Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report

Prepared By

Houston-Galveston Area Council

With

Texas Department of Transportation
Texas A&M Transportation Institute

January 14, 2021

Acknowledgements

Cooperation between groups and individuals has been paramount to the success of the *Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program Report*. Stakeholder groups are detailed on page 93 of this report.

Disclaimer Notice

Technical Report Documentation Page

<table>
<tr><td>1. Report No.</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Resilience and Durability to Extreme Weather in the H-GAC Region Pilot Program</td><td>5. Report Date
January 14, 2021</td></tr>
<tr><td>6. Performing Organization Code:</td></tr>
<tr><td colspan="2">7. Author(s)
Houston-Galveston Area Council
Sambidi, Pramod PhD; Lee, Sungmin;
Ranatunga, Thushara PhD; Janhsen, Kathy;
Dang, David; Vo, Kathryn; Ronneberg, Kristina
Texas A&M Transportation Institute
Prozzi Jolanda; Birt Andrew; McFalls Jett</td><td>8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Houston-Galveston Area Council
3555 Timmons Lane, Suite 120
Houston, TX 77027</td><td>10. Work Unit No.</td></tr>
<tr><td>11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590</td><td>13. Type of Report and Period Pilot Final Report</td></tr>
<tr><td>14. Sponsoring Agency Code</td></tr>
<tr><td colspan="3">15. Supplementary Notes</td></tr>
<tr><td colspan="3">16. Abstract
To address threats posed by extreme flood events, storm surge, and sea level rise in the region, the Houston-Galveston Metropolitan Planning Organization, in collaboration with the Texas Department of Transportation, partnered with the Federal Highway on the Administration on Resilience and Durability to Extreme Weather Pilot Program applied research in 2018. The goals were to (1) Assess the criticality and vulnerability of regional transportation assets to extreme weather events; (2) Develop a suite of recommendations for local governments for a more resilient transportation network; and (3) Use analysis from the Pilot Program to inform future publications and project selection criteria. The Pilot Program team analyzed two types of transportation infrastructure assets: Major Roads and Bridges. The team ran scenarios for flooding, storm surge, and sea level rise events to assess the impact on identified assets, specifically assessing criticality and vulnerability. Out of the 762 centerline freeway miles and 6,440 major road miles assessed in the region, 92 centerline freeway miles (12%) and 551 major road miles (9%) were highly critical. Thirteen percent of freeway centerline miles and 12% of major road miles were highly vulnerable to flooding, storm surge, and sea-level rise.</td></tr>
</table>

The intersection between the criticality and vulnerability assessments—known as the Criticality-Vulnerability Matrix—was developed by the team to identify assets that are both highly critical and highly vulnerable and therefore a priority for mitigation strategies in the Pilot Program area. Around 9.5 freeway centerline miles and 48 miles of major roads were highly critical and highly vulnerable to extreme weather events. The Pilot Program team developed the online Regional Resilience Tool to display the criticality and vulnerability of road segments. The lessons learned from the Pilot Program team's analysis can be considered in four major areas: data availability and quality, data analysis, access to this Pilot Program's findings, and commitment to collaborate and continue transportation resilience planning. The findings of the Pilot Program will be integrated into current and future planning studies, including the Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

17. Key Words Vulnerability, Criticality, Flooding, Storm Surge, Sea Level Rise, Resilience, LiDAR Data, Depth Grid, DEM, DSM, Hurricane Harvey, Hurricane Ike, Network Redundancy, Economic Impact, Adaptation, Mitigation	18. Distribution Statement No restrictions.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 239	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

Located along the Texas Gulf Coast, the Houston-Galveston region is an important and fast-growing economic hub, employing more than 3.1 million people and contributing 27% of the state's total gross domestic product each year. However, the region is also vulnerable to flooding.

Areas along the coast are inherently vulnerable to the forces of nature, particularly tropical storms, hurricanes, and stalled storm fronts. However, the propensity for flooding in the Houston-Galveston region has increased with regional growth and the removal of nature-based infrastructure that naturally mitigates flood risks. Extreme flood events, storm surge, and sea level rise pose a threat to multiple types of infrastructure, specifically transportation infrastructure necessary for moving goods and people in the region.

To address these threats, the Houston-Galveston Metropolitan Planning Organization (MPO), in collaboration with the Texas Department of Transportation (TxDOT), was selected to partner with the Federal Highway Administration (FHWA) on a Resilience and Durability to Extreme Weather applied research in 2018.

Defining Criticality and Vulnerability

Criticality measures which transportation assets are crucial to the region's routine functions and economic activities.

Vulnerability determines which transportation assets are most susceptible to probable regional climate stressors.

The applied research cooperatively funded the Resilience and Durability to Extreme Weather in the H-GAC (Houston-Galveston Area Council) Region Pilot Program (H-GAC Region Resilience Pilot Program or Pilot Program). This Pilot Program uses the FHWA's Vulnerability Assessment Framework to assess the vulnerability and risk of a transportation asset to extreme weather impacts or other current and future environmental conditions under *multiple* scenarios.

The goals of the H-GAC Region Resilience Pilot Program are to:

- Assess the criticality and vulnerability of regional transportation assets to extreme weather events
- Develop a suite of recommendations for local governments to use for a more resilient transportation network (see Adaptation Strategies on page 82).
- Use analysis from the Pilot Program to inform future publications and project selection criteria

Assessing Transportation Infrastructure Assets

The Pilot Program team (the team) analyzed two types of transportation infrastructure assets for the Pilot Program: Major Roads and Bridges. The team ran scenarios for flooding, storm surge, and sea level rise events to assess the impact on identified assets, specifically assessing the criticality— which assets are highly critical to the region's routine functions and economic activities— and vulnerability— which assets are highly vulnerable to the climate stressors the region is likely to face.

Criticality Assessment Results

Out of the 762 centerline freeway miles and 6,440 major road miles in the region, 92 centerline freeway miles (12%) and 551 centerline major road miles (9%) were found to be highly critical.

Vulnerability Assessment Results

With respect to vulnerability, 13% of freeway centerline miles and 12% of major road centerline miles were found to be highly vulnerable to flooding, storm surge and sea-level rise.

Criticality-Vulnerability Matrix

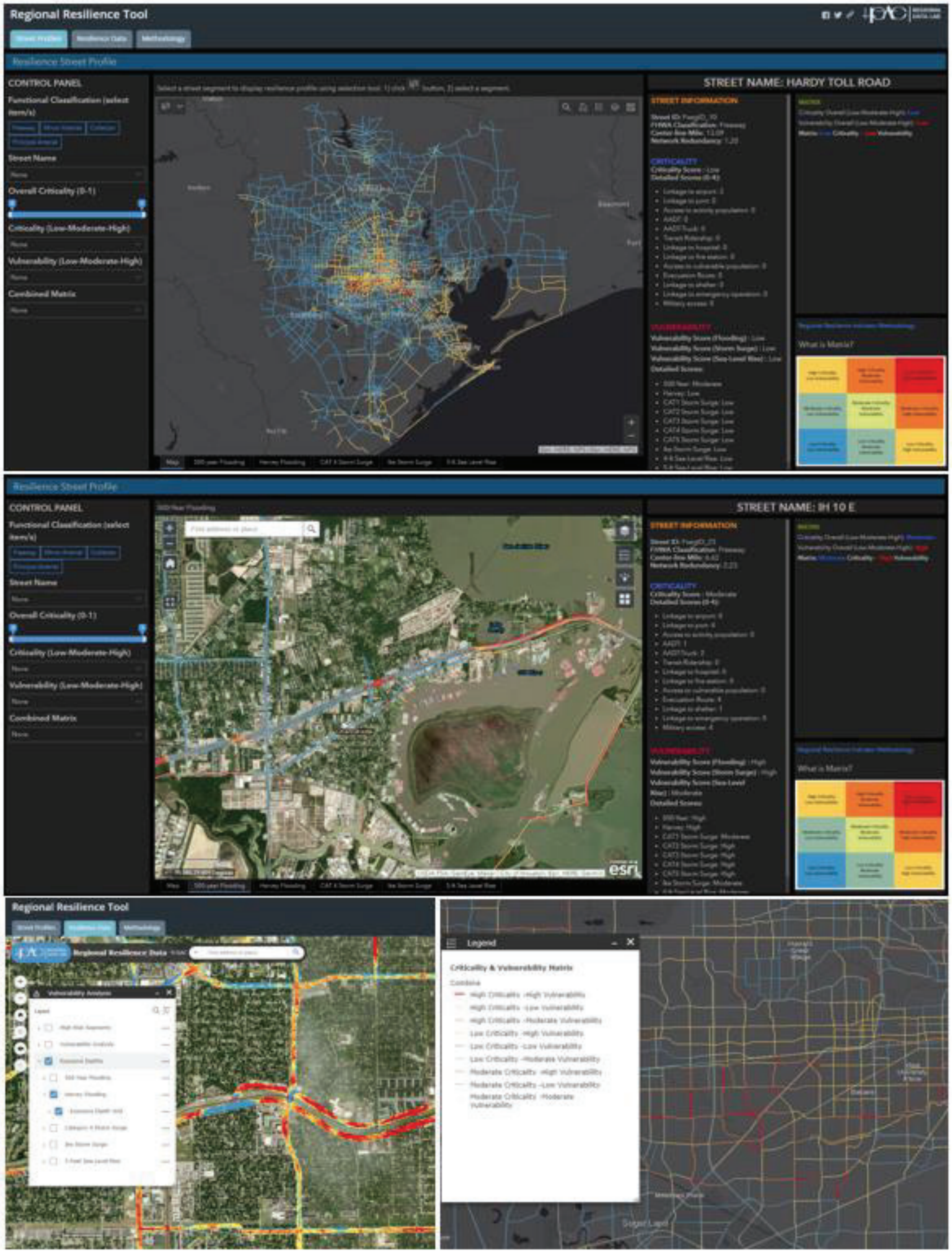
The intersection between the criticality and vulnerability assessments—known as the Criticality-Vulnerability Matrix—was developed by the team to identify those assets that are both highly critical and highly vulnerable and therefore a priority for mitigation strategies in the Pilot Program area. **Around 9.5 centerline miles of freeway and 48 centerline miles of major roads were found to be highly critical and highly vulnerable to extreme weather events.**

Regional Resilience Tool

As part of the Pilot Program, the team developed the online Regional Resilience Tool[1] to display the criticality and vulnerability of road segments. The tool also includes the modeled flood exposure depth grid data that identifies the specific parts of the road segment vulnerable to flooding. This information is useful in planning road improvements and developing mitigation strategies. Figure 1 shows the home landing page for the tool.

[1] https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

Figure 1- Regional Resilience Tool Landing Page



Adaptation Strategies

Using best practices set forth by the FHWA and stakeholder input, the team identified 25 Adaptation Strategies. These strategies identify implementable options to protect vulnerable and critical assets, providing criteria that local governments can consider when selecting a strategy. Figure 2 lists the 25 strategies.

Figure 2 - Adaptation Strategies

25 ADAPTATION STRATEGIES

STORMWATER MANAGEMENT

1.Increase Number of Swales & Ditches
2.Retention & Detention Ponds
3.Depressed & Raised Medians
4.Bioswales (Biofiltration Swales)
5.Green Infrastructure

MAINTENANCE

6.Culvert Cleaning & Maintenance

PLANNING/SOCIAL

7.Stormwater Management Plan
8.Land Use Planning/ Climate Justice
9.Relocate or Abandon Roads
10.Shelter-In-Place
11.Evacuation Route Identification & Planning
12.Prohibiting Overweight/ Oversize Vehicles
13.Sensor Technologies & Monitoring Programs

INFRASTRUCTURE

14.Enhanced Road Surface
15.Enhanced Sub-Grade
16.Hardened Shoulders
17.Raised Road Profile
18.Geosynthetics/ Geo Textiles
19.Permeable Pavement

OTHER

20.Maintain & Restore Wetlands
21.Beach Nourishment & Dune Restoration
22.Vegetation (as Erosion Control)
23.Seawalls & Revetments
24.Wave Attenuation Devices
25.Debris Deflectors for Bridge Protection

Next Steps and Recommendations

The Houston-Galveston Area Council MPO values the findings of this report and acknowledges that this is the first step toward a more resilient transportation system for the region. The findings of the Pilot Program will be integrated into current and future planning studies, including the Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

The Low-Impact Development Study will expand on the 25 Adaptation Strategies and incorporate additional analysis of implementable options for decision-makers and developers to adopt within the public right-of-way. Understanding the criticality and vulnerability of major roads and bridges will enable more careful articulation of climate impacts on hurricane routes and route alternatives in the Regional Transportation Plan and Sub-Regional Studies. While most of the planning studies will continue this Pilot Program's focus on resiliency for vehicle travel, the Houston-Galveston MPO will study the impacts of flood and stormwater on active transportation modes like bicycling and walking. Through context-sensitive design, the Complete Streets Program, a movement to ensure that roadways provide for the mobility and safety of all, will identify the nexus between impacts on all travel modes— with specific focus on filling in the gap of active transportation— and localized flooding to determine resilient strategies for roadway, bikeway, and walkway design.

This report will provide decision-makers the necessary tools and expert information to incorporate resiliency into the project selection process and evaluation criteria for the Transportation Improvement Program, a fiscally constrained financial plan of transportation projects approved to receive federal funding over the next four-years, and associated funding.

INTRODUCTION

The Houston-Galveston region consistently ranks as one of the fastest-growing metropolitan areas in the United States, leading the nation's economic growth potential. From 2010 to 2018, jobs in the region increased from around 2.5 million to almost 3.1 million (U.S. Census Bureau, 2020).

Employment is projected to increase to approximately 4.8 million by 2045. The projected job growth is expected to be greatest in the urban core within TX-8 Beltway (Beltway 8). The population in the region has increased, rising from approximately 3.1 million residents in 1980 to 6.8 million in 2018—an increase of nearly one million residents per decade. This growth trend is expected to continue and, by 2045, the region will be home to about 10.7 million people (Houston-Galveston Area Council, 2018).

The region consistently floods, as areas along the coast are inherently exposed to the forces of nature, particularly tropical storms, hurricanes, and stalled storm fronts. However, the propensity for flooding has increased with regional growth and the loss of the natural eco-region that naturally mitigates flood risks.

The frequency of extreme flood events in the region is increasing (SeaLevelRise.org, 2020). Since 1953, there have been 70 hurricanes, 51 flood events, and 37 severe storms declared Federal Emergency Management Agency (FEMA) Disasters in the Houston-Galveston region (Federal Emergency Management Agency, 2019).

An increase in extreme flood events generated a renewed focus on and interest in flooding, as evidenced by some of the priorities in the Texas State Legislature's 86th Legislative session.[2]

AEP and Extreme Flood Events

Extreme flood events have an annual exceedance probability (AEP) of 10 % (AEP 10), which serves as a threshold for flooding events that will cause disruption.

For example, flooding associated with Hurricane Harvey, a Category 4 hurricane that hit the Texas gulf coast in August 2017, had an AEP of 0.1%, based on the updated Atlas 14 index, so it would be classified as greater than a 1,000-year event.

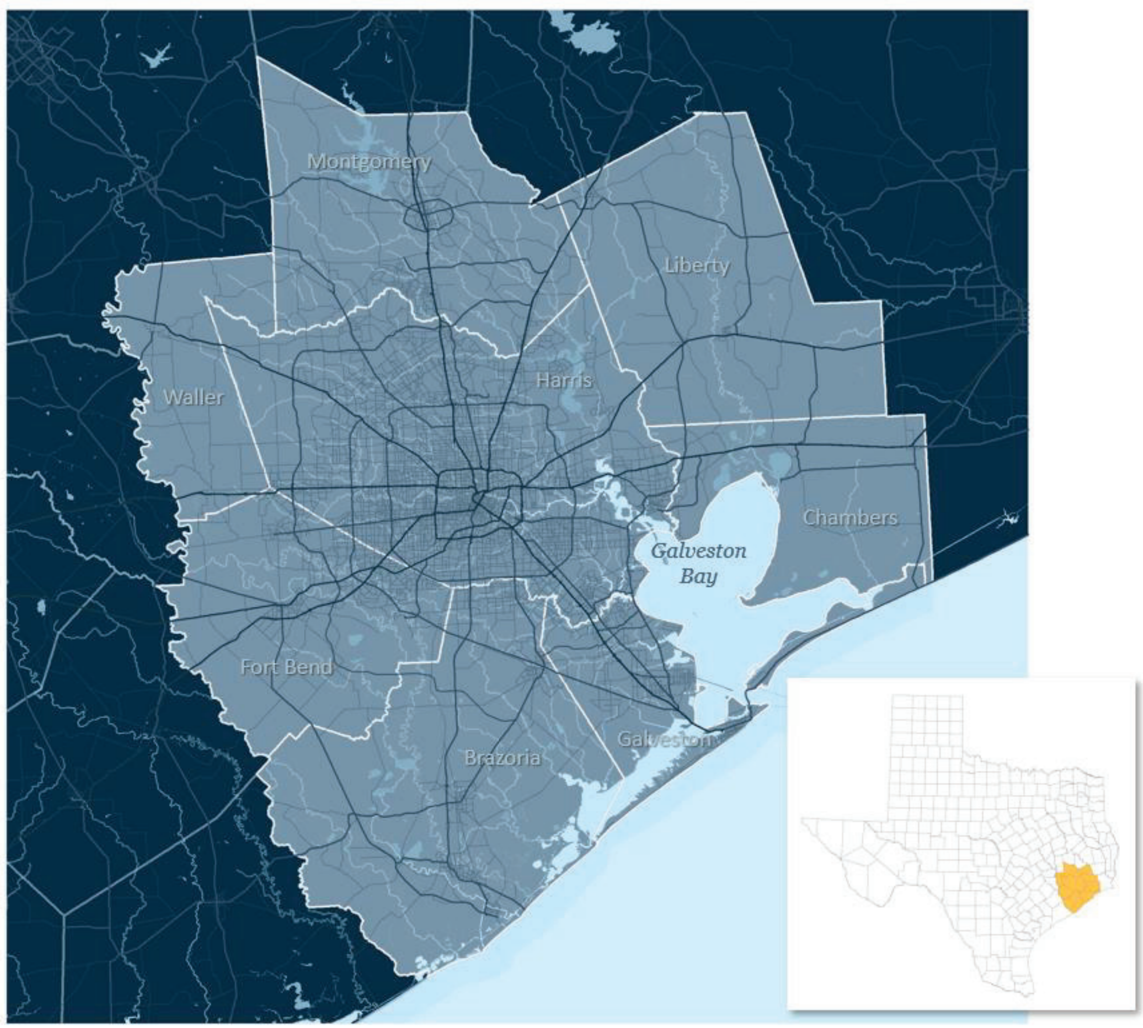
An extreme flood event can occur in a matter of hours, days, or weeks, and can range from a service disruption to the complete destruction of an asset.

[2] https://www.texastribune.org/2019/05/16/texas-house-passes-bills-to-help-pay-for-flood-projects-statewide/

Study Area

Spanning over 8,000 square miles, the Houston-Galveston MPO region consists of an 8-county Transportation Management Area (TMA)[3] and is characterized by its diversity of built and natural environments. The most significant natural boundary for the region is the Gulf of Mexico. Figure 3 shows the Houston-Galveston MPO region.

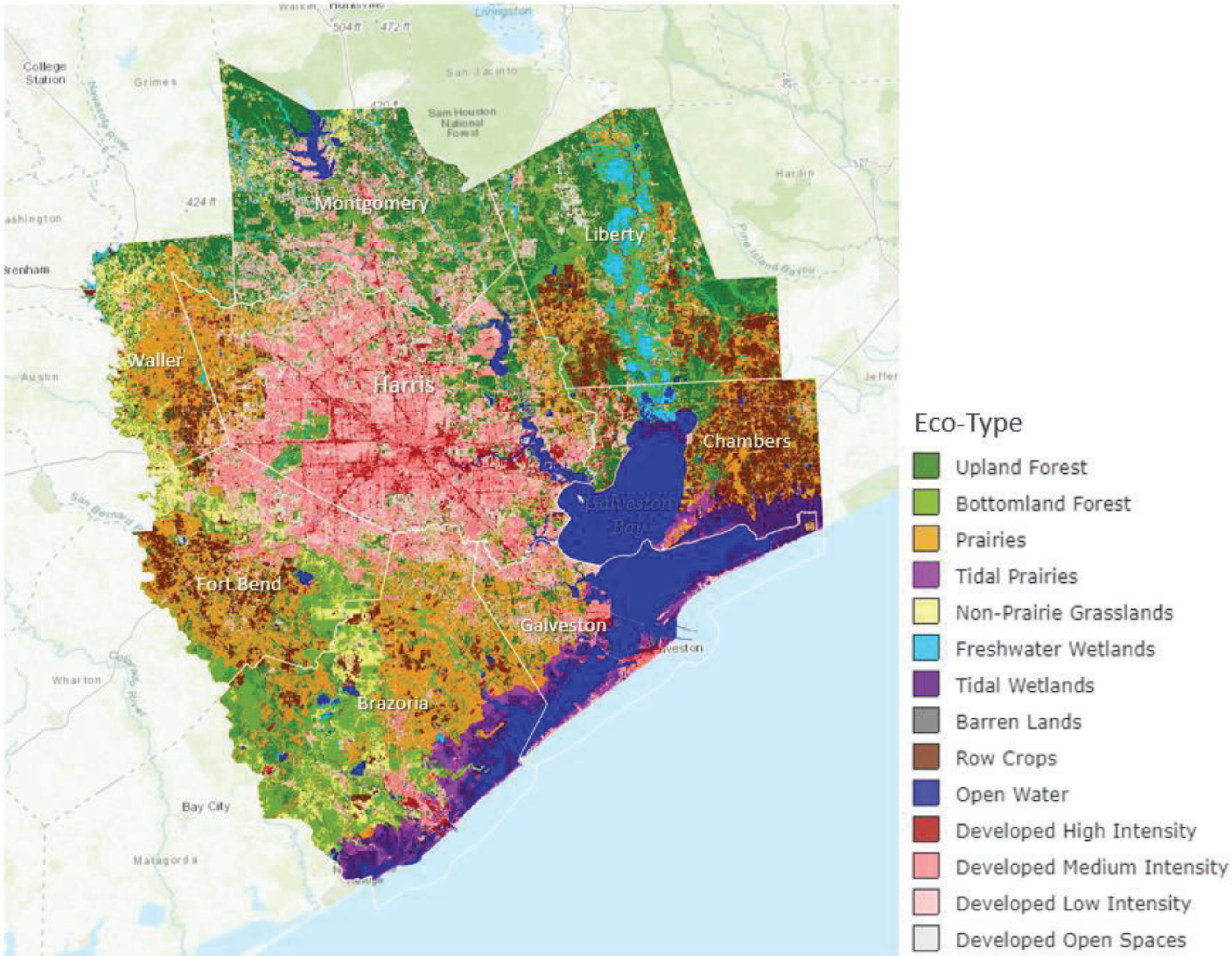
Figure 3 – Houston-Galveston MPO Area Map



Despite being one of the nation's fastest growing regions— well known for its expansive urban and suburban development– its natural eco-regions, such as forests, prairies, bottomlands, coastal plains, wetlands, and bays, remain prominent (see Figure 4). ***In fact, almost 40% of the region's land cover is categorized as forest, grass, or wetland and 99% of residents live within five miles of a major stream.***

[3] Brazoria, Chambers, Fort Bend, Galveston, Harris, Montgomery, Liberty, and Waller counties comprise the Houston-Galveston TMA.

Figure 4 – Eco-Regions in the Houston-Galveston Region



These natural eco-regions provide valuable benefits to the region by purifying the water and air, trapping carbon emissions, buffering the force of waves and currents, managing floodwaters, securing groundwater, preventing erosion, and more.

Natural eco-regions are crucial to the region's health and resilience. Numerous efforts are underway to protect the eco-regions through conservation easements and restoration projects led by local organizations, including the Bayou Land Conservancy, the Katy Prairie Conservancy, Houston Audubon, and the Galveston Bay Foundation. The Houston-Galveston Area Council (H-GAC) recently updated its Eco-Logical[4] base map and tool, which identifies the various regional ecotypes including prairies, wetlands, and upland and

4 https://www.h-gac.com/eco-logical

bottom land forests. The tool was created to assist efforts to preserve wildlife habitats and ecological diversity as the region plans for the expansion of infrastructure to accommodate population growth and increased mobility. In addition, the development of a Regional Conservation Framework is currently underway through partnerships with local governments and private landowners. This Framework will outline goals, priorities, and best practices for incorporating conservation features in land use planning.

While there are many benefits associated with the region's extensive economic and population growth, there are also consequences, many of which affect the natural environment. All infrastructure projects—whether residential, commercial, transportation, or other—require a transition from natural to built infrastructure or from permeable to impermeable surfaces. While new construction often seeks to mitigate habitat loss, water contamination, and flooding, impermeable surfaces can still result in increased flooding.

The Houston-Galveston region is particularly prone to flooding. Recent events, such as the Memorial Day Flood (2015), Tax Day Flood (2016), and Hurricane Harvey (2017), demonstrate the region's vulnerability to inland and coastal flooding.

As a result of Hurricane Harvey, which produced 50 inches of rain over seven days, H-GAC's *2045 Regional Transportation Plan* identified more than $3.1 billion in potential investment to mitigate the flood risk to critical regional and local highways (Clark, 2017). However, the investments identified in the plan accounted for those areas impacted by Hurricane Harvey flooding and did not model for other extreme weather scenarios.

The Resilience and Durability to Extreme Weather Pilot Program

To provide communities adversely impacted by changing weather patterns and flood events an opportunity to explore vulnerability strategies, the FHWA began to partner with state and regional entities on a series of Resilience and Durability to Extreme Weather Pilot Programs in 2010. This program helps communities develop tools to improve transportation infrastructure durability and resilience.

At the time of this publication, the FHWA had sponsored more than 50 pilot projects, each seeking to meet one or more of the following programmatic goals: (1) integrate resilience and durability into agency practices; (2) use available tools and resources to assess the vulnerability and risk of transportation projects or systems; or (3) deploy a resilience solution and monitor its performance (U.S. Department of Transportation, 2020).

The Houston-Galveston Area Council Region Resilience Pilot Program

H-GAC's previous work in resiliency focused on identifying vital infrastructure using Hurricane Harvey data or identifying mitigation projects that could be implemented within the region to address specific vulnerabilities, without in-depth analysis of criticality (Houston-Galveston Area Council, 2018).

The H-GAC Region Resilience Pilot Program used the FHWA's Vulnerability Assessment Framework to assess the vulnerability and risk of the transportation system to current and future extreme weather impacts and environmental conditions under multiple scenarios.

The goals of the H-GAC Region Resilience Pilot Program are to:

- Measure the criticality and vulnerability of regional transportation assets to extreme weather events
- Develop a suite of recommendations for local governments to use for a more resilient transportation network (see Adaptation Strategies on page 82)
- Use analysis from the Pilot Program to inform future publications and project selection criteria

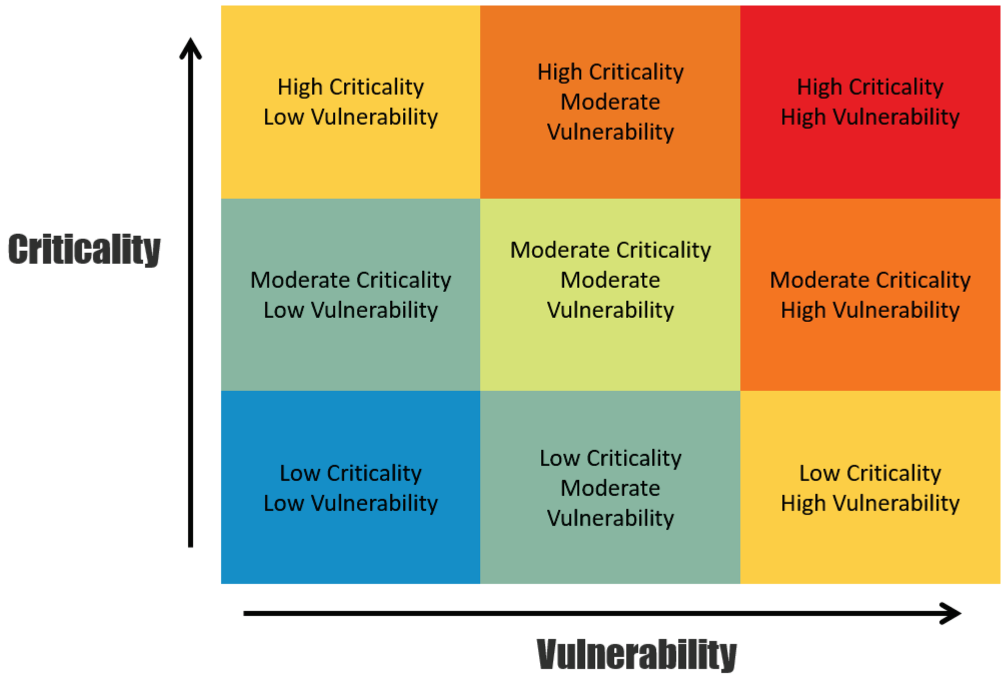
The objective of this planning effort is to provide local governments and partners with tools to plan resiliently and to improve the quality of life of residents and employees throughout the region.

This Pilot Program supports long-range transportation planning in two ways:

1. Criticality and Vulnerability
   The criticality assessment for the Pilot Program identifies transportation assets that are imperative to the region's routine functions and economic activities (see Criticality Assessment on page 41). The vulnerability assessment identifies transportation assets that are susceptible to the climate stressors the region is likely to face (see Vulnerability Assessment on page 46).

   The Criticality / Vulnerability Matrix (see Figure 5) assesses the intersection between the two variables to identify and prioritize specific transportation assets in the Pilot Program area necessitating resilient mitigation strategies.

Figure 5 – Criticality / Vulnerability Matrix



2. Adaptation Strategies
The first step in increasing the region's resilience and mitigating flood risks is identifying which transportation assets are considered both highly critical and highly vulnerable. The second step is to develop strategies to illustrate how those assets might be protected. The team identified 25 Adaptation Strategies (see Figure 6) to showcase the various options decision-makers may use to protect vulnerable and critical transportation assets.

Figure 6 – Adaptation Strategies

25 ADAPTATION STRATEGIES

STORMWATER MANAGEMENT

1.Increase Number of Swales & Ditches
2.Retention & Detention Ponds
3.Depressed & Raised Medians
4.Bioswales (Biofiltration Swales)
5.Green Infrastructure

MAINTENANCE

6.Culvert Cleaning & Maintenance

PLANNING/SOCIAL

7.Stormwater Management Plan
8.Land Use Planning/ Climate Justice
9.Relocate or Abandon Roads
10.Shelter-In-Place
11.Evacuation Route Identification & Planning
12.Prohibiting Overweight/ Oversize Vehicles
13.Sensor Technologies & Monitoring Programs

INFRASTRUCTURE

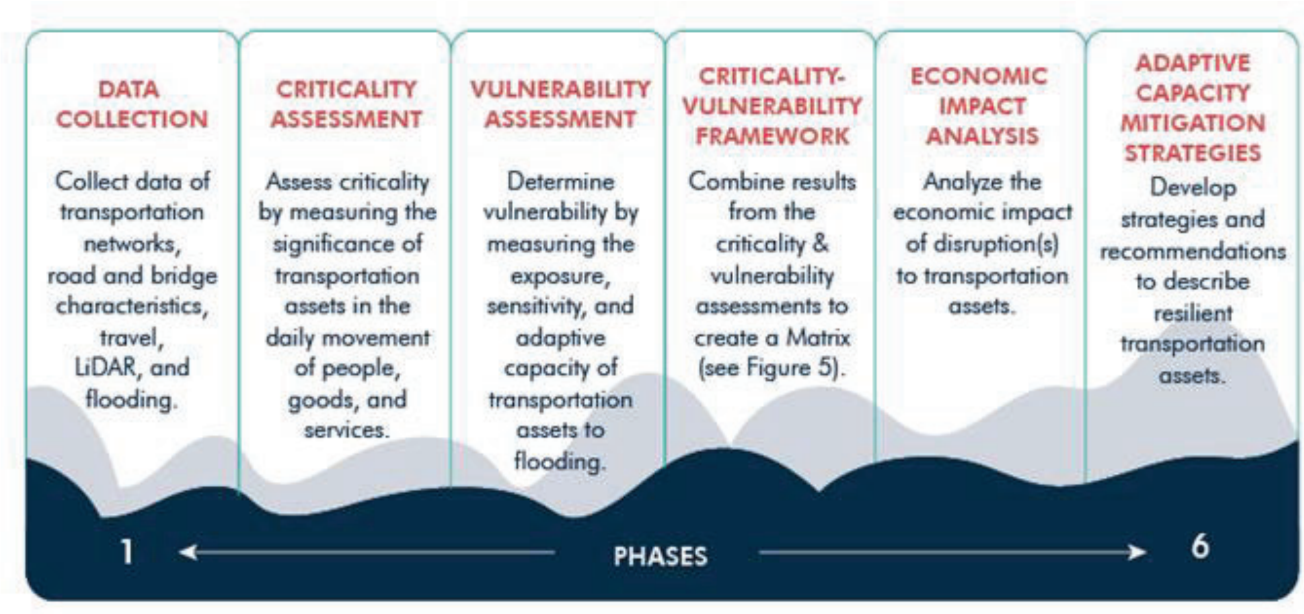
14.Enhanced Road Surface
15.Enhanced Sub-Grade
16.Hardened Shoulders
17.Raised Road Profile
18.Geosynthetics/ Geo Textiles
19.Permeable Pavement

OTHER

20.Maintain & Restore Wetlands
21.Beach Nourishment & Dune Restoration
22.Vegetation (as Erosion Control)
23.Seawalls & Revetments
24.Wave Attenuation Devices
25.Debris Deflectors for Bridge Protection

The analysis and recommendations outlined in the Pilot Program were developed over two years, following the phased approach detailed in Figure 7.

Figure 7 – Pilot Program Phased Approach



ASSETS AND SCENARIOS

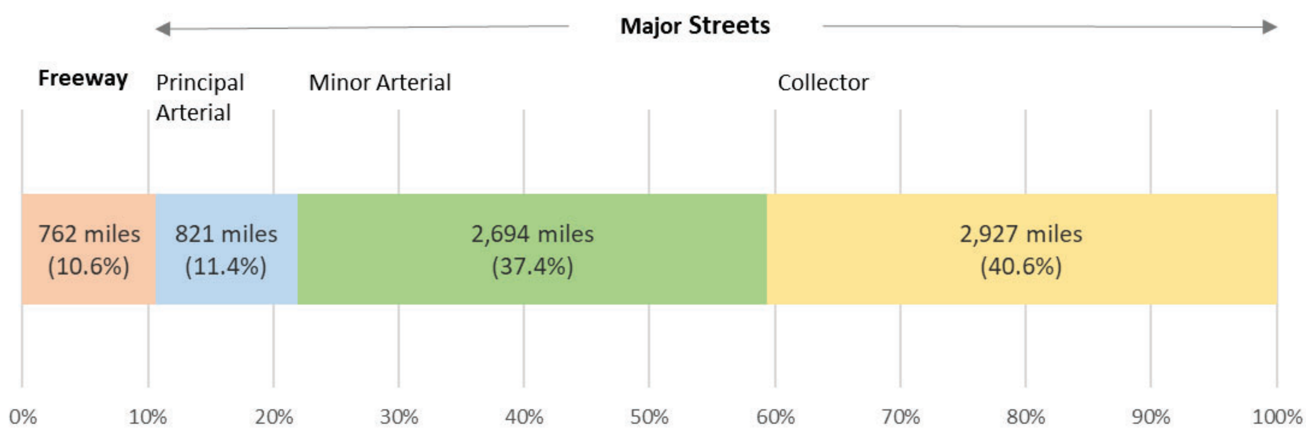
Relevant transportation infrastructure assets must be identified before conducting the criticality or vulnerability assessments. For the Pilot Program, the team studied two types of transportation infrastructure assets within the region: Major Roads and Bridges.[5]

Type 1: Major Roads

The team considered 83 freeway segments (762 centerline miles) and 7,696 major roads (6,442 centerline miles), including major arterials, minor arterials, and collectors, shown in Figure 8.

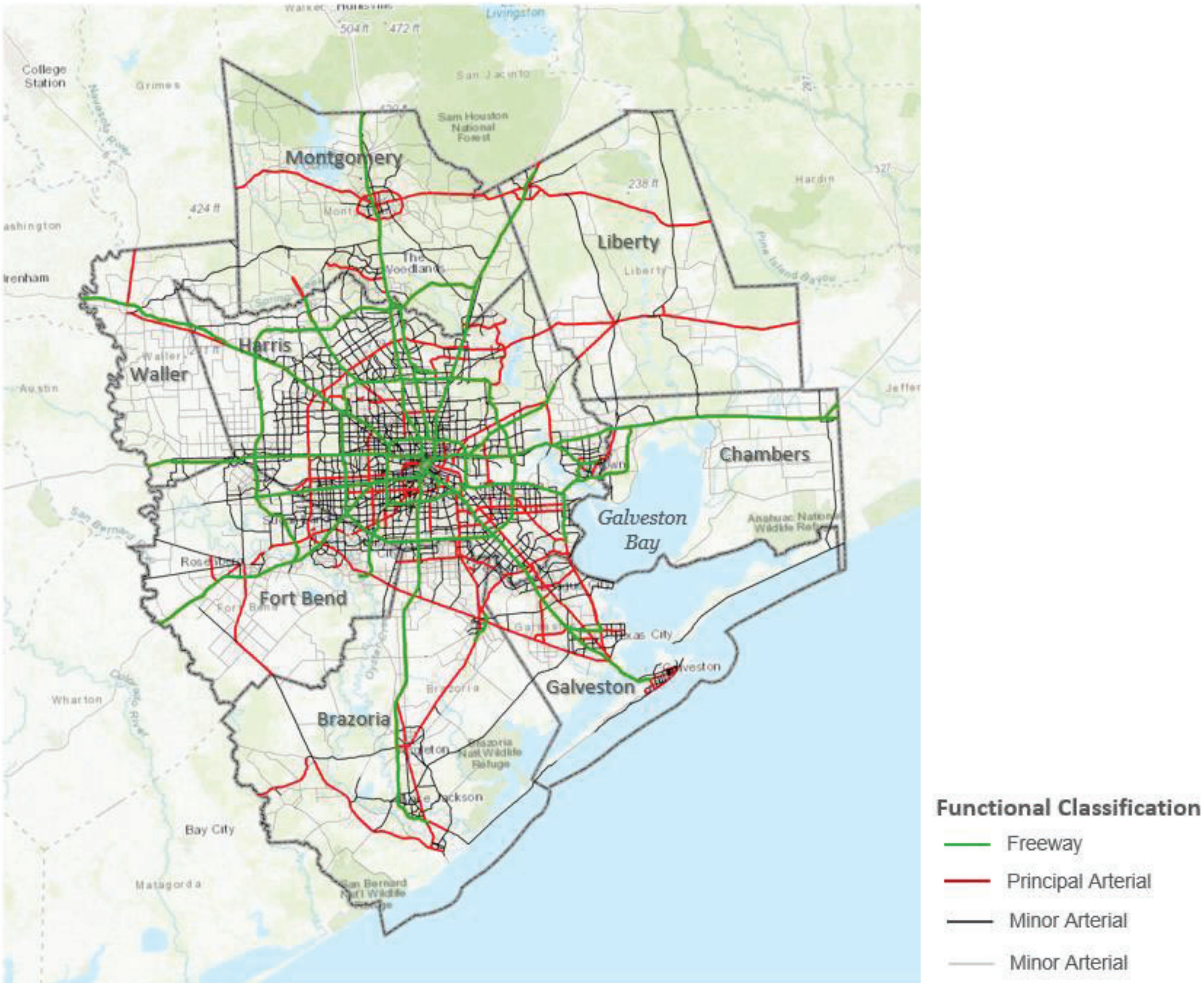
To identify these assets, the team downloaded the most current version of the roadway database, released in late 2018, from the TxDOT's Geospatial Roadway Inventory Database (GRID). The roadway database is a polyline feature representing the centerline of the roads. To produce road inundation area maps, the team converted the road network into an area feature— where the area between linear and curvilinear objects is accounted for— and used in further analysis for the Pilot Program. The TxDOT Major Road Network in the Pilot Program Area are shown in Figure 9.

Figure 8 – Major Roads in Pilot Program Study



[5] The datasets were initially acquired from TxDOT Roadway Inventory Database and Bridge Inspection databases in GIS feature class formats and processed for the Pilot Program requirements.

