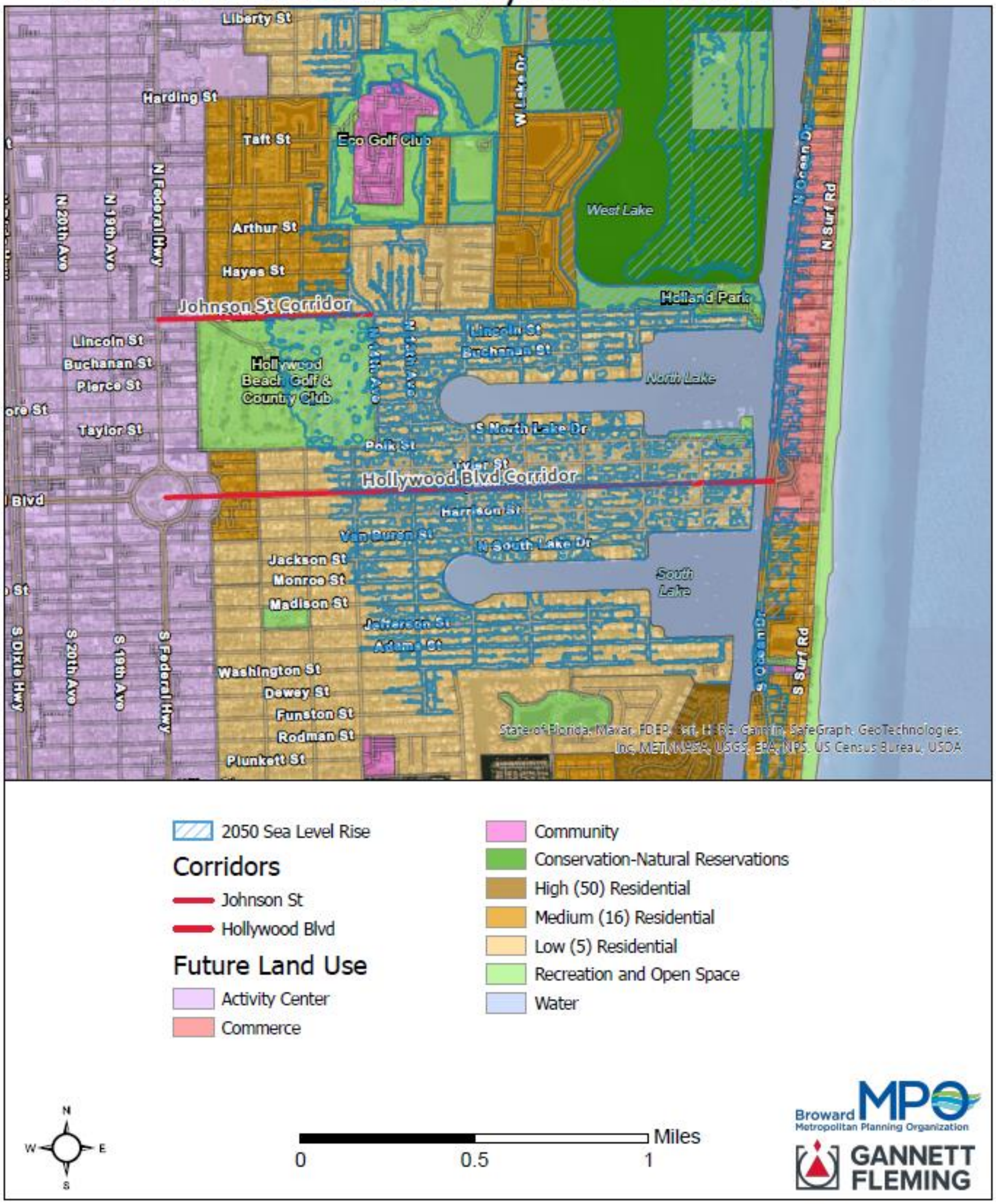
The identification of program-ready projects requires a complete application of this framework. Given the data gaps indicated previously, and the steps skipped for the POC, no program-ready projects can be identified at this time. However, incorporating resilience into the transportation network can be accomplished through the either the identification of a program-ready project that is prioritized based on the discrete need for a response strategy, or the incorporation of a response strategy as a part of a broader project.

Current Land Use
Johnson Street & Hollywood Blvd Corridors

Future Land Use
Johnson Street & Hollywood Blvd Corridors



Future Land Use & 2050 SLR
Johnson Street & Hollywood Blvd Corridors



Appendix B: Technical Working Group (TWG) Presentation

The third TWG meeting presentation that was given on April 12th, 2022 is available on the MPO website.

Appendix C: Responses to TWG Member Comments on Technical Working Group Presentation

Response to TWG member comments on the framework presentation are provided in the table below.

Comment	Response
The 8 resiliency projects in the MTP – is this framework more general or are those project a test of the framework?	The 8 corridors identified in the 2045 MTP will be used to test the framework. Identifying corridors in the MTP was too high level so it was determined a more detailed analysis is required for resiliency.
Definitions (Hazards is more consequences than hazards) Ensure definition page and source	The Tech Memo contains a glossary that defines hazard as an event or condition that may cause injury, illness, or death to people or damage to assets. Hazards are linked to stressors, which are defined as a condition, event, or trend related to climate variability and change that can exacerbate hazards.
We need to be able to look at silos but at the end of the day, we are looking at stressors in combination. Future conditions maps that consider multiple factors and compounding effects.	The framework and analysis methodology presented anticipates multiple stressors with the toolbox providing a menu of possible actions that then need to be prioritized based on risk and other factors.
Request to add increased water flow / velocity and volume as a risk under SLR and a request to add accelerated asset deterioration of metal structures and material due to increased saltwater exposure in establish impacts.	Increased water flow velocity and / or volume is defined in the Tech Memo as a risk that occurs due acute events such as flash floods and other high-volume, short-duration precipitation events so this risk is not considered for SLR. The potential effects of increased saltwater exposure to metal structures resulting in increased deterioration is not considered since metal structures along the coast should already be designed to withstand saltwater spray. The risk of a high water table due to sea level rise is considered.

Coordination with partners appears assumed in this framework and it should be more clearly specified when and where in the process participation from partners is required. The most likely partners are the roadway owners.	The Tech Memo describes the need to identify stakeholders at the outset of the process and specifies which steps require further consultation and engagement with the identified stakeholder group. Responsibilities of project sponsors are outlined and in many cases the end physical infrastructure asset owners are the likely project sponsors.
Reiteration that establishing common definitions in the glossary is important. The references used to identify the stressors are important for consistency. Do we plan to reference specific resilience-related guidelines, ordinances, and regulations such as the Broward County Seawall Regulation? What guidelines do you use? Also, in regards to the implementation of the efforts, what are the long-range impacts?	The resilience framework and process as presented and described in the Tech Memo is not asset, site, location or project specific and thus does not reference particular guidelines, ordinances, and regulations. However, the need to identify, engage, and consult with relevant stakeholders is part of the process and through this stakeholder engagement and consultation relevant guidelines, ordinances, and regulations should be identified. In terms of adaptation strategy implementation and potential long-range impacts, the framework calls for the establishment of a benefits realization framework that includes success metrics and assumed benefit return periods for projects.
Recently there was an ice shelf collapse in the Antarctic. How will these sorts of unexpected events be considered?	This will be an ever-evolving framework. We are using the latest climate change models and projections consistent with those adopted by the South Florida Regional Climate Change Compact. As these models and projections are updated this framework will be updated accordingly. Typically, projections are updated after the IPCC updates its emissions scenarios every 6 to 7 years. Adaptation strategies are also selected based on a range of possible outcomes and a risk-based approach in an effort to account for some level of uncertainty.
What is already planned for the 8 resilience corridors from the 2045 MTP? If there are already plans to invest substantial amounts of money in those corridors perhaps it would be worthwhile to undertake additional analysis prior to committing to investments. Connectivity is also	Delaying decision making until additional information is available is known as real options analysis and in certain instances can be a valuable approach. However, there is also a need to balance delaying decision making with the long project time horizons for many infrastructure projects and the inherent uncertainty in the analysis of climate change

important so there is not just a view of one's city. Coordination and cooperation across jurisdictional boundaries are important.	projections. Coordination and cooperation across jurisdictional boundaries are important. As part of the framework there is consideration of prioritizing investments where partners are proactive and cooperative.
It is unclear why or how social vulnerability and community resilience are considered and what these terms mean. Considering land use and zoning is further into the process even though projects could impact adjacent development. Consider earlier consideration of land use and zoning.	Community resilience and social vulnerability are defined in the glossary of the Tech Memo. These are relatively new concepts and considerations in climate change adaptation planning but they are increasingly important and are receiving greater attention from funding sources. While land use and zoning are considered later in the process, there are feedback loops so that particular issues related to land use and zoning could potentially trigger a reevaluation of the selected adaptation strategies.
It was noted that the SFWMD planned to launch new rainfall projects on April 27th.	Staff members of the Broward MPO planned to attend the SFWMD event.
Post-Meeting Comments	
General: Program-ready projects - Will such projects include projects with a resilience/adaptation component and standalone resilience/adaptation projects?	The framework intends to consider whether or not resilience can be considered as part of most or all projects in identified analysis areas such as the 8 resilience corridors in the 2045 MTP but the framework also can result in standalone resilience projects.
Slide 5: You previously explained that groundwater table rise falls under the sea level rise stressor. This could create the impression that groundwater table rise is limited to the coast. I recall a presentation on the results from modeling of surface and groundwater interactions done by Broward County with the USGS which showed, as expected, the highest groundwater table rise at the coast (1' rise in the groundwater table with a 1' rise in sea level) but also showed groundwater table rise extending a considerable distance inland. It seems saltwater intrusion also should be recognized as part of the picture with	While the high water table risk is linked to the SLR stressor in the framework, the potential causes of high water table as defined in the Glossary of the Tech Memo include high amounts of rainfall, seasonal changes, and landward intrusions of seawater due to sea level rise in coastal areas. As noted in the comment, the greatest amount of groundwater table rise is expected along the coast. The framework intends to consider the predominant risks for each stressor. Over time, as the state of climate change science continues to evolve then high water table could also be considered with the precipitation stressor.