Figure 9 – TxDOT Major Road Network in Pilot Program Area



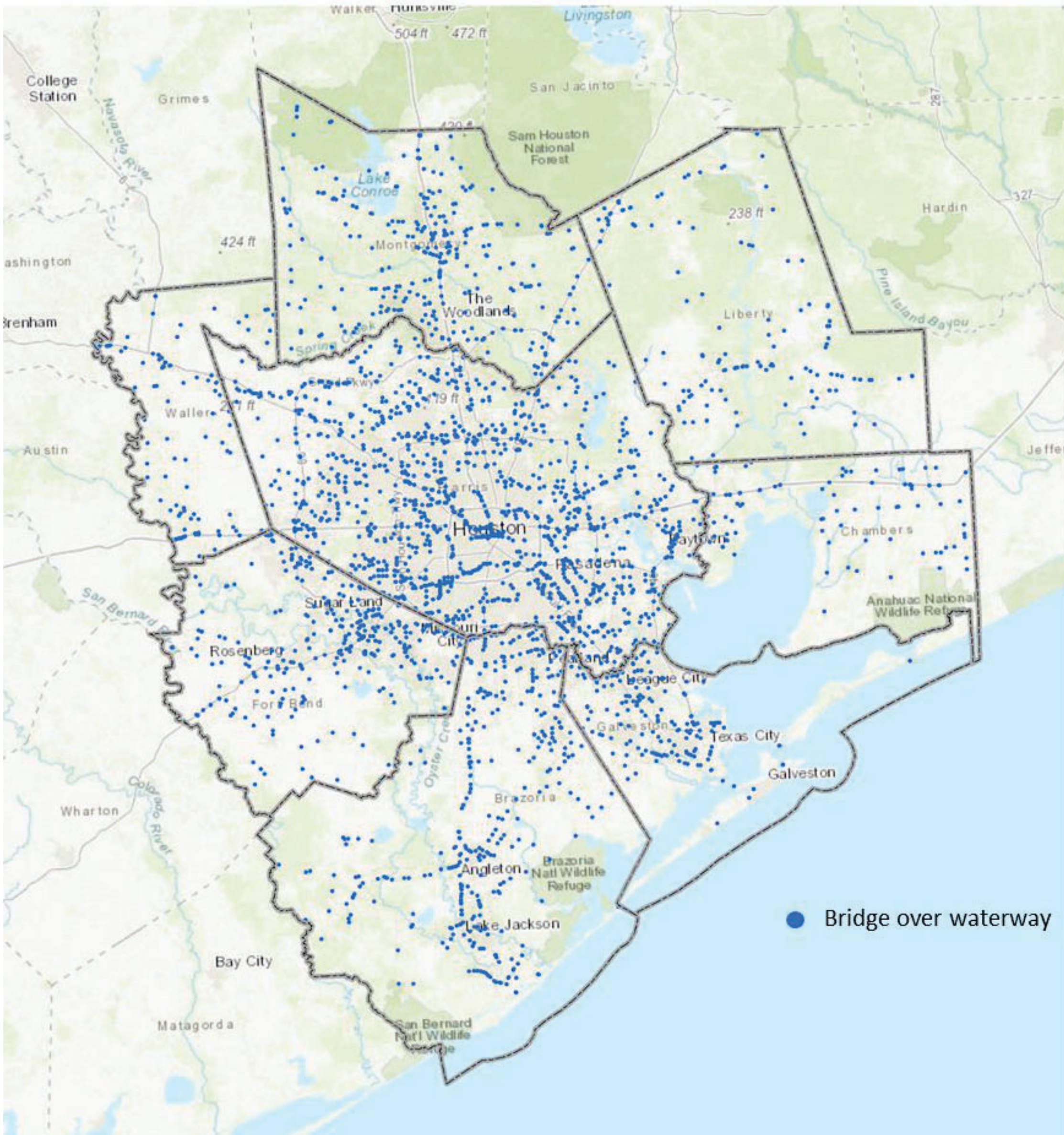
Type 2: Bridges

The team considered 3,489 bridges over waterways for the Pilot Program.

To identify this asset type, the team downloaded the most recent bridge data, released in 2018, from the TxDOT Bridge Inspection Database. The dataset is a statewide point dataset of bridge locations maintained by the Bridge Division of TxDOT and contains a record for each bridge structure on public roadways in Texas. This includes bridges maintained by TxDOT, toll authorities, counties, municipalities, and other jurisdictions.

Bridge inventory from TxDOT is a point marker and does not include the area coverage or span of the bridges. To create the bridge feature with area coverage, the team combined bridge data with the area information generated from LiDAR point cloud. The LiDAR data used in this analysis (see Exposure Assessment page 47) was a classified point cloud that included the bridge as one of its classifications. Using ArcGIS LiDAR processing tools and Python 3.6 scripting, the team extracted the bridge area and generated a regularized bridge feature dataset. By overlaying the TxDOT bridge inventory point data with the extracted bridge area feature, the team developed the final bridge area dataset and assigned the related TxDOT bridge identification numbers. The TxDOT Bridge over Waterway Inventory in Pilot Program Area is shown in Figure 10.

Figure 10- TxDOT Bridge over Waterway Inventory in Pilot Program Area



Scenario Development

To appropriately assess risk for the identified transportation assets, the team developed 11 scenarios to model flooding, storm surge, and sea level rise impacts in the Pilot Program area. These scenarios were based on historic data of extreme weather events in the region and feedback received from stakeholders early in the Pilot Program (see Stakeholder Engagement on page 93).

- Flooding
  1. 100-Year Flood
  2. **500-Year Flood**
  3. **Hurricane Harvey**

- Storm Surge
  1. Category 1 Storm
  2. Category 2 Storm
  3. Category 3 Storm
  4. **Category 4 Storm**
  5. Category 5 Storm
  6. **Hurricane Ike**

- Seal-Level Rise
  1. Sea Level Rise 4ft (National Oceanic and Atmospheric Administration)
  2. **Sea Level Rise 5ft (National Oceanic and Atmospheric Administration)**

The **bold scenarios were used for the detailed analysis presented throughout the remainder of this report.*

Flooding

Climate change has adversely affected the region with associated flooding. Fueled by an increasingly warm Gulf of Mexico, as shown in Figures 11 and Figure 12, future hurricanes are projected to be larger and more intense than past storms. Atmospheric warming and moisture retention, in combination with warm Gulf waters, causes more water evaporation of the Gulf; as temperatures increase, hurricanes will continue to worsen (Blackburn, 2019).

Figure 11 – Western Gulf of Mexico average and high temperature trends from 1976 to 2015, RICE SSPEED Center

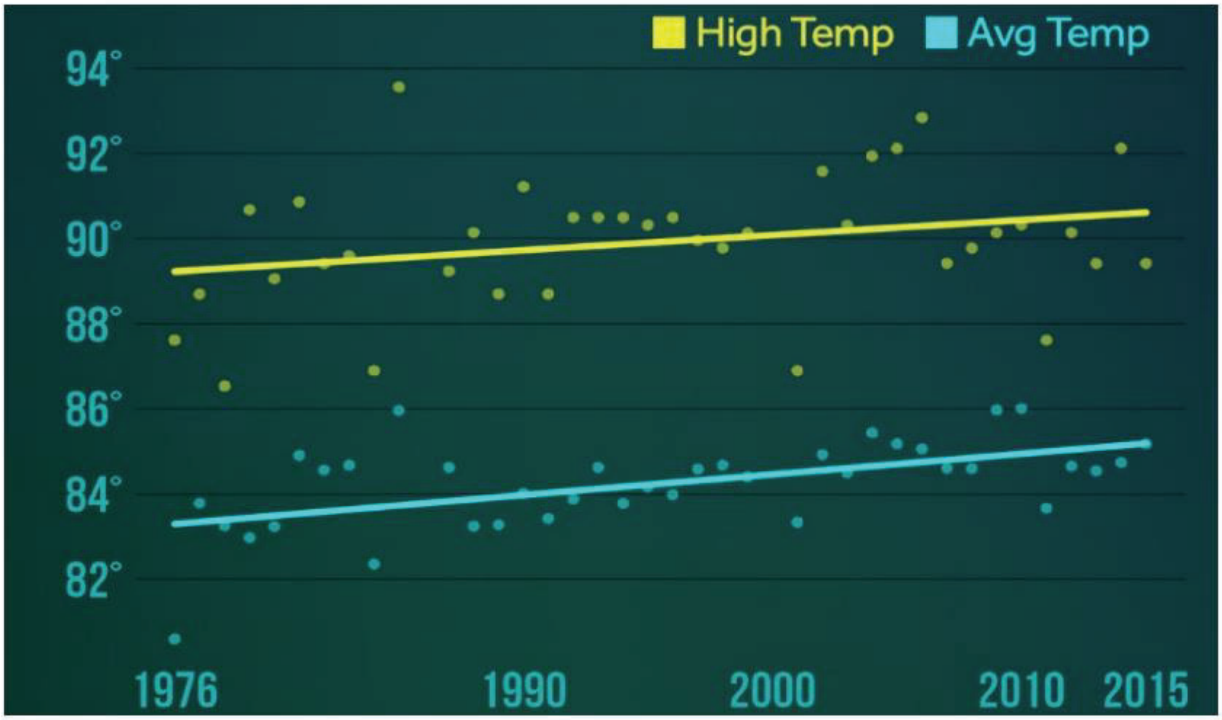
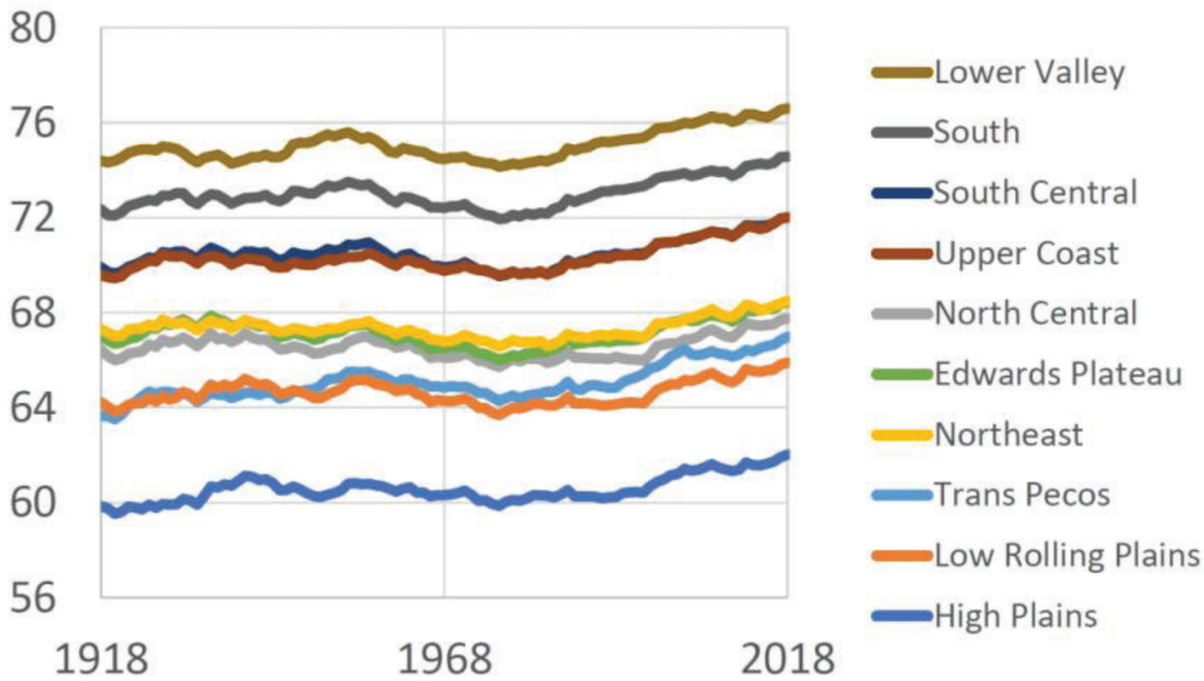


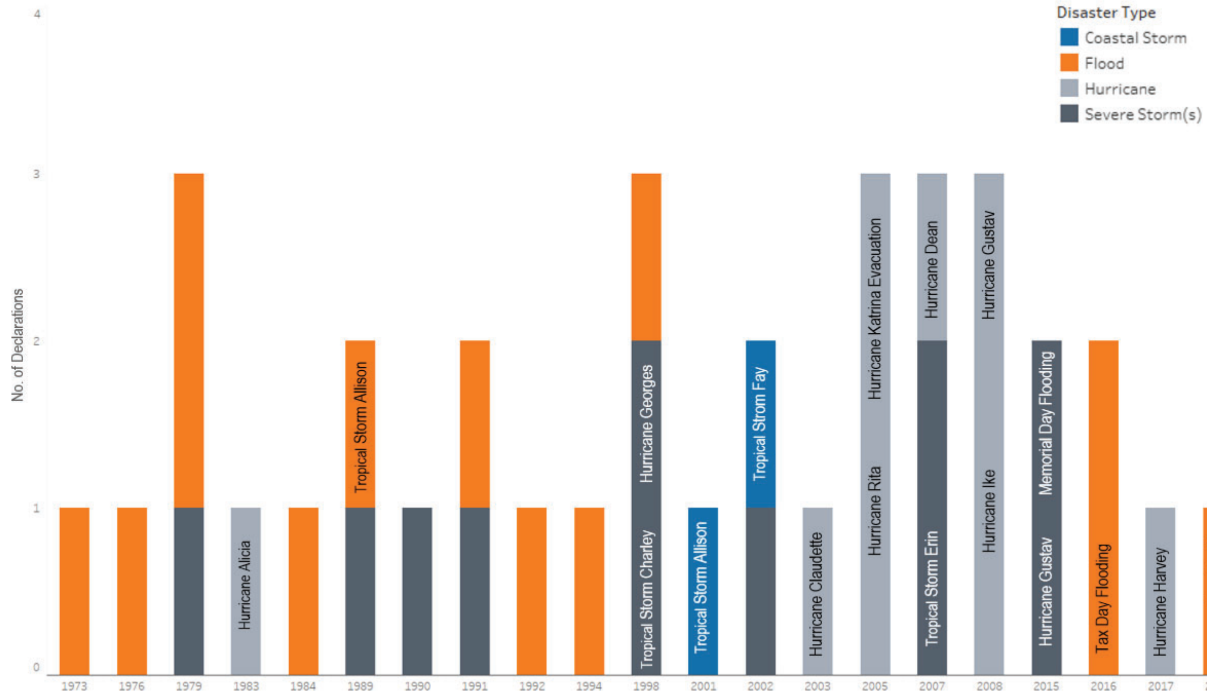
Figure 12 –10-Year Average Texas Temperatures (F°)



The region is under constant threat of extreme flooding events. Since 2015, the region experienced the Memorial Day flood (May 2015), the Halloween flood (October 2015), the Tax Day flood (April 2016), Hurricane Harvey (August 2017)— a Category 4 hurricane that produced a flood event that became one of the most damaging natural disasters in U.S. history— and Tropical Storm Imelda (September 2019).

With the increased storm frequency and intensity, concerns surrounding flooding have increased, particularly the feeling that the region is experiencing a "new normal" and another devastating flooding event is imminent. Flooding Related to Presidential Disaster Declarations (1953 – 2019) is shown on Figure 13.

Figure 13 – Flooding Related to Presidential Disaster Declarations (1953 – 2019)



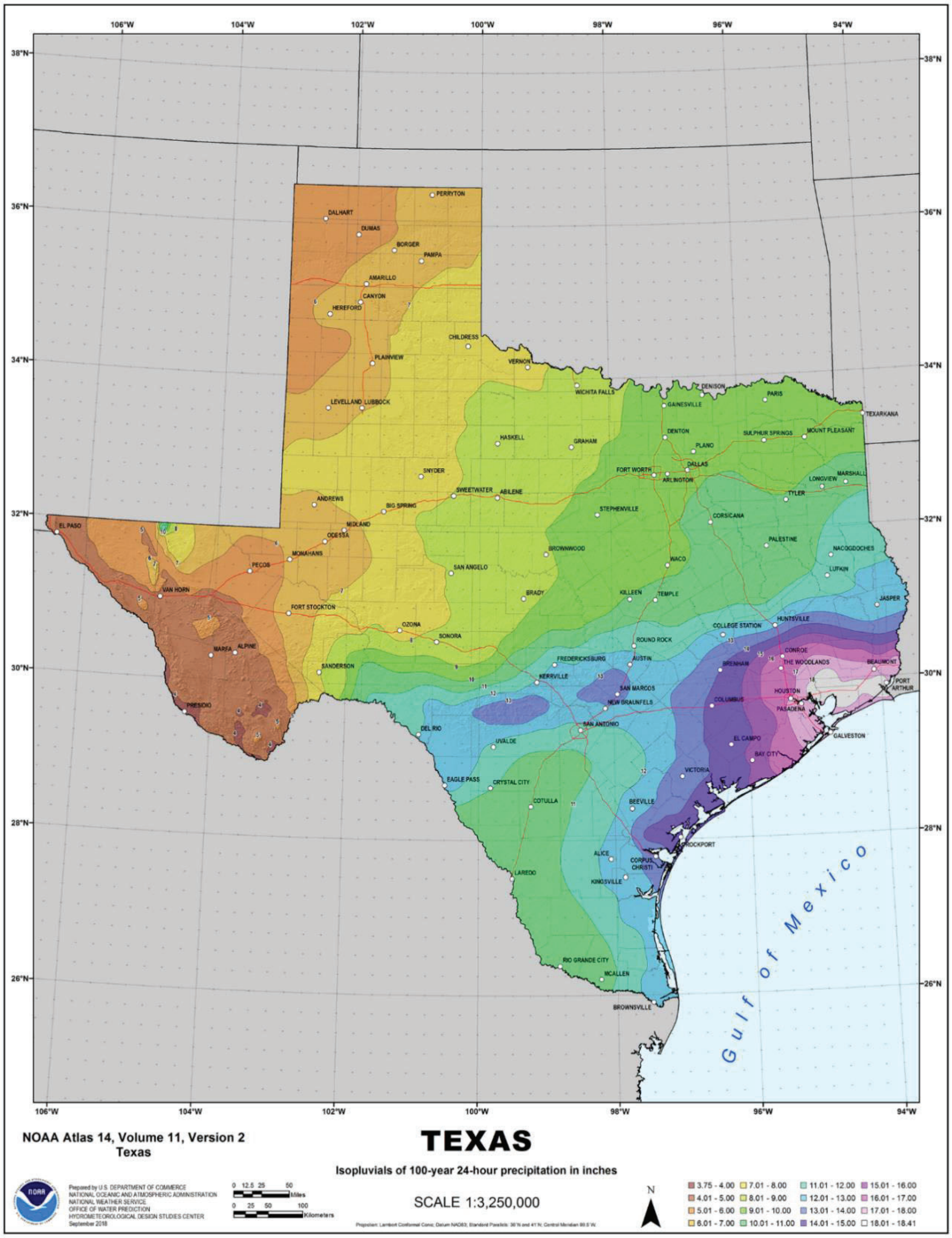
To better understand flooding associated with rainfall, the team looked to Atlas 14. Commissioned by the National Oceanic and Atmospheric Administration (NOAA) and implemented by the Hydrometeorological Design Studies Center with the Office of Water Prediction, Atlas 14 has been completed across most of the United States and was updated for Texas. Isopluvials of 100-year 24-hour precipitation in inches for Texas is shows in Figure 14. Note: a 100-year event is a storm that has a 1% likelihood of occurring in any given year.

What is NOAA Atlas 14?

The NOAA Atlas 14 presents a new analysis of rainfall data through 2017. It demonstrates that 100-year rainfall events in the Pilot Program area have increased to 17 inches in 24 hours from the previous 13 inches in the same time frame, which was based on The U.S. Weather Bureau Technical Paper No. 40 (TP-40) published in 1961. This represents a 30% increase in a 100-year rainfall event (Climate Discovery, 2020).

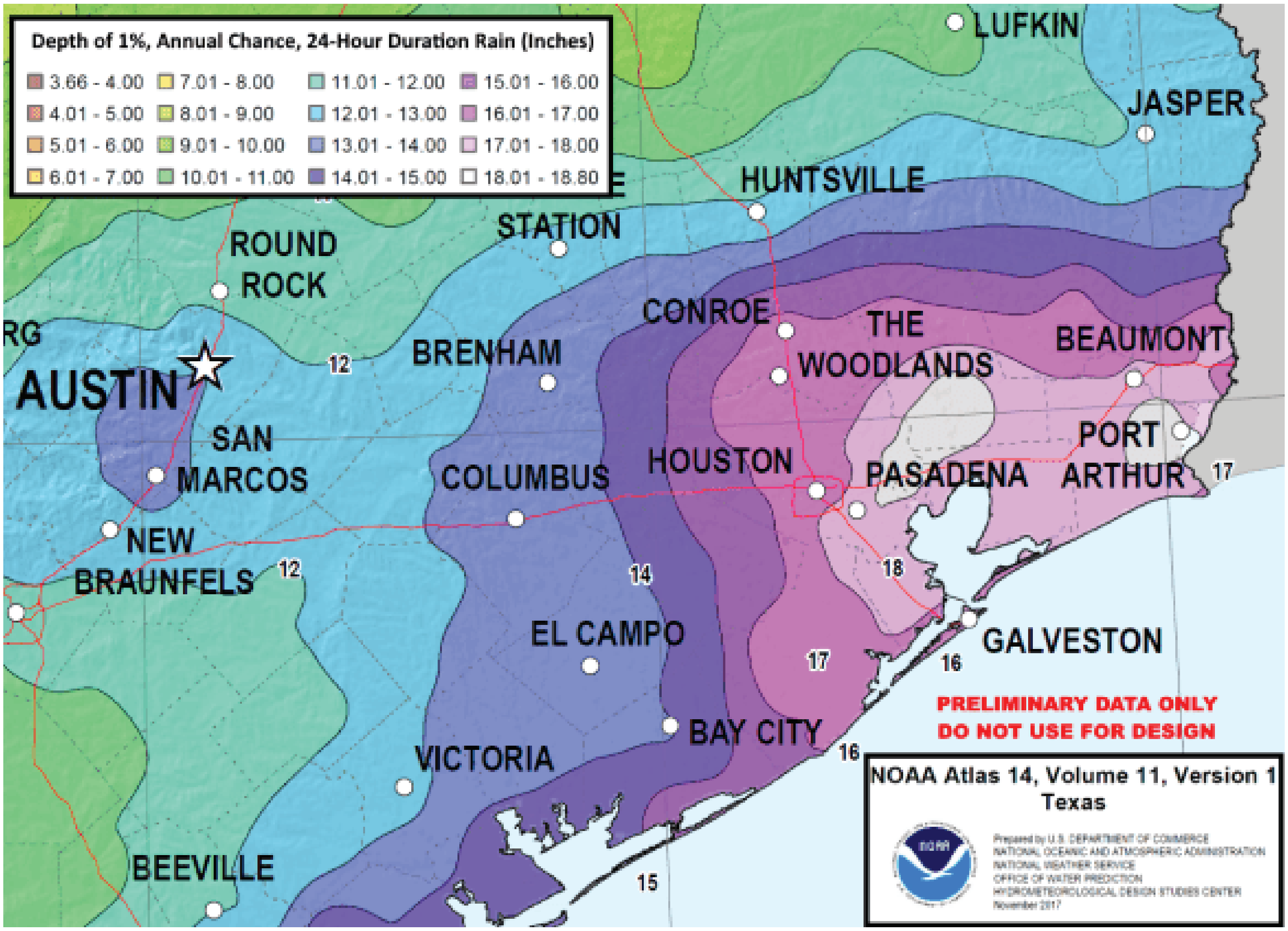
In Houston, the 100-year storm in our old climate was 12.5 inches in 24 hours. The new Atlas 14 shows the Houston 25-year storm is now 12.1. The 100-year storm total has increased to 17.9 inches, an increase of 43%. Harris County Commissioners Court unanimously adopted to implement new standards requiring developers to build enough detention to offset flooding in the 500-year floodplain. Previously, county requirements only covered the 100-year floodplain. The new rules will be effective until FEMA flood maps are updated (Community Impact Newspaper, 2020).

Figure 14 - NOAA Atlas 14, Texas: Isopluvials of 100-year 24-hour precipitation in inches



The team modeled three flood levels: **100-year flood**, **500-year flood**, and **Hurricane Harvey**. The models use 100-year and 500-year flooding from interpolating high-water depths using FEMA National Hazard maps for 100-year and 500-year floodplains. Isopluvials of 100-year 24-hour precipitation in inches for the Houston region is shows in Figure 15.

Figure 15 – NOAA Atlas 14, Houston region: Isopluvials of 100-year 24-hour precipitation in inches

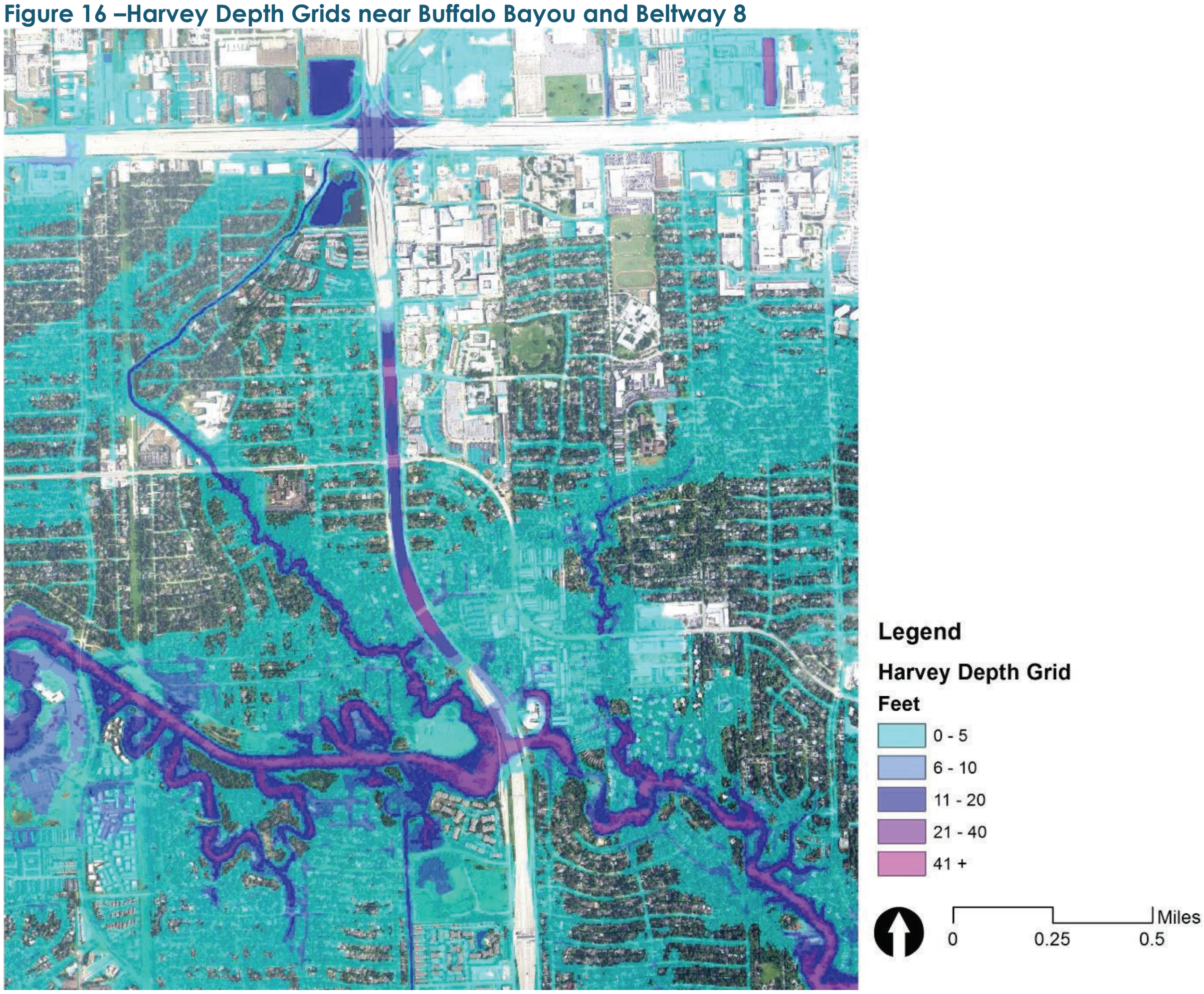


For flood modelling, the Hurricane Harvey model came from the FEMA Harvey Depth Grid, which included the following notes:

- Based on observed water levels at stream gauges interpolated along rivers, down-sampled to 5-meter resolution Digital Elevation Model (DEM)
- Depth grids are updated with new observed peak crest as they become available
- Extents validated with remote sensing
- Use for determining damage levels on specific structures

Harvey depth grids near Buffalo Bayou and Beltway 8 are shown in Figure 16.

Figure 16 –Harvey Depth Grids near Buffalo Bayou and Beltway 8

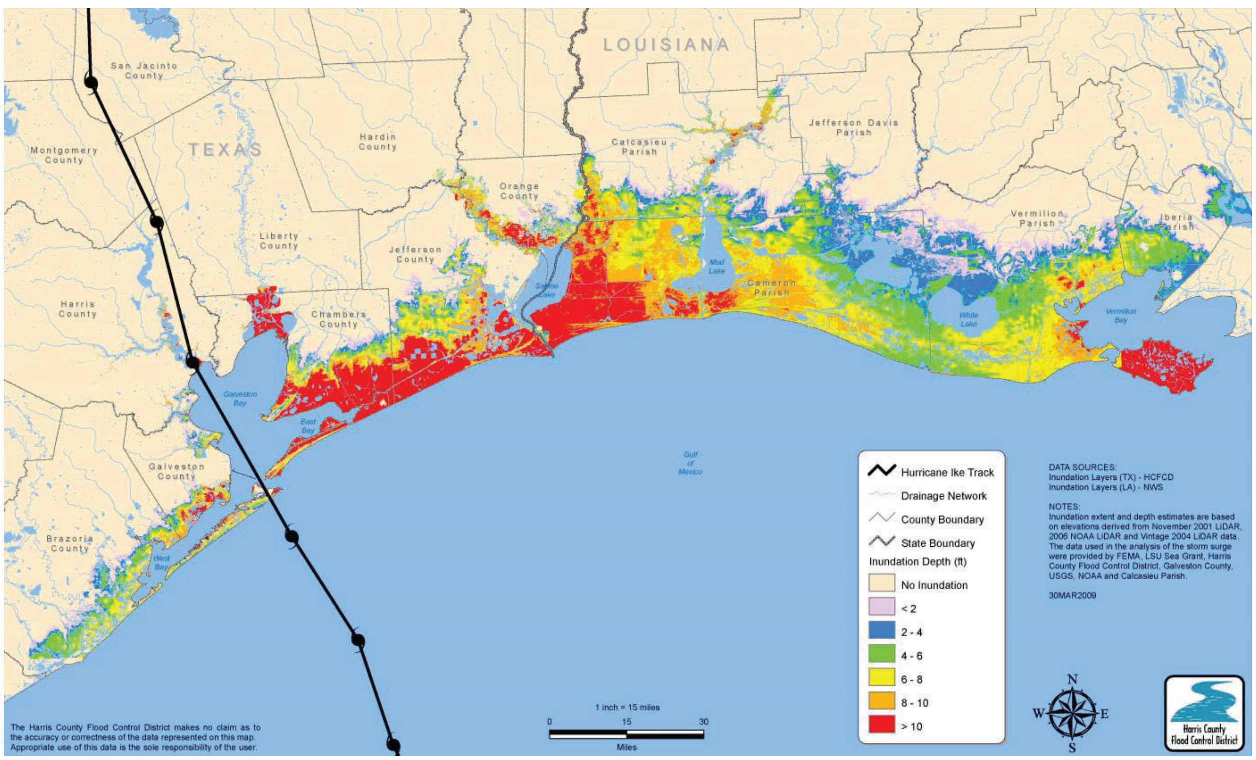


Storm Surge

Storm surge is defined by NOAA as "the abnormal rise of water generated by a storm, over and above the normal tide… expressed in terms of height above predicted or expected tide levels". Storm surge impacts coastal areas and generally occurs where winds are blowing onshore.

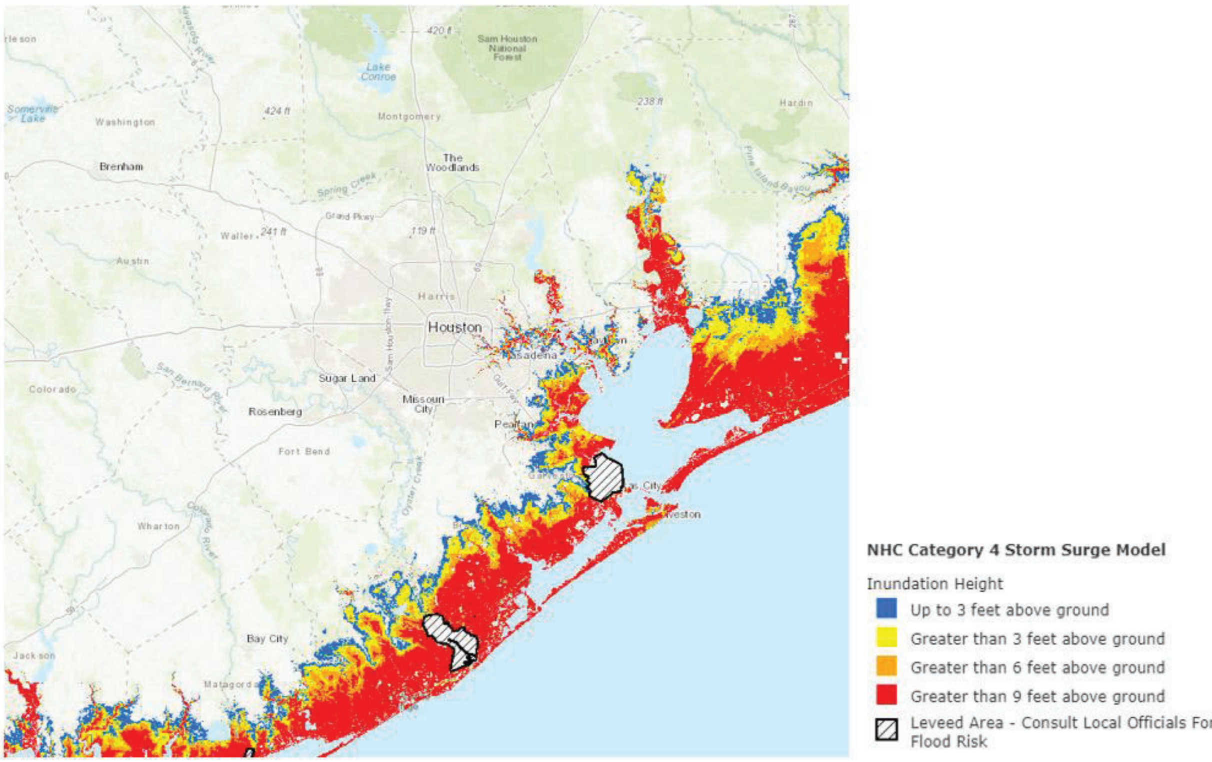
In 2001, the massive rainfall that occurred with Tropical Storm Allison was considered an anomaly. Allison doubled Houston's previous 24-hour rainfall record with 26-inch rain in east Harris County in a 24-hour period. When Hurricane Ike, a Category 2 storm, hit the region in 2008, it generated a larger than normal surge for a storm of its size. Hurricane Ike submerged most of the land east of Galveston Bay to 17 feet above sea level (see Figure 17). After Ike, the National Weather Service changed their hurricane classification program to separate the storm category from the prediction of storm surge. This differentiation analyzes wind speed separate from other factors, such as the size of the hurricane-force wind field.

Figure 17 – Ike Storm Surge Inundation Map



For the Pilot Program, the team modeled six storm levels: Category 1, Category 2, Category 3, Category 4, Category 5, and, for historical reference, Hurricane Ike. The models use the Maximum of Maximums (MOM) from tens of thousands of simulated storms from the National Hurricane Center's Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (see Figure 18). Simulated storms moving from all forward directions retain the highest surge values and represent a worst-case scenario for the storm category modeled.

Figure 18 –SLOSH Model's Category 4 Inundation Map



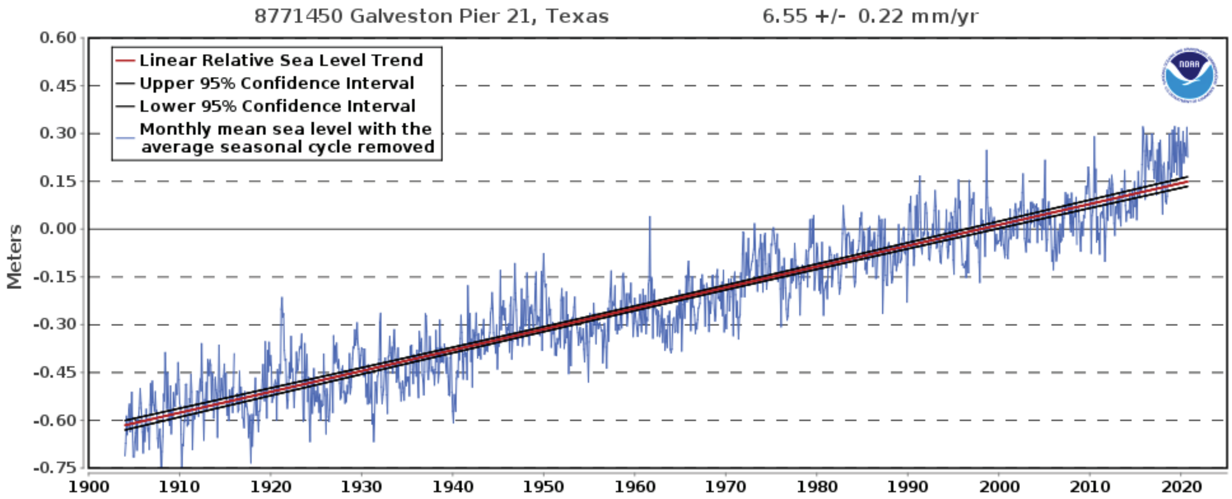
Sea Level Rise

Independent of rainfall events, sea levels are rising due to warming oceans, increased melting of land-based ice, such as glaciers and ice sheets, and land subsidence. Rising sea level inundates low-lying wetlands and dry land, erodes shorelines, contributes to coastal flooding, and increases the flow of salt water into estuaries and nearby groundwater aquifers. Higher sea level makes coastal infrastructure more vulnerable to damage from storms (EPA's Report on the Environment, 2020).

NOAA measures the sea level from Pier 21 on the bay side of Galveston Island. Over the past 100 years, sea level at Pier 21 has risen more than two feet. At 0.25 inch (6.55 mm)/year, Galveston has one of the highest- measured rates of sea level rise in the country (Galveston Bay Report Card, 2020).

As sea levels rise, existing coastal flooding worsens and beaches erode, eventually submerging wetlands and dry land. As of spring 2020, the State of Texas has planned over $12 billion in sea level rise solutions, which include storm surge protection, drainage and erosion control, and flood mitigation projects (Figure 19 shows relative sea level trend at the Galveston Pier 21 tide gauge).

Figure 19 – Relative Sea Level Trend from Galveston Pier 21



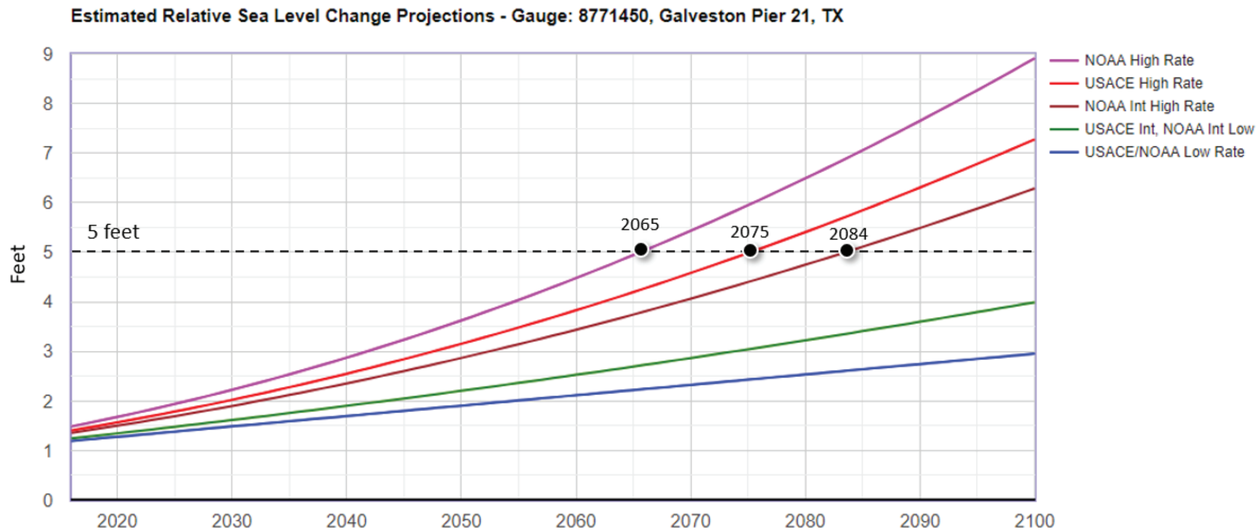
Experts are not certain how fast the ocean will warm, or ice will melt. However, they expect water levels to continue to rise faster in the future (National Oceanic and Atmospheric Administration, 2019). Therefore, scientists from the NOAA and the US Army Corps of Engineers (USACE) have made predictions based on ranges from low to high.