potential impacts to pavement subgrades, etc. County staff and SFWMD staff may have already weighed in on all of this and obviously are best situated to speak to these subjects.	
Slide 6: With a rising groundwater table reducing soil storage/infiltration capacity and current and growing concerns with the functionality of largely gravity-driven drainage systems in the county (including the primary drainage system operated by the SFWMD), should reduced drainage capacity be noted somehow in relation to the inundation/flooding climate-related risk under Precipitation and Sea Level Rise? Should saltwater intrusion be added under Sea Level Rise?	The toolbox links potential hazards and physical infrastructure impacts to climate and weather-related risks that are linked to stressors. It is acknowledged there can be overlapping hazards and risks across stressors. Asset damage and / or failure as well as premature asset degradation due to increased salinity are considered and linked to multiple risks and stressors. Root cause analysis should inform whether a particular adaptation strategy is appropriate to address the underlying problem associated with a particular hazard-risk-stressor (e.g., saltwater intrusion in groundwater or reduced drainage capacity).
Slide 7: Consider expanding Mobility Impacts/Reduced Mobility to include accessibility as the ability to reach desired destinations (Mobility and Access Impacts/Reduced Mobility and Access). The reference to examples of practice tools brings to mind additional tools applied in studies such as the USACE South Atlantic Coastal Study or SACS (e.g., for Tier 1 and Tier 2 risk assessments). Does the framework provide for recognizing and capturing, as appropriate, completed or pending complementary work?	The framework is broadly defined in order to accommodate a variety of potential adaptation strategies and site-specific considerations. Mobility impacts are broadly defined in the Tech Memo to include temporary or permanent disruptions, including detours. An exhaustive listing of relevant completed and pending studies was not compiled as part of the framework definition. However, relevant prior and pending efforts should be identified when engaging and consulting with the identified stakeholder group.

Slide 8: Should quality of life be added to the last bullet on adverse effects?	The bubble graphic depicting the linkage between climate and weather-related risks, hazards, impacts, and costs is illustrative and is noted as such in the Tech Memo. The identification and quantification of benefit / cost categories, such as quality of life, would need to be addressed on a case-by-case basis in the performance of a benefit-cost analysis. Reduction in quality of life could be considered as part of direct and / or indirect social and economic costs.
Slide 13: Will the MPO's toolbox be coordinated with/supplemented by other toolboxes/tools (e.g., FDEP's web-based Sea Level Impact Projection (SLIP) studies tool which identifies potential adaptation strategies and the SACS Library of Measures and Cost)?	For purposes of this Transportation Resiliency Framework Study the toolbox was prepared as a standalone product that considered the state-of-the-practice in terms of adaptation strategies. Over time, the toolbox should evolve to include additional adaptation strategies and consider updated research. Eventually the toolbox may evolve into a more user-friendly, web-based tool.
Slide 14: Suggested addition: "dynamic, risk-based approach."	This suggestion was noted. In the Tech Memo there is additional detail regarding risk-based approaches including probabilistic assessments, which are dynamic in nature.
Slide 15: Does the broader transportation network extend into neighboring counties (consistent with climate change impacts not following county lines)? Should a bullet be added on consideration of/coordination with plans, actions, and investments of local, state, or other partners (e.g., county and municipal governments conducting vulnerability assessments and implementing resilience-related projects, development of the county resilience plan, etc.)? Another consideration might be engagement of the business community. One example is the Palm Beach North Resilience Action plan being developed through a collaborative effort involving 10 municipalities and the Palm Beach North Chamber of	This suggestion was noted. The identification of the stakeholder group is not, and should not, be constrained to particular jurisdictional boundaries. Including the business community and surrounding jurisdictions is a good suggestion. The Tech Memo provides greater detail on benefit-cost analysis approaches. USDOT's approach for TIGER Grants is referenced as the standard but this approach is broad, flexible, and capable of incorporating a variety of factors.

Commerce. Stormwater management efforts also might be considered, including those being pursued by the SFWMD (e.g., identification and implementation of adaptation strategies by basins as part of the agency's Flood Protection Level of Service Program). The mention of benefit-cost calculations relating to adaptation strategies brings to mind Volpe Center work on this subject.	
Slide 16: Regarding extra weight for "willing, capable partners," suggest providing for the possibility of willing partners that lack capability (because of limited staff, etc.) and could benefit from technical or other assistance.	This suggestion was noted. The Tech Memo provides greater detail on programmatic considerations. Results of the proof of concept indicate that the lack of data, and the capability and resources to provide required data, is a known issue for several of the resilience corridors identified in the 2045 MTP.

Appendix D: Template Memorandum of Understanding (MOU)

This appendix provides a template MOU that the Broward MPO can use a foundation when it considers entering into a MOU with other entities for actions that support resiliency in decision making. The structure below describes the purpose and need of the MOU as well as the roles and responsibilities of the respective parties related to supporting resiliency actions in planning and project development.

RESILIENCE ADAPTATION ACTIONS

MEMORANDUM OF UNDERSTANDING (MOU)

This Memorandum of Understanding (MOU) is made and entered into as of (**INSERT MONTH and DAY**, **YEAR**) by and between the Broward Metropolitan Planning Organization (MPO), and the (**INSERT NAME OF PARTY 2**), collectively referred to as the "Parties".

I. Background

A. Broward MPO recognizes that climate change presents risks and exposes vulnerabilities that threaten long-term human and environmental health, social wellbeing, the economic vitality of the community. Therefore, the Broward MPO has resolved to take action by developing and implementing resilience actions to mitigate possible risks and increase system resilience.

B. Broward MPO defines resiliency as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

C. In 2015 the Broward MPO, and its partner MPOs in Miami-Dade and Palm Beach Counties, along with Monroe County, completed the FHWA-sponsored project, *South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project* (Pilot Study), to conduct climate change and extreme weather vulnerability assessments of the regional transportation network from sea level rise, storm surge and heavy precipitation-induced flooding, and to analyze options for adapting and improving resiliency. Following this Pilot Study, in 2016 the Broward MPO conducted the *Extreme Weather and Climate Change Risk to the Transportation System in Broward County Florida* (Second Phase Study) to define the parameters of climate change. The Second Phase Study focused on effects of climate stressors on the Broward County roadway network and added the effects of climate change on temperature and how changes in temperature affect transportation infrastructure. Expanding on the findings of these two studies, the Broward MPO conducted a Transportation Resiliency Framework Study (Framework Study) to identify and address network vulnerabilities from climate change, and to support incorporation of preparedness into project planning, design, and construction. The MPO intends to use the Framework to enhance resiliency planning in the MPO's 2050 Metropolitan Transportation Plan and future efforts.

D. Broward MPO is continuously engaged in regional resiliency initiatives to collaborate and enhance resiliency practices that support the MPO's goals (Move People and Goods, Create Jobs, Strengthen Communities). This collaboration and associated efforts are helping to incorporate resilience into the decision-making process.

II. Statement of Purpose

A. By working together, agreements between counties, cities, and local communities can help to accelerate the response to climate change and enhance the South Florida Region's resilience. In 2009, the Southeast Florida Regional Climate Change Compact (Compact) was established as a partnership between Broward, Miami-Dade, Monroe, and Palm Beach Counties, to work collaboratively to reduce regional greenhouse gas emissions, implement adaptation strategies, and build climate resiliency across the Southeast Florida region. The Compact published its first Regional Climate Action Plan (RCAP) in 2012 with the intent to update every five years. RCAP 2.0 was released in 2017 and RCAP 3.0 is being developed in 2022.

B. System resiliency can be improved by additional collaboration and by taking actions at the planning level and / or as part of project development, where a variety of resilience-related adaptation strategies could be considered and implemented.

C. Broward MPO's Resiliency Toolbox can be used a starting point to support the identification of adaptation strategies that can improve system resiliency.

D. National research and local experience have shown that the impacts of climate change tend to disproportionately impact marginalized communities, such as communities of color, low-income communities, the elderly, and people experiencing disabilities.

III. Responsibilities

Through this MOU, the "Parties" agree to:

A. Coordinate and cooperate to ensure that resiliency adaptation actions developed are equitable and address the needs of Broward County communities.

B. Collaborate on actions to promote adaptation and resiliency, with a focus toward maximizing benefits for climate adaptation.

C. Use the best available data, frameworks, processes, and tools to address the impacts of climate change on systems / assets and to address the benefits and costs of different resiliency adaptation actions (e.g., maintenance activities, infrastructure improvement projects, operational activities, etc.).
D. Establish data requirements when required data is not available and determine the party responsible for data gathering.
E. Consider natural or "green" infrastructure solutions that maximize ecological benefits while providing protection when identifying resiliency adaptation actions.
F. Apply the standard resilience analysis methodology established in the Broward MPO's Transportation Resiliency Framework Study to projects reviewed and evaluated by the Broward MPO.
G. Make reasonable efforts to incorporate resiliency considerations in project planning, design, and delivery when particular adaptation strategies are identified for projects, including the modification of design guidelines and / or standards to account for the best available climate change projection data for sea level rise, storm surge, temperature, precipitation, and other applicable stressors.