Figure 20 shows the range of the NOAA and USACE high and intermediate forecast for Galveston Pier 21. Currently, the USACE high forecast, shown as the darkest red line, is the most likely projection.

How is Sea Level Rise Measured?

Sea levels are measured every 6 minutes using equipment such as satellites, floating buoys off the coast, and tide gauges to measure the exact sea level as local sea levels accelerate and change. (SeaLevelRise.org, 2020)

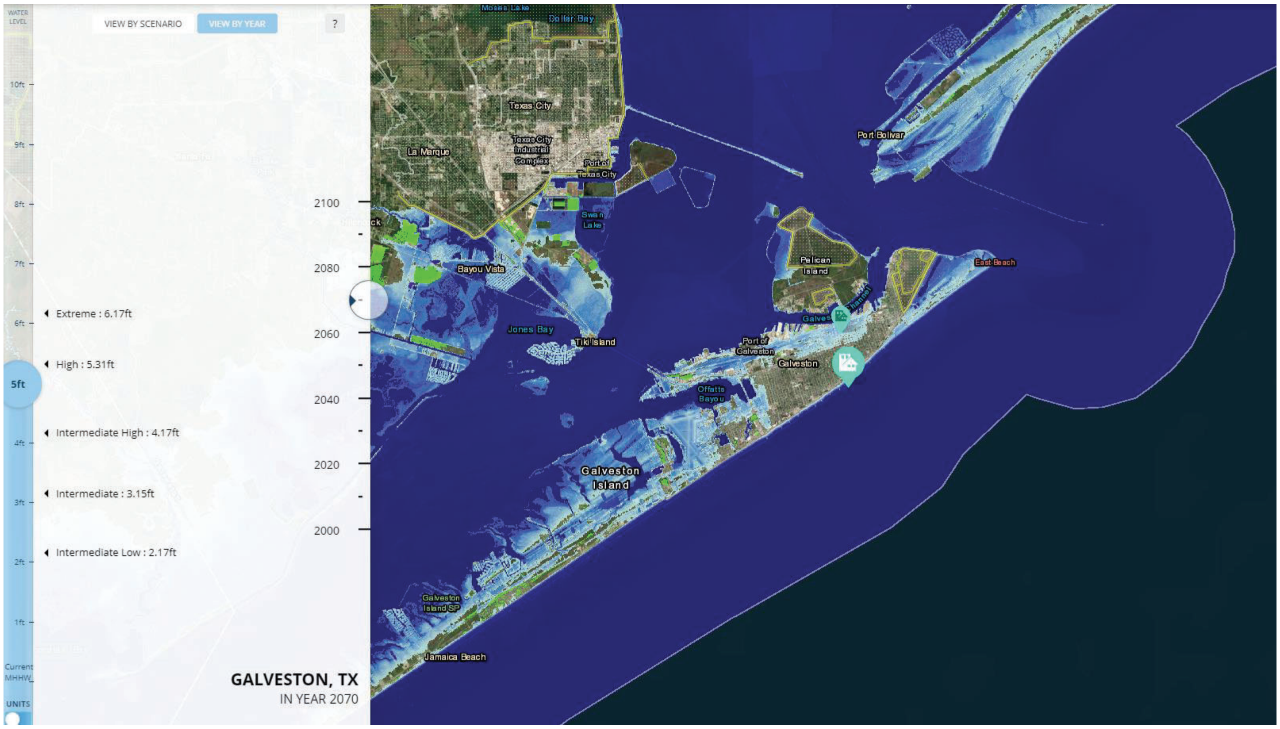
Figure 20 – Galveston Pier 21 Sea Level Rise Forecasts



Source: Sea-Level Change Curve Calculator, US Army Corps of Engineers

Per the NOAA Sea Level Rise Viewer, the sea level of Galveston Pier 21 area with 'High' scenario will reach 5 feet higher than current Mean Higher High-Water level around 2070 (see Figure 21).

Figure 21 – NOAA Sea Level Rise Model (5ft)



ASSESSMENTS

A crucial element to the Pilot Program is the identification of highly critical and highly vulnerable transportation assets and infrastructure in the region. Once identified, these assets are modeled using the 11 scenarios identified by the Pilot Program team.

The results of these identification assessments can be used as justifications for further economic analysis and infrastructure improvement proposals. To identify these assets objectively and systematically, the team conducted two data-driven, GIS-based assessments:

- **criticality assessment** identifies transportation assets that are crucial to the region's routine functions and economic activities; and
- **vulnerability assessment** identifies transportation assets that are most susceptible to probable regional climate stressors.

Those assessments were used to conduct further analysis:

- **criticality-vulnerability assessment** identifies those assets that are both highly critical and highly vulnerable, and therefore a priority for mitigation strategies in the Pilot Program area; and
- **economic impact analysis** estimates the economic impact of short-term transportation network disruptions to the region.

For this Pilot Program, the team studied two types of transportation infrastructure assets within the region: Major Roads and Bridges.[6]. Major Roads include freeways and major roads, including major arterials, minor arterials, and collectors. Roadway Bridges include waterway bridges only. Other transportation asset types, such as railways, transit facilities and pipelines, are not considered in the Pilot Program.

[6] The datasets were initially acquired from TxDOT Roadway Inventory Database and Bridge Inspection databases in GIS feature class formats and processed for the Pilot Program requirements.

Criticality Assessment

By analyzing the regional transportation system and economic activities in a disruption-free scenario, the criticality assessment aims to identify transportation assets that provide vital support to a functioning regional transportation network.

The team evaluated four transportation criticality perspective categories in the assessment, weighted based on feedback from stakeholders:

1. *Socioeconomic importance – 20% in the overall criticality assessment*
   Assessed by considering how each transportation asset contributes to the regional economy and provides access to key employment, trade, and travel hotspots. The specific indicators included in this category are service to activity population, links to airports, and water ports.

2. *Usage and operational importance – 40% in the overall criticality assessment*
   Assessed by considering the volumes and types of traffic that each transportation asset holds. The specific indicators included in this category are- Average Annual Daily Traffic (AADT), AADT- truck, and transit ridership.

3. *Health and safety importance – 30% in the overall criticality assessment*
   Assessed by considering how each transportation asset provides access to healthcare and safety facilities and connects underserved areas and population. The specific indicators included in this category are links to hospitals and fire stations and service to vulnerable population.

4. *Emergency preparedness importance – 10% in the overall criticality assessment*
   Assessed by considering what roles each transportation asset plays in a state of emergency. The specific indicators included in this category are evacuation routes, links to shelters and emergency operation centers (EOC), and access to military facilities.

For each category, the team selected and analyzed multiple indicators to capture related characteristics of each transportation asset. For each transportation asset, the team categorized selected indicators and scored them based on their attributes and importance to the transportation network. Scores range from 0 to 4 for most indicators, with 4 suggesting highest criticality for an asset. All data analysis was performed using SAS and ArcGIS.

The result of the criticality assessment is the aggregated criticality index, derived from the weighted summary of all scores of individual indicators. The weighting schemes were generated by the team after analyzing polling results from a stakeholder engagement meeting (see Stakeholder Engagement on page 93).

The team ranked aggregated criticality scores and cumulatively standardized them on a scale of 0 to 1, with 1 representing the most highly critical roadway in the region. After normalization, roadways with an index higher than 0.67 were considered highly critical to the regional transportation system; roadways with an index between 0.33 to 0.66 were considered moderately critical; and the remaining roadways on the index were considered lowly critical.

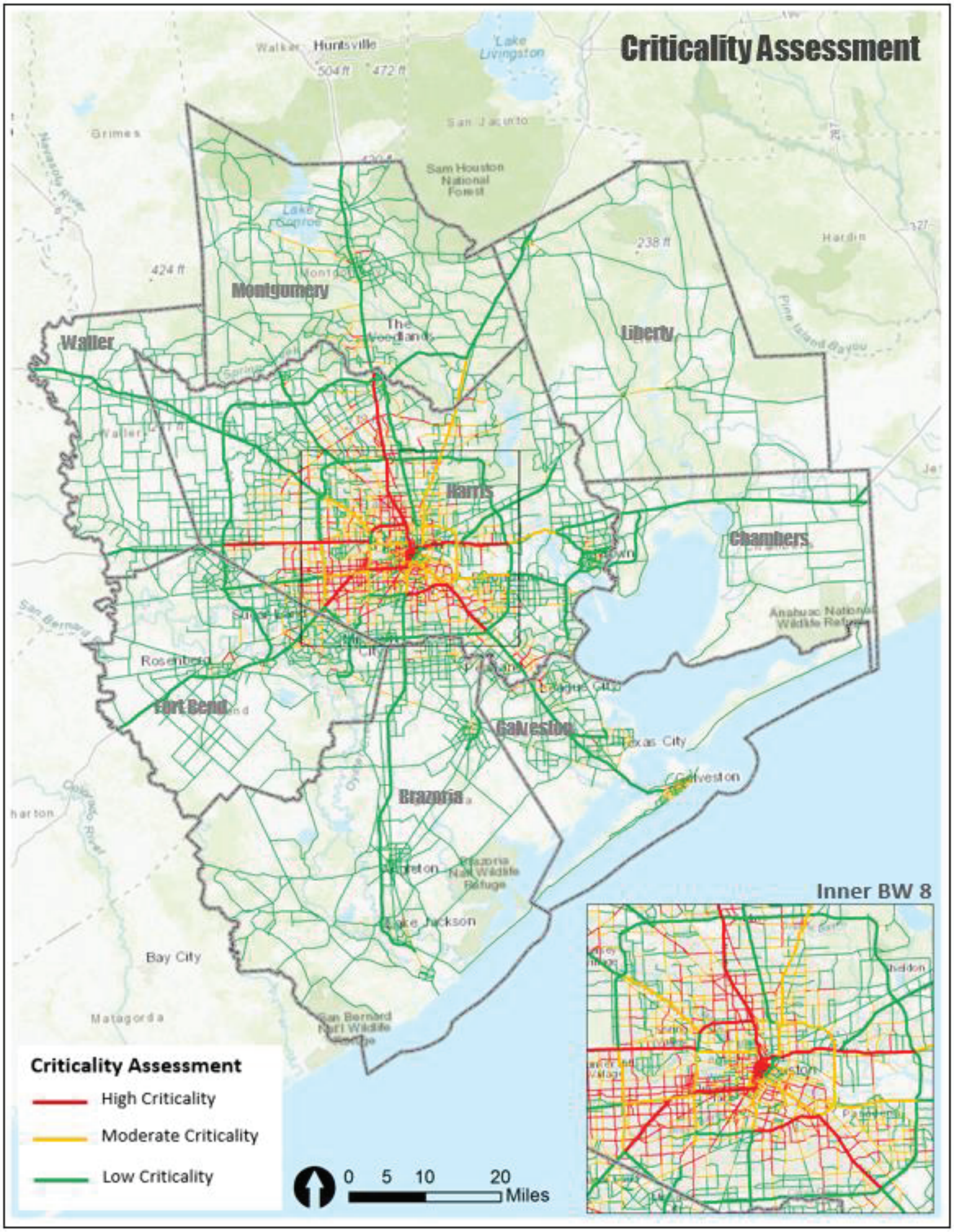
A single assessment for all roadways considering traffic levels and importance to the regional network could lead to substantial bias toward freeways. To mitigate this issue, staff ensured all data processing procedures, such as scoring, weighting, ranking, and standardization, were conducted separately for freeway segments and major road segments.

Detailed methodology of the criticality assessment, including indicator selection and calculation, weight schemes and data sources, as well as results for each assessment component, are specified in Appendix A on page 101.

Criticality Assessment Results

Criticality results are shown in Figure 22. Among a total of 762 centerline freeway miles and 6,440 major road miles, 92 centerline miles of freeways and 551 centerline major road miles are highly critical, accounting for 12% of freeway miles and 9% of major road miles.

Figure 22 – Criticality Assessment Results



For freeways, all highly critical assets are within Harris County, home to the city of Houston and the economic center of the Houston-Galveston MPO region. Apart from 6 miles of US-59 in Montgomery County that are classified as moderately critical, all freeway segments outside Harris County are considered to be of low criticality.

Similarly, 93% of highly critical major roads are in Harris County—only 44% of the regional total centerline miles. Conversely, rural counties, such as Chambers, Liberty and Waller, collectively have less than 4% of major road centerline miles classified as highly critical. Detailed centerline mile distributions by county and criticality category are shown in Figures 23 and 24.

Figure 23 – Freeway Criticality by County

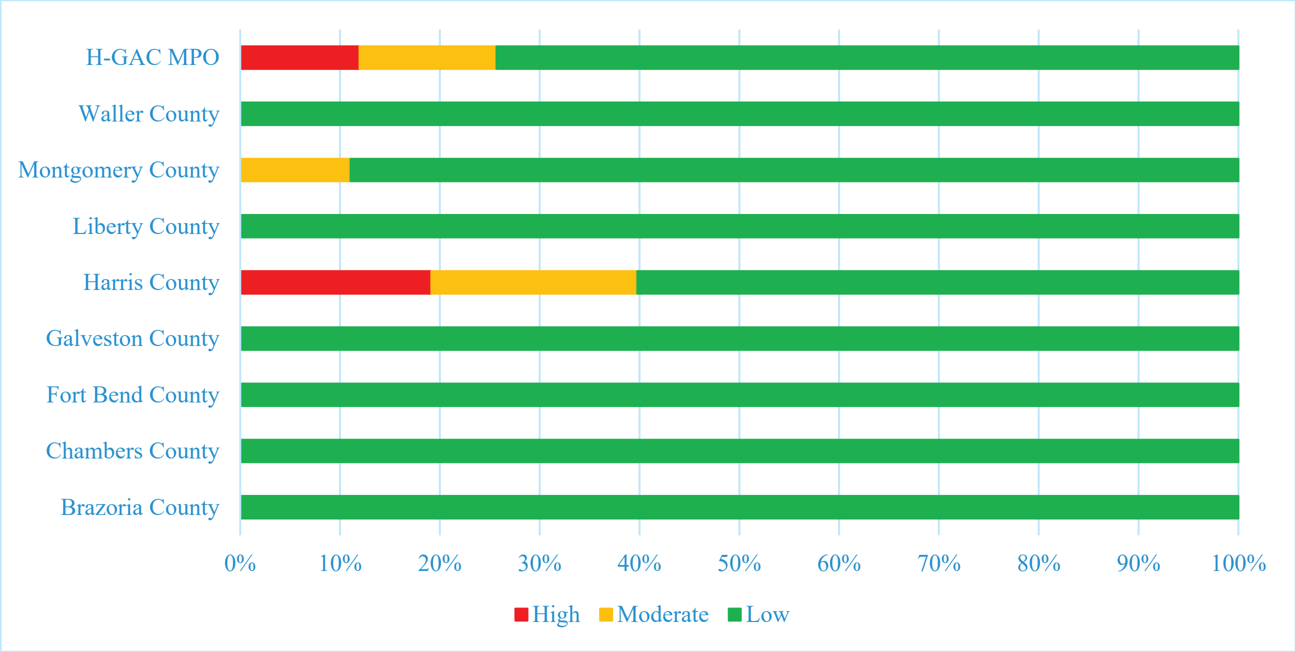
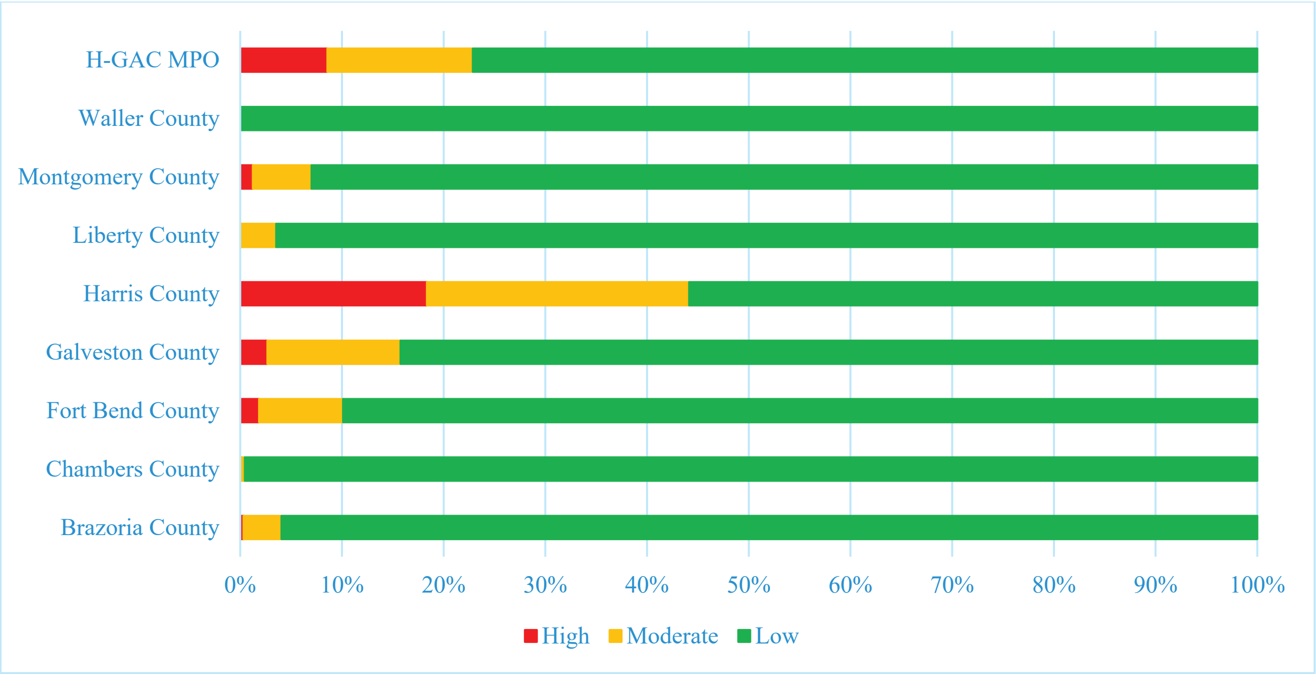


Figure 24 – Major Road Criticality by County



Highly and moderately critical road segments are largely concentrated in the city of Houston and surrounding suburbs. Freeways connecting major employment centers, such as Houston downtown, the Energy Corridor, and Galleria area are highly critical, mostly due to their high socioeconomic importance, usage, and operational importance. Highly critical local roads are almost entirely within the 610 Loop in the city of Houston.

Outside of Harris County, the highly critical major roads are mostly near major neighborhoods in communities, such as Sugar Land, The Woodlands, Pearland, and Galveston. Please refer to the Appendix A on page 101 for criticality results by specific indicators. Criticality scores for individual indicators can also be accessed from the online Regional Resilience Tool[7].

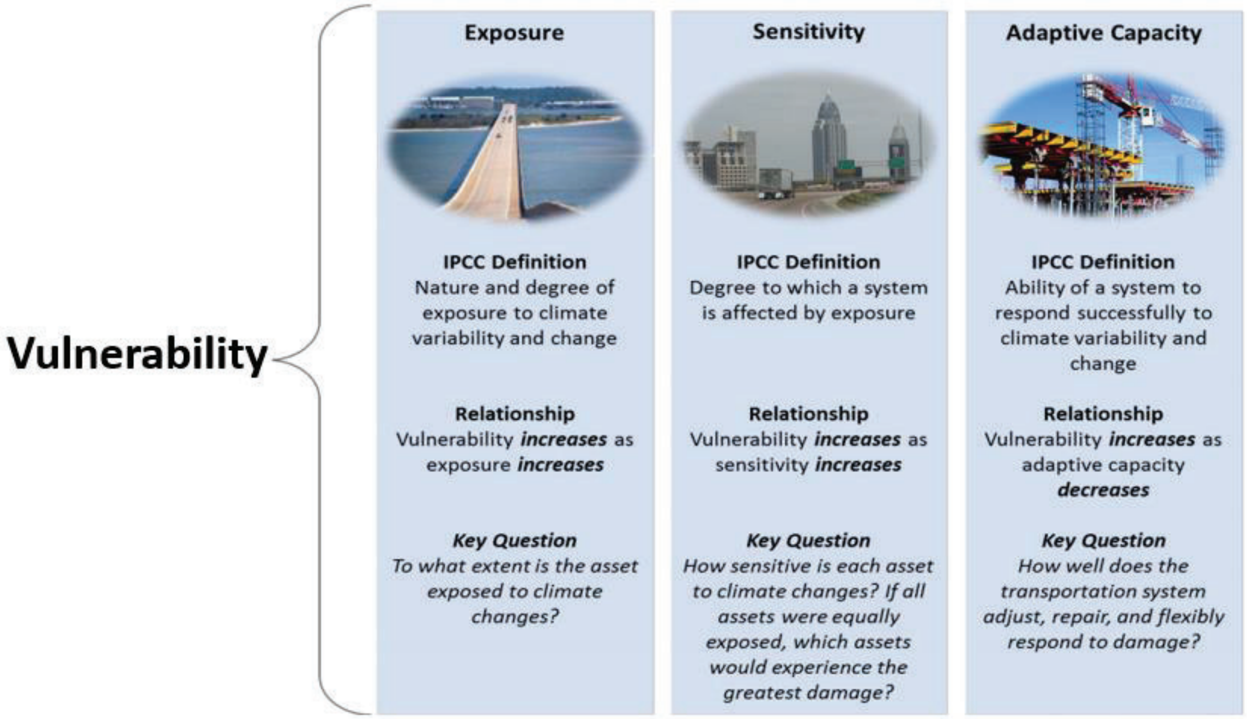
[7] https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

Vulnerability Assessment

The vulnerability assessment is the core component of the Pilot Program. The key objective of the vulnerability assessment is to comprehensively evaluate the capacity of a transportation asset to endure and recover from climate exposures and service disruptions in extreme weather events.

The vulnerability assessment assesses the probability of the occurrence of disruption of a transportation asset due to extreme weather and, should the disruption occur, the consequences of the disruption. Vulnerability assessment includes three components: Exposure, Sensitivity, and Adaptive Capacity (see Figure 25).

Figure 25 – Vulnerability Assessment Components (FHWA, 2015)



In each assessment section, indicators derived from geospatial analysis are used to evaluate the risk component. The vulnerability assessment structure resembles the U.S. Department of Transportation / FHWA Vulnerability Assessment Scoring Tool (VAST). However, to achieve enhanced data customization in the assessment, the team used SAS and ArcGIS for the data analysis in the assessment instead of VAST.

Exposure Assessment

Exposure is the critical component of the vulnerability assessment as it indicates whether a road segment or a bridge is flooded or not based on a given flooding scenario. To measure the level of flooding, the following factors are needed:

1. **Ground Elevation** - To measure the ground and surface elevation, the team used the 2018 LiDAR data. The ground elevation is measured using the DEM, which is a bare-earth raster grid usually representing the surface of the earth.

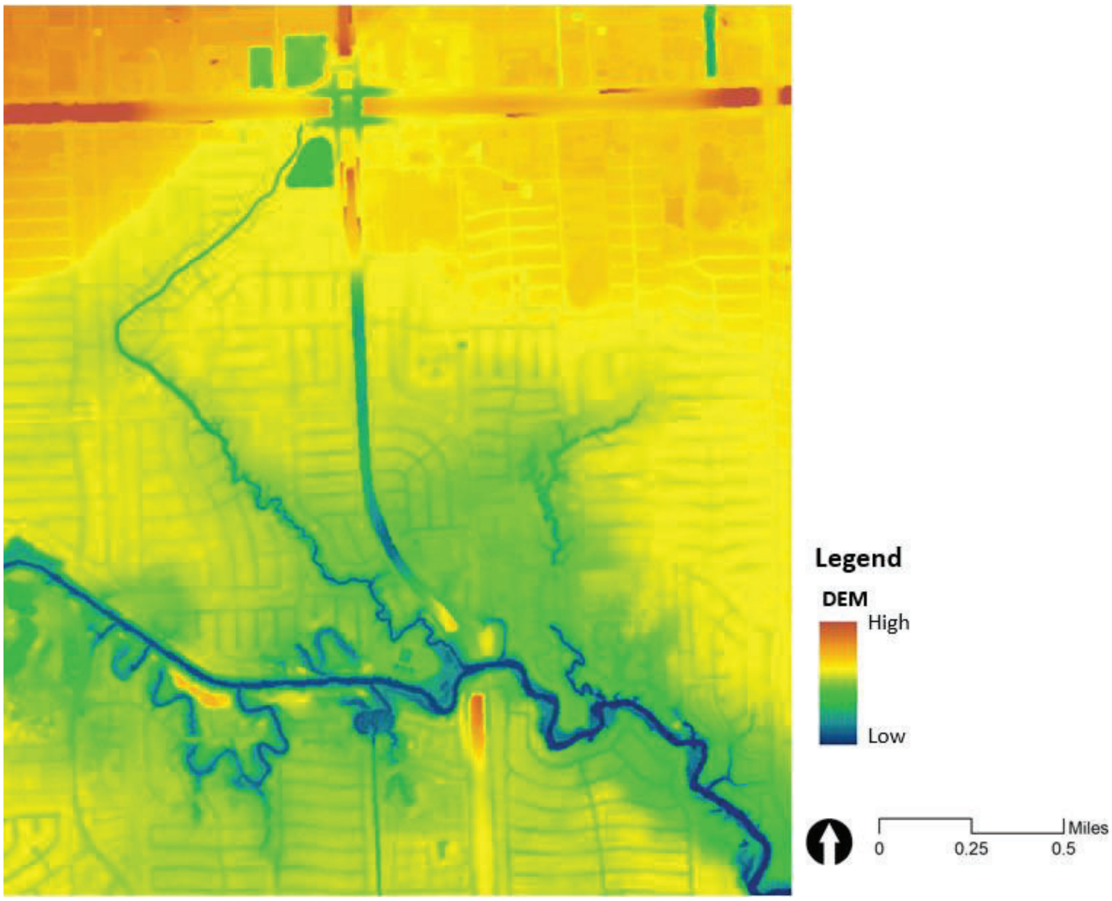
   Once above-ground natural and built features, such as trees and other types of vegetation, roads, bridges, buildings, powerlines, etc., are filtered out, a smooth DEM is produced. For this effort, the team measured ground surface level and heights with respect to the DEM value at a specific location.

   Figure 26 shows the Buffalo Bayou and part of Beltway 8 South at a lower elevation compared to the surrounding area.

What is LiDAR?

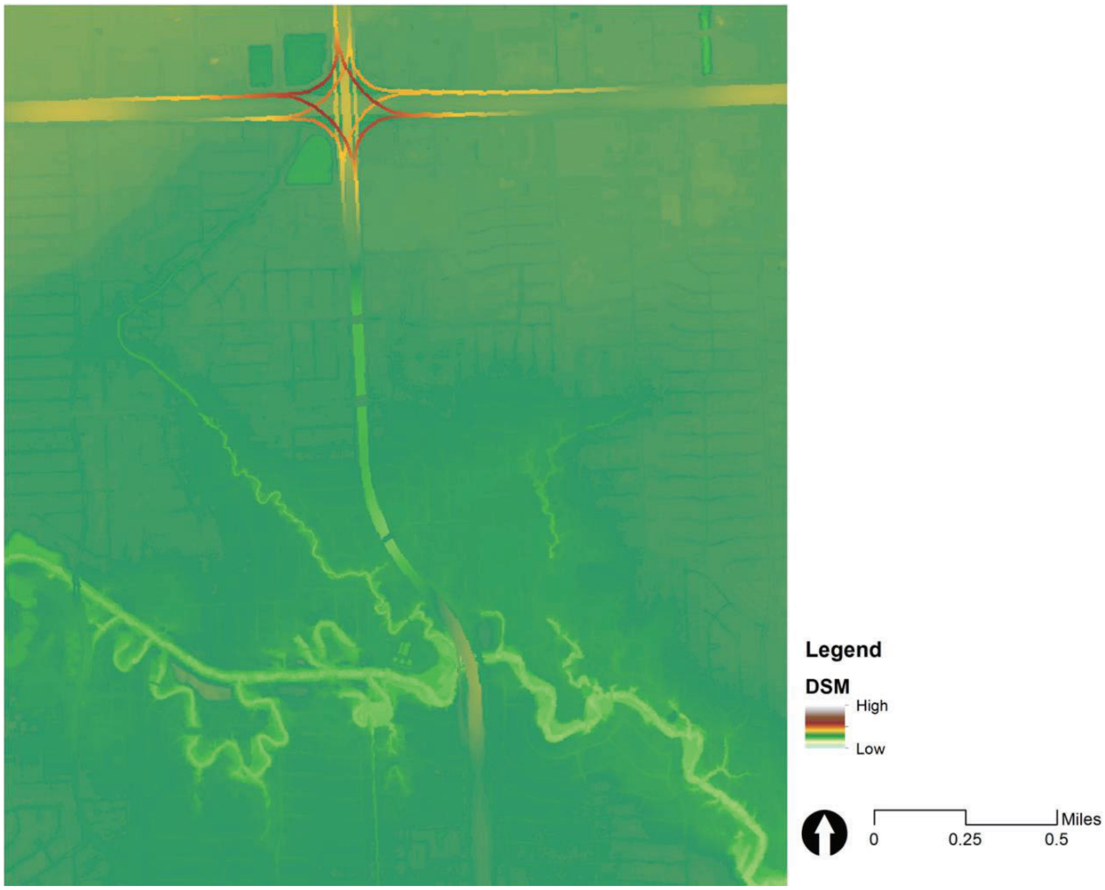
LiDAR is a remote sensing technology that measures distance, elevation, or surface by illuminating a target with a laser and analyzing the reflected light. The acronym for LiDAR commonly refers to Light Detection and Ranging. LiDAR is popularly used as a technology for creating high resolution maps and data representing surfaces and elevations.

Figure 26 – Digital Elevation Model at the intersection of Beltway 8 and Interstate 10



2. **Surface Elevation-** To obtain the height information of transportation infrastructure assets, an altitude model is required in addition to DEM. The altitude model used by the team is the Digital Surface Model (DSM), an elevation model that contains the elevation of terrain as well as above-ground natural and built features. Figure 27 shows the highly elevated ramps connecting Beltway 8 and Interstate 10 in dark red. It also shows Buffalo Bayou and part of Beltway 8 South at the lowest elevation in light green.

Figure 27 – Digital Surface Model at the intersection of Belt Way 8 and Interstate 10



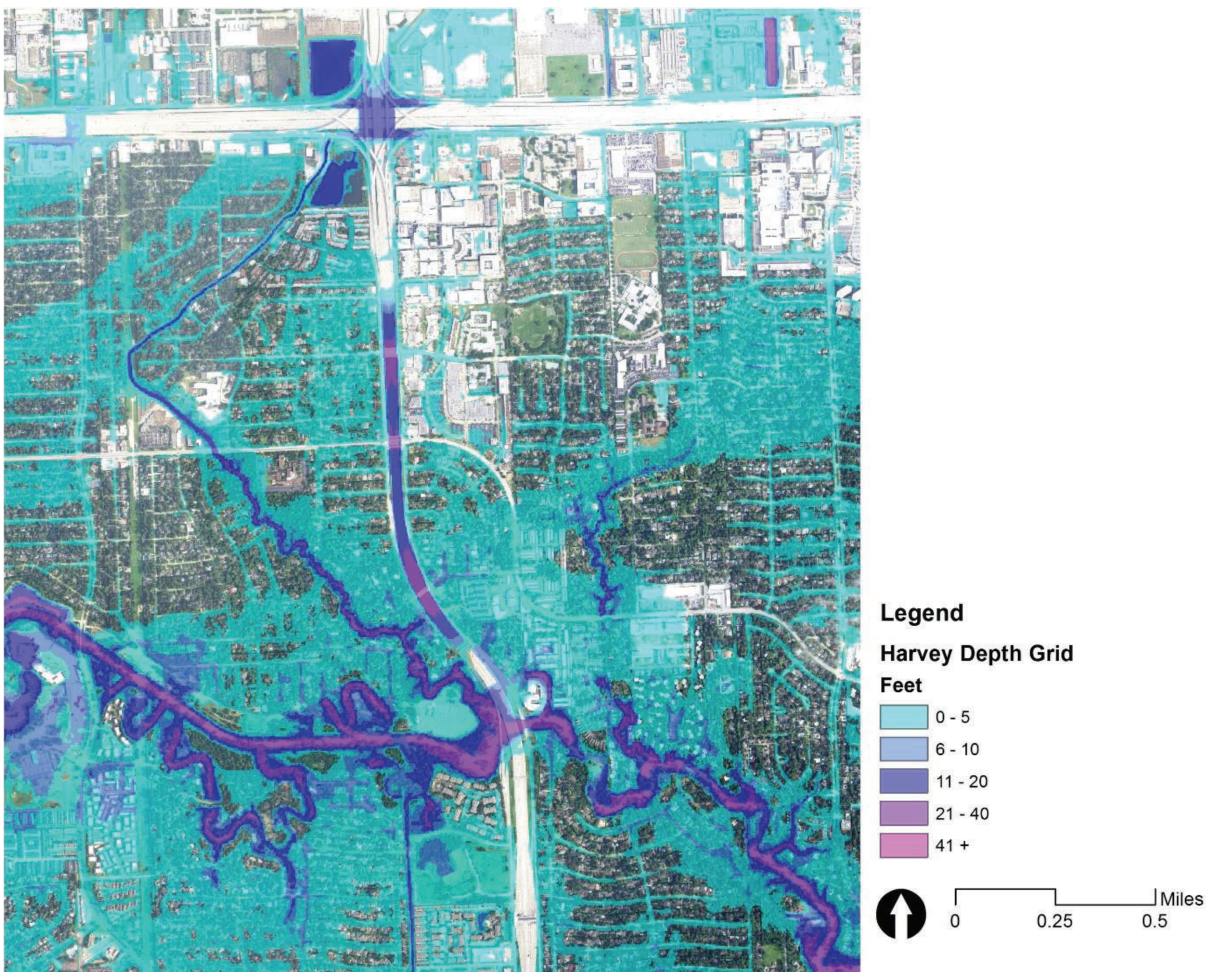
3. **Water Depth**- One of the primary ways to communicate flood risks and inform actions that can be taken to reduce flood risks is through grid datasets on water depth. These datasets provide detailed information of flooding depth, probability of flooding, and other flooding characteristics. Like pixels in an image or picture, a grid is a digital raster dataset that defines geographic space as an array of equally sized square cells arranged in rows and columns. The value in each grid represents the magnitude of flooding characteristics at a given location.

   The Water Surface Elevation (WSEL) grid is generally the first raster dataset that will be produced as part of a flood risk study. A separate WSEL grid is produced for each flood event (e.g. 1% annual-chance, 0.2% annual-chance, 1% annual-chance future conditions, 1%-plus, etc.) or flood scenario for which modeled elevations are available.

Each WSEL grid provides the modeled WSEL values within the inundation extent of that flood event or scenario. The team collected the WSEL data for the Pilot Program from FEMA (100-Year flooding, 500-Year flooding, and Hurricane Harvey) and NOAA (Storm Surge, Hurricane Ike, and Sea-Level Rise).

To identify areas that are outside the floodplain, but are prone to flooding, the team spatially interpolated FEMA's 100-year and 500-year flood zone boundaries. The interpolation yielded a spatially continuous WSEL for each flooding event. The team calculated the flood depth grid data for each scenario by measuring the difference between WSEL and DEM. Figure 28 shows FEMA's Harvey Flood Depths Grid data near Beltway 8 and Interstate 10. It shows parts of Beltway 8 South under water and Buffalo Bayou overflowing into surrounding areas.

Figure 28 – Digital Surface Model at the intersection of Belt Way 8 and Interstate 10



4. **Exposure Depth**- Exposure depth grid is a 5-by-5-meter raster grid representing flood level on top of a structure, such as a roadway or bridge section. The value of exposure depth grid is equal to the difference between roadway/bridge surface elevation, or DSM, and flood WSEL (see Figures 29 and 30). Exposure depth for roadway segments and bridges was measured using the various water depth data mentioned in the previous section.

Figure 29 – Roadway/Bridge section elevation measured from DSM and flood water elevation measured by WSEL

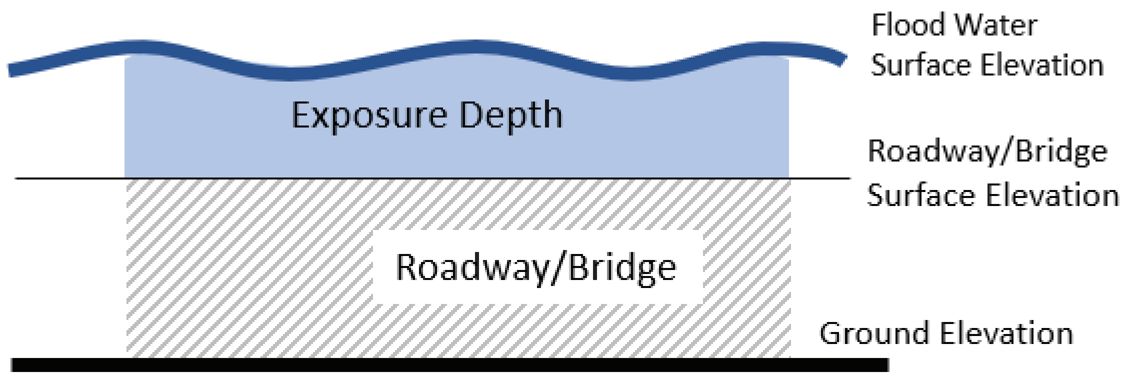
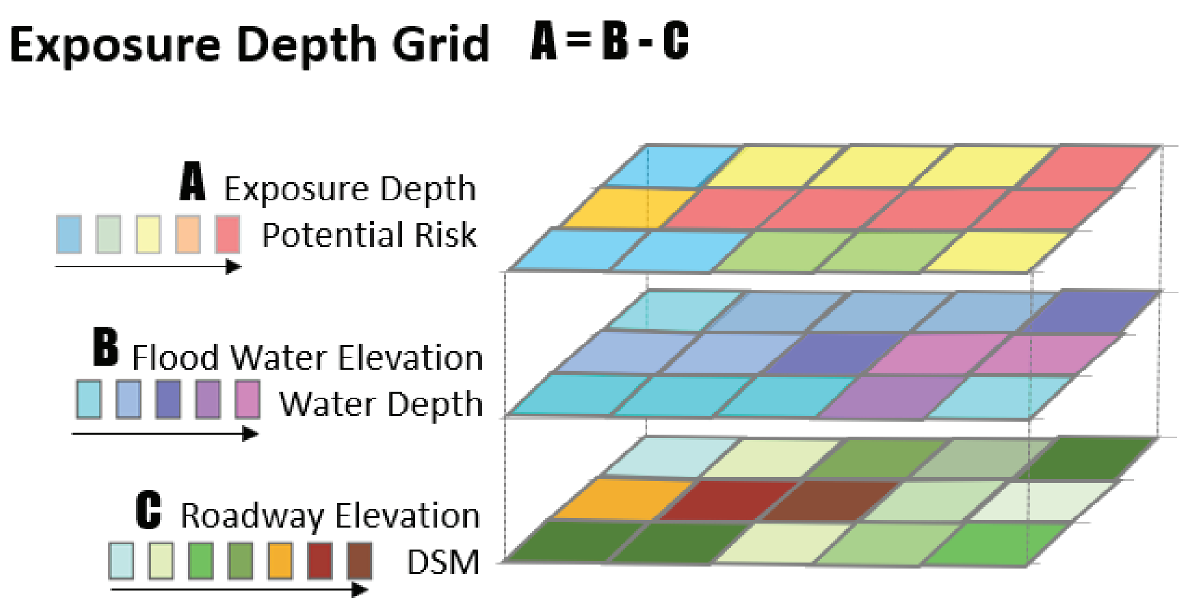


Figure 30 – Exposure Depth Grid



The roadway exposure level indicates how at risk a roadway is to an exposure type. The five levels used are detailed in Table 1. Note: the team defines risk as service disruption to roads and bridges in the event of floods, storm surges, and sea level rise. In the Pilot Program, flood depth is used as the risk exposure level to assess the intensity/duration of disruption. The Pilot Program assumes that as the flood depth increases, so does the intensity/duration of interruptions.

Table 1– Roadway Exposure Level

Exposure Description	Exposure Level
Not exposed/ Less than 0 foot of flood water	No exposure or low risk
0 - 1 foot of flood water	Medium-low risk
1 - 2 feet of flood water	Medium risk
2 - 3 feet of flood water	Medium-high risk
More than 3 feet of flood water	High risk

The bridge exposure level uses different scales to reflect the safe operation of a bridge, as detailed in Table 2.

Table 2– Bridge Exposure Level

Exposure Description	Exposure Level
6 + feet below deck	No exposure or low risk
Water level 4-6 feet below deck	Medium-low risk
Water level 2-4 feet below deck	Medium risk

Water level within 2 feet below deck	Medium-high risk
Water level above bridge deck	High risk

Figure 31 shows the modeled Hurricane Harvey exposure depth grid data at the intersection of Beltway 8 and Interstate 10. The figure shows parts of Beltway 8 and Wilcrest Road (parallel to Beltway 8) as high risk for flooding. These segments were flooded from Hurricane Harvey as Buffalo Bayou overflowed.