The particular responsibilities of Broward MPO are as follows:

A. Support the execution of the standard resilience analysis methodology, providing data and other resources to the extent practical.
B. Make the Resiliency Toolbox available to provide an initial listing of candidate adaptation strategies.
C. Identify the best available climate change projection data for sea level rise, storm surge, temperature, precipitation, and other applicable stressors, using the measures in the Compact when possible.
D. Support the determination of which future emissions scenarios and time horizons should be applied when considering the medication of design guidelines and / or standards.
E. Provide support and coordination as it relates to identifying, engaging, and communicating with stakeholders who are typically involved in resiliency-related actions and decision making.

The particular responsibilities of (**Party 2, e.g., State, County, city / local government**) are as follows:

A.
B.

IV. Means of Implementation

The "Parties" each act towards their own strategies to implement and achieve their individual and regional goals and targets. While some strategies will be unique to particular "Parties", others can be shared and/or modified by other "Parties" including through resiliency-related adaptation projects.

A.

B.

V. Agreement Period

The "Parties" agree to review the on-going relevance of the MOU every (**Insert Years**).

THE UNDERSIGNED, BY EXECUTION OF THIS MEMORANDUM OF UNDERSTANDING, HEREBY ACKNOWLEDGE THAT EACH HAS READ THIS AGREEMENT, UNDERSTANDS IT, HAS THE REQUIRED LEGAL AUTHORITY OF THE SIGNER'S GOVERNING BODY TO EXECUTE IT, AND AGREES TO ITS TERMS AND CONDITIONS.

Broward MPO

____

Signature

____

Title

Date: ____________________________

(Insert Party 2)

____

Signature

____

Title

Date:_____________________________

Appendix E: Case Studies

The three case studies described below were selected to provide examples of resiliency-related actions in other communities that are applicable to the Broward MPO. The Roadway Base Clearance Study is the closest geographically and highlights the importance of developing site-specific data for engineering design considerations. For example, there are substantial differences between the rates of sea level rise in the Lower and Upper Keys. This case study also demonstrates that design guidelines and standards may not account for the most up-to-date climate projections.

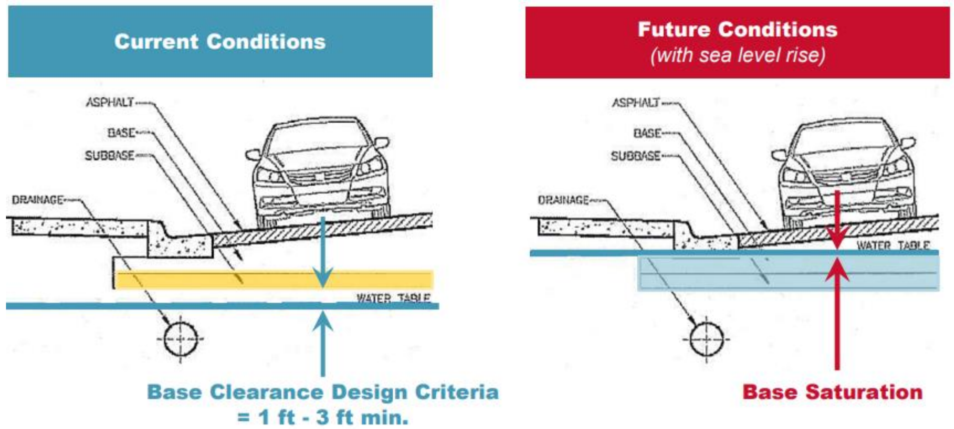
Case study two describes lessons learned in the New York City region after Hurricane Sandy and how the region has been preparing for future storms. Transportation system resiliency was analyzed at the regional, subarea, and facility levels. How one MPO, the North Jersey Transportation Planning Authority (NJTPA), defines communities of concern / environmental justice communities is described. While the New York City area MPOs and transportation organizations have taken impressive steps to address climate change risks, there are still significant barriers to effective adaptation. This case study highlights the challenges programmatic concerns present to the adaptation strategies.

The third and final case study discusses New York City's Comprehensive Waterfront Plan, which provides a10-year vision guided by three "beacons" or values: equity, resiliency, and health. NYC's Comprehensive Waterfront Plan encourages consideration of climate risk in all infrastructure investment, land use planning, and operational strategies. The Plan discusses strategies to address persistent inequities such as increased chronic flooding, urban heat, limited housing choices, uneven access to waterfront spaces, etc. This case study highlights the importance of considering equity as it relates to addressing climate change risks.