Figure 31 – Exposure Depth Grid along Beltway 8

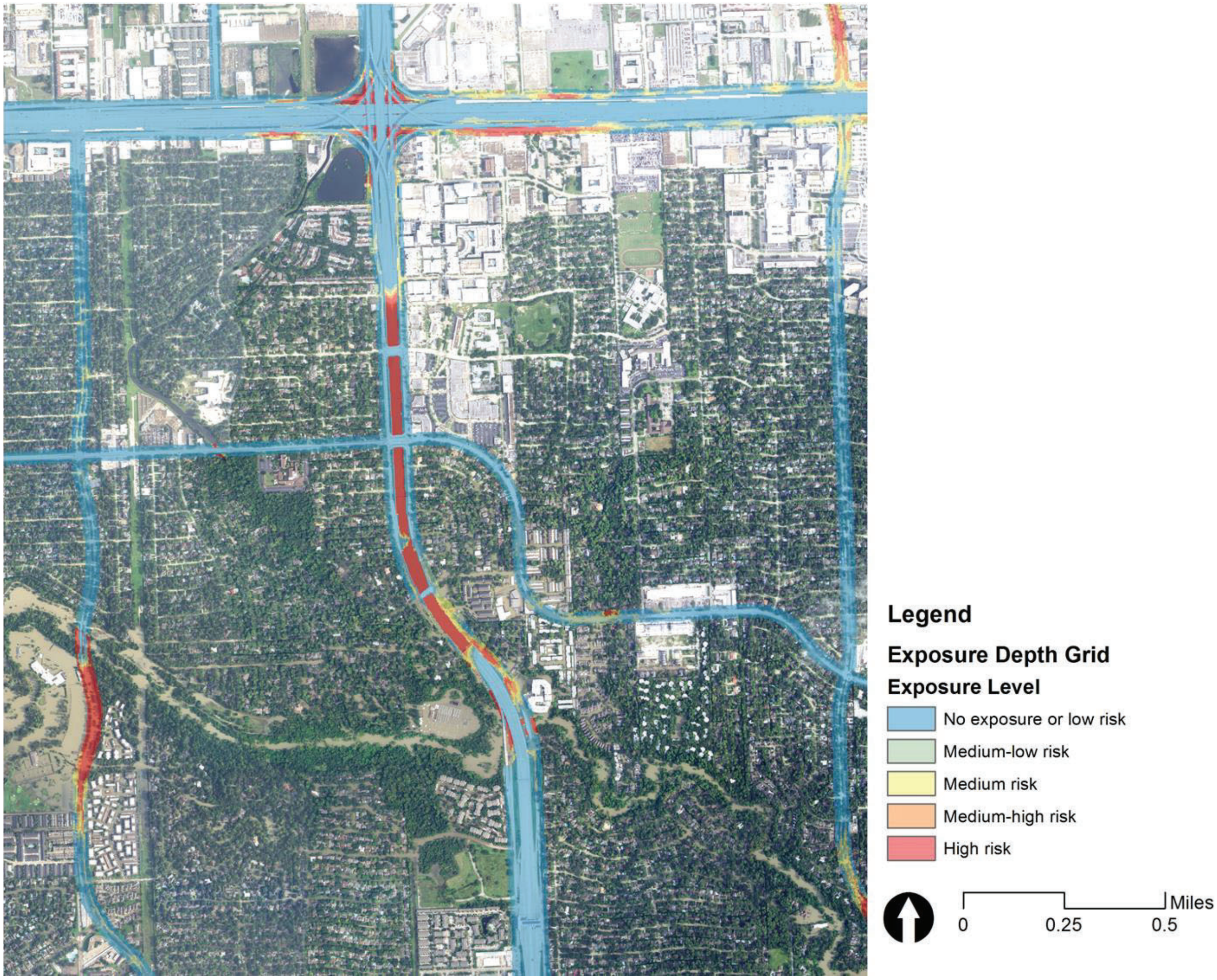


Figure 32 shows the exposure depth grid data for Highway 288 at Holly Hall Street. The model estimates a portion of the highway at this location as high risk for flooding even though it is outside the 500-year flood plain. This estimate is validated by the flooding that occurred on September 22, 2020, because of Tropical Storm Beta.

Figure 32 – Model Exposure Depth Grid Data at Highway 288 and Holly Hall Street

Figure 33, an image from ABC 13, shows the same portion of the Highway 288 flooded as indicated by the modeled high-risk exposure depth grid data. Detailed methodology of the LiDAR data processing and flood modeling are documented in Appendix B on page 124.

Figure 33 – SkyDrone 13 video shows flooding on Highway 288 (ABC 13, 2020)

Sensitivity Assessment

Sensitivity measures whether an asset will be damaged or disrupted when exposed to the given stressor. The team used indicators related to transportation asset structures, conditions, and disruption histories to assess transportation asset sensitivity. The factor considered for the sensitivity assessments include bridge age, structural evaluation, channel conditions, scour ratings, pavement condition, and past closures related to flooding.

Adaptive Capacity Assessment

Adaptive capacity measures how well the transportation system can cope with damage or disruption to a specific transportation asset. Indicators related to repair cost and network redundancy are used in this report.

Network redundancy, or detour ratio, is the total additional travel a through-bound vehicle would experience because of a street segment closure. Detour ratio is measured by direct and detour travel time between two points. Higher detour ratios indicate much longer detour routes relative to the shortest path route. Smaller detour ratios indicate that comparable detour paths are available within the system, and therefore suggest low redundancy for the shortest path route. Travel times are calculated using ESRI Network Analyst. The network redundancy calculation is detailed in Figure 34 and the transportation detour ratio is shown in Figure 35.

Figure 34 – Network Redundancy Calculation

Redundancy (Detour Ratio): Average of A-B & B-A

$$\text{A-B} = \frac{\textit{Minutes of Detour Route (A-B)}}{\textit{Minutes of Direct Route (A-B)}} = \frac{2}{1} = 2 \qquad \text{B-A} = \frac{\textit{Minutes of Detour Route (B-A)}}{\textit{Minutes of Direct Route (B-A)}} = \frac{2}{1} = 2$$

** In case of one-way street/freeway system, A-B is not same with B-A.*

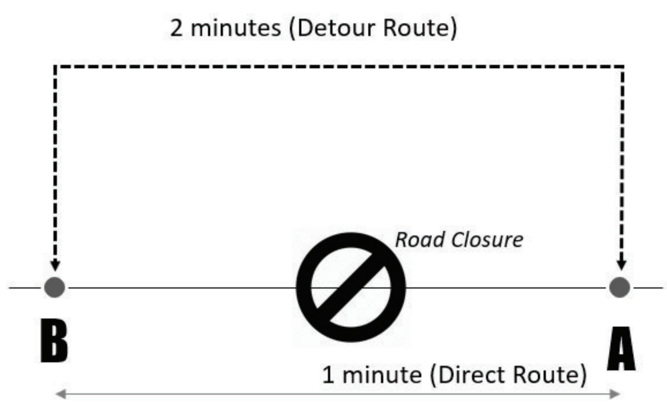
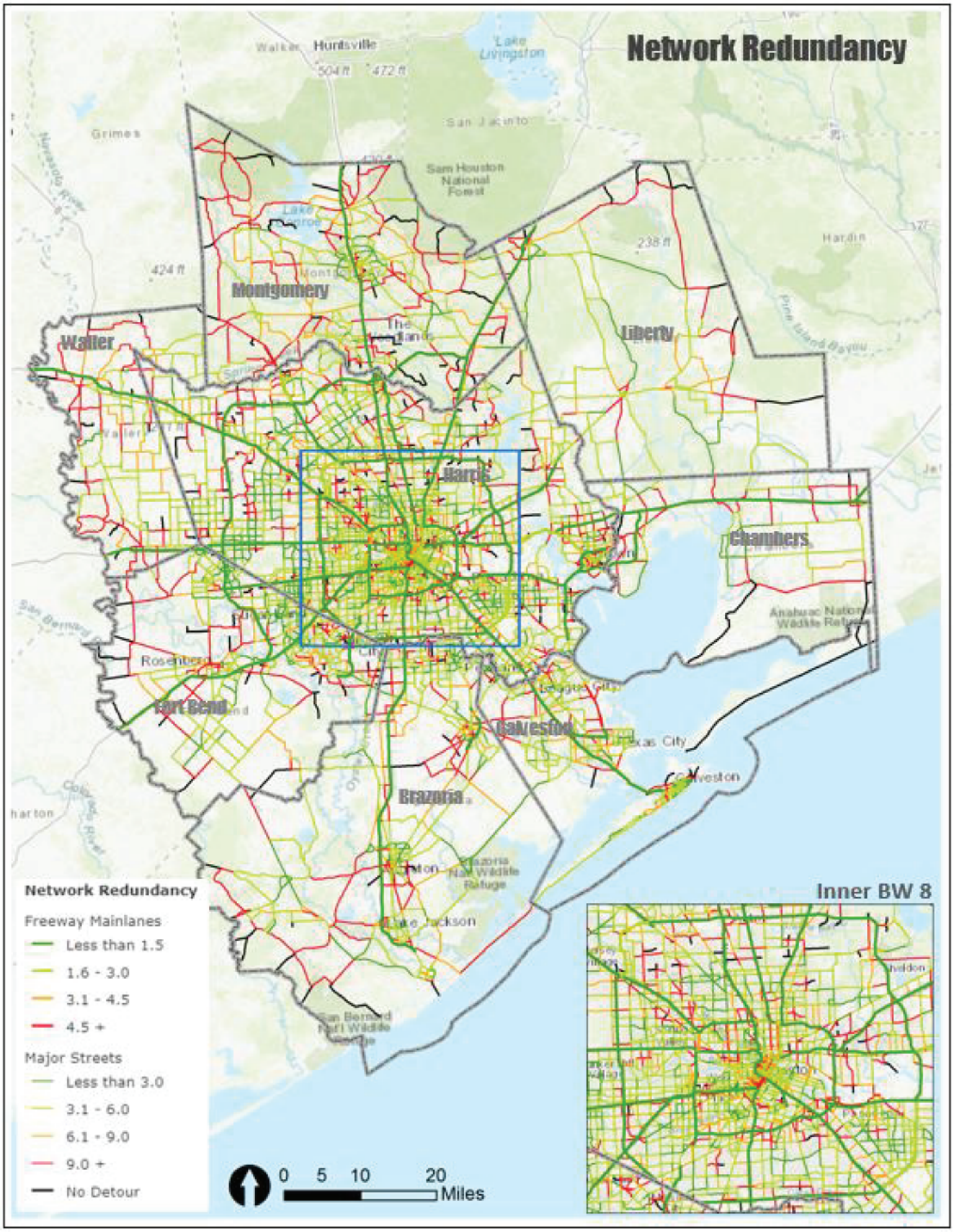


Figure 35 – Transportation Detour Ratio



Overall Vulnerability Index

The aggregated vulnerability index is calculated as a weighted summary of the exposure index, sensitivity index, and adaptive capacity index (see Figure 36). The team conducted calculations for freeway segments and major road segments separately to remedy ranking bias toward freeways.

The final vulnerability index is cumulatively standardized from 0 to 1, with 1 representing asset most vulnerable to the given climate stressor. An index higher than 0.67 indicates high vulnerability of a transportation asset, an index between 0.33 to 0.66 indicates moderate vulnerability, and an index lower than 0.33 indicates low vulnerability or not exposed at all.

Figure 36 – Vulnerability Index Range

Types	High	Moderate	Low
Overall Score	≥ 0.66	< 0.66 and ≥ 0.33	< 0.33

Vulnerability scores for bridges are not presented separately in this report but are combined with the road segments. For road segments with bridges, the number of high-risk bridges on each centerline mile is calculated and used as an additional indicator to calculate the final vulnerability score, and this indicator is given a 30% weight. The final vulnerability score of a road segment with bridge includes 70% of road segment (excluding bridge portion) vulnerability score and 30% of bridge vulnerability score. The vulnerability scores for individual bridges for various climate stressors are presented in the online Regional Resilience Tool[8].

Detailed methodology of the vulnerability assessment, including climate model simulation, indicator selection and categorization, weight schemes and data sources, as well as results for each assessment component, are documented in Appendix B on page 124.

[8] https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

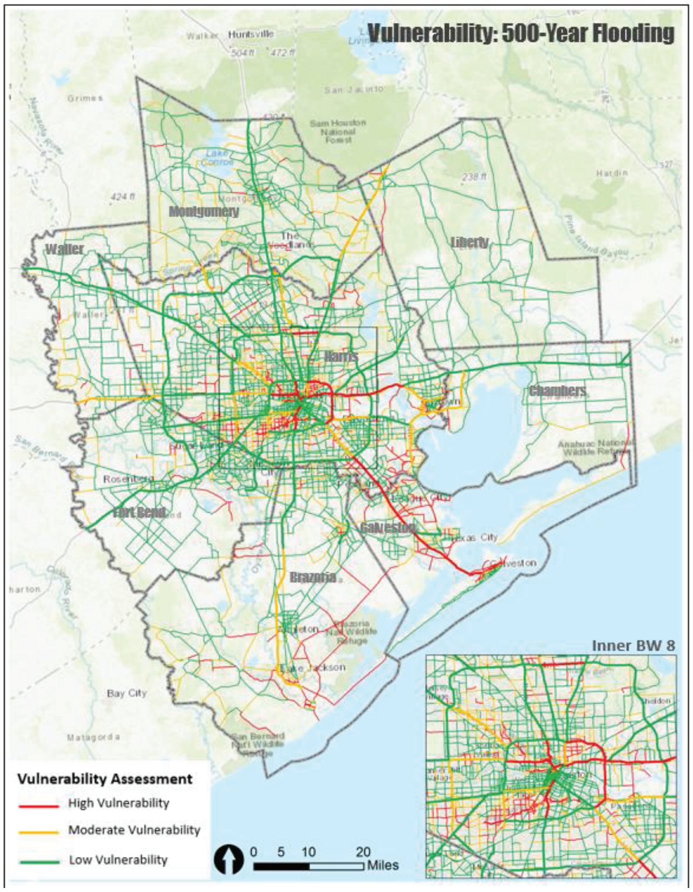
Vulnerability Assessment Results

For each climate scenario, including 500-Year flooding, Hurricane Harvey, Category 4 storm surge, Hurricane Ike, and 5-foot Sea-Level Rise, the vulnerability assessment results are presented separately.

500-Year Flooding Events

For 500-year flooding events, 11% of freeways and 11% of major roads centerline miles are classified as highly vulnerable in the region. Among highly vulnerable freeways, 58 miles are in Harris County and 24 miles are in Galveston County. For major roads, 365 miles in Harris County, 164 miles in Brazoria County, and 114 miles in Brazoria County are considered highly vulnerable. Road segments alongside bayous and coastlines are more likely to be highly vulnerable to flooding events. Figure 37 shows vulnerability for 500-year flooding modeled for the region.

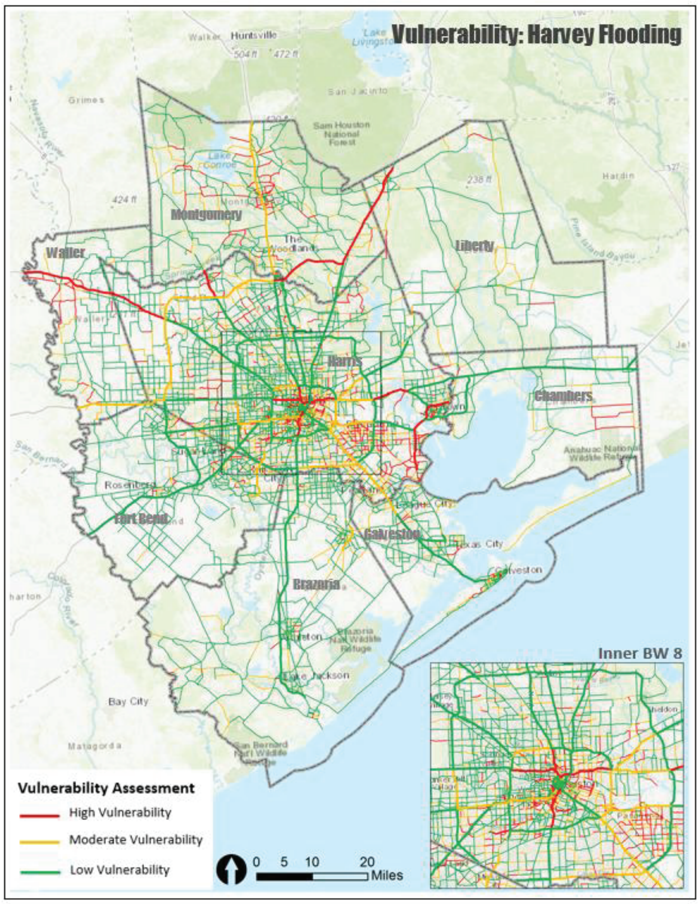
Figure 37 – 500-year flooding event vulnerability results



Hurricane Harvey Flooding Event

Flooding caused by Hurricane Harvey in 2017 is more severe than a modeled 500-year flooding event, with more than 14% of freeways experiencing high vulnerability. As Hurricane Harvey's rainfall was more concentrated in inland areas, Harris and Montgomery counties saw the highest high vulnerability miles. Around 10% of major roads in the region experienced high vulnerability for Hurricane Harvey, with the clear majority located in Harris County, along Buffalo Bayou and the Houston Ship Channel. Figure 38 shows vulnerability for Hurricane Harvey flooding modeled for the region.

Figure 38 – Hurricane Harvey flooding event vulnerability results

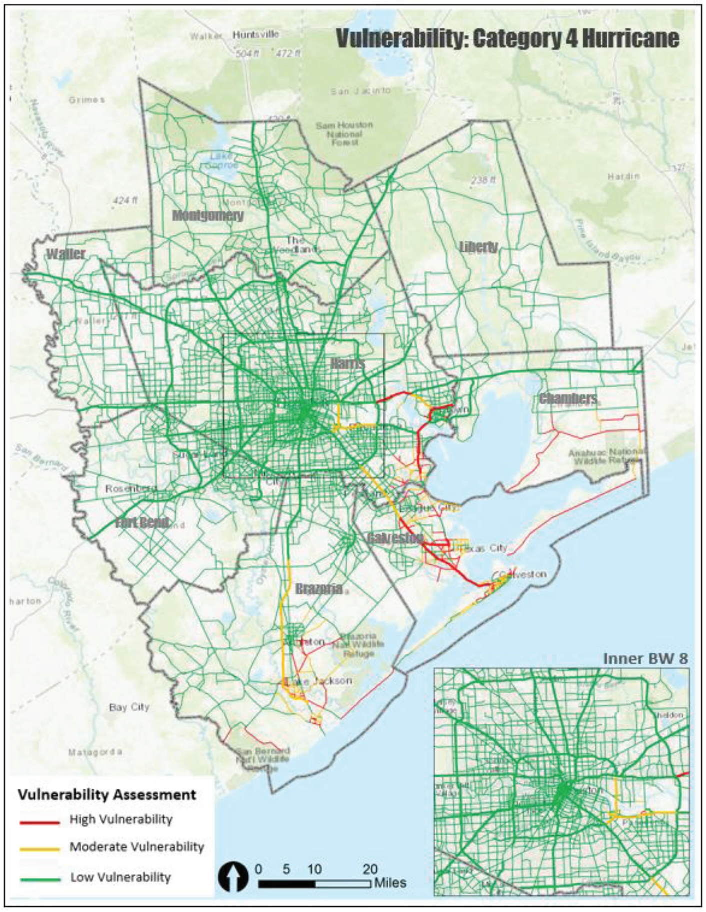


Category 4 Hurricane Storm Surge

Road segments that are highly vulnerable to Category 4 storm surge are densely located in the coastal areas of Galveston, Harris, and Brazoria counties. Around 7% of freeways are highly vulnerable to storm surges. About 4% of major roads are highly vulnerable to storm surges, most located in Galveston, Brazoria, and Chambers counties. Most inland roads are not impacted by coastal storm surge.

Figure 39 shows vulnerability for Category 4 storm surge modeled for the region.

Figure 39 – Category 4 hurricane storm surge vulnerability results

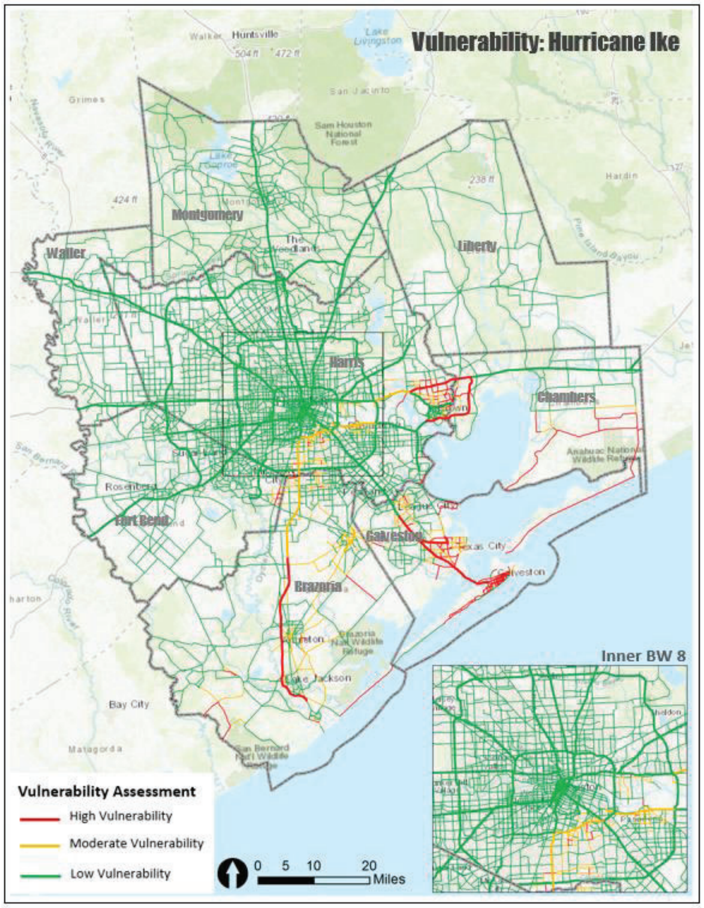


Hurricane Ike Storm Surge

As a Category 4 hurricane, Hurricane Ike had a higher impact on the region's transportation system compared to NOAA's storm surge model. For Hurricane Ike, 11% of freeways experienced high vulnerability, with most them in Brazoria and Galveston counties. As for major roads, 5% of the regional miles were highly vulnerable. Local roads in Chambers and Harris counties, along Buffalo Bayou and around Galveston Bay and Trinity Bay, were among the most vulnerable.

Figure 40 shows vulnerability for Hurricane Ike storm surge modeled for the region.

Figure 40 – Hurricane Ike storm surge vulnerability results

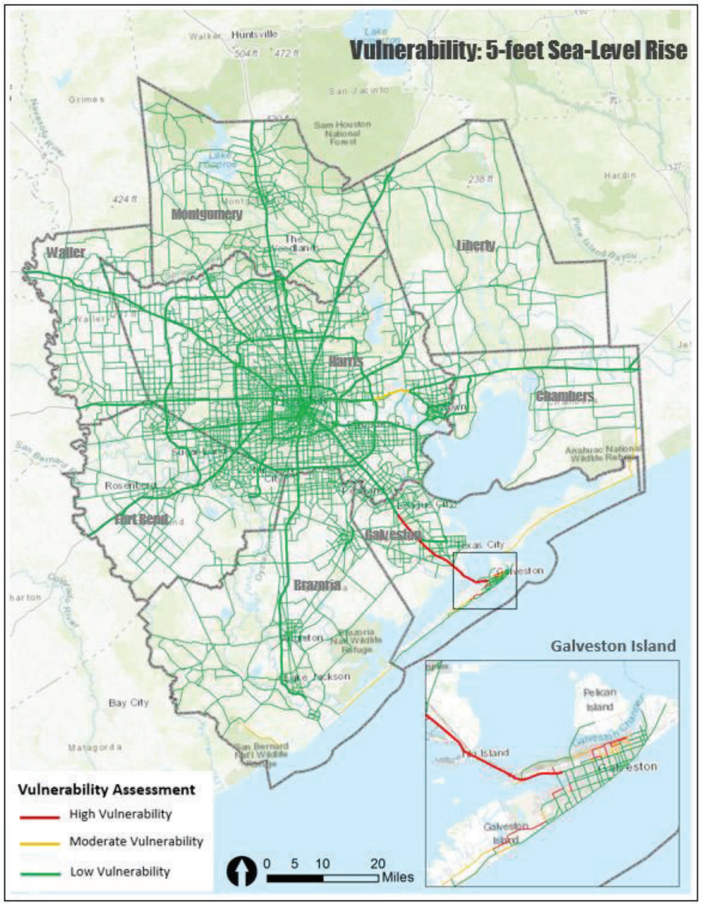


Sea Level Rise

Sea level rise of 5 feet is likely to affect Galveston County only. Interstate 45 connecting Galveston Island and the mainland is the only freeway likely to be highly vulnerable. All major roads that are highly vulnerable are located on Galveston Island.

Figure 41 shows vulnerability for 5-feet sea level rise modeled for the region.

Figure 41 – 5-feet Sea Level Rise vulnerability results



Composite Scoring

After consolidating results from different climate scenarios for each climate stressor, the team constructed a composite score for each natural hazard.

Flood Vulnerability = 500-year Flood Vulnerability (50%) + Harvey Flooding (50%)

Storm Surge Vulnerability = Category 4 Hurricane Storm Surge (50%) + Ike Storm Surge (50%)

Sea Level Rise Vulnerability = 5-feet Sea-level Rise (100%)

Combined Vulnerability = Flood Vulnerability (50%) + Storm Surge Vulnerability (35%) + Sea-level Rise Vulnerability (15%)

The percentage of road segments (freeways and major roads) of different vulnerability classifications are shown in Figure 42. Around 10% of freeway centerline miles are highly vulnerable to inland flooding, and around 21% are moderately vulnerable in the Houston-Galveston MPO region. The entire segment of Interstate 9 that crosses Liberty County is estimated to highly vulnerable to inland flooding.

Figure 42 – Freeway Vulnerabilities Against Inland Flooding

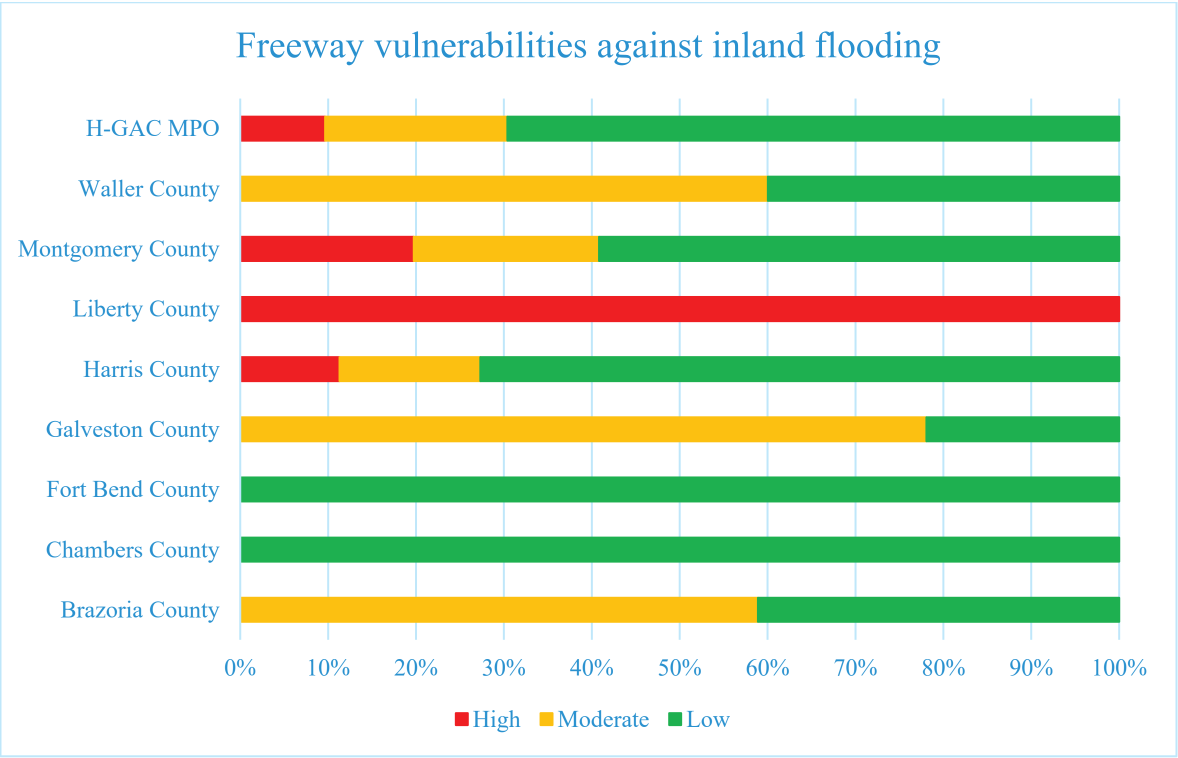


Figure 43 shows that around 11% of major road centerline miles are highly vulnerable to inland flooding, and around 19% are moderately vulnerable in the region. Every county in the region has some segments of major roads that are highly vulnerable to inland flooding.

Figure 43 – Major Road Vulnerabilities Against Inland Flooding

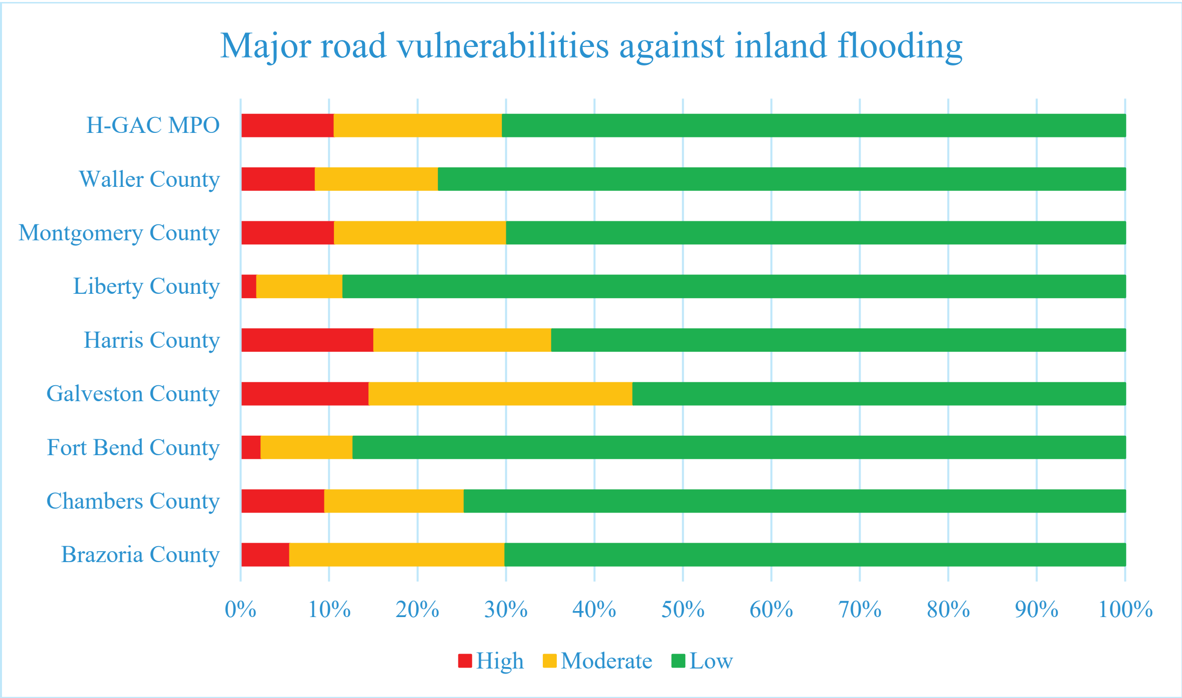


Figure 44 shows that around 8% of freeway centerline miles are highly vulnerable to coastal storm surge, and around 8% are moderately vulnerable in the region. Most of the freeway segments in Galveston (91%) and Brazoria County (59%) are highly vulnerable to flooding related to coastal storm surge.

Figure 44 – Freeway Vulnerabilities Against Coastal Storm Surge

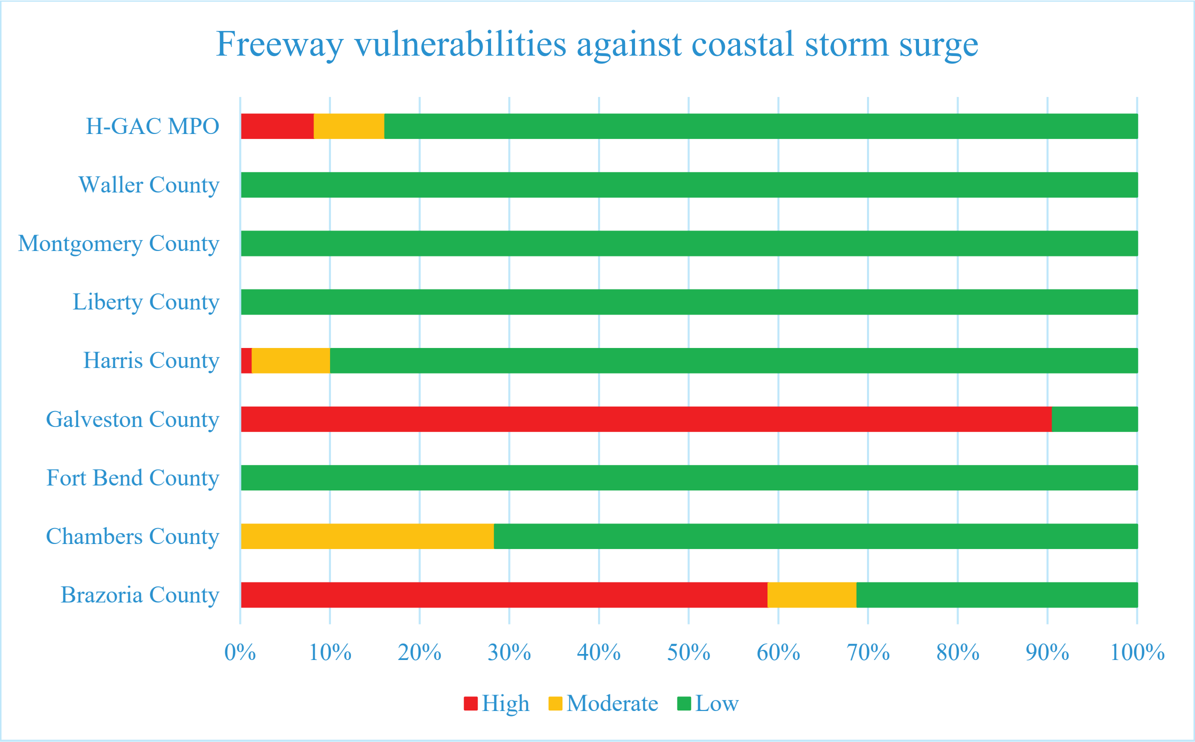


Figure 45 shows that around 4% of major road centerline miles are highly vulnerable to coastal storm surge, and around 5% are moderately vulnerable in the region. In Galveston County, 32% of major road centerline miles are highly vulnerable to coastal flooding.

Figure 45 – Major Road Vulnerabilities Against Coastal Storm Surge

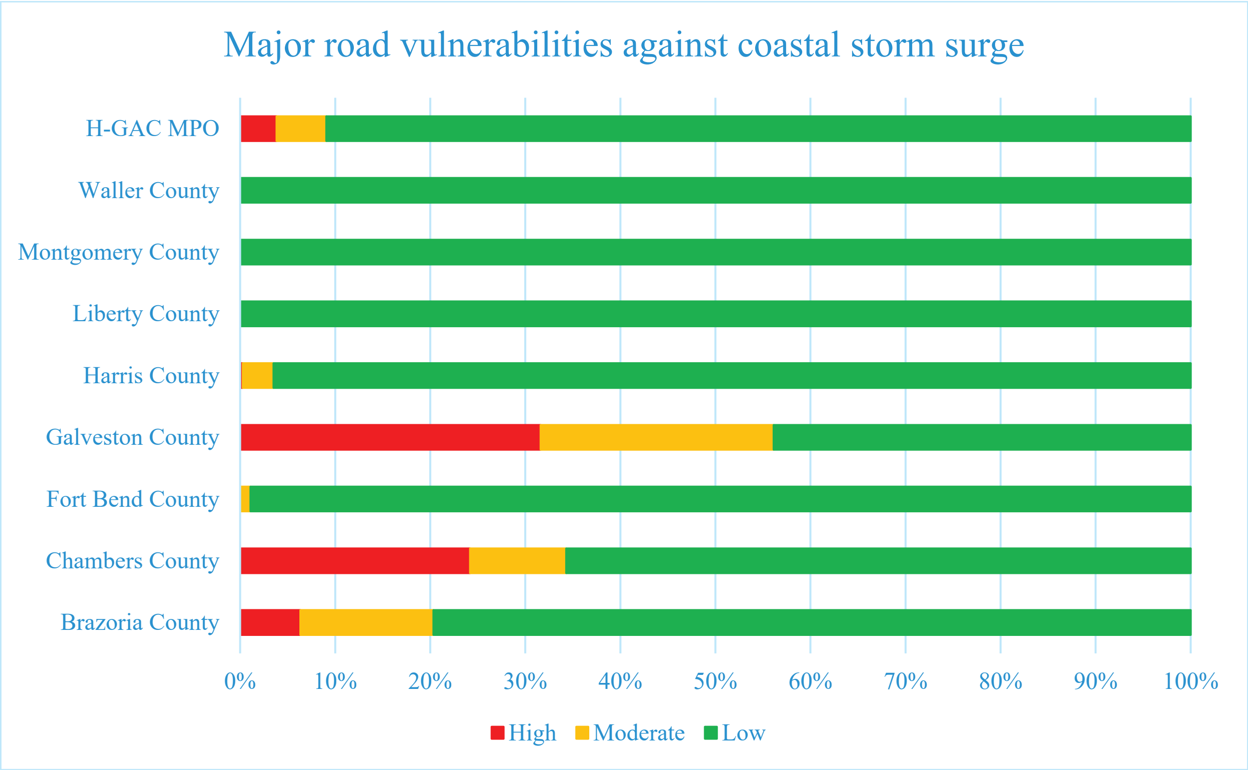


Figure 46 shows that around 13% of freeway centerline miles are highly vulnerable to flooding related to all climate stressors combined, and around 20% are moderately vulnerable in the region. Most of the freeway segments in Galveston (69%) and Brazoria (59%) counties are highly vulnerable to flooding related to all climate stressors combined.