Study of Roadway Base Clearance for State Roads in Monroe County, FL (2018)

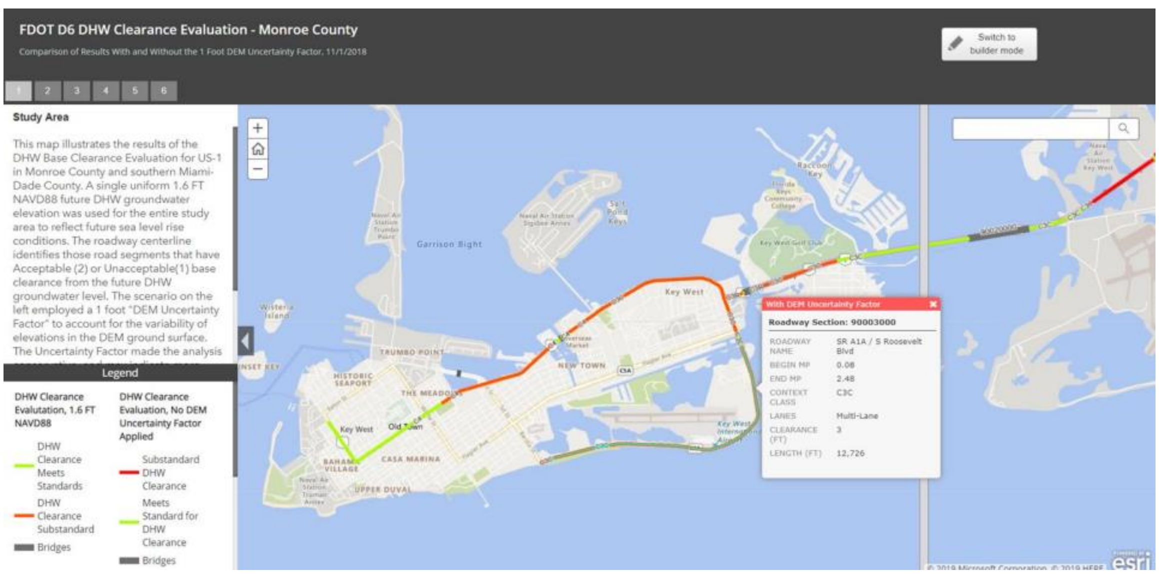
Florida DOT's (FDOT) District 6 sponsored a study to review roadway pavement base clearance requirements potentially affected by future sea level rise (SLR). SLR will increase groundwater levels in coastal areas, resulting in an increase in the Design High Water (DHW) elevation for pavement base clearance. In this study DHW refers to water elevations in coastal areas that may occur due to tidal fluctuations. DHW elevation is identified in FDOT's Flexible Pavement Design Manual. Base Clearance Water Elevation (BCWE) is identified in the same Manual and describes the base clearance above high water that is critical for good pavement performance.

In areas of low base clearance there can be construction problems and additional costs associated with dewatering that would likely be required to achieve compaction. This study identified roadway segments where potential pavement treatment or reconstruction may be required to meet future base clearance requirements. However, results of the study did not propose specific DHW elevation for project design or construction for those segments where substandard base clearance conditions may arise in the future. The figure below depicts the potential impacts of SLR on roadway base clearance requirements.



Source: Miami-Dade County

This study was a screening-level review of the potential impacts of SLR on the future DHW elevation of the existing State Highway System in Monroe County. The scope of this study did not include an analysis of historical water elevations at specific project locations, analysis of storm surge flooding, analysis of erosion of roadway pavements and embankments due to wave action, groundwater modeling, future changes in precipitation or temperature, data collection and review of soils survey information, or an evaluation of costs and benefits for adaptation strategies to potentially mitigate substandard pavement base clearance.



GIS Screening of State Highways Impacted by DHW and Base Clearance Requirements

FDOT design standards and manuals, such as the Drainage Manual, do require consideration of SLR. However, current guidance requires analysis using a straight-line regression extrapolation based on the design service life of the project. Using historical straight-line regression analysis for some locations, particularly in the Lower Keys, does not account for more recent SLR trends, which indicate annual increases that exceed the straight-line extrapolated rate. Recent SLR trends published by NOAA for Vaca Key, Marathon and Key West demonstrate a steady increase in linear rates that exceeded the values utilized in FDOT's Drainage Manual at the time of publication.

Current design guidelines may require calculation of SLR based on the rate of historical SLR that does not account for recent increases in linear rates of SLR, nor for accelerated SLR projection scenarios from the US Army Corp of Engineers (USACE), NOAA, and the Intergovernmental Panel on Climate Change (IPCC). Thus, at the time of publication of this study DHW elevation was likely to be underestimated if accelerated SLR projection scenarios were not considered. Results of this study emphasize the importance of accounting for the best available projections in design standards. Some local jurisdictions in South Florida do have more stringent standards that require consideration of SLR projections.

Post Hurricane Sandy Transportation Resilience Study in New York, New Jersey, and Connecticut (2017)

The most destructive hurricane of the 2012 season, Hurricane Sandy, toppled infrastructure and pummeled communities in its path. Bridges, roads, railways, and airports were knocked out, washed away, and submerged in water. Sandy's record-breaking storm surge prompted the Federal Highway Administration (FHWA) to launch a study geared toward enhancing the resilience of transportation infrastructure in the New York, New Jersey, and Connecticut metro regions and then leverage the study's lessons learned to prepare infrastructure for the next big storm.

The study began by capturing the damage and disruption to the region's transportation system. Using information collected from Hurricane Sandy, as well as past Hurricanes, the study team assessed vulnerability and risk to the transportation system in the region at three scales: regional, subarea, and facility. At the regional level, the study provides information that can be used by transportation agencies throughout the study area. At the subarea level, the study team tested two multimodal corridors and a coastal network of critical facilities. At the facility level, the region's transportation agencies selected individual facilities (roads, bridges, tunnels, rail, and ports) for engineering-informed assessments.

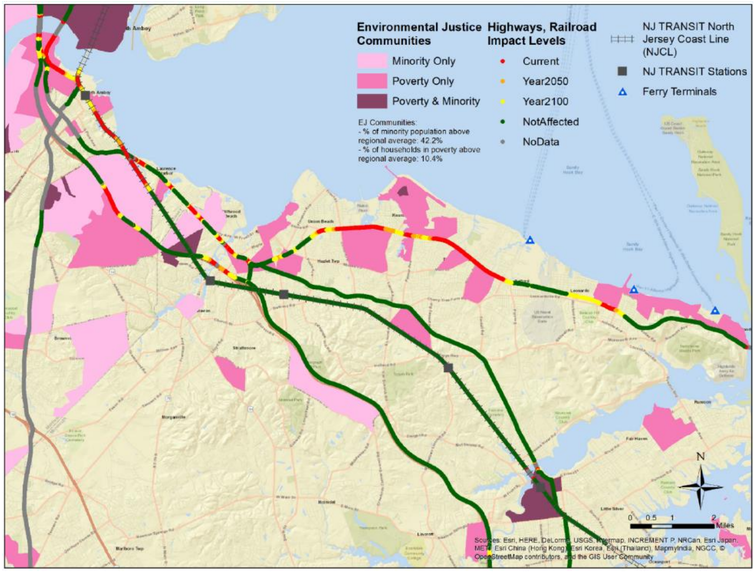
Hurricane Sandy coincided with the highest tide of the month causing sea levels along the coast to rise to record heights. This inundated roadway and transit facilities, shutting some down for several weeks. Damage to the regional highway system included extensive washouts, bridge damage, inundation of tunnels, and flooding of low-lying mechanical and electrical equipment. Bridge piers and foundations were also compromised due to the scouring of sediment and rocks from channel bottoms as water flowed into and out of major channels. Transit systems in the study area faced similar damage to the regional highway system.

Long-term impacts of the corrosive saltwater on electrical components resulted in disruptions even four years after Hurricane Sandy, ranging from escalators electrically malfunctioning to power outages in rail yards and signals. Repairs to solve these problems typically occur over a long period of time. New York's Canarsie Tube, which services the MTA's L Train, under the East River became inundated during Hurricane Sandy. While most of the water was pumped out the effects of the salt water began to affect the electrical and metal components of the tunnel. It was not until 2019 that the tunnel was repaired over an 18-month shutdown.

Climate projections prepared by government agencies, research institutions, and not-for-profit organizations all lent themselves to the project team's efforts. Data and analysis tools such as the National Flood Hazard Layer (NFHL), Digital Flood Insurance Rate Maps (DFIRMS), and Digital Elevation Models were used by the team to assess vulnerability and risk. At the regional level, the team focused primarily on potential exposure to climate stressors. At the subarea level, the team expanded the vulnerability assessment to look at exposure, sensitivity, and adaptive capacity. At the individual facility level, the team looked at the facility and component-specific vulnerabilities and risks over the remaining useful lives of the assets.

To determine the potential exposure of the region's key transportation facilities to storm surge and precipitation, the study team used Geographic Information Systems (GIS) to conduct an intersection analysis, which identified where roads, rail lines, and facilities lie within the boundaries of a 100-year or 500-year flood plain, or where they lie within the extent of storm surge predicted to be associated with Category 1 through 4 storms. In limited parts of the study area, the team used digital elevation models to help screen facilities that are elevated on a natural or human-made embankment and would not be exposed to adjacent flood waters. The regional exposure analysis revealed a high potential for the region's critical transportation facilities throughout the study area to be impacted by climate stressors.

As part of this study the research team identified "Communities of Concern" as defined by the New Jersey Transportation Planning Authority (NJTPA) and depicted in the figure below. These environmental justice communities were established based on American Community Survey (ACS) data that indicated where minority populations are above the regional average, households in poverty are above the regional average, or where both of these conditions exist. Decision-making techniques can identify appropriate adaptation paths that consider timing of risks, need to avoid adverse impacts such as those that disproportionately affect environmental justice communities, and account for costs and feasibility.