Figure 46 – Freeway Vulnerabilities Against All Climate Stressors

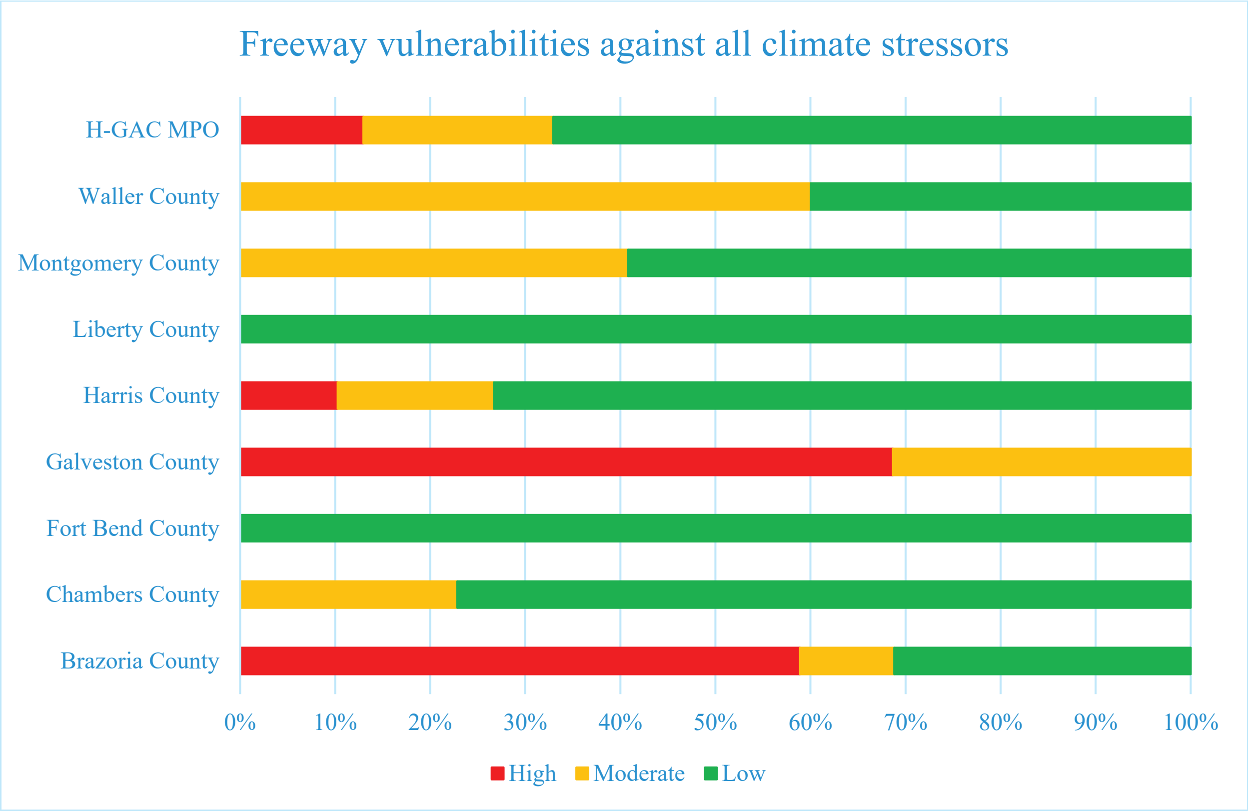
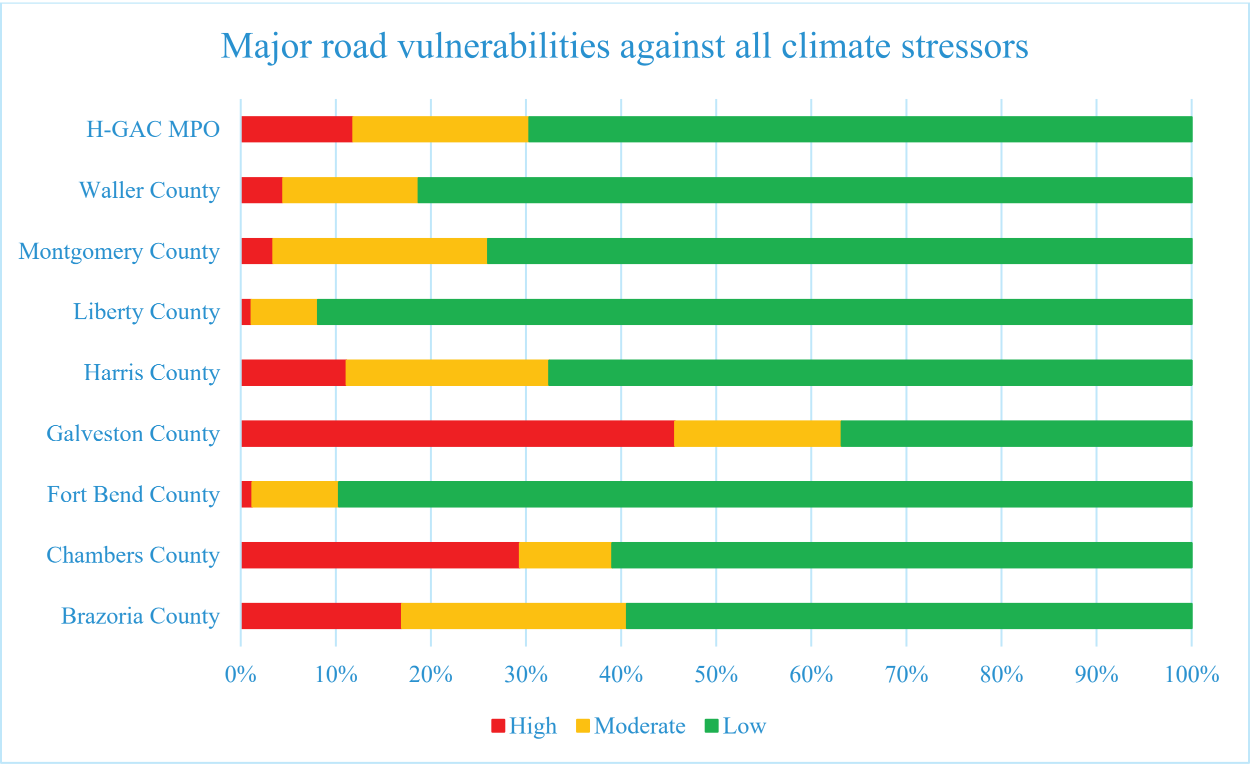


Figure 47 shows that around 12% of major road centerline miles are highly vulnerable to flooding related to all climate stressors combined, and around 19% are moderately vulnerable in the region. The vulnerability scores for individual road segments and bridges for various climate stressors are presented in the online Regional Resilience Tool[9].

Figure 47 – Major Road Vulnerabilities Against All Climate Stressors

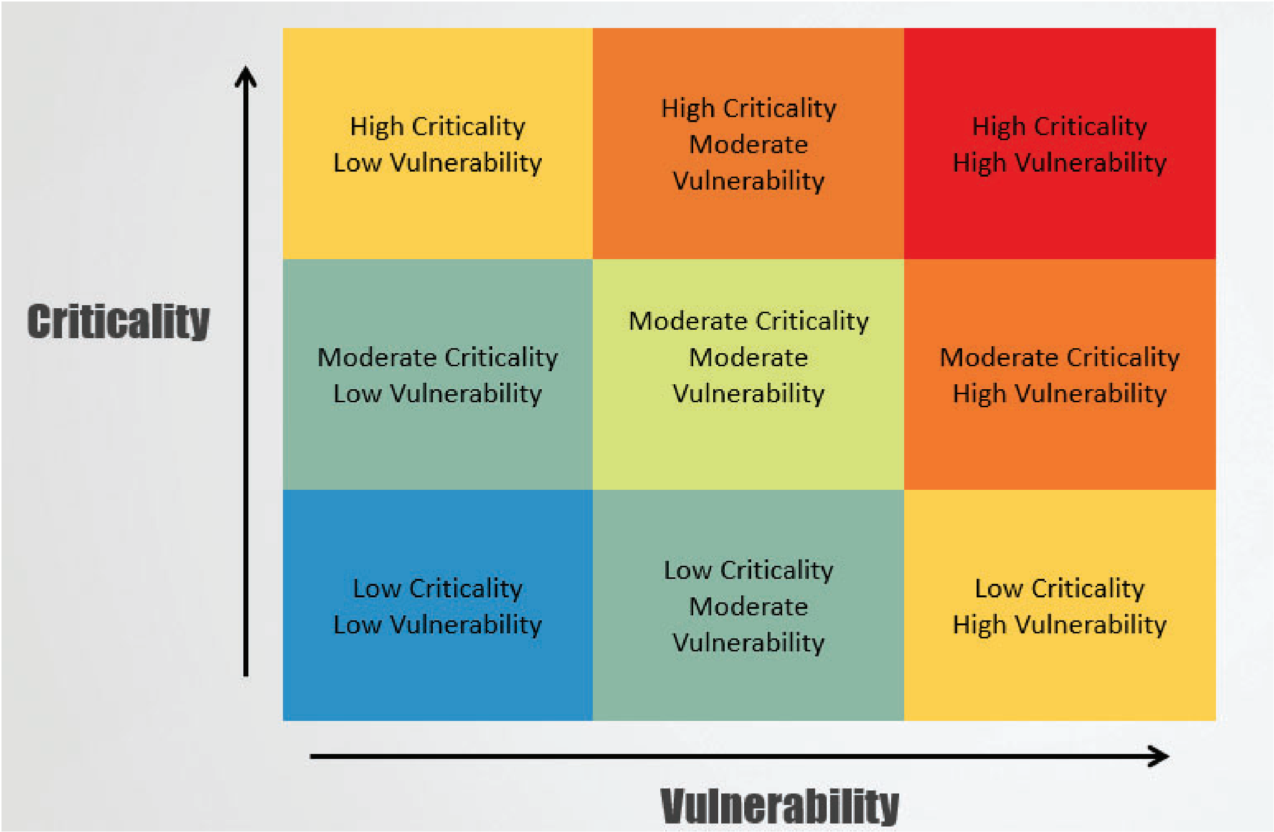


[9] https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

Criticality-Vulnerability Matrix

The team constructed a criticality-vulnerability matrix (CVM) for all road segments in the region, as shown in Figure 48. The team developed a CVM for each climate scenario of flooding, storm surge, and sea level rise, as well as a combined scenario CVM. The criticality values for transportation assets are the same across the various CVMs, however the vulnerability values differ with respect to a given climate scenario. Highly critical and highly vulnerable road segments are considered high risk transportation assets that require further improvement or reinforcement to contribute to a resilient regional transportation network against natural disaster. The road segments that are moderately critical and highly vulnerable, or highly critical and moderately vulnerable, can also be considered at risk resilient projects.

Figure 48 – Criticality - Vulnerability Matrix



Figures 49, 50, and 51 show the composite of vulnerability and criticality of transportation assets in the flooding, storm surge, and sea level rise scenarios, respectively. Road segments that are highly critical and highly vulnerable are color-coded in red. Figure 52 shows the composite of vulnerability and criticality of transportation assets for all climate stressors combined.

Figure 49 – Criticality - Vulnerability Matrix: Flooding

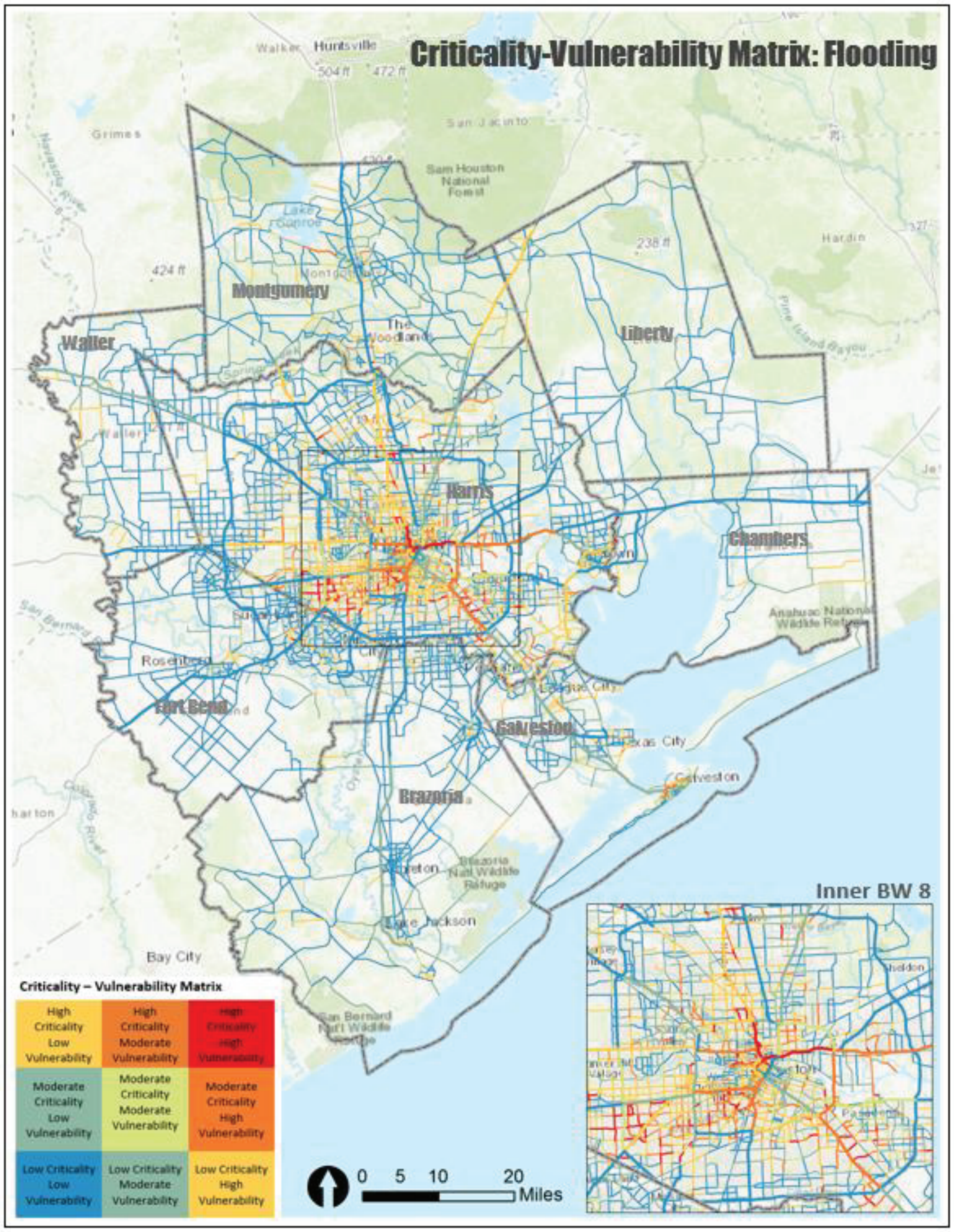


Figure 50 – Criticality - Vulnerability Matrix: Storm Surge

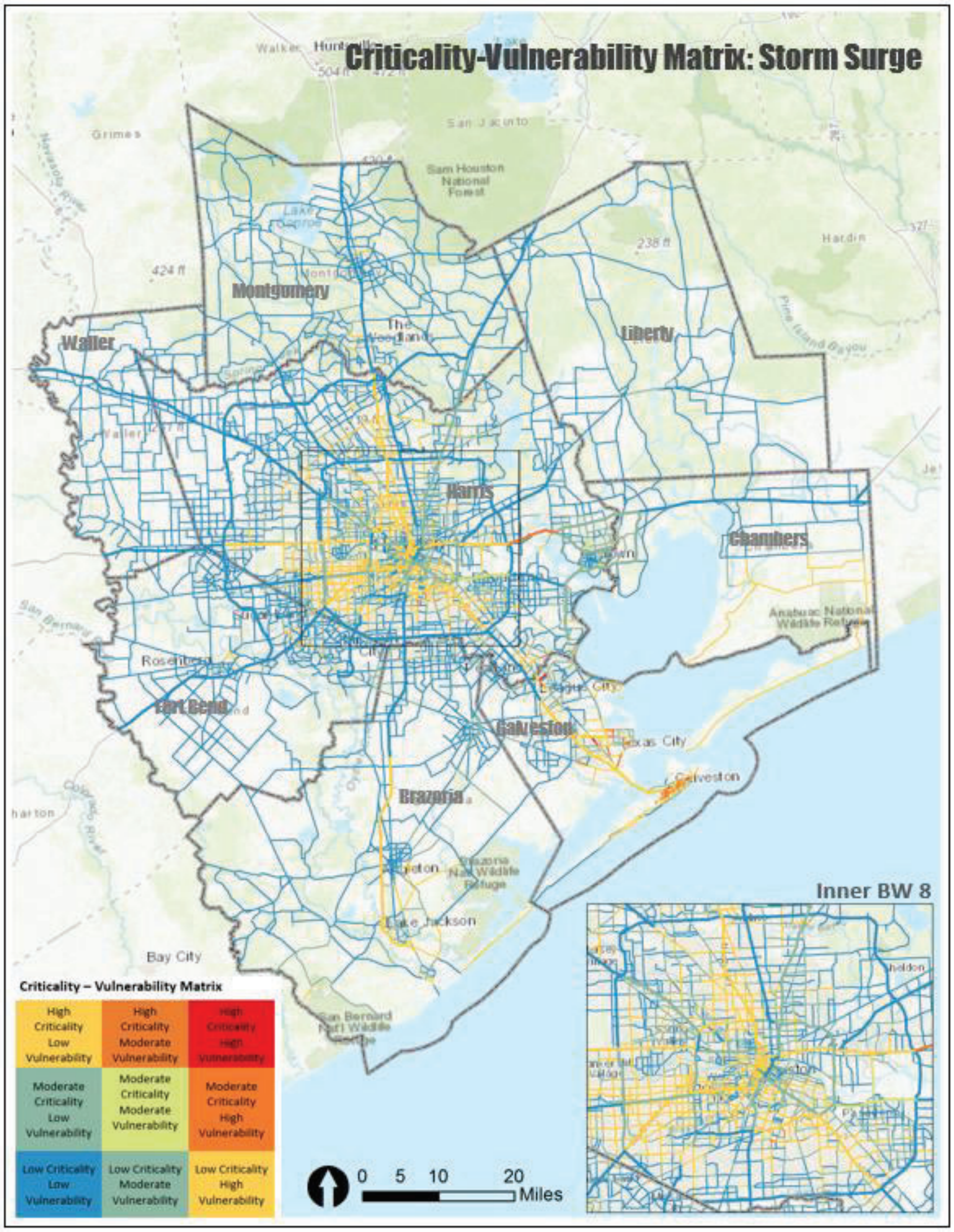


Figure 51 – Criticality - Vulnerability Matrix: Sea-Level Rise

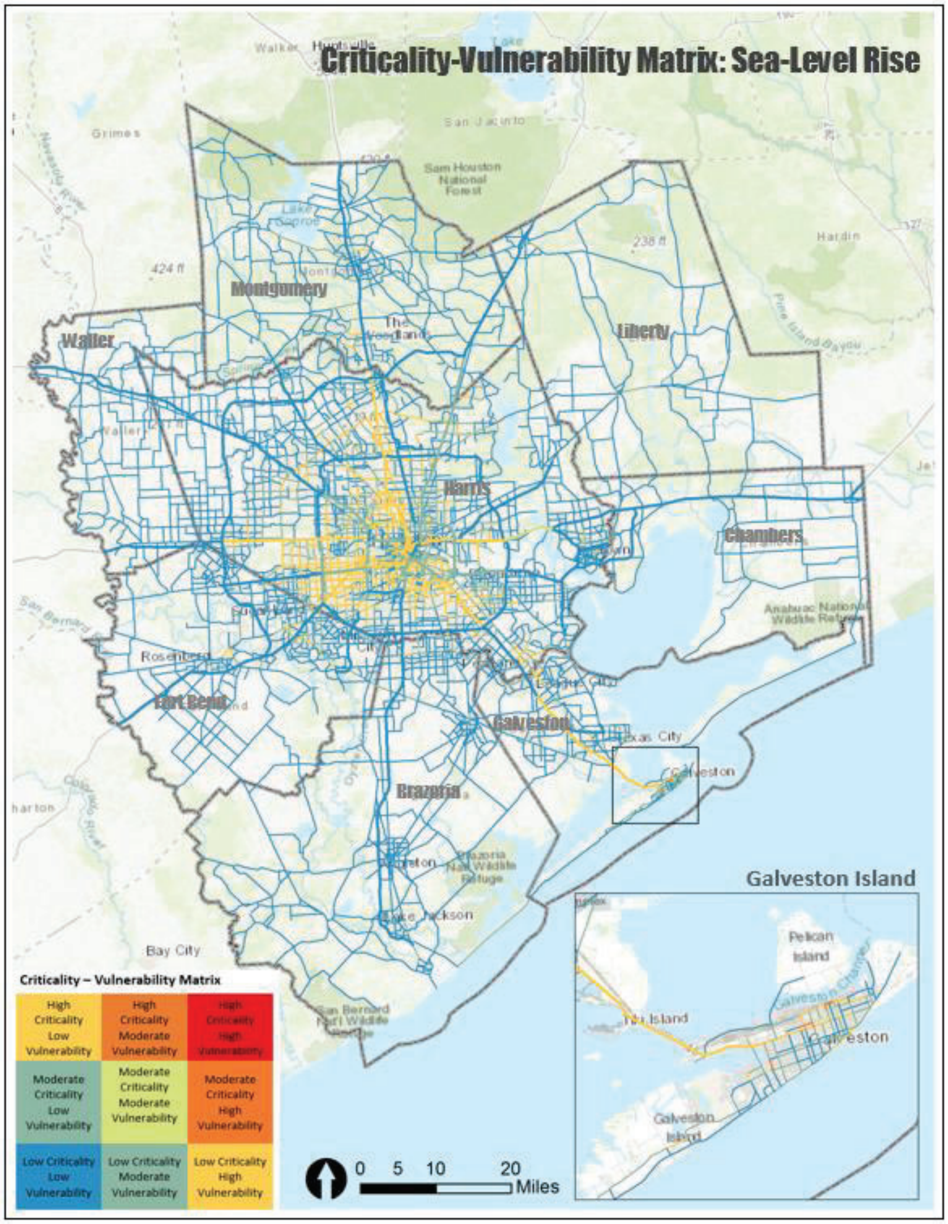


Figure 52 – Criticality - Vulnerability Matrix: Combine

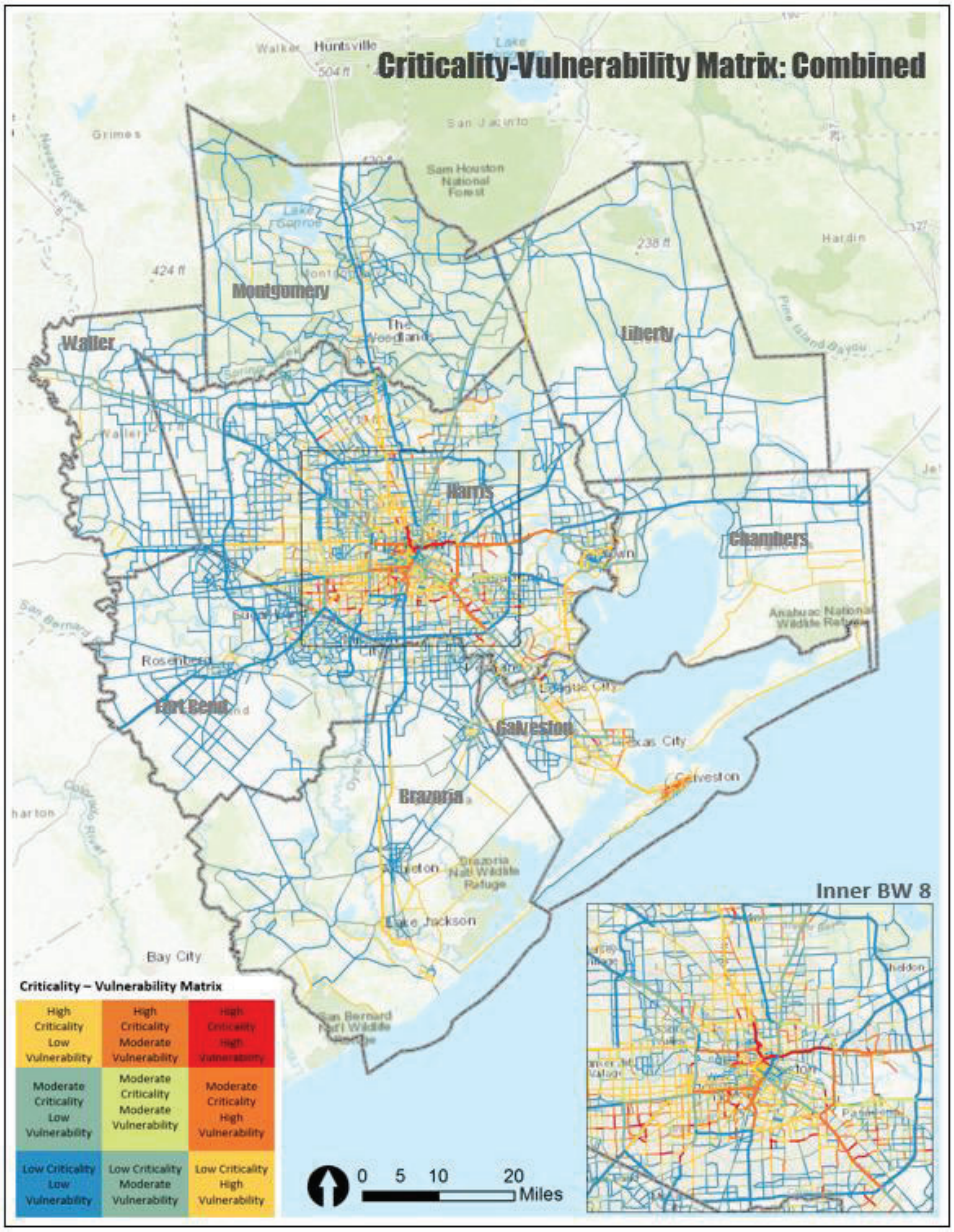


Table 3 and Figure 53 present the criticality and vulnerability summary of freeway centerline miles in the Houston-Galveston MPO region. Around 10 miles of freeway centerline miles are estimated to be highly critical and highly vulnerable, whereas around 43 miles are estimated to be highly critical and moderately vulnerable or moderately critical and highly vulnerable.

Of the 762.2 freeway centerline miles in the region, the Pilot Program estimates around 3.11 miles of Interstate 45 and around 6.37 miles of Interstate10 East are highly critical and highly vulnerable.

Table 3 - Summary of Freeway Centerline Mile Criticality and Vulnerability

Matrix Summary

Matrix	Miles	%
Total	762.2	100.0%
High Criticality -High Vulnerability	9.5	1.2%
Moderate Criticality -High Vulnerability	23.2	3.0%
High Criticality -Moderate Vulnerability	20.2	2.6%
Low Criticality -High Vulnerability	66.2	8.7%
High Criticality -Low Vulnerability	61.5	8.1%
Moderate Criticality -Moderate Vulnerability	18.3	2.4%
Low Criticality -Moderate Vulnerability	113.7	14.9%
Moderate Criticality -Low Vulnerability	63.1	8.3%
Low Criticality -Low Vulnerability	386.5	50.7%

Freeways Details (excerpt)

Matrix	Name	Miles
High Criticality – High Vulnerability	I-45	3.11
	IH 10 E	6.37
High Criticality -Moderate Vulnerability	GULF FWY/IH 45	8.05
	IH 10 E	6.68
	IH 69	5.45
Moderate Criticality -High Vulnerability	IH 10 E	6.62
	IH 10 W	5.66
	IH 69	0.85
	SOUTH FWY/SH 288	3.89
	SOUTH LOOP E	6.14
High Criticality – Low Vulnerability	IH 10 W	19.50
	IH 45	2.39
	IH 69	7.84
	NORTH FWY/IH 45	21.01
	NORTH LOOP	4.90
	SOUTH LOOP E	5.83
Low Criticality – High Vulnerability	GULF FWY/IH 45	21.07
	SH 146	16.18
	SH 288	28.94

Figure 53 – Criticality - Vulnerability Matrix: Combine Freeways

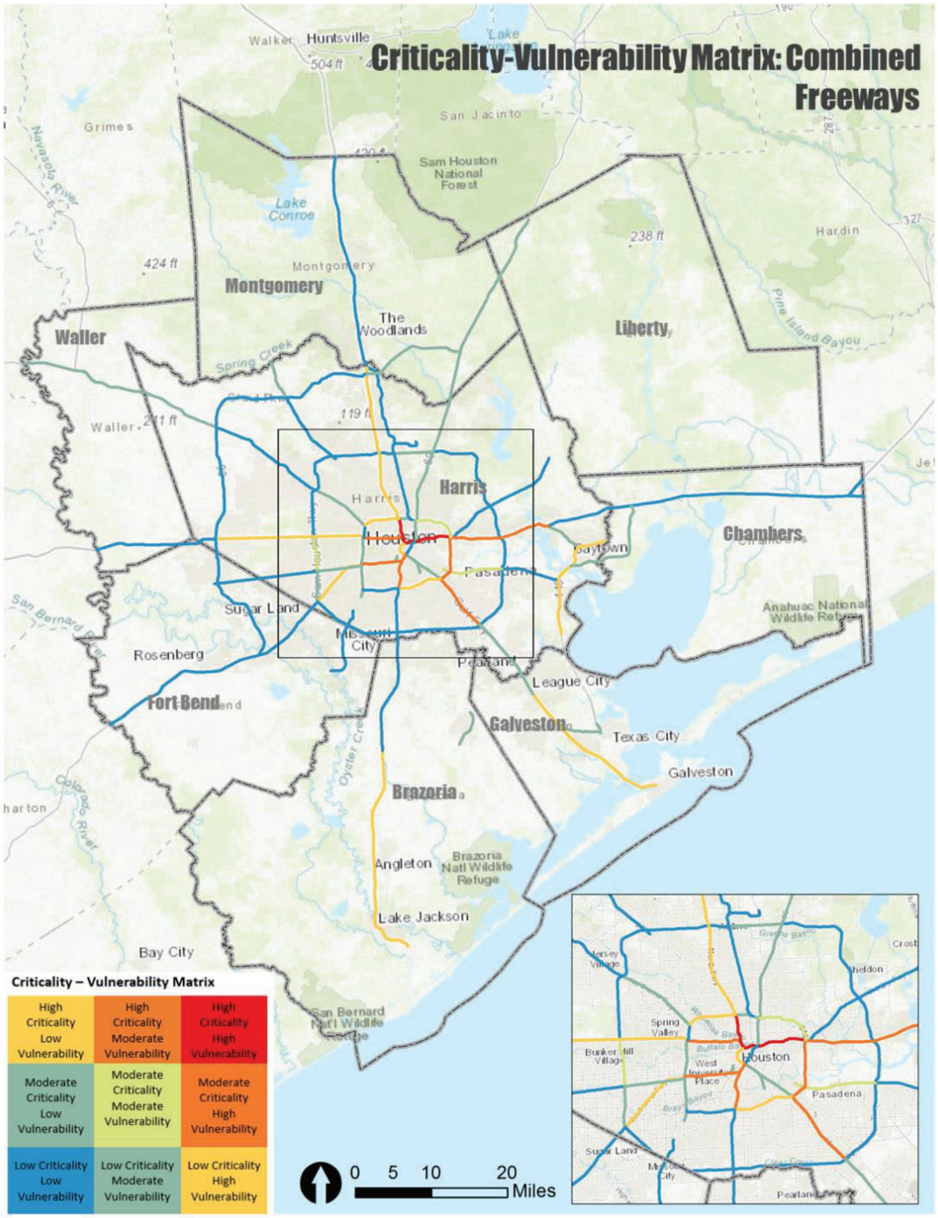


Table 4 and Figure 54 show the criticality and vulnerability summary of major road centerline miles in region. Of the 6,442 major road centerline miles evaluated, 48 miles are estimated to be highly critical and highly vulnerable, whereas around 259 miles are estimated to be highly critical and moderately vulnerable or moderately critical and highly vulnerable. The criticality and vulnerability scores for individual road segments for various climate stressors are presented in the online Regional Resilience Tool[10].

Table 4 – Summary of Major Road Centerline Mile Criticality and Vulnerability

Matrix Summary

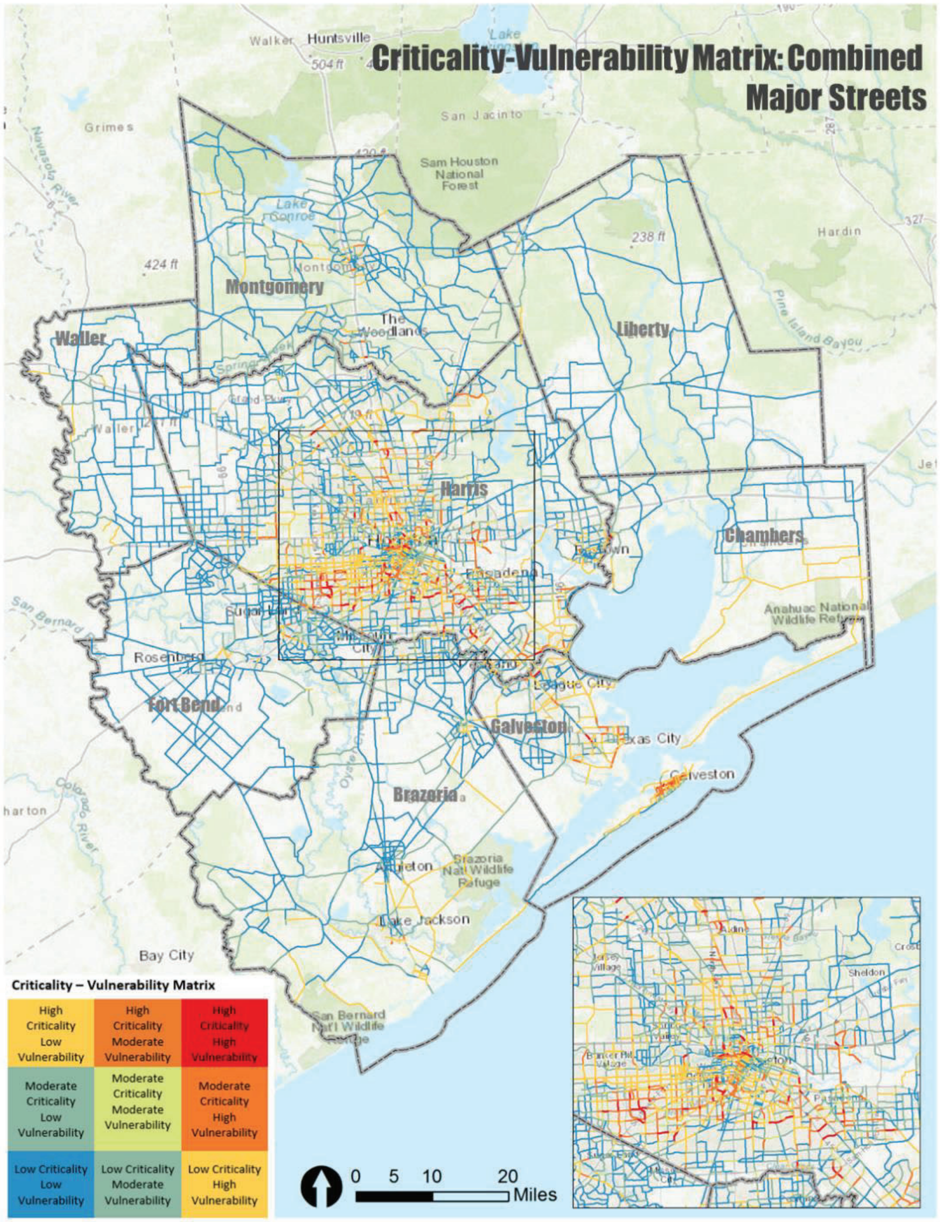
Matrix	Miles	%
Total	6,442.0	100.0%
High Criticality -High Vulnerability	48	0.7%
Moderate Criticality -High Vulnerability	119	1.9%
High Criticality -Moderate Vulnerability	140	2.2%
Low Criticality -High Vulnerability	595	9.2%
High Criticality -Low Vulnerability	364	5.7%
Moderate Criticality -Moderate Vulnerability	191	3.0%
Low Criticality -Moderate Vulnerability	861	13.4%
Moderate Criticality -Low Vulnerability	611	9.5%
Low Criticality -Low Vulnerability	3,512	54.5%

Principal Arterials Details (excerpt)

Matrix	Name	Miles
High Criticality -High Vulnerability	BROADWAY (Galveston)	2.617
	SH 3	1.537
	BROADWAY (Houston)	0.777
	COLLEGE	1.199
	CULLEN	0.735
	FAIRMONT PKWY	1.021
	FEDERAL	0.462
	FM 1960	0.142
	KIRBY DR	0.635
	LOCKWOOD DR	0.620
	MEMORIAL DR	0.637
	MONROE	0.134
	NASA RD 1	1.237
	OLD SPANISH TRAIL	0.102
	SH 35	0.794
	SH 146/LOOP 201	0.239
	SHAVER	0.437
	SPENCER HWY	0.463
	LOOP 336	0.119

[10] https://hgac.maps.arcgis.com/apps/MapSeries/index.html?appid=deae412562ab461ead3a1f0908ab22ee

Figure 54 – Criticality - Vulnerability Matrix: Combine Major Streets



Economic Impact Analysis

Cost-benefit analyses inform prioritization of projects for transportation investment. The Pilot Program examines how to estimate potential economic loss associated with transportation network disruption due to the various climate stressors. The Pilot Program does not cover the construction or repair costs of roadway and bridge improvements as they can be calculated directly based on the actual costs for similar projects in the region or based on the historical cost databases and bid tabulations from other projects.

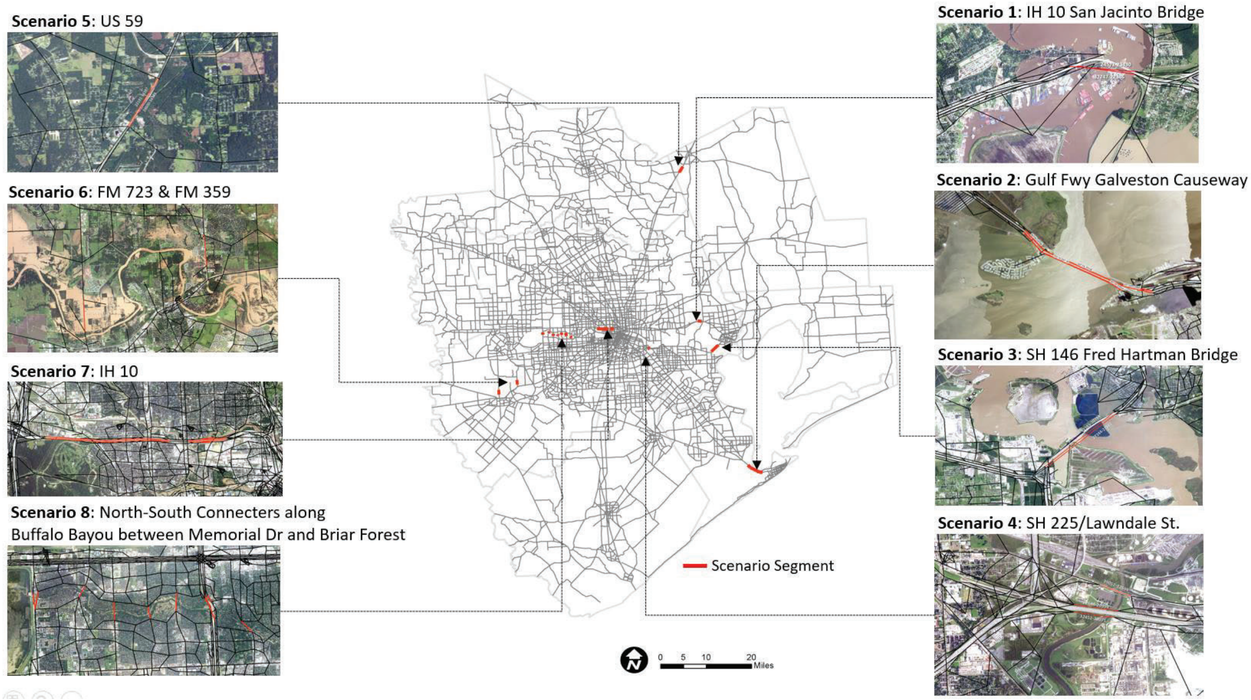
For the Pilot Program, the team used Regional Economic Models, Inc. (REMI) TranSight[11], a software package for estimating the economic impact of transportation investments. The model measures the economic impact associated with the addition of a new road or disruption to an existing road by comparing changes in vehicle miles traveled (VMT) and vehicle hours traveled (VHT) between the base scenario and alternate scenario.

The Pilot Program investigates 10 scenarios in which a specific transportation network is disrupted because of an extreme weather event. Figure 55 shows the road segments selected for the economic impact analysis. All road segments selected are identified to be vulnerable to at least one of the extreme weather events.

Scenario 9 includes road segments from scenarios 1, 3, and 4, whereas scenario 10 includes road segments from scenarios 1 to 8. Please refer to the Appendix C on page 155 for a detailed description of each road segment and its vulnerability to flooding.

[11] https://www.remi.com/wp-content/uploads/2019/07/TranSight-Model-Documentation.pdf

Figure 55 – Transportation Assets Selected for the Economic Impact Analysis



The Pilot Program assumes transportation network disruptions caused by extreme weather occurred in 2020. The team ran the regional travel demand model for each of the 10 disruption scenarios. The model output components, including VMT, VHT, and total vehicle trips, were then entered into the economic model for economic impact analysis. The team compared the results from the economic model to the 2020 baseline scenario used in H-GAC's *2045 Regional Transportation Plan*[12] to determine loss in Gross Domestic Product (GDP), which is defined as the market value of all final goods and services produced in a regional economy.

Results

Table 5 shows the results from economic impact analysis for the 10 scenarios.

As expected, the consolidated scenario (scenarios 1-8 combined) demonstrated the largest impact to the region. If the disruptions last one week, the region would lose around $27 million dollars in GDP.

[12] The region's long-range transportation plan, which prioritizes transportation projects in the eight-county Houston-Galveston region, can be viewed here: http://2045rtp.com/

Among the individual scenarios, the Gulf Freeway Galveston Causeway had the highest impact on the economy with a loss of $11.5 million for one week of disruption. This road segment is critical as it links Galveston Island to the mainland.

Table 5 – H-GAC Transportation Network Resilience Summary

GDP Loss (Million of Fixed Dollars in 2020) by Scenarios

Scenario	Description	Annual	Month	Week	Day
Scenario 1	IH 10 San Jacinto Bridge	206.9	17.2	4.0	0.6
Scenario 2	Gulf Freeway Galveston Causeway	599.2	49.9	11.5	1.7
Scenario 3	SH 146 Fred Hartman Bridge	205.6	17.1	4.0	0.6
Scenario 4	SH 225/Lawndale St.	191.5	16.0	3.7	0.5
Scenario 5	US 59	182.5	15.2	3.5	0.5
Scenario 6	FM 723 & FM 359	173.6	14.5	3.3	0.5
Scenario 7	IH 10	215.3	17.9	4.1	0.6
Scenario 8	North-South Connecters along Buffalo Bayou between Memorial Dr and Briar Forest	494.8	41.2	9.5	1.4
Scenario 1+3+4		431.0	35.9	8.3	1.2
Scenario 1-8		1,407.5	117.3	27.1	4.0

Source- H-GAC Travel Demand Data and REMI Transight

Like the scenarios used in the Pilot Program, the economic impact associated with a disruption to any given road segment can be conducted using the economic model or any other similar process. The loss in GDP can then be compared with costs of various adaptation strategies (see Adaptation Strategies on page 82). By consulting benefit cost values, decision-makers in the region can prioritize projects to develop a roadway network that is resilient to future extreme weather events.

ADAPTATION STRATEGIES

This section of the report identifies potential strategies and criteria needed to protect vulnerable and critical assets from flooding, sea level rise, storm surge, or a combination thereof. The applicability of each strategy is dependent on factors such as budget, topography, and exposure to the specific type of event.

Methodology

Adaptation strategies seek to reduce total cost to the system by making changes to the vulnerability and criticality of transportation infrastructure. The implementation of a specific adaptation strategy is, however, determined by the context and the total cost to the system.

Specific considerations in the selection of an adaptation strategy include:

- Applicability (when, where, what - topography)
- Implementation requirements (prerequisites, e.g., wide median)
- Vulnerabilities protecting against (flooding, storm surge, sea-level rise)
- Ease of implementation / time to implement
- Upfront costs / implementation cost
- Maintenance requirements / costs
- Resilience and other benefits
- Limitations

These different considerations must be compared for different resiliency adaptation strategies using a multi-criteria analysis. This report identifies various adaptation strategies and provides the following information for each:

- Effectiveness
- Implementation requirements
- Ease of implementation
- Cost of implementation
- Maintenance cost

Table 6 lists the 25 adaptation strategies included in the Pilot Program with a short description of activities and the vulnerabilities the strategy addresses. More detailed narrative descriptions, intended applications, benefits, and limitations of each strategy are detailed in Appendix E on page 187.

Table 6 – HGAC Transportation Network Resilience Summary

Strategy	Description	Vulnerability Protecting Against
Stormwater Management*		
Strategy 1: Increase Number of Swales and Ditches	Drains stormwater away from road infrastructure toward larger stormwater facilities (e.g., channels, detention/retention ponds, permanent water bodies).	Flooding
Strategy 2: Retention and Detention Ponds	Collects stormwater and releases it at a rate that prevents flooding or erosion.	Flooding
Strategy 3: Bioswales (Biofiltration Swales)	Collects, redirects, and filters stormwater.	Flooding
Strategy 4: Depressed and Raised Medians	Conveys stormwater away from roadways by creating positive drainage or conveyance.	Flooding
Strategy 5: Green Infrastructure	Increases infiltration and slow peak flow rate of stormwater, which decreases local flooding.	Flooding
Maintenance		
Strategy 6: Culvert Cleaning/Maintenance	Ensures optimal water flow through the stormwater management system.	Flooding
Planning		
Strategy 7: Stormwater Management Plan	Uses a functional plan to address existing stormwater system conditions, the operation and maintenance of existing facilities, and the required capacity when adding new facilities.	Flooding
Strategy 8: Land Use Planning/Climate Justice	Plans the physical layout of a community and identifies where development occurs and open space for preservation. Aids resiliency through adoption of land use codes and zoning regulation.	Flooding, Sea Level Rise, Storm Surge
Strategy 9: Relocate or Abandon Roads	Identifies roads that have experienced repeated damage or flooding in the past. Helps mitigate future risks and further damage.	Flooding, Sea Level Rise

Strategy	Description	Vulnerability Protecting Against
Strategy 10: Shelter-in-Place	Provides guidance, advice, incentives, or lawful orders to certain populations to remain in place during a threat to prevent or minimize the use of road networks during floods.	Flooding
Strategy 11: Evacuation Route Identification and Planning	Provides a safe means for potentially impacted communities to evacuate in advance of an extreme weather threat.	Flooding, Storm Surge
Strategy 12: Prohibiting Overweight/Oversized Vehicles	Prohibits heavy loads on weakened pavements in the immediate aftermath of a flooding event to prevent sudden failure or severe damage.	Flooding
Strategy 13: Sensor Technologies and Monitoring Programs	Employs sensors to monitor rainfall, runoff, water levels, and the general condition of the stormwater system.	Flooding
Infrastructure		
Strategy 14: Enhanced Road Surface	Protects surface of the pavement against damage caused by water flowing over the pavement.	Flooding
Strategy 15: Enhanced Sub-Grade	Enhances and hardens sub-grade to prevent damage/failure to pavement structures caused by inundation.	Flooding, Storm Surge
Strategy 16: Hardened Shoulders	Provides additional lateral support to prevent road damage during inundation.	Flooding, Storm Surge
Strategy 17: Raised Road Profile	Allows roads to remain passable in extreme events and extends service life of the road. May be more vulnerable to wave action.	Flooding, Sea Level Rise, Storm Surge
Strategy 18: Geosynthetics/Geo Textiles	Strengthens pavement and mitigates erosion.	Flooding, Storm Surge
Strategy 19: Permeable Pavement	Slows, filters, and cleans stormwater runoff by installing porous surfaces.	Flooding
Other		
Strategy 20: Maintain and Restore Wetlands	Reduces erosion and flooding, stores water during droughts, acts as a natural barrier to the spread of fires and minimizes the impacts of storms by slowing the speed and reducing the height and force of waves.	Flooding

Strategy	Description	Vulnerability Protecting Against
Strategy 21: Beach Nourishment and Dune Restoration	Controls erosion, flooding, and storm damage by acting as a buffer against high winds and waves.	Sea Level Rise, Storm Surge
Strategy 22: Vegetation (as Erosion Control)	Reduces soil loss by binding soil particles and absorbing the impact of raindrops, reduces velocity of runoff, allowing infiltration.	Flooding
Strategy 23: Seawalls and Revetments	Protects coastlines by redirecting the energy of waves back to the ocean water.	Sea Level Rise, Storm Surge
Strategy 24: Wave Attenuation Devices	Protects shorelines by reducing and reflecting the energy of waves while allowing water to pass through.	Storm Surge
Strategy 25: Debris Deflectors for Bridge Protection	Protects bridge structures by deflecting and preventing debris from making direct contact with the bridge structure.	Flooding

*Many of the stormwater management adaptation strategies listed may offer limited effectiveness when used as a stand-alone strategy. Yet when included in combination with other strategies become a larger hydraulic system, which becomes a highly effective overall strategy.

Resiliency Adaptation Strategies to Address Vulnerability and Criticality

For the Pilot Program, the team used low, moderate, and high categories to evaluate proposed resiliency adaptation strategies in protecting critical and vulnerable infrastructure. Strategies are evaluated for their impact on vulnerability and criticality as follows:

- Vulnerability – the ability or suitability of the strategy to mitigate flooding or reduce the long-term deleterious effects of flood events that occur because of rainfall events, storm surge or sea level rise disturbances.
- Criticality – the suitability of the strategy for protecting assets considering the assets' importance or criticality to the broader transportation system.

In this context, a highly vulnerable asset is one that is extremely prone to flooding (measured in terms of frequency, duration, and/or flood depth); while a low vulnerability asset is one that is of low risk of flooding following a disturbance event (i.e., severe rainfall, storm surge, or sea level rise).

Similarly, a highly critical asset is one that considered to be disproportionately important to the partial or normal functioning of the transportation system; while a low criticality asset is one that, even if flooded, will cause only a minor impact on the normal functioning of the transportation system.

To complete the evaluation outlined in Table 7, the team addressed the following questions:

- **Vulnerability questions**- How effective is the strategy at mitigating the impacts of a disturbance (rainfall, storm surge, or sea-level rise) on an asset? Here, efficacy was further broken down into cases where the strategy may reduce the frequency, incidence or severity of flooding, or help prevent long term damage to the asset.
- **Criticality question** - What are the costs and reliability associated with employing the strategy and, based on these criteria, is the strategy best suited to protecting high, low or medium criticality assets?

Given the nature of the specified disturbance events, the team assumed that it is possible that a strategy may be highly effective or reliable for reducing the impact of flooding for assets subject to low flood risk, but that the same strategy may be less effective for protecting assets subject to high flood risk. To illustrate this principal, many hydraulic structures are designed to accommodate a disturbance event (e.g., rainfall) up to a certain intensity and duration, after which they are designed to fail, or at least have limited capability to prevent inundation.

In other cases, engineered structures are designed to offer more reliable (complete) protection against such disturbances (often at a much higher cost). Adopting the spirit of resilience planning, both strategies may provide useful adaptive capacity against disturbance events, if a fair assessment of their limitations (efficacy and cost) is conducted.

Similar caveats were incorporated into the assessment of the suitability of a strategy for protecting critical infrastructure. Here, the study team worked on the principal that critical infrastructure requires strategies that offer the most effective and reliable (fail safe) protection from disturbance events, and that this reliability may warrant the extra cost associated with implementing the strategy. It should be noted therefore, that although certain engineering strategies may be specifically targeted to protecting critical infrastructure, they may also provide valuable protection to less critical assets that are associated with the identified critical asset.

Table 7 – Assessment of Resiliency Adaptation Strategies

		Criticality			Vulnerability			Climate Stressor		
Resilience Strategy	Low	Mod	High	Low	Mod	High	Flooding	Storm Surge	Sea Level Rise	Comments
Strategy 1: Increase Number of Swales and Ditches	X			X			X			Swales and ditches are a cost-effective method for reducing the frequency and duration of standing water in areas with low flood risk. While they may help reduce the duration of floods in high flood risk areas, they cannot reliably prevent standing water during moderate or severe flood events. Therefore, swales and ditches are best used to protect infrastructure that is of low criticality to the transportation system.
Strategy 2: Retention and Detention Ponds		X			X		X			When integrated into a well-designed stormwater management system, retention and detention basins can be designed to prevent standing water during medium and low flood events, as they can be effectively engineered to reduce standing water (flood risk) beyond the capabilities of swales and ditches alone. This makes them useful for protecting infrastructure that is moderately critical to the transportation system.
Strategy 3: Bioswales (Biofiltration Swales)	X			X			X			Bioswales have similar application characteristics to swales and ditches, but with the additional benefit of providing aesthetic and water purification benefits.
Strategy 4: Depressed and Raised Medians		X			X		X			This strategy provides additional drainage structures designed to protect roadway flooding during moderate rainfall events. This makes them useful for protecting infrastructure that is moderately critical to the transportation system.

Strategy 5: Green Infrastructure	X	X		X	X		X			Green infrastructure can be used to reduce the risk of flooding (severity, duration and frequency) in areas of low to medium risk to flooding. It is best employed as an area wide strategy to improve the operational reliability of low and/or moderately critical assets.
Strategy 6: Culvert Cleaning/Maintenance		X	X		X		X	X		Culvert cleaning helps restore the designed engineered capacity of drainage systems. Regular maintenance of the stormwater system is useful system wide. However, more frequent surveys and maintenance around flood prone and functionally important (critical) infrastructure may help improve the reliability of the stormwater management system in these areas.
Strategy 7: Stormwater Management Plan		X	X		X		X			Hydrological structures are usually designed to prevent flooding up to a specified rainfall event (e.g., a 50-year storm). If highly critical infrastructure can be identified, structures can be redesigned to accommodate the stormwater arising from more severe storm events (e.g., 100-year storms), thereby providing a mechanism to protect moderate and highly critical infrastructure.
Strategy 8: Land Use Planning/Climate Justice		X	X		X		X	X	X	Land use planning establishes a comprehensive set of goals for floodplain managements, regulations, and policies to prevent the development of moderate or highly critical infrastructure in flood prone areas.
Strategy 9: Relocate or Abandon Roads	X					X	X		X	By definition, this strategy only applies to non-critical infrastructure that is highly vulnerable to flooding. The rationale for this strategy is that the abandonment of low criticality or highly redundant infrastructure will provide long-term maintenance cost savings that can be redirected to other resilience strategies.
Strategy 10: Shelter-in-Place	X	X	X	X			X			Occasionally, even infrastructure that has a low risk of flooding may become inundated. By definition this means moderate and high-risk infrastructure

										will also be flooded. During these system-wide outages, a shelter in place strategy may represent a 'worst-case' scenario designed to protect all infrastructure within the system (i.e., high, medium and low criticality infrastructure).
Strategy 11: Evacuation Route Identification and Planning	X	X	X		X	X	X	X	X	During moderate flood events, or when severe flood events can be reliably predicted, select transportation routes can be identified that remain reliably traversable. These alternative routes can be used to evacuate flood prone areas to reduce the risk of damage (repair and safety costs) to high, medium and low critical infrastructure.
Strategy 12: Prohibiting Overweight/Oversized Vehicles			X	X	X	X	X			For infrastructure prone to high, medium or low flood risk, temporary bans on heavy duty vehicles may be useful to protect the integrity of infrastructure. Such temporary prohibitions may help prolong the life and maintenance costs of highly critical infrastructure.
Strategy 13: Sensor Technologies and Monitoring Programs			X		X	X				Monitoring programs comprise networked sensors capable of providing real time information on stormwater flows, and historical data useful for assessing and understanding the cause of floods. When employed in flood prone areas, they can provide a useful early warning system with the aim of preventing floods, protecting critical infrastructure from outages, and for triggering interventions such as traffic diversions that may can reduce the cost of critical outages.
Strategy 14: Enhanced Road Surface		X	X	X			X			Infrastructure that has a low risk of flooding may occasionally become partially inundated with standing water (i.e., there is some standing water on the roads, but there is enough drainage to ensure standing water remains minimal). Under circumstances when inundation risk is low, but surface water can accumulate, an enhanced road surface may improve the safety of

										travelers and help maintain the operational capacity of moderate and highly critical infrastructure.
Strategy 15: Enhanced Sub-Grade			X		X	X	X	X		Enhancing the sub-grade of highly critical and moderately or highly vulnerable infrastructure can be an effective strategy for reducing long-term costs associated with repairing and maintaining such infrastructure.
Strategy 16: Hardened Shoulders		X	X	X	X		X	X		During an extreme weather event, vehicles may be required to use the shoulder of a road for safe transport. This can be an effective strategy for improving the reliability of high and moderately critical infrastructure that is subject to a low or moderate risk of flooding.
Strategy 17: Raised Road Profile			X		X	X	X	X	X	Raised road profile should be used for highly vulnerable infrastructure due to the typically high costs and potential impacts on nearby communities. However, raising the road profile provides a very reliable method for reducing the risk of inundation for highly flood prone assets.
Strategy 18: Geosynthetics/Geo Textiles		X	X		X	X	X	X		Geosynthetics or geotextiles can help prevent damage to infrastructure caused when flooding does occur. Although they are not designed to prevent or mitigate floods, they can be used to prevent long term damage to high or moderately critical infrastructure that may otherwise occur because of floods.
Strategy 19: Permeable Pavement	X			X			X			This strategy helps to reduce run off and is specifically designed to help reduce standing water. Limitations on the mechanical integrity of permeable pavement design limits its application to less critical infrastructure.
Strategy 20: Maintain and Restore Wetlands	X	X	X		X	X	X			Wetlands provide a natural, system wide approach to managing flooding. They can be used to help protect areas prone to moderate or low flood risk.
Strategy 21: Beach Nourishment and Dune Restoration		X	X		X	X		X	X	Restoration of beaches and dunes offer a natural, system wide strategy for protecting against standing water in

										moderate and high flood risk areas. Because it is a system wide strategy, it is effective at protecting low, moderate and highly critical infrastructure.
Strategy 22: Vegetation (as Erosion Control)	X	X		X	X		X			Infrastructure that has a low or moderate risk of flooding can be partially protected from inundation by using vegetative buffers. Such buffers may reduce the severity and duration of rare inundation events and help retain the operational capacity of low and moderately critical infrastructure.
Strategy 23: Seawalls and Revetments		X	X		X	X		X	X	This strategy offers a high level of protection against flooding of moderately and highly vulnerable infrastructure. The high implementation cost makes this strategy most suitable for maintaining the serviceability of moderately and highly critical infrastructure.
Strategy 24: Wave Attenuation Devices		X	X		X	X		X		Wave attenuation devices are a high cost, but effective and reliable method of reducing flooding of high and moderately vulnerable infrastructure. Due to their high installation costs, they are best targeted as a solution to protect highly or moderately critical infrastructure.
Strategy 25: Debris Deflectors for Bridge Protection		X	X		X	X				High and moderately critical bridge assets subject to frequent or severe flood events can be protected using debris deflectors. Although this strategy does not help reduce flooding, it can be used to maintain the operational integrity of such assets and reduce long term maintenance and repair costs.

STAKEHOLDER ENGAGEMENT

Meaningful discussions with stakeholders about challenges, opportunities and needs is crucial to any project's success. For this Pilot Program, the team worked with a diverse stakeholder group. A list of external stakeholders is included in Table 8.

External Stakeholder Discussions

Kick-Off Meeting

On May 22, 2019, the team conducted a kickoff meeting with regional stakeholders to discuss the importance of resiliency, provide an overview of the types of projects underway, review assessment data, and discuss indicator and criticality selection data.

Draft Findings and Recommendations Meeting

On May 12, 2020, the team presented draft findings and recommendations to regional stakeholders, specifically meeting to review the intersection between the criticality and vulnerability assessments, as well as discuss proposed Adaptation Strategies to improve transportation resilience.

On July 15, 2020, the team presented draft findings and recommendations to the Transportation Advisory Committee. On July 24, 2020, that same content was presented to the Transportation Policy Council.

One-on-One Partner Discussions

In addition to stakeholder meetings, the team coordinated directly with key partners that were conducting and / or participating in resiliency efforts in the Pilot Program area.

Table 8 – Pilot Program Stakeholders

Entity	Entity Type
Harris County Office of Emergency Management	Emergency Management
Federal Highway Administration	Federal Government Agency
U.S. Army Corps of Engineers - Southwest Division	Federal Government Agency
Government Land Office	Federal Government Agency
U.S. Geological Survey	Federal Government Agency
Army Corps of Engineers	Federal Government Agency
Federal Highway Administration - Texas Division	Federal Government Agency
Harris County Flood Control District	Flood Control District
Houston-Galveston Area Council	Municipal Planning Organization
Harris County	Municipal Planning Organization - County
Galveston County	Municipal Planning Organization - County
Montgomery County	Municipal Planning Organization - County

Waller County	Municipal Planning Organization - County
Fort Bend County	Municipal Planning Organization - County
Brazoria County	Municipal Planning Organization - County
Chambers County	Municipal Planning Organization - County
Liberty County	Municipal Planning Organization - County
City of Houston	Municipal Planning Organization - Other Local Government
Greater Houston Flood Mitigation Consortium	Nonprofit
Houston Advanced Research Center	Nonprofit
100 Resilient Cities	Nonprofit
Texas Department of Transportation	State Agency
METRO Transit Authority	Transit Provider
Houston TranStar	Transit Provider
Rice University SSPEED Center	University
Rice University Kinder Institute	University
Texas A&M	University
Texas A&M Transportation Institute	University (Affiliate)

Internal and Peer Discussions

Resilience & Durability Peer Exchange

On December 13, 2018, the team participated in a peer exchange with other Resilience and Durability Pilot teams to discuss the details of this Pilot Program, specifically focusing on the proposed approach and methodology.

Internal Resiliency Workgroup Meeting

Following the May 22, 2019 kick-off meeting, it became apparent that greater H-GAC internal coordination was needed to better define critical infrastructure and provide input on other elements of the Pilot Program. As such, a diverse group of staff members whose work touches on resiliency was assembled on July 24, 2019, to learn about the Pilot Program and solidify approach consensus on criticality.

On January 16, 2020, the team met with H-GAC's Travel Demand Modeling (TDM) staff to discuss models to estimate potential economic loss associated with transportation network disruption due to the various climate stressors. The team discussed various disruption scenarios based on the criticality and vulnerability scores. The TDM staff conducted the economic impact analysis using the economic model for a set of finalized scenarios provided by the Pilot Program team.

NEXT STEPS AND RECOMMENDATIONS

Maintaining optimal quality and performance of transportation assets is critical to Houston-Galveston region's economic vitality, quality of life, and natural and built environments.

Conclusions

Criticality and vulnerability assessment of transportation assets to extreme weather events is an important risk management exercise for the Houston-Galveston region. The methodology used to measure criticality and vulnerability scores of road segments and bridges required collection, integration, and analysis of diverse datasets.

This Pilot Program has developed an approach for analyzing the impact of extreme weather events to regional transportation assets that can be replicated and updated over time. Importantly, the Pilot Program not only provides tools to identify critical and vulnerable assets, but also recommends adaptation strategies that can be used to mitigate the losses related to extreme weather events. The Pilot Program also describes how transportation planning agencies can conduct economic impact analysis for project benefit-cost analysis.

The key outcomes of the Pilot Program are:

- Measured criticality scores of road segments to the region's routine functions and economic activities;
- Measured network redundancy of road segments;
- Estimated road and bridge elevation using LiDAR data;
- Estimated location specific flood exposure depth data of road segments and bridges for various flooding scenarios;
- Identified road segments that are outside the FEMA floodplain, but prone to flooding.
- Measured vulnerability score of road segments and bridges to extreme weather events including flooding, storm surge, and sea-level rise
- Developed Criticality and Vulnerability Matrix to categorize road segments based on their criticality and vulnerability scores. Road segments that are highly critical and highly vulnerable should be considered as top priority for mitigation strategies in the Pilot Program area;
- Developed Regional Resilience Tool to display the criticality and vulnerability scores of road segments and bridges for various flooding scenarios; and
- Developed 25 Adaptation Strategies to identify implementable options to protect highly vulnerable and highly critical assets, providing criteria that local governments can consider when selecting a strategy.

Lessons Learned

The following are lessons learned that would be of use to others considering a similar type of analysis. These lessons learned can be considered in four major areas: data availability and quality, data analysis, access to this Pilot Program's findings, and commitment to collaborate and continue transportation resilience planning.

Data availability and quality - The availability and quality of data is one of the most important factors for the overall success of the Pilot Program. Most of the data required for this study was readily available, however there are many instances where the team reconsidered the data analysis approach because of data unavailability or poor quality. Future studies and programs would benefit if certain types of datasets, such as transportation asset characteristics, were collected and maintained periodically by transportation and planning agencies across the region. For example, the transportation assets managed by TxDOT has better asset characteristics as compared to assets managed by other transportation planning agencies. In addition, it would be helpful to maintain a comprehensive database of transportation assets that were impacted by previously flooding events.

Access to 2018 LiDAR data was also very critical for this Pilot Program as it reflected recent developments, including newly constructed highways, streets, and bridges. The DEM and DSM data generated from the LiDAR data was used to accurately measure the road and bridge elevations. It also allowed to spatially interpolate FEMA flood zone boundaries to identify road segments that are outside the flood zone but are vulnerable to flooding. Availability of FEMA's Hurricane Harvey water depth grid data and H-GAC's Hurricane Harvey flooding imagery was helpful for this Pilot Program.

To better assess the economic impact related to flood damage, future studies would need more accurate repair costs for infrastructures, including flood depth damage function. Determining direct flood damage is commonly done using depth-damage curves, which denote the flood damage that would occur at specific water depths per asset or per land-use class

Data analysis - This Pilot Program used SAS, ArcGIS and ENVI (image analysis software is used by GIS professionals) for data processing and analysis. This Pilot Program required challenging technical processing, including developing DSM using LiDAR data, calculating network redundancy, modeling flooding exposure depth data, and calculating criticality and vulnerability scores for road segments and bridges. Most of this analysis requires powerful computer processing capabilities and expertise in the modeling software.

The methodology applied in this Pilot Program can also be used to assess flood damage to other built environments, such as residential homes, commercial buildings, farmland, airport runways, and port facilities.

Access to Pilot Program findings- Often, findings from the Pilot Program are limited to some paper maps and reports. However, the findings from Pilot Program are presented on the interactive web mapping application/tool, which is accessible to everyone. The tool provides criticality and vulnerability scores of all the road segments and bridges analyzed. In addition, the tool also identifies specific locations of road segments that are vulnerable to flooding in any given scenario. Easy access to this information will help transportation agencies in the H-GAC MPO identify the vulnerable road segments and develop mitigation strategies.

Commitment to collaborate and continue transportation resilience planning - Meaningful discussion with stakeholders about challenges, opportunities, and needs was crucial to success. A regional, multi-jurisdictional approach to resilience planning is needed to develop and deploy resilience solutions to future extreme weather events. The criticality and vulnerability results from this Pilot Program along with recommended adaptation strategies could be incorporated into ongoing planning and decision-making processes.

Next Steps

The Houston-Galveston MPO values the findings of this Pilot Program and acknowledges that this is the first step toward a more resilient transportation system for the region. The findings of the Pilot Program will be integrated into current and future transportation planning studies, including Low-Impact Development Study, Regional Transportation Plan, Transit-Oriented Development Study, Complete Streets Program, Sub-regional Studies, and a Region-wide Resiliency Study.

The Low-Impact Development Study will expand on the 25 Adaptation Strategies and incorporate additional analysis of implementable options for decision-makers and developers to adopt within the public ROW. Understanding the criticality and vulnerability of major roads and bridges will enable more careful articulation of climate impacts on hurricane routes and route alternatives in the Regional Transportation Plan and Sub-Regional Studies. While most of the planning studies will continue this Pilot Program's focus on resiliency for vehicle travel, the Houston-Galveston MPO will study the impacts of flood and stormwater on active transportation modes like bicycling and walking. Through context-sensitive design, the Complete Streets Program will identify the nexus between impacts on all travel modes —with specific focus on filling in the gap of active transportation– and localized flooding to determine resilient strategies for roadway, bikeway, and walkway design.

REFERENCES

ABC 13 Eyewitness News. (2020). SkyDrone 13 video shows flooding on Highway 288. Retrieved from https://abc13.com/tropical-storm-beta-houston-weather-flood-flooding/6502682/

Blackburn, Jim. (2019). "Houston-Area Surge Flooding and Its Effects on Regional and National Security." Retrieved from https://www.bakerinstitute.org/media/files/files/a504bad8/bi-research-blackburn-houstonflooding-050119.pdf

Clark, Alan. (2017). "Impact of Hurricane Harvey on the State's Transportation Infrastructure in the Houston-Galveston Metropolitan Area and Recommendations on How Best to Rebuild Assets Efficiently and Effectively." Retrieved from http://2045rtp.com/documents/plan/Appendix%20J%20-%20Resiliency.pdf

Climate Discovery. (2020). Atlas 14: Texas – The 100-year Storm is Now the 25-year Storm, Already: Climate Understatement of the Year. Retrieved from https://climatediscovery.org/atlas-14-texas-the-100-year-storm-is-now-the-25-year-storm-already/#:~:text=them%20a%20lot.-,Atlas%2014%3A%20Texas%20%E2%80%93%20The%20100%2Dyear%20Storm%20is%20Now,12.5%20inches%20in%2024%20hours.&text=The%20100%2Dyear%20storm%20total,an%20increase%20of%2043%20percent

Community Impact Newspaper. (2020). New Harris County floodplain rules draw concern over development costs. Retrieved from https://communityimpact.com/houston/city-county/2019/07/17/new-harris-county-floodplain-rules-draw-concern-over-development-costs/

Federal Emergency Management Agency. (2019). Disaster Declarations Summaries. Retrieved from https://www.fema.gov/data-sets

Federal Emergency Management Agency. (2018), Guidance for Flood Risk Analysis and Mapping. Retrieved from https://www.fema.gov/media-library-data/1523562952942-4c54fdae20779bb004857f1915236e6c/Flood_Depth_and_Analysis_Grids_Guidance_Feb_2018.pdf

Federal Highway Administration. (2015). FHWA Vulnerability Assessment Tools. Retrieved from http://onlinepubs.trb.org/onlinepubs/conferences/2015/ClimateChange/67.CassandraBhat.pdf

Houston-Galveston Area Council. (2012). Regional Hazard Mitigation Plan – 2011 Update. Retrieved from http://videos.h-gac.com/CE/hazard/2011-Hazard-Mitigation-Plan.pdf

Houston-Galveston Area Council. (2018). Chapter 4: Regional Growth and Travel Patterns. 2045 Regional Transportation Plan. Retrieved from http://2045rtp.com/documents/plan/Chapter-4-Regional-Growth.pdf

Houston Advanced Research Center & Galveston Bay Foundation. (2020). Galveston Bay Report Card. Retrieved from https://www.galvbaygrade.org/coastal-change/#sea-level

National Oceanic and Atmospheric Administration. (2019). Climate Change: Global Sea Level. Retrieved from https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

SeaLevelRise.org. (2020). Overview: Texas' Sea Level Is Rising. Retrieved from https://sealevelrise.org/states/texas/

U.S. Census Bureau: Longitudinal Employer-Household Dynamics Program. (2020). Quarterly Workforce Indicators. Retrieved from https://ledextract.ces.census.gov/static/data.html

U.S. Department of Transportation: Federal Highway Administration. Resilience and Durability to Extreme Weather Pilot Program. (2020). Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/resdurpilot.cfm

U.S. Environmental Protection Agency. (2020). Report on the Environment: Sea Level. Retrieved from https://www.epa.gov/report-environment

Appendices

APPENDIX A: CRITICALITY ASSESSMENT

Detailed Methodology

For the Pilot Program, the criticality assessment only applies to roadway segments. Bridges are not assessed for criticality as all bridges are a part of a road segment. Freeways and major roads are analyzed separately in the Pilot Program, but the underlying methods of analysis are identical. Four categories of importance are analyzed in the assessment and contribute to the aggregated criticality index:

1. Socioeconomic importance
2. Usage and operational importance
3. Health and safety importance
4. Emergency preparedness importance

Socioeconomic importance: indicators in this category include access to airports, access to port facilities and access to activity population. This category is given a weight of 20% in the calculation of the aggregated criticality index.

Access to airports:

Measures how each roadway segment provides access to the two commercial airports in the region, Bush Intercontinental Airport (IAH) and William Hobby Airport (HOU). For each segment, travel times to both IAH (T_{IAH}) and HOU (T_{HOU}) are calculated. For segments that are closer to IAH, T_{IAH} is used in the scoring criteria. For segments that are closer to HOU, T_{HOU} is used in the scoring criteria.

Scoring criteria:

For freeways:

Score=4 when T_{IAH} <4 mins or T_{HOU}<3 mins

Score=3 when T_{IAH} 4-8 mins or T_{HOU} 3-4 mins

Score=2 when T_{IAH} 8-12 mins or T_{HOU} 4-5 mins

Score=1 when T_{IAH} 12-15 mins or T_{HOU} 5-6 mins

Score=0 when T_{IAH} 15+ mins or T_{HOU} 6+ mins

For major roads:

Score=4 when T_{IAH} <8 mins or T_{HOU}<2 mins

Score=3 when T_{IAH} 8-10 mins or T_{HOU} 2-3 mins

Score=2 when T_{IAH} 10-13 mins or T_{HOU} 3-4 mins

Score=1 when T_{IAH} 13-16 mins or T_{HOU} 4-6 mins

Score=0 when T_{IAH} 16+ mins or T_{HOU} 6+ mins

Data source: GIS transportation network analysis by H-GAC staff.

Access to port facilities:

Measures how each roadway segment provides access to port facilities in the region. For each segment, travel time *t* is calculated as the drive time to the nearest port facility.

Scoring criteria:

For freeways:

Score=4 when t <3 mins

Score=3 when t 3-4 mins

Score=2 when t 4-5 mins

Score=1 when t 5-9 mins

Score=0 when t 9+ mins

For major roads:

Score=4 when t < 2 mins

Score=3 when t 2-3 mins

Score=2 when t 3-5 mins

Score=1 when t 5-12 mins

Score=0 when t 12+ mins

Data source: GIS transportation network analysis by H-GAC staff.

Access to activity population:

Measures how each roadway segment supports the commute of local activity population, defined as the combination of residential population and job count in each location. The access is measured by statistic *p*, which is calculated as the proportion of activity population that can be reached within 15 minutes of drive from the segment compared to the activity population of the entire region. The statistic *p* is displayed as a percentage.

Scoring criteria:

For freeways:

Score=4 when p > 30%

Score=2 when p 15-30%

Score=0 when p <15%

For major roads:

Score=4 when p > 30%

Score=2 when p 10-30%

Score=0 when p < 10%

Data source: GIS transportation network analysis by H-GAC staff; US Census Bureau.

Usage and operational importance: indicators in this category include annually averaged daily traffic (AADT), annually averaged daily truck traffic (AADTT) and transit passenger rides. This category is given a weight of 40% in the calculation of the aggregated criticality index.

AADT:

AADT is the most direct and accurate indicator measuring the usage and operational importance of a road segment. It records the annual average daily traffic on each road segment.

Scoring criteria:

Score=4 when AADT among top 5%

Score=3 when AADT among top 5-10%

Score=2 when AADT among top 10-25%

Score=1 when AADT among top 25-50%

Score=0 when AADT below median level

Data source: H-GAC Travel Demand Model.

AADTT:

AADTT reflects the importance of a road segment to goods transportation, trade and manufacture activities. It records the annual average daily truck traffic on each road segment.

Scoring criteria:

Score=4 when AADTT among top 5%

Score=3 when AADTT among top 5-10%

Score=2 when AADTT among top 10-25%

Score=1 when AADTT among top 25-50%

Score=0 when AADTT below median level

Data source: TxDOT Road Inventory File

Transit rides:

This indicator measures the importance of a road segment in the regional public transit system. It records the daily passenger trips made on the road segment. In the analysis, only major road segments are considered. All freeways are given a value of 0.

Scoring criteria:

Score=4 when transit trips > 20,000

Score=3 when transit trips 15,000-20,000

Score=2 when transit trips 5,000-15,000

Score=1 when transit trips < 5,000

Score=0 when the segment does not have transit ridership

Data source: Houston METRO

Health and safety importance: indicators in this category include access to hospitals, access to fire stations, and service to vulnerable population. This category is given a weight of 30% in the calculation of the aggregated criticality index.

Access to hospitals:

This indicator describes the accessibility a road segment provides to the nearest hospital facility. In the analysis, urgent care centers and emergency medical services facilities are not considered as hospitals. In the calculation of the indicator, both travel time to the nearest hospital (*t*) and household-based trip (*h*) are normalized into the scale of 0-1, yielding variables *R(t)* and *R(h)*. Accessibility index is constructed as *A*=1+*R(h)*-*R(t)*, and is then normalized into the scale of 0-1, yielding index rank-based index *R(a)*.

Scoring criteria:

Score=4 when R(a) > 0.95

Score=3 when R(a) 0.9-0.95

Score=2 when R(a) 0.75-0.9

Score=1 when R(a) 0.5-0.75

Score=0 when R(a) < 0.5

Data source: GIS transportation network analysis by H-GAC staff.

Access to fire stations:

This indicator describes the accessibility a road segment provides to the nearest fire station. In the calculation of the indicator, both travel time to the nearest fire station (*t*) and household-based trip (*h*) are normalized into the scale of 0-1, yielding variables *R(t)* and *R(h)*. Accessibility index is constructed as *A*=1+*R(h)*-*R(t)*, and is then normalized into the scale of 0-1, yielding index rank-based index *R(a)*.

Scoring criteria:

Score=4 when R(a) > 0.95

Score=3 when R(a) 0.9-0.95

Score=2 when R(a) 0.75-0.9

Score=1 when R(a) 0.5-0.75

Score=0 when R(a) < 0.5

Data source: GIS transportation network analysis by H-GAC staff.

Service to vulnerable population:

This indicator measures how a road segment provides access and service to economically and socially challenged communities (vulnerable populations). H-GAC staff have previously calculated vulnerability population index for each census block in the H-GAC area, considering several demographic and economic factors, including but not limited to elderly, racial monitories, disability, poverty, carless, and limited English proficiency. Statistic *Vp* is the vulnerable population index derived from the analysis, ranging from 0 to 100 with 100 indicating that the census block has the highest vulnerable population density in the region. The statistic *Vp* of the nearest census block to a road segment is assigned to the road.

Scoring criteria:

Score=4 when Vp > 95

Score=3 when Vp 90-95

Score=2 when Vp 75-90

Score=1 when Vp 50-75

Score=0 when Vp < 50

Data source: GIS analysis by H-GAC staff; US Census Bureau.

Emergency preparedness importance: indicators in this category include evacuation route status, access to emergency shelters, access to FEMA EOCs and military access (national strategic highway status). This category is given a weight of 10% in the calculation of the aggregated criticality index.

Evacuation route:

This is a binary indicator to show that whether the road segment is part of the designated emergency evacuation route.

Scoring criteria:

Score=2 when it is part of a designated evacuation route

Score=0 when it is not part of a designated evacuation route

Data source: TxDOT Road Inventory File

Access to shelters:

This indicator describes the accessibility a road segment provides to the nearest emergency shelter. In the calculation of the indicator, both travel time to the nearest shelter (t) and household-based trip (h) are normalized into the scale of 0-1, yielding variables $R(t)$ and $R(h)$. Accessibility index is constructed as $A=1+R(h)-R(t)$, and is then normalized into the scale of 0-1, yielding index rank-based index $R(a)$.

Scoring criteria:

Score=4 when $R(a) > 0.95$

Score=3 when R(a) 0.9-0.95

Score=2 when R(a) 0.75-0.9

Score=1 when R(a) 0.5-0.75

Score=0 when $R(a) < 0.5$

Data source: GIS transportation network analysis by H-GAC staff; FEMA

Access to FEMA EOCs:

The indicator measures how the road segment provides access to FEMA EOCs. Travel time t refers to the drive time from the road segment to the nearest EOC.

Scoring criteria:

For freeways:

Score=4 when t <2 mins

Score=3 when t 2-3 mins

Score=2 when t 3-4 mins

Score=1 when t 4-5 mins

Score=0 when t 5+ mins

For major roads:

Score=4 when t < 1 mins

Score=3 when t 1-2 mins

Score=2 when t 2-3 mins

Score=1 when t 3-5 mins

Score=0 when t 5+ mins

Data source: GIS transportation network analysis by H-GAC staff; FEMA

Military access:

This is a binary indicator showing that whether the road segment provides military access. The criteria include whether it is part of the strategic highway network or it is within 5-minute driving distance to the Ellington Airfield.

Scoring criteria:

Score=2 when at least one criterion is met

Score=0 when no criterion is met

Data source: GIS transportation network analysis by H-GAC staff; FHWA

After indicators from all categories are calculated, a weighted summary is performed for the indicators. For each category, the combined score ranges from 0 to 12, with 12 indicating the highest criticality. The weighted total of all indicators also ranges from 0 to 12, given that the weights sum up to 100%. A ranking-based cumulative standardization to the scale of 0 to 1 is performed to the weighted total, yielding the final criticality score for all road segments, with 1 suggesting the highest importance. As stated previously, the criticality assessments are performed separately for freeways and major roads. Although the metrics differ, the methodology does not differ for the two classes.

Criticality Maps

Figures 57 – 69 depict the criticality of linkages to socio-economically important locations in the H-GAC MPO region.