Exposure areas with environmental justice communities. Source: NJTPA

MPOs and transportation organizations have taken impressive steps to address climate change risks, but there are significant barriers to effective adaptation. Insufficient data, such as spotty historical data and useable transportation facility data, can leave a gap in understanding and reduce accuracy. Legal and regulatory hurdles, such as obstacles to right-of-way acquisition, lawsuits from impacted owners, and environmental impact assessments, can also hinder adaptation strategies and delay or block a project. Limited sources of funding for transportation adaptation projects can also prevent adaptation projects from taking place.

New York City Comprehensive Waterfront Plan (2021)

The New York City Comprehensive Waterfront Plan is a 10-year vision, driven by the climate justice principle that all New Yorkers should live, learn, work, and play in safe, healthy, resilient, and sustainable environments, even as the climate changes. The City released its first Comprehensive Waterfront Plan in 1992 and since then much of NYC's waterfront has been cleaned up and transformed to address critical needs for housing, jobs, and open space. The latest Comprehensive Waterfront Plan builds upon the vibrancy of the current waterfront while also putting forth new strategies for an equitable, resilient and healthy waterfront in the face of climate change.

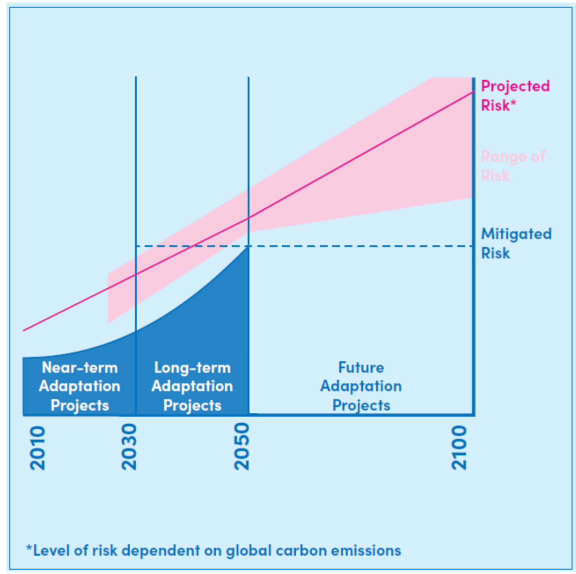
This Plan's 10-year vision is guided by three "beacons" or values: equity, resiliency, and health. These values inspired the planning process for the Plan in addition to the Plan itself. The values are interdependent, none can be achieved in isolation. In the context of the Plan, an equitable waterfront means that all waterfront communities can access quality affordable housing, well-paying jobs, and safe, attractive open spaces. The Plan defines a resilient waterfront as one where residents and communities have the capacity to cope with the everyday stresses of climate change and minimize disruptions from extreme heat and flooding. A healthy waterfront is defined in the Plan as one where people, natural areas, and wildlife can all flourish and support each other's well-being. The Plan discusses strategies to address persistent inequities such as increased chronic flooding, urban heat, limited housing choices, uneven access to waterfront spaces, etc.

Building upon the three values, the Plan is organized by six interconnected and interdependent topic areas, each with its own vision for the next 10 years of NYC's waterfront: Climate Resiliency & Adaptation, Waterfront Public Access, Economic Opportunity, Water Quality & Natural Resources, Ferries, and Governance. The Climate Resiliency and Adaptation theme has the goal of focusing on expanding climate risk awareness and action, using climate risk information in public policies and investments, supporting the housing needs of waterfront residents, managing risks from flooding in NYC's coastal communities, and promoting the design of climate-resilient buildings and infrastructure systems.

NYC has hundreds of miles of waterfront parklands, public spaces, and recreational in-water access sites that are critical resources. These resources supply New Yorkers with valuable open space, recreational amenities, and community gathering spots. The goal of Waterfront Public Access is to expand public access to the waterfront with an emphasis on equity by bridging access gaps in historically underserved areas, supporting growing waterfront communities, promoting opportunities to get onto and into the water, shaping the design and programming of public waterfront open spaces to reflect public use needs, and promoting good stewardship of public spaces on the waterfront.

To realize the goals of the Plan and address the combined challenges of competing demands of the waterfront, rising sea levels, and a changing climate, NYC must improve its coordination of building and maintaining critical shoreline infrastructure across agency jurisdictions and different levels of government. Successful implementation of the Plan will involve collaborating with the owners of privately-owned shoreline areas, design and engineering practitioners, and local communities.

The Plan encourages NYC to consider climate risk in all infrastructure investment, land use planning, and operational strategies. An illustration of mitigation of this risk is depicted in the adjacent figure. Development of the Plan was the result of broad, deep collaboration across agencies and organizations. NYC's Department of City Planning hopes to inspire New Yorkers with this vision for an equitable, resilient, and healthy waterfront. The Plan takes into account the future vision for NYC's waterfront and develops the climate change adaptation tools needed to support development. These efforts will extend beyond flooding and heat to affect people, places, and systems across NYC, requiring consideration of climate risk in all infrastructure investment, land use planning, and operational strategies.



Source: NYC Mayor's Office of Climate Resiliency

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