Figure 56 – Criticality-Access to Airports

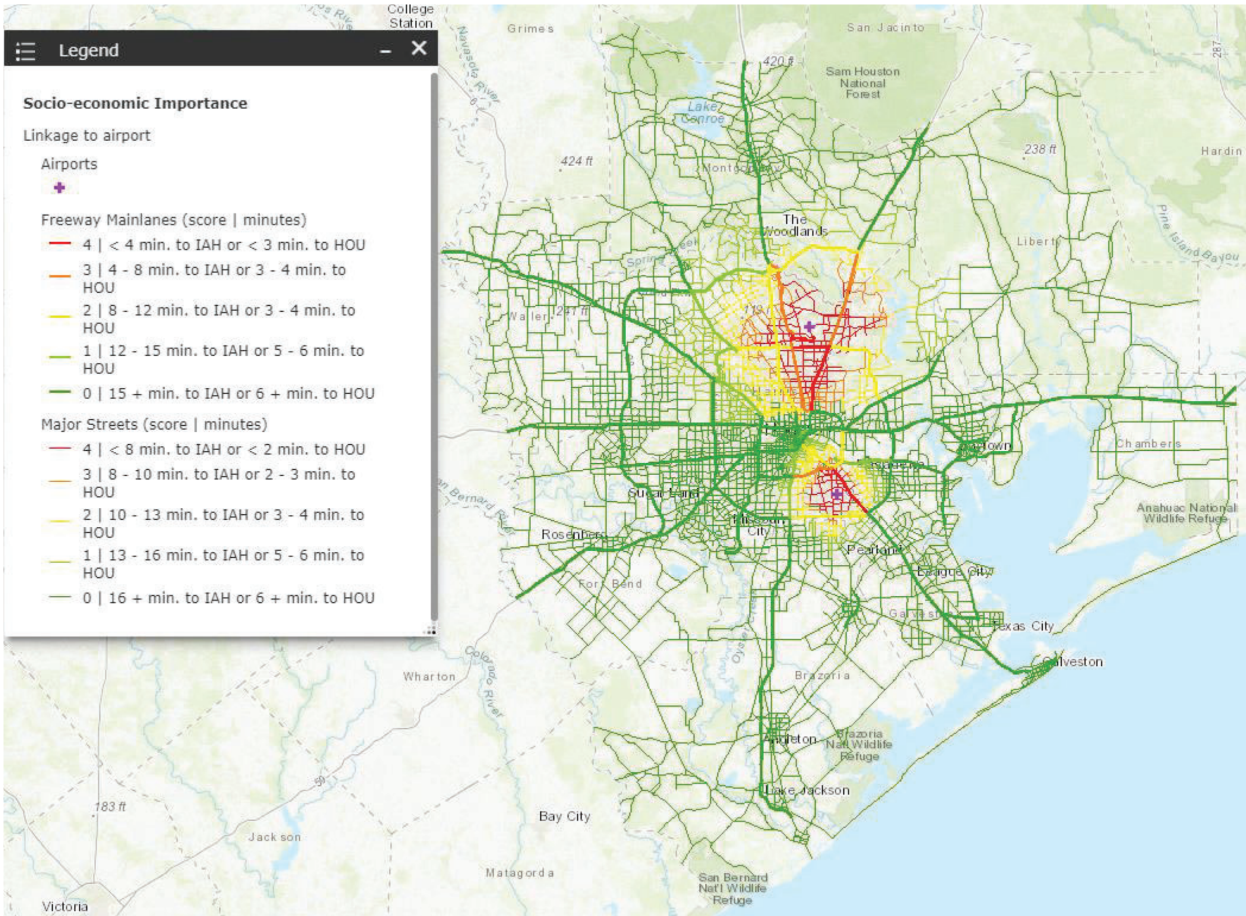


Figure 57 – Criticality-Access to Port Facilities

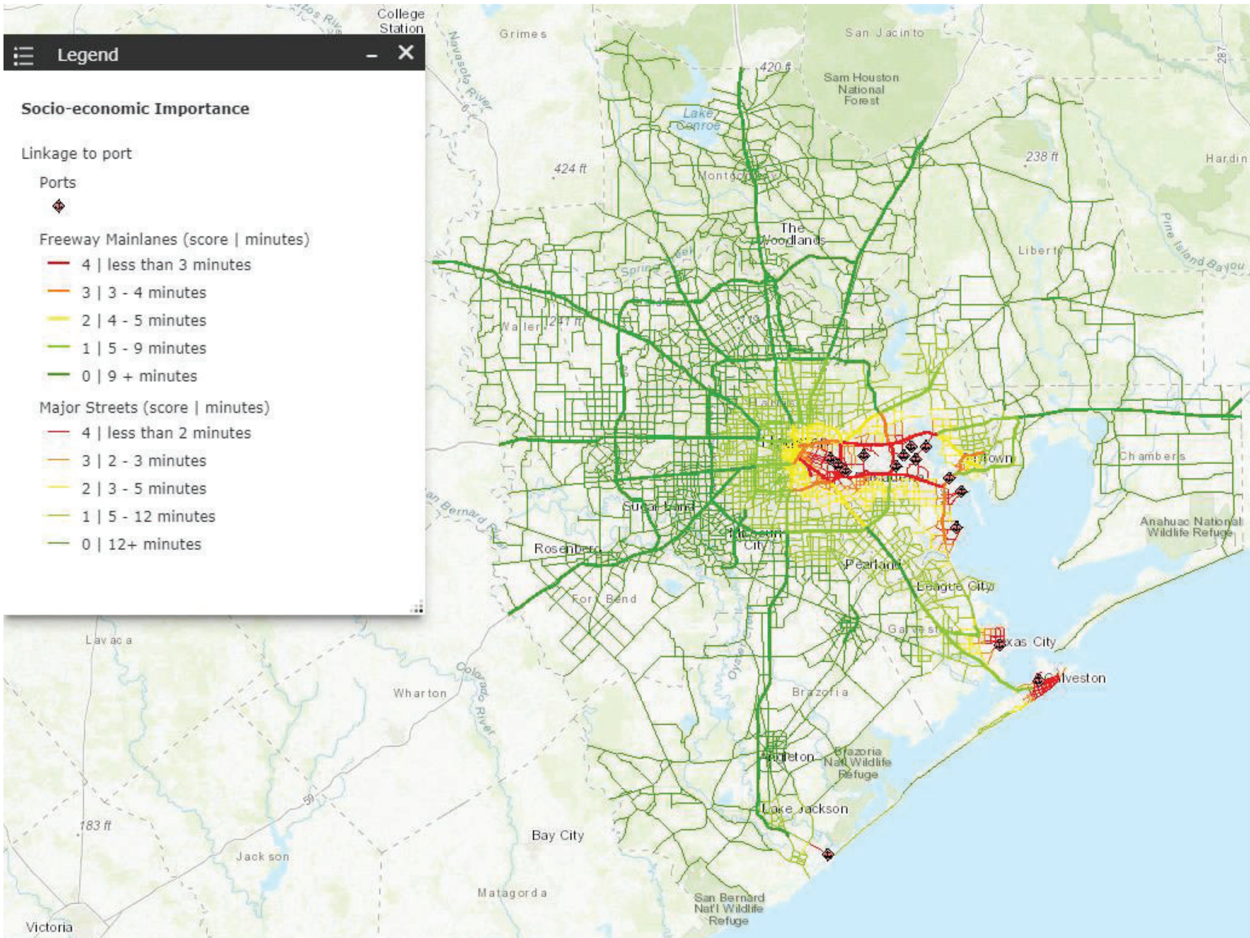


Figure 58 – Criticality-Access to Activity Population

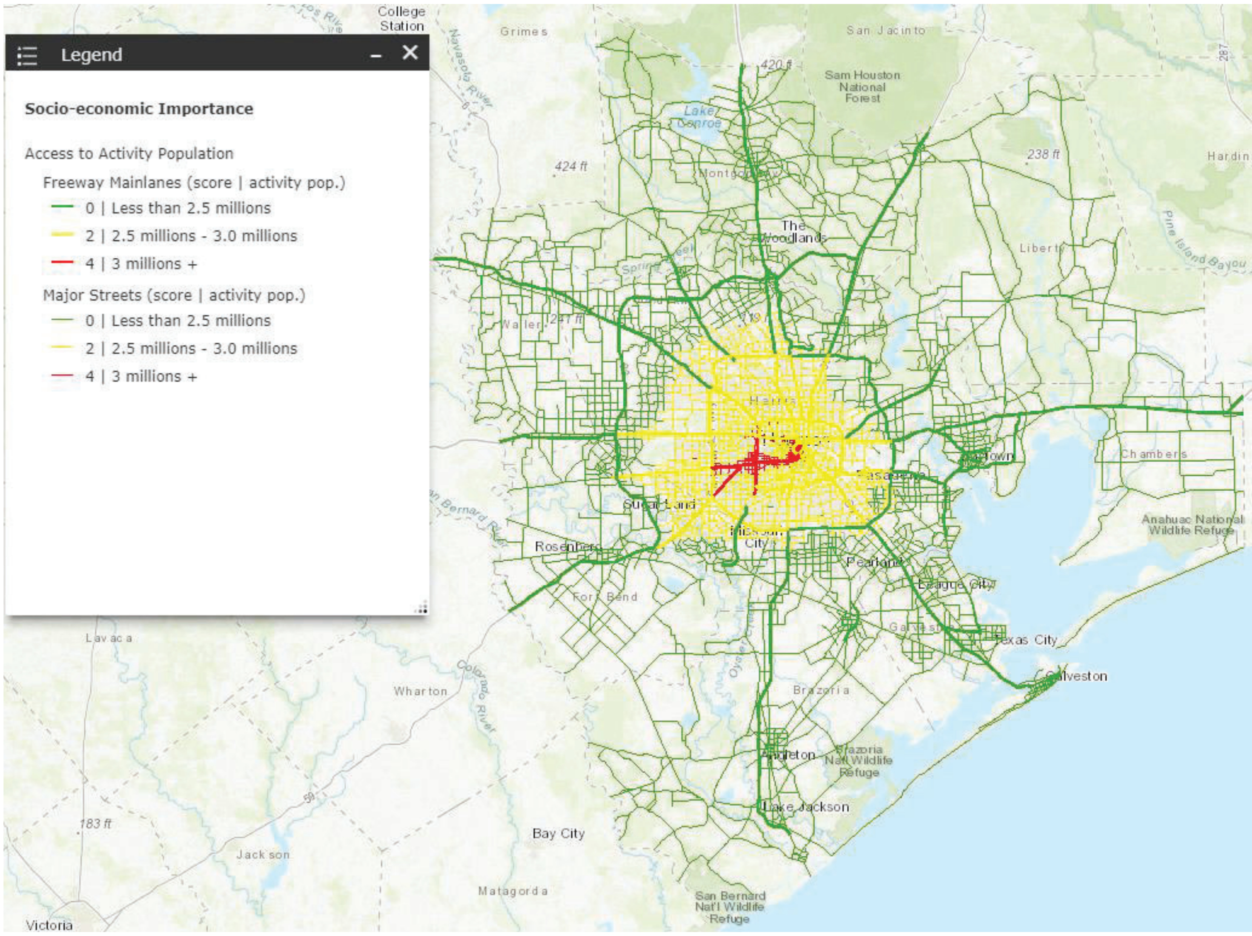


Figure 59 – Criticality-Annually Averaged Daily Traffic

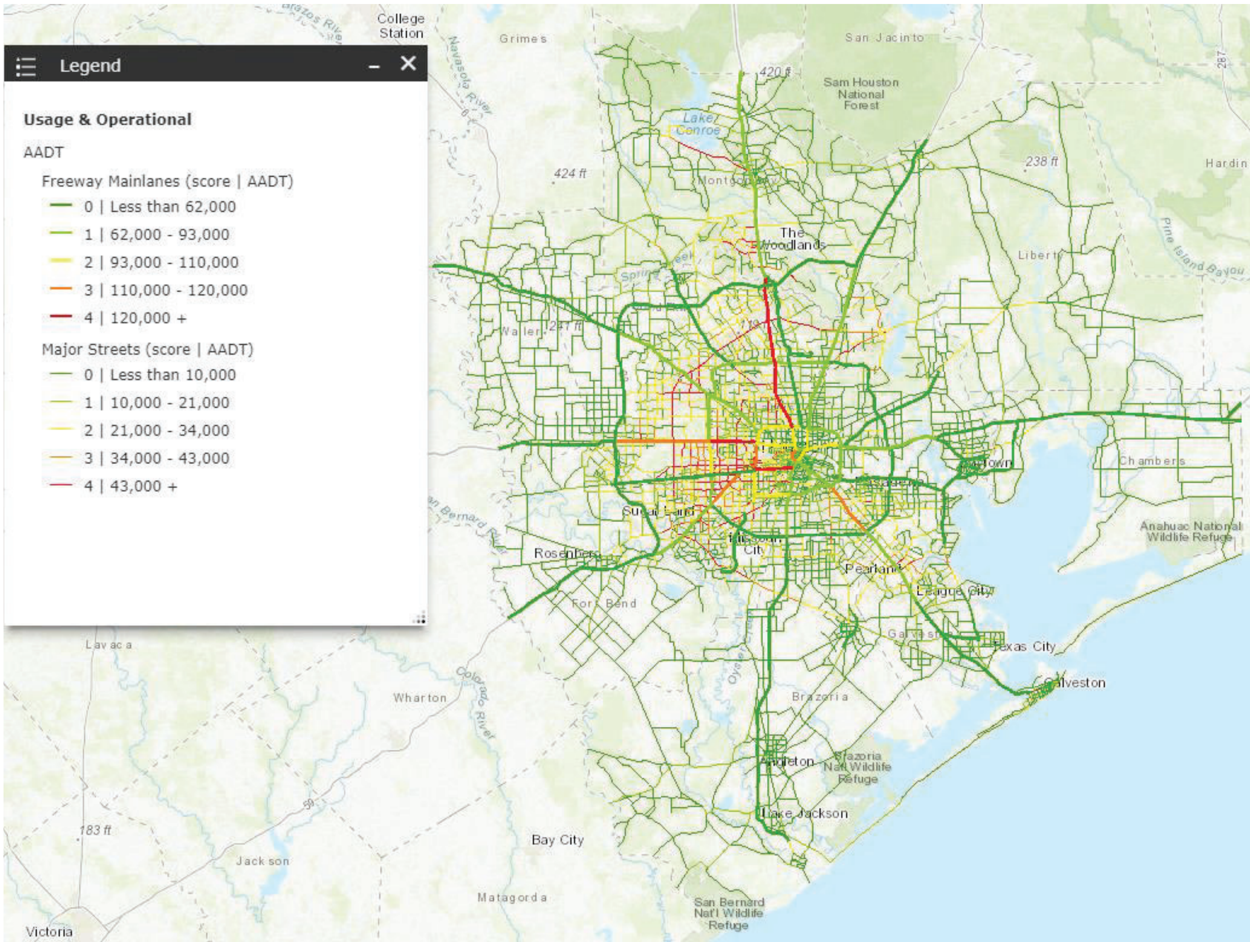


Figure 60 – Criticality-Annually Averaged Daily Truck Traffic

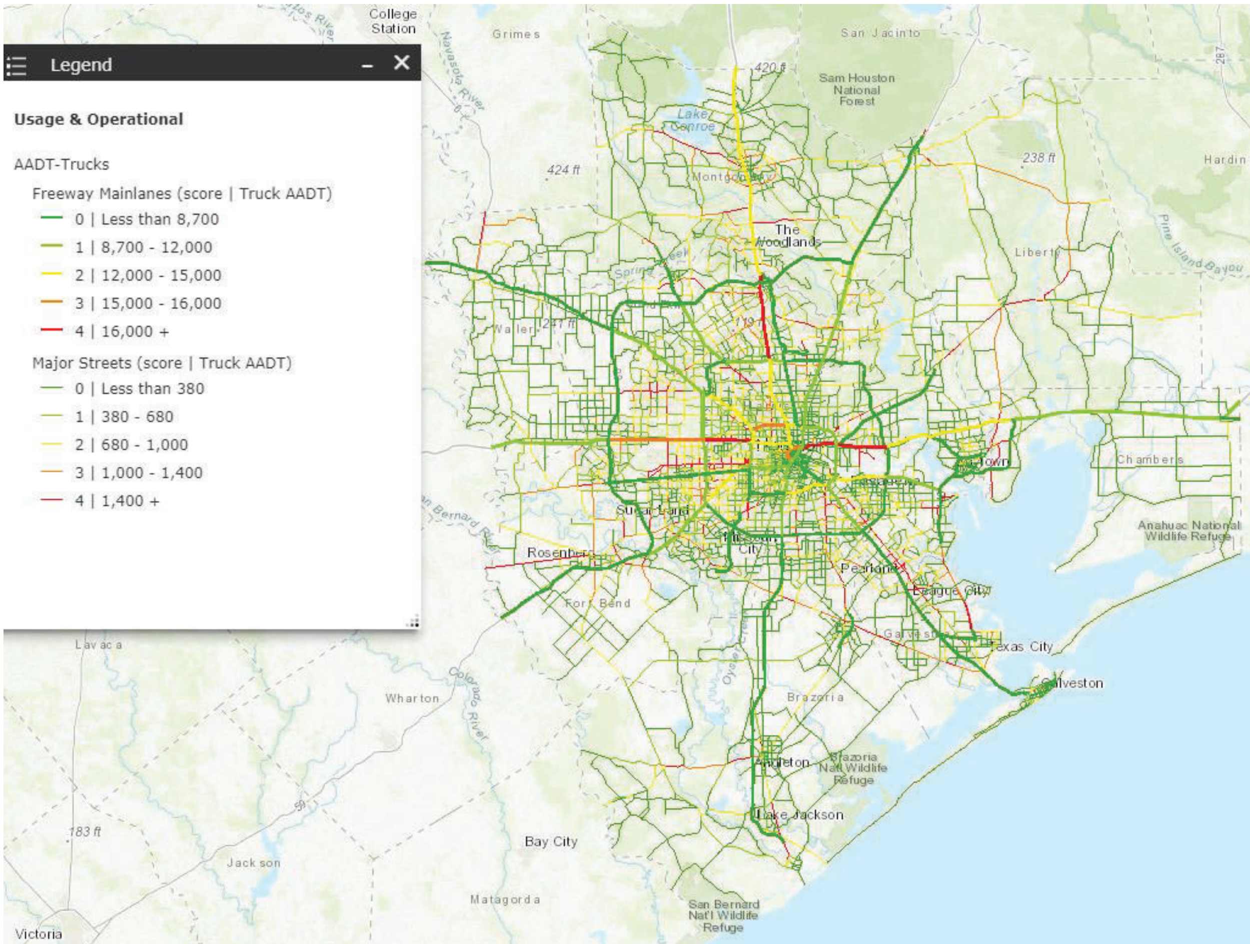


Figure 61 – Criticality-Transit Rides

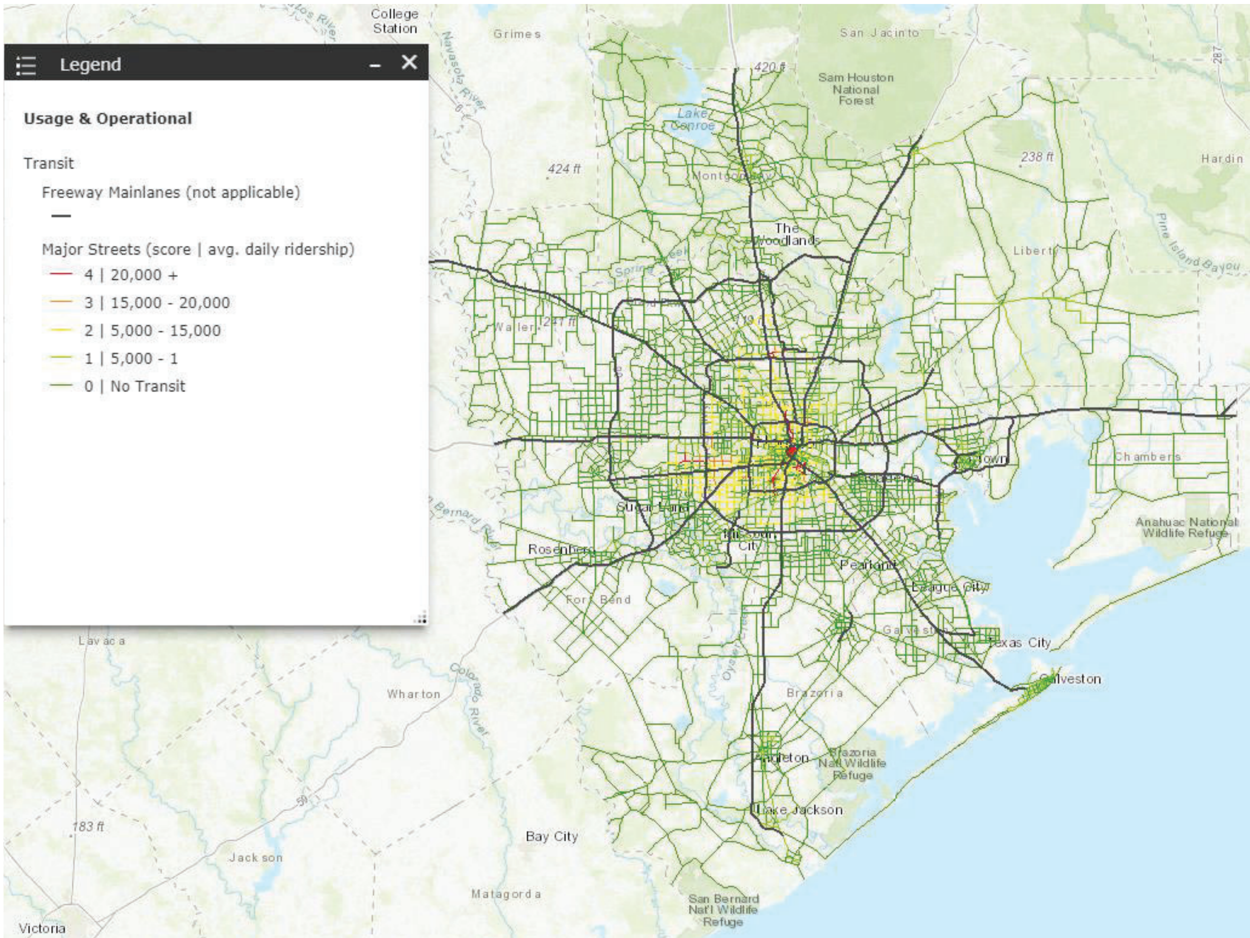


Figure 62 – Criticality-Access to Hospitals

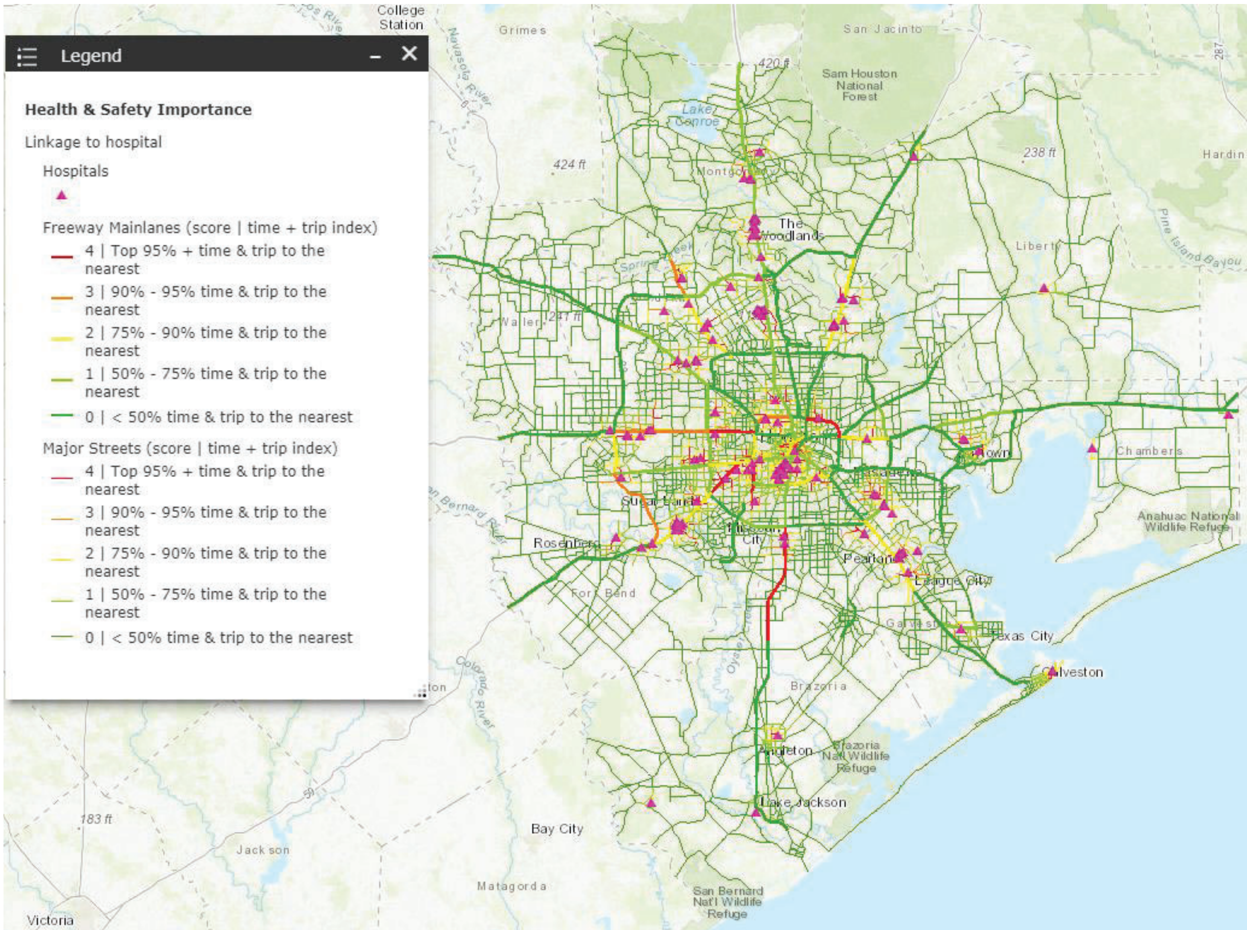


Figure 63 – Criticality-Access to Fire Stations

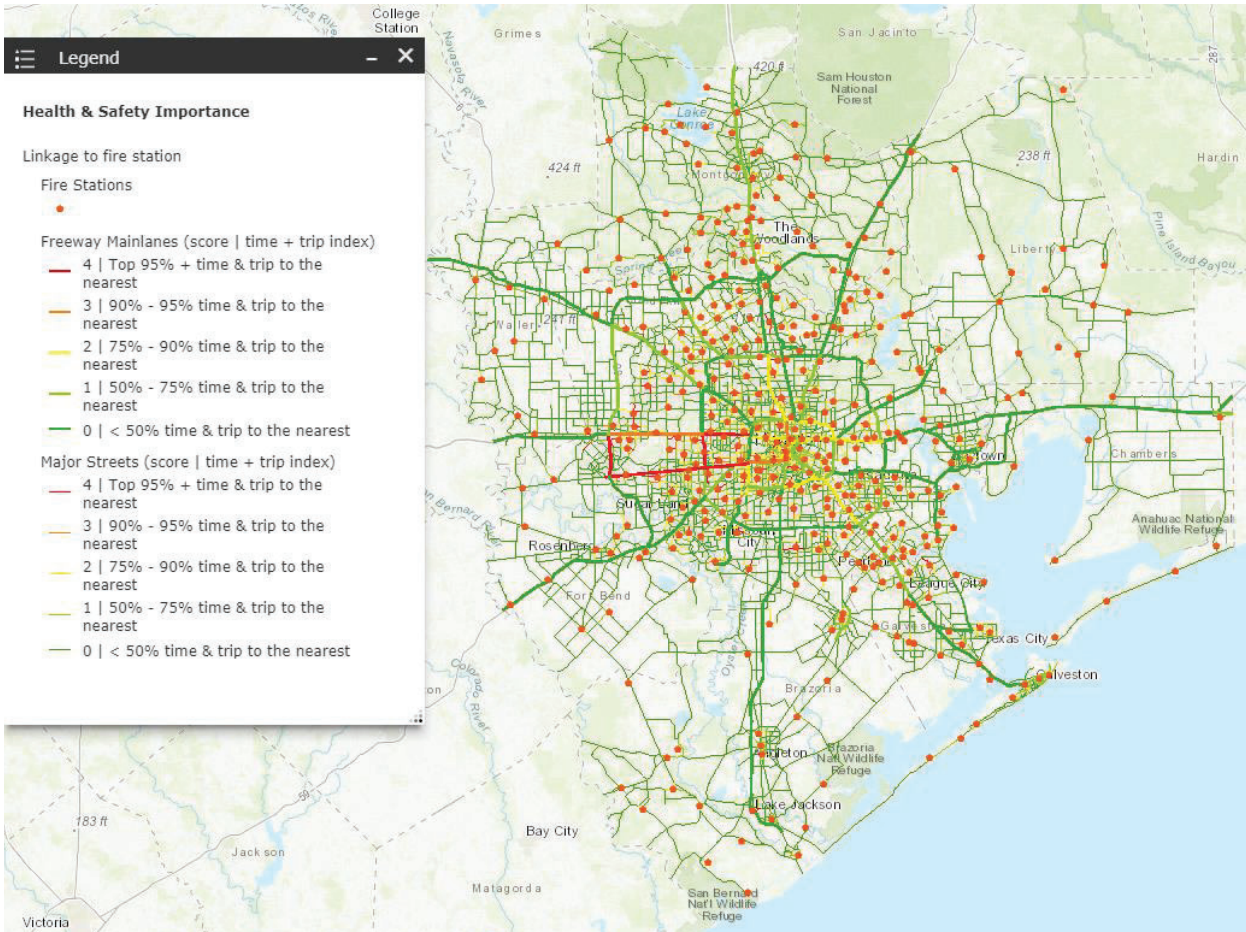


Figure 64 – Criticality- Services to Vulnerable Populations

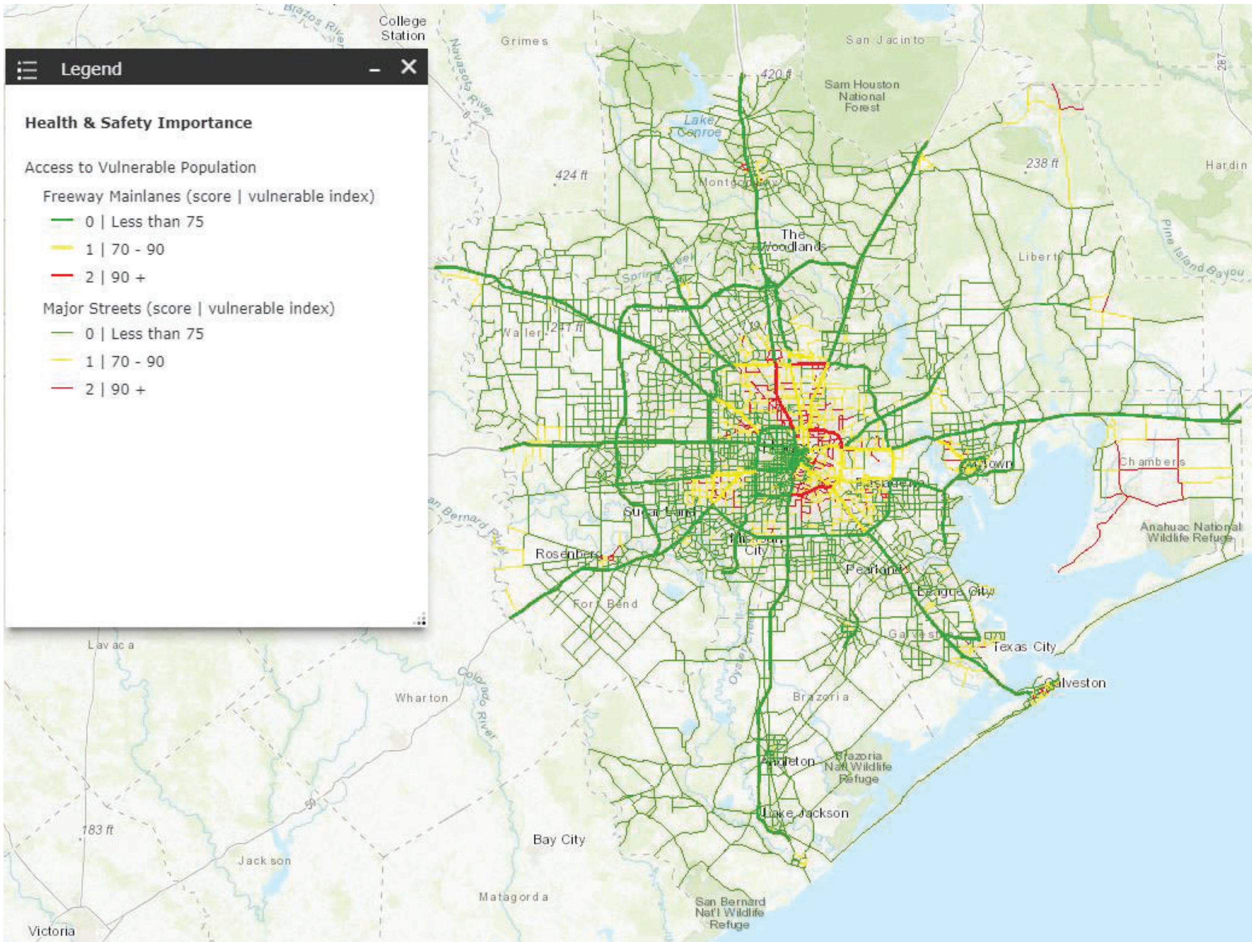


Figure 65 – Criticality-Evacuation Route

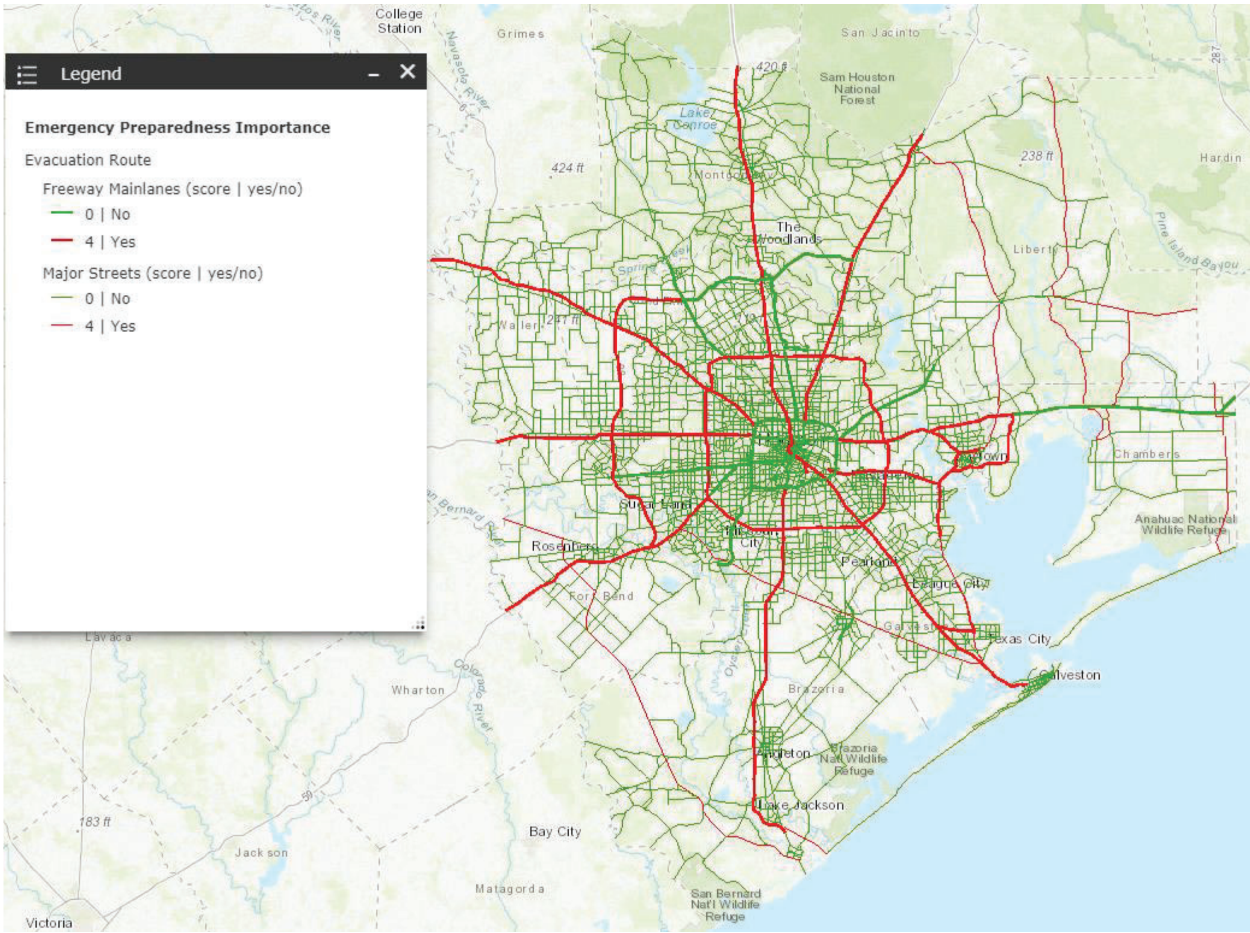


Figure 66 – Criticality-Access to Shelters

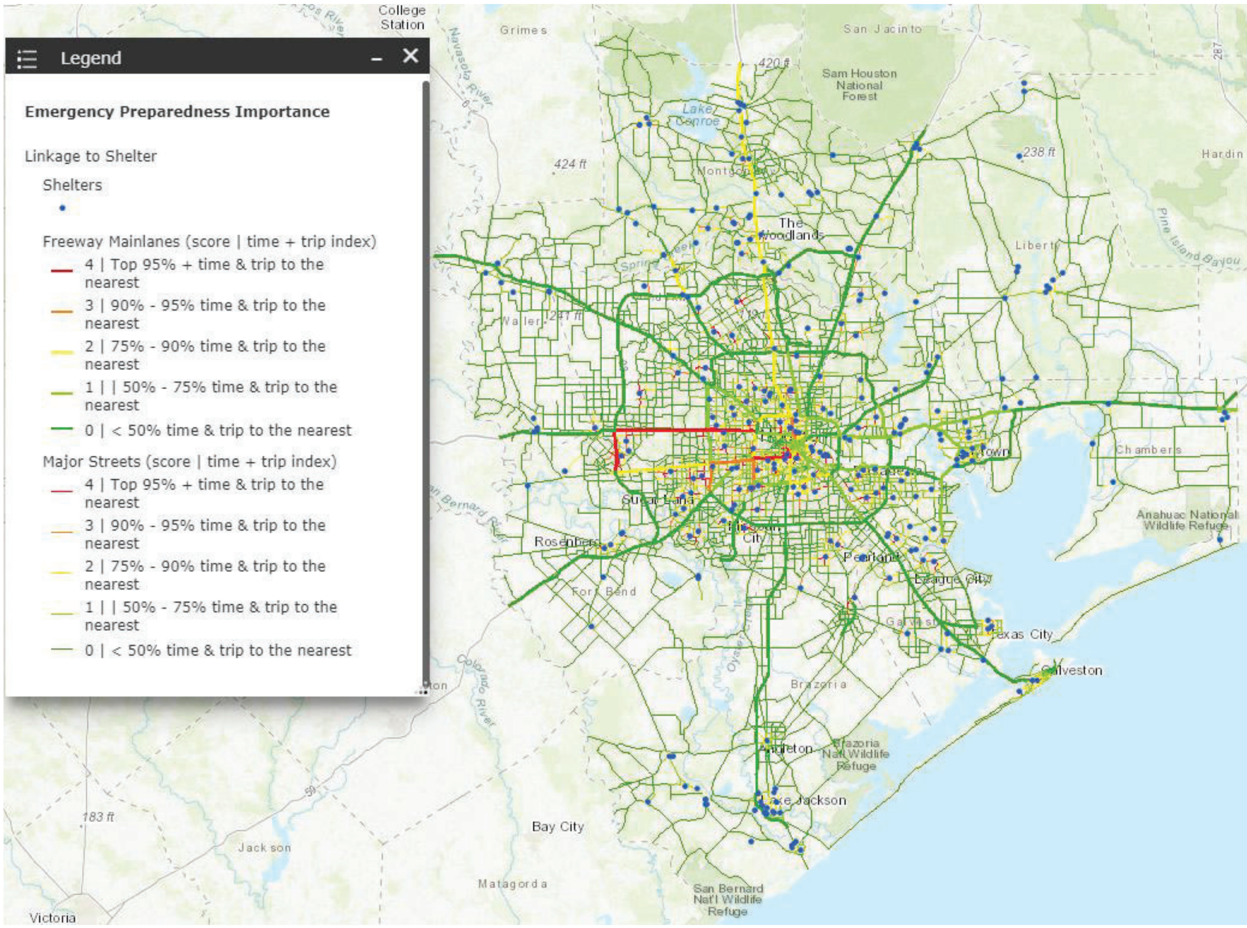


Figure 67 – Criticality-Access to FEMA EOCs

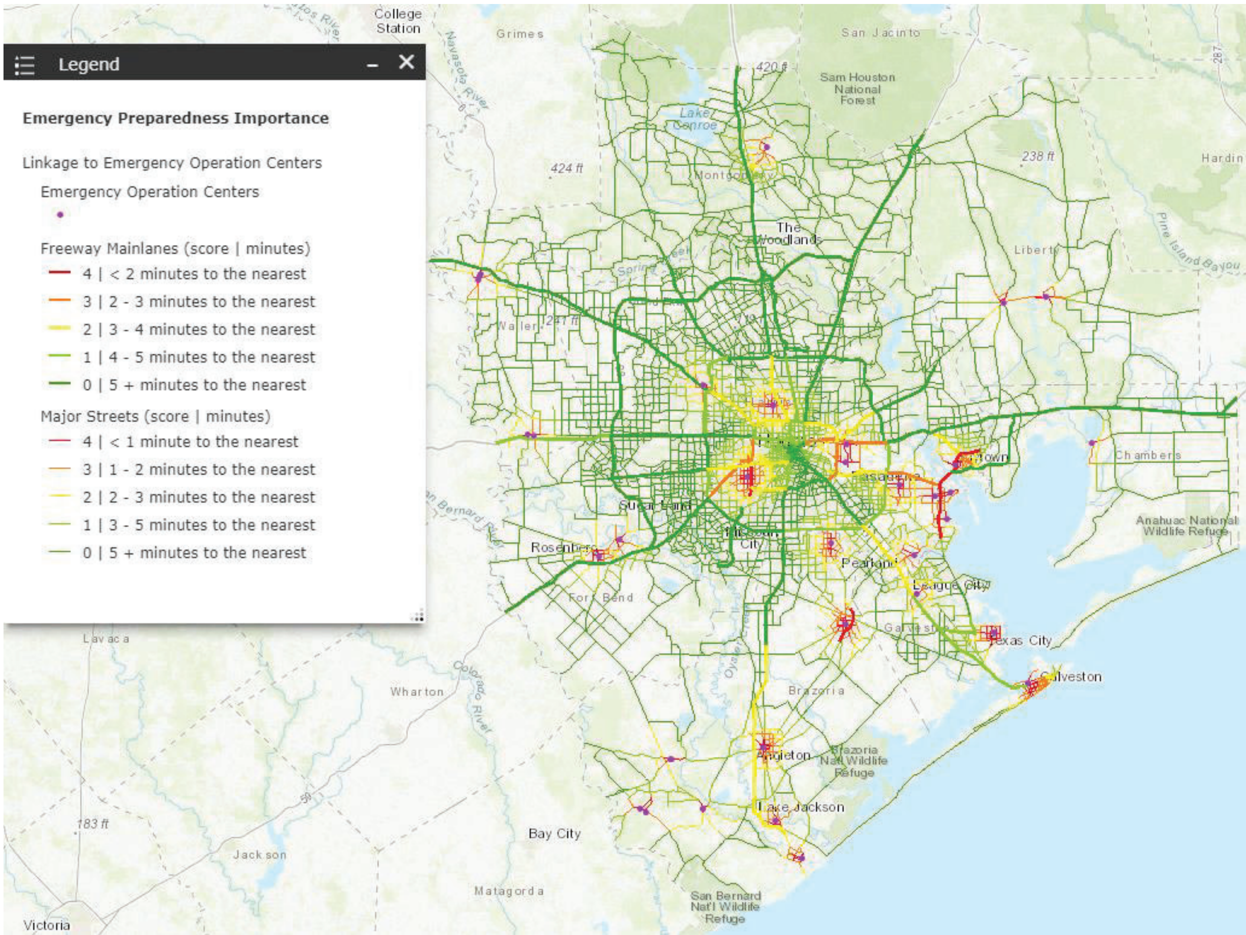
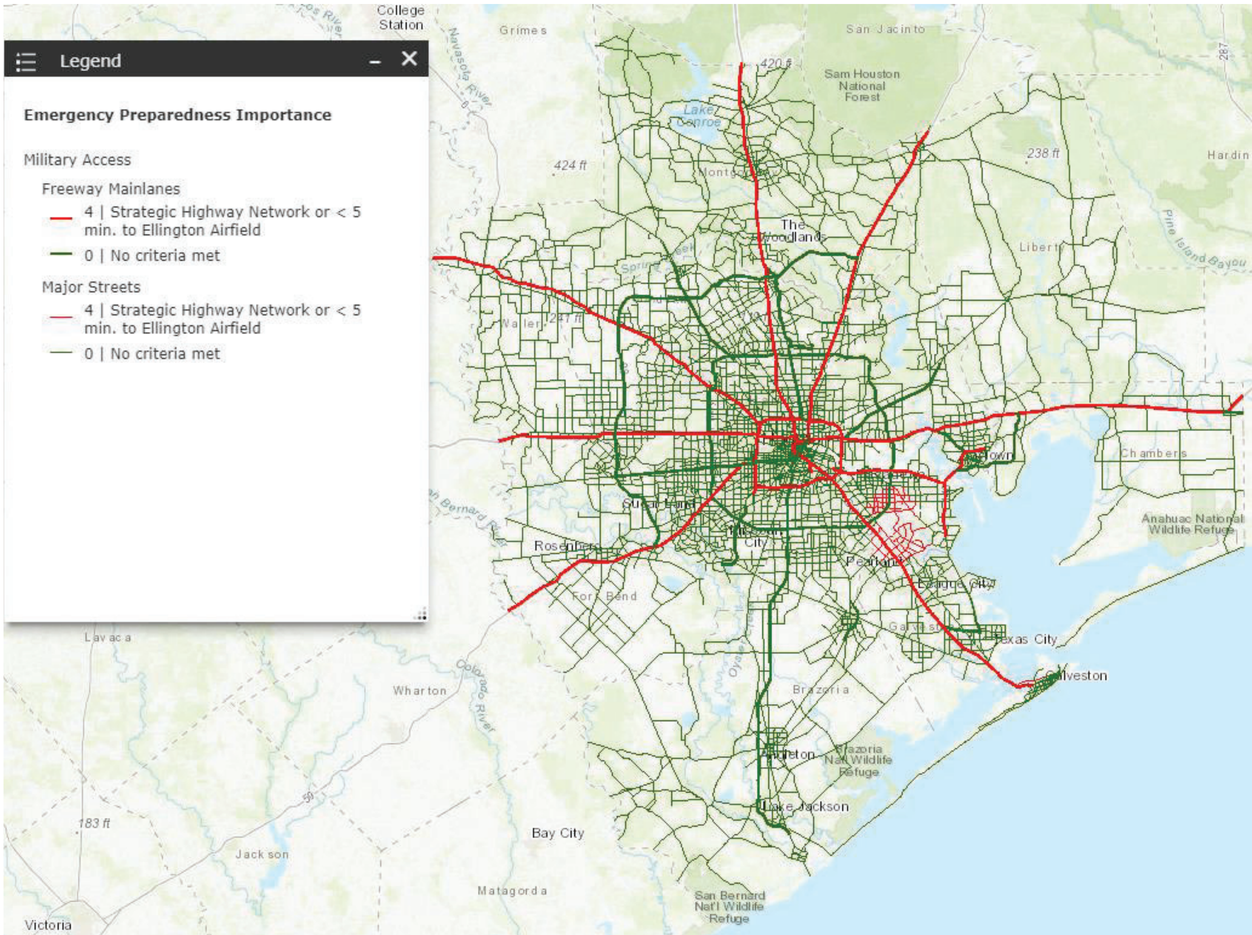


Figure 68 – Criticality-Military Access



APPENDIX B: VULNERABILITY ASSESSMENT

Detailed Methodology

Exposure Assessment

To assess the exposure to each transportation asset, high-resolution, multi-scenario climate and hydrology modeling was performed for the region. Based on stakeholder inputs, three climate stressors are analyzed in the Pilot Program: inland flooding, coastal storm surge, and sea level rise. For each climate stressor, the following climate scenarios in Table 9 are considered.

Table 9 – Inland Flooding

Climate Stressor	Scenario	Data source
Inland flooding	100-year flooding	FEMA floodplain map
	500-year flooding	FEMA floodplain map
	Hurricane Harvey flooding	National Hurricane Center
Coastal storm surge	Category 1 hurricane storm	NOAA
	Category 2 hurricane storm	NOAA
	Category 3 hurricane storm	NOAA
	Category 4 hurricane storm	NOAA
	Category 5 hurricane storm	NOAA
	Hurricane Ike	National Hurricane Center
Sea level rise	4-foot sea level rise	NOAA
	5-foot sea level rise	NOAA

The team processed LiDAR data and Flood Depth data to measure the flood exposure depth of roads and bridges.

LiDAR Data and Flood Modeling

The primary properties of the transportation infrastructures assets used in this Pilot — above-ground height and width— were mainly derived from the LiDAR data. Two types of LiDAR data products were used in the feature extraction process:

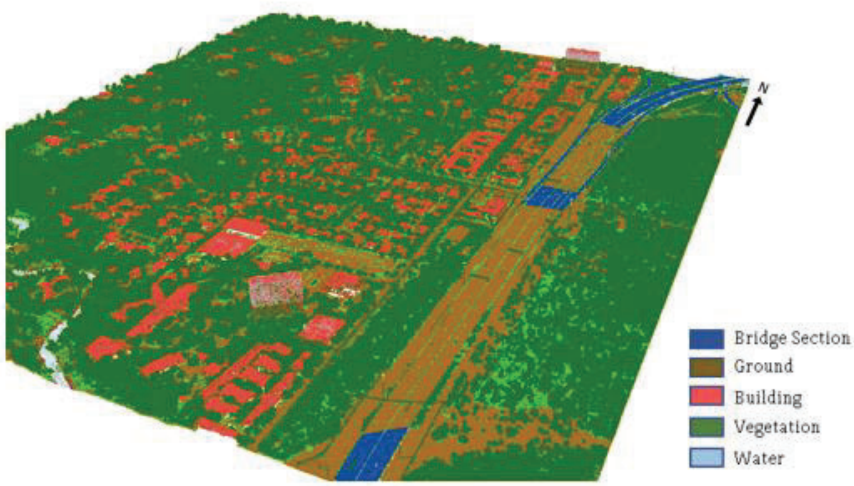
- H-GAC's 2018 LiDAR product

this dataset covers the all counties within the Houston-Galveston MPO Pilot Program area except Fort Bend County.

- TNRIS 2014 LiDAR product
  this dataset covers the Fort Bend County area.

Figure 70 shows a 3-D image of classified LiDAR point cloud data for the uptown area of Houston.

Figure 69 – A 3D image of example classified LiDAR point cloud – Uptown, Houston



Estimating the Above-Ground Heights

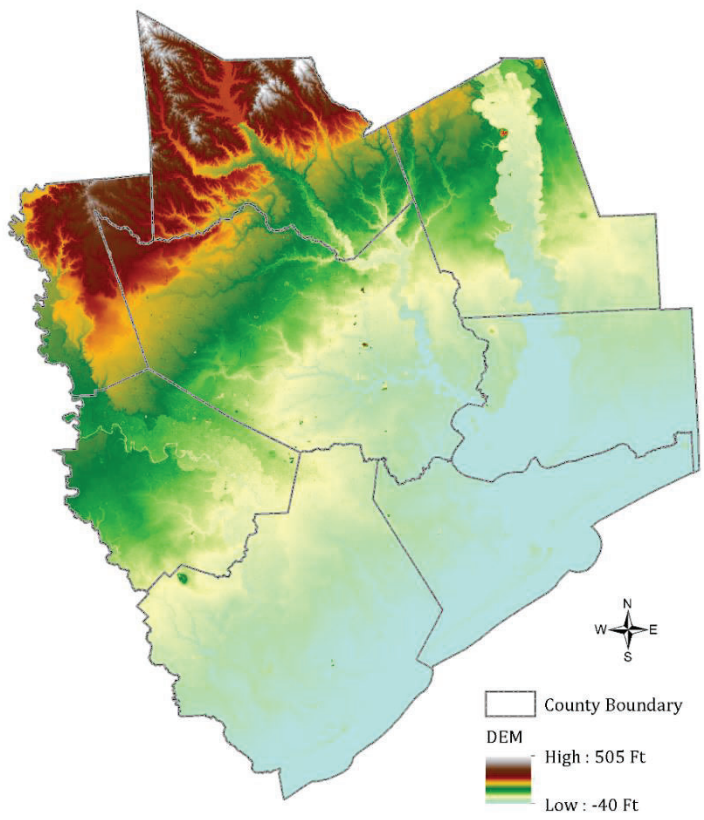
Above-ground height is measured from the underlying ground surface. To estimate above-ground heights, the DEM, a bare-earth raster grid usually representing the surface of the earth, was used. Once above-ground natural and built features, such as trees and other types of vegetation, roads, bridges, buildings, powerlines, etc., are filtered out, a smooth digital elevation model is produced. For this effort, the ground surface level and heights were measured with respect to the DEM value at a specific location.

To obtain the height information of transportation infrastructure assets, an altitude model is required in addition to DEM. The altitude model used by the team is the DSM, an elevation model containing the elevation of terrain as well as above-ground natural and built features.

Generation of DEM

There are various DEM products available to use in land surface analysis (see Figure 71 for a DEM map of the Houston-Galveston MPO region). Currently, the team uses the U.S. Geological Survey's 10-meters resolution DEM for most of its regional elevation related data analysis. The accuracy of the DEMs primarily depends on the spatial resolution of raster grid cells and the intensity of measurement points used in the DEM development. To obtain accurate and improved resolution DEM data for this Pilot Program, a new DEM was generated using the two LiDAR datasets. The spatial densities of both the LiDAR point clouds were very high, which was less than 0.5 meters. These two datasets made generating a high-resolution DEM product feasible. The primary GIS data analytical package used in this Pilot Program, ArcGIS, consists of various tools in developing DEM from LiDAR point clouds. Using a combination of spatial analysis tools in ArcGIS, a DEM with 5-meter resolution was generated.

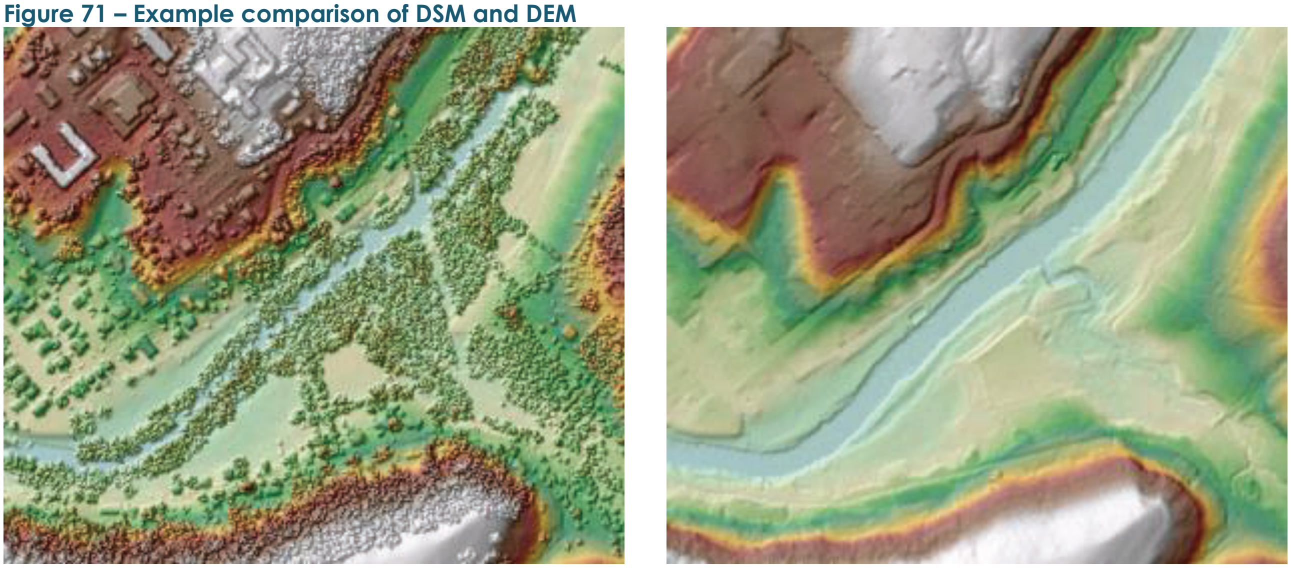
Figure 70 – DEM map of Houston-Galveston MPO region



Generation of DSM

LiDAR has become the primary technology to generate DSM data, including flood modeling. The first return of the LiDAR point cloud that reflects from the surfaces of above-ground features is often referred as the DSM. A comparison of DSM and DEM is shown in Figure 72.

Figure 71 – Example comparison of DSM and DEM



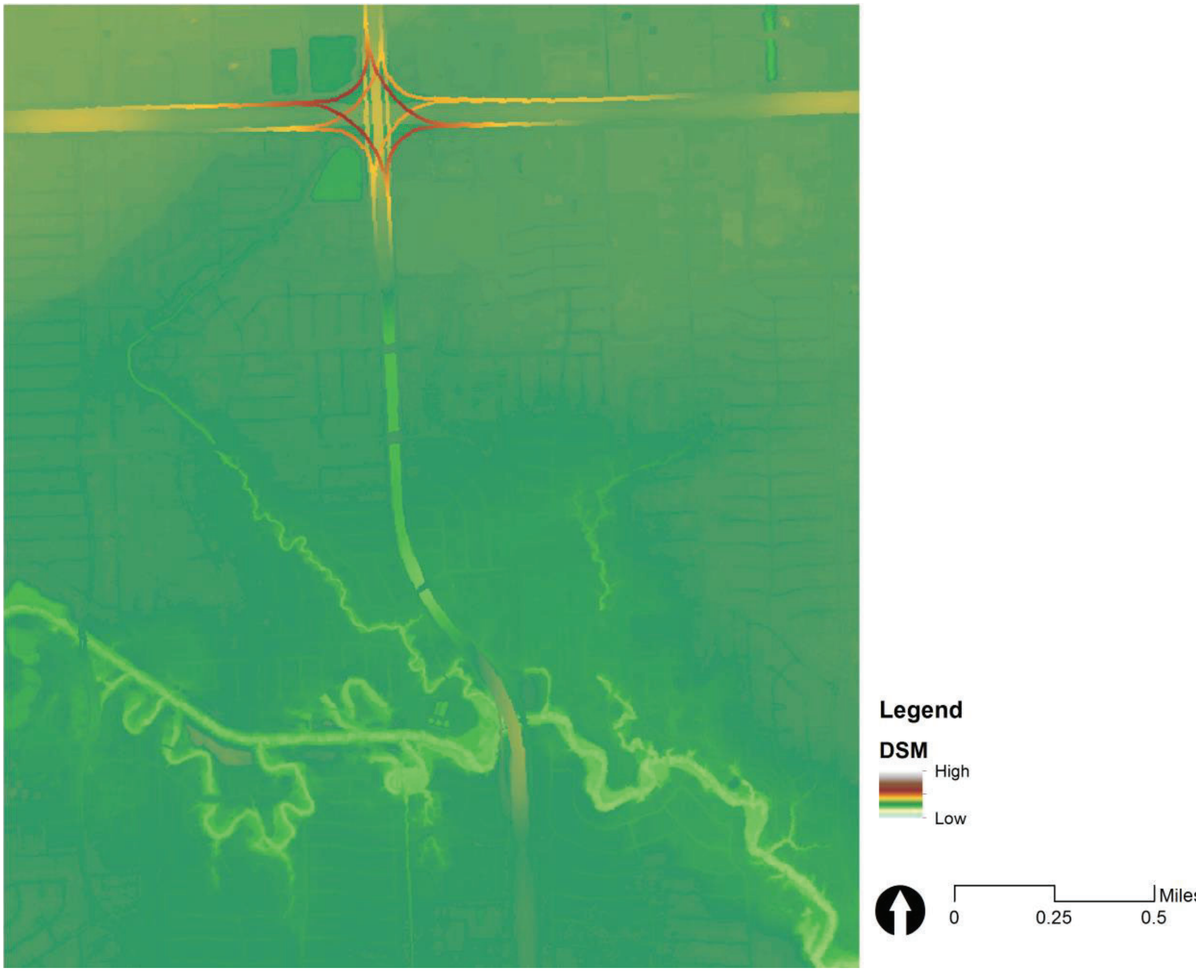
Source: ESRI

Processing LiDAR data to develop DSM for the region analyzed in this Pilot Program is a complex process requiring powerful computer processing capabilities. To avoid these processing requirements in measuring the heights of transportation assets, the team exclusively used point clouds classified into land features including roads and bridges. The point cloud classification schemes in both the LiDAR products consisted with bridges and ground classified point clouds. The Ground class included the road features. A DSM with 5-meters resolution is created only by selecting the Bridge and Ground point clouds.

The above-ground height of the bridges and road network was then estimated by subtracting the DEM value from the DSM value in overlaying pixels. The subtraction process produced a raster file with 5-meters spatial resolution where the pixel value represents the height of the infrastructures at a certain location.

Figure 73 shows the highly elevated ramps connecting Beltway 8 and Interstate 10 in dark red. It also shows the Buffalo Bayou and part of Beltway 8 South at the lowest elevation in light green.

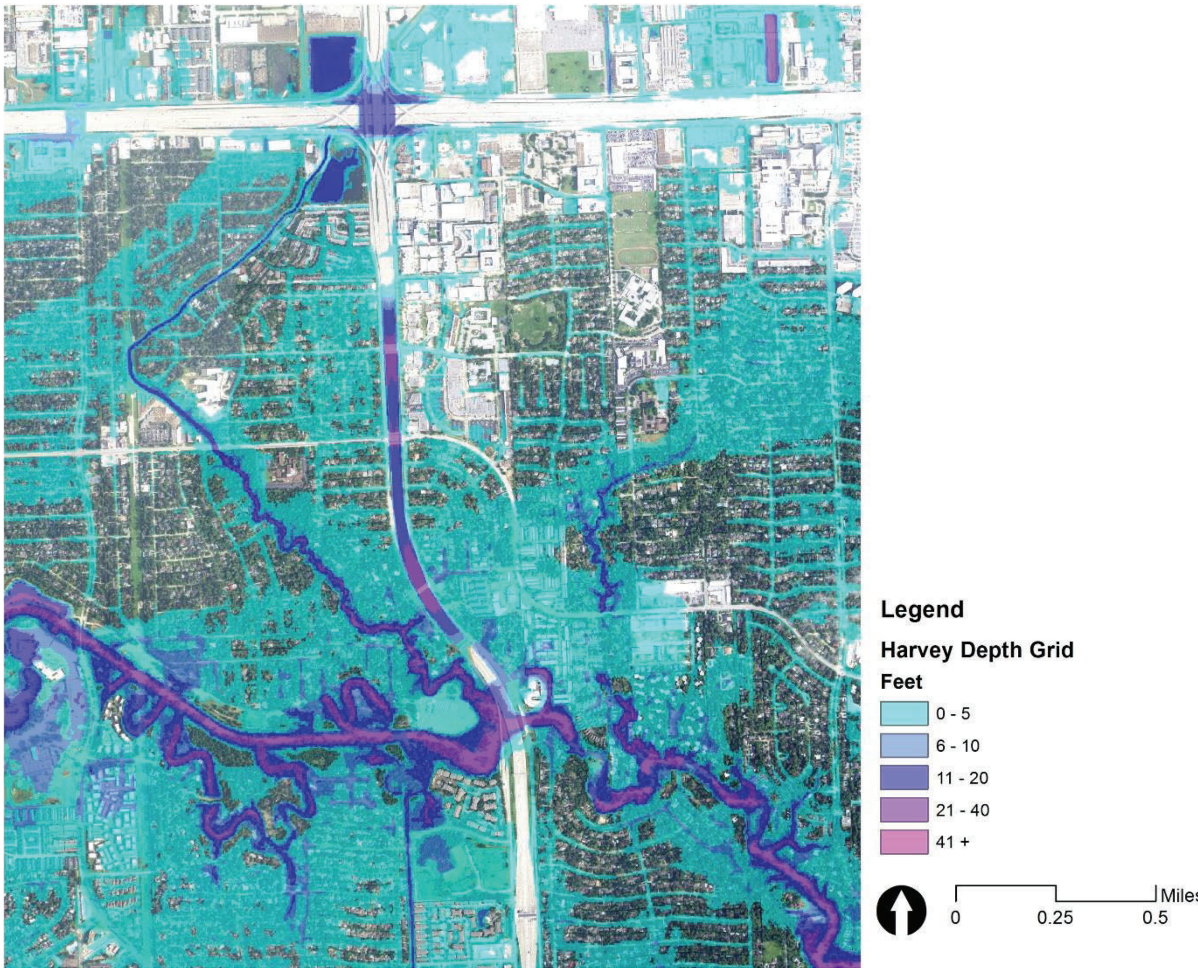
Figure 72 – Digital Surface Elevation for Bridges and Roadway Sections around IH 10 and BW 8



Depth Grid

Providing detailed information of flooding depth, probability of flooding, and other flooding characters in the form of grid datasets is one of the primary ways to communicate flood risk and inform actions that can be taken to reduce flood risks. Like pixels in an image or picture, a grid is a digital raster dataset that defines geographic space as an array of equally sized square cells arranged in rows and columns. The value in each grid represents the magnitude of flooding characteristics at a given location (Guidance for Flood Risk Analysis and Mapping, FEMA, 2018). Figure 74 shows the Harvey Depth Grid for beltway 8 at interstate 10 south.

Figure 73 – Harvey Depth Grid (BW 8 at IH-10 South)



The creation of a depth grid involves the following general steps that may be performed universally across all GIS platforms:

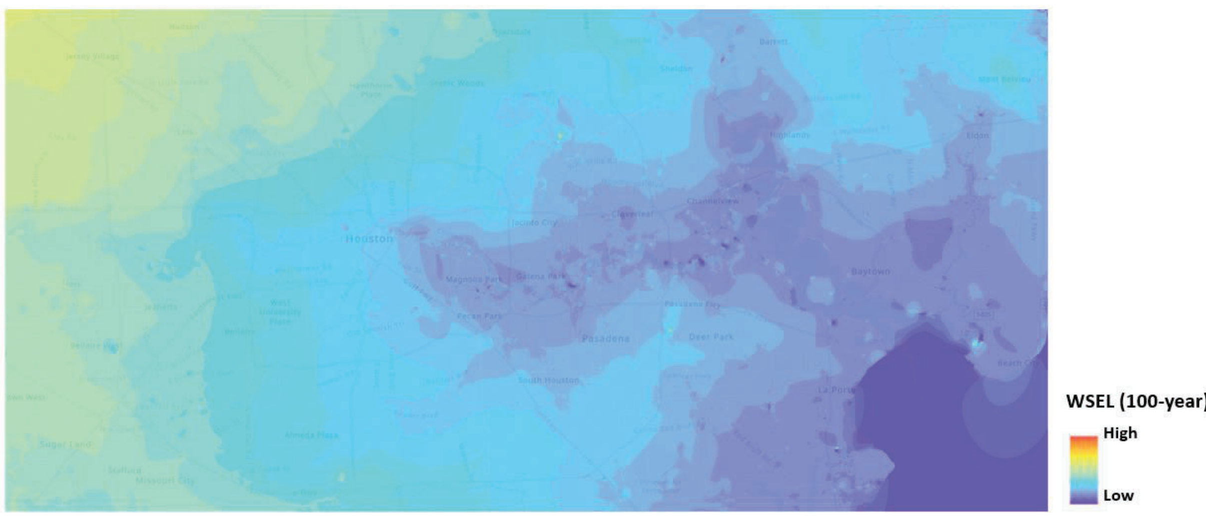
1. Develop the water surface elevation grid.
2. Develop a ground source grid using the same topographic information used in the engineering analysis to produce the flood elevations.
3. Subtract the ground elevation grid from the WSEL grid for the return period or scenario for the computation of the depth grid.
4. Remove any negative values from the resulting depth grid (by either removing the cells or setting them to depths of zero, depending on project preference and/or mapped regulatory floodplain depiction).

Water Surface Elevation Grids

The WSEL grid is generally the first raster dataset that will be produced as part of a flood risk study. A separate WSEL grid is produced for each flood event (e.g. 1% annual-chance, 0.2% annual-chance, 1% annual-chance future conditions, 1%-plus, etc.) or flood scenario for which modeled elevations are available.

Each WSEL grid provides the modeled WSEL values within the inundation extent of that flood event or scenario. The WSEL grid is the source from which many of the other raster datasets, such as the depth and percent-annual-chance grids, are generated. Figure 75 show the WSEL for 100-year flooding.

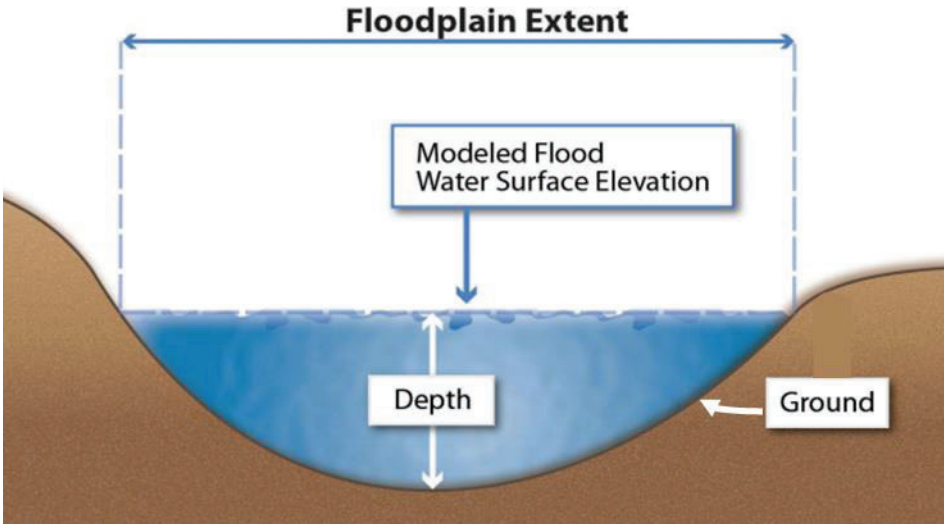
Figure 74 – WSEL for 100-year Flooding



Flood Depth Grids

In its simplest form, a flood depth grid is nothing more than the WSEL grid minus the grid representing the ground elevation using DEM. By subtracting the ground elevation value from the water surface elevation value for each return period or flood scenario, the depth values for each depth grid cell are computed. Ideally, the topographic data used for the development of any depth grid should be the same source used to generate the effective floodplain boundaries to ensure consistent and accurate results. Figure 76 shows the floodplain extent, comprised of modeled flood water surface elevation, depth, and the ground.

Figure 75 – Flood Depth (Guidance for Flood Risk Analysis and Mapping, FEMA, 2018).



Inland flood Modeling: *100- and 500-year*

Two sources of GIS data were used to create flood depth grids: FEMA flood risk maps and DEMs.

FEMA flood risk maps are developed as part of FEMA's flood hazard mapping program. FEMA identifies flood hazards, assesses flood risks, and partners with states and communities to provide accurate flood hazard and risk data to guide them to mitigation actions.

FEMA flood risk maps are derived from hydrological and hydraulic models, which translate historical spatial-temporal patterns of rainfall to hydrological processes, such as soil storage, surface run off, channel flow, and tidal information.

The development of such models is time consuming and requires specialized skills and knowledge. FEMA works with local partners, such as the Harris County Flood Control District to develop models per national guidelines, maintain the information required to validate these models, and report local flood risk maps to the federal mapping program.

Despite the complexity of the models used to generate the FEMA maps, the maps are relatively simple as they are designed to be nationally consistent and useful to a wide range of stakeholders. Primarily, the maps delineate flood zone, translated to 100- and 500-year flood risk, and the location of flood plains.

Flood Zone

Flood hazard areas identified on FEMA maps—referred to as the flood zone--are listed as a Special Flood Hazard Area (SFHA). SFHAs are the area that will be inundated by the flood event having a 1% chance of being equaled or exceeded in any given year. The 1% annual chance flood is also referred to as the base flood or 100-year flood. SFHAs are labeled as Zone A, Zone AO, Zone AH, Zones A1-A30, Zone AE, Zone A99, Zone AR, Zone AR/AE, Zone AR/AO, Zone AR/A1-A30, Zone AR/A, Zone V, Zone VE, and Zones V1-V30.

Moderate flood hazard areas, labeled Zone B or Zone X are shown in Figure 77, and are the areas between the limits of the base flood and the 0.2% annual-chance (or 500-year) flood. The areas of minimal flood hazard, which are the areas outside the SFHA and higher than the elevation of the 0.2-percent-annual-chance flood, are labeled Zone C or Zone X.

Figure 76 – FEMA Flood Map

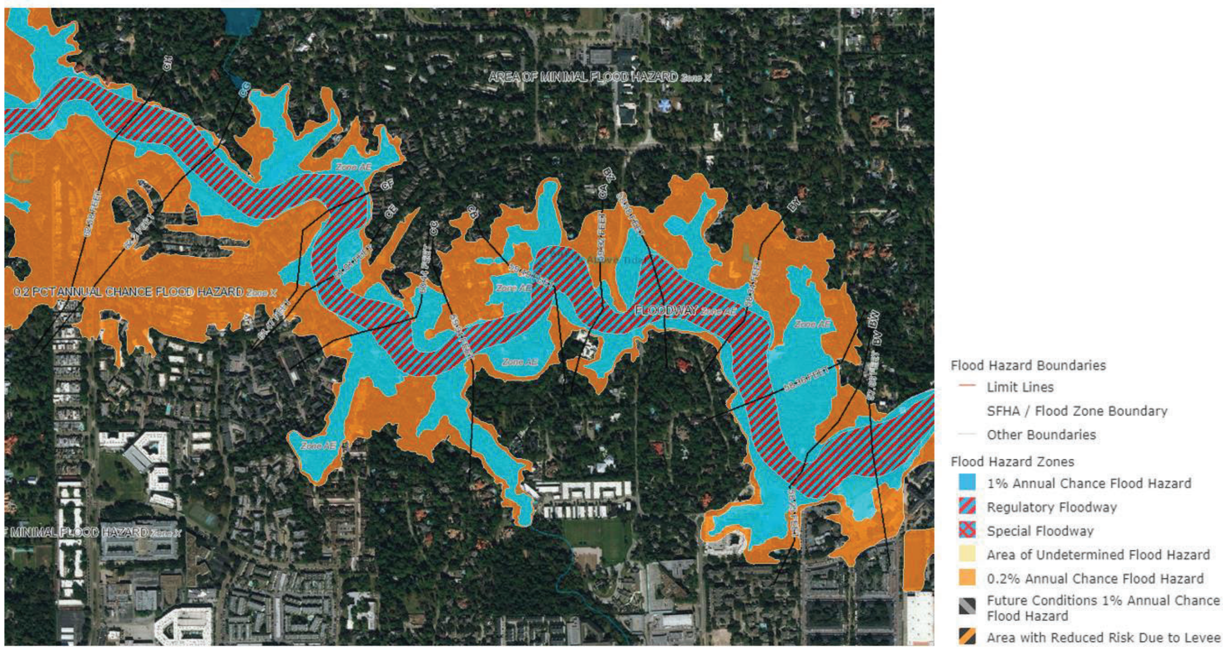


Table 10 shows the moderate to low risk areas, Table 11 shows the high-risk areas, and Table 12 shows the areas of undetermined risk.

Table 10 – Moderate to Low Risk Areas

Zone	Description
B and X	**Between the limits of the 100-year and 500-year Floodplain**, area with a 0.2% (or 1 in 500 chance) annual chance of flooding. This zone is also used to designate base floodplains of lesser hazards, such as areas protected by levees from 100-year flood, or shallow flooding areas with average depths of less than one foot or drainage areas less than 1 square mile
C and X	500-year Floodplain, area of minimal flood hazard.

Table 11 – High Risk Areas

Zone	Description
A	**100-year Floodplain**, areas with a 1% annual chance of flooding. Because detailed analyses are not performed for such areas, no depths or base flood elevations are shown within these zones.
AE A1-30	**100-year Floodplain**. The base floodplain where base flood elevations are provided. AE Zones are now used on new format FIRMs instead of A1-A30 Zones.
AH	**100-year Floodplain**, areas with a 1% annual chance of shallow flooding, usually in the form of a pond, with an average depth ranging from 1 to 3 feet. Flood elevations derived from detailed analyses are shown at selected intervals within these zones.
AO	**100-year Floodplain**, river or stream flood hazard areas, and areas with a 1% or greater chance of shallow flooding each year, usually in the form of sheet flow, with an average depth ranging from 1 to 3 feet. Average flood depths derived from detailed analyses are shown within these zones.
AR	Areas with a temporarily increased flood risk due to the building or restoration of a flood control system (such as a levee or a dam).
A99	**100-year Floodplain**, areas with a 1% annual chance of flooding that will be protected by a federal flood control

system where construction has reached specified legal requirements. No depths or base flood elevations are shown within these zones.

Table 12 – Undetermined Risk Areas

Zone	Description
D	Areas with possible but undetermined flood hazards. No flood hazard analysis has been conducted. Flood insurance rates are commensurate with the uncertainty of the flood risk.

The following analyses were conducted for FEMA flood data:

1. FEMA flood zone areas were aggregated into polygons delineating 100-year flood areas and 500-year flood areas.

2. A LiDAR-driven, 3-meter by 3-meter DEM was used to determine the elevation of the outer boundary of each polygon within the two flood risk categories. Elevations were calculated at the vertex of each flood risk polygon. This yielded a boundary representing the maximum local elevation (high-water marks) associated with 100- or 500-year flood event.

3. Flood elevation boundaries were spatially interpolated using ESRI ArcMap interpolation tool, Natural Neighbor, to provide a continuous surface of the elevation of local floodwater heights. The interpolation yielded a spatially continuous estimate of WSEL for each risk flooding event. The water surface elevations were overlaid onto the DEM to yield estimates of the flood depth relative to the underlying topography of the area. Flood depth was calculated as the difference between water surface elevation and the elevation of the underlying topography.

The algorithm used by the Natural Neighbor interpolation tool finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value. It is also known as Sibson or "area-stealing" interpolation. Its basic properties are that it's local, using only a subset of samples that surround a query point, and interpolated heights are guaranteed to be within the range of the samples used. It does not infer trends and will not produce peaks, pits, ridges, or valleys that are not already represented by the input samples. The surface passes through the input samples and is smooth everywhere except at locations of the input samples. Figures 77-81 model various FEMA data for the Houston-Galveston MPO region.

Figure 77 – FEMA Flood Zone Map for the region (2019)

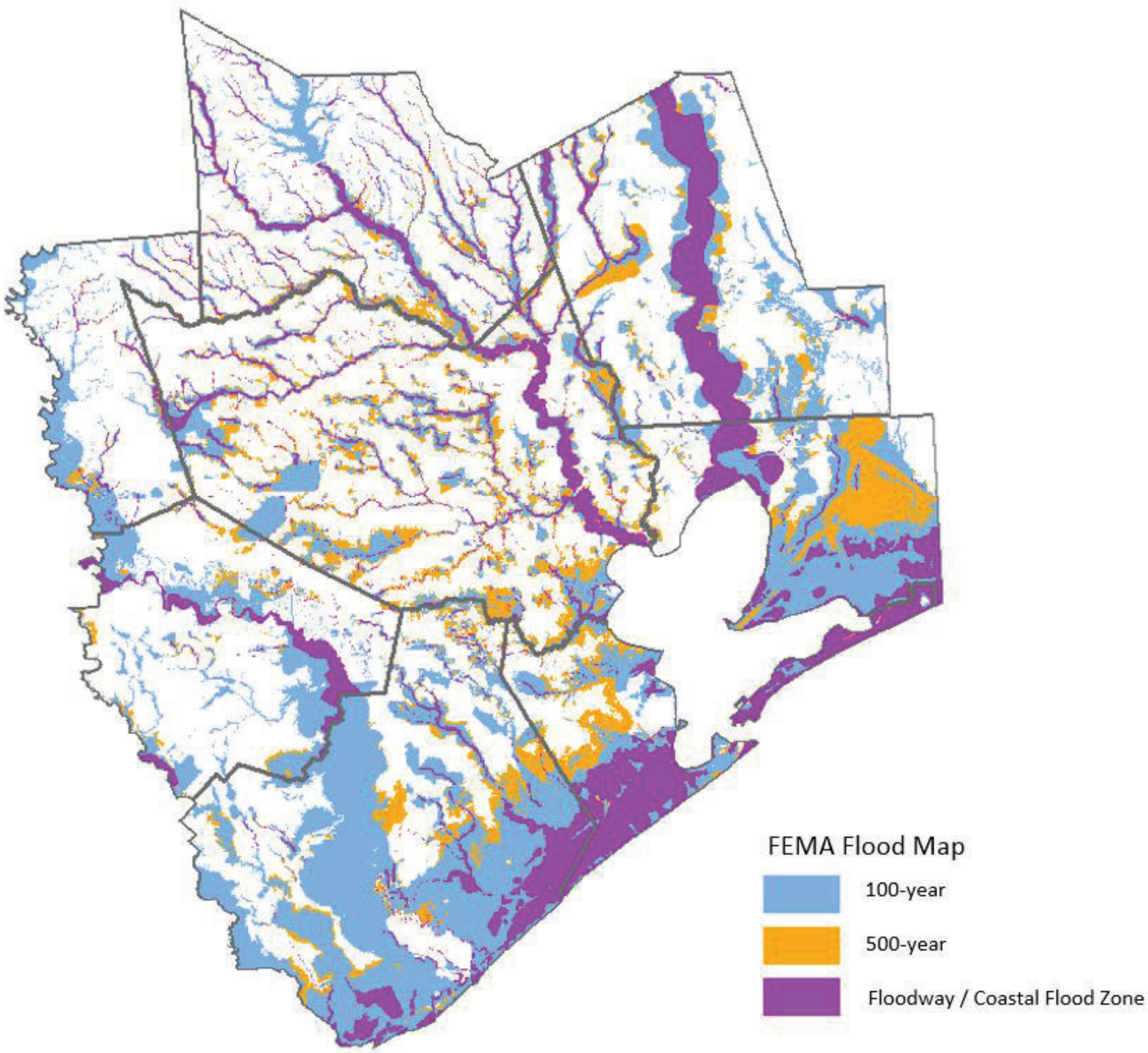


Figure 78 - 100-Year Flooding Water Surface Elevation Model (WSEL) Map for the region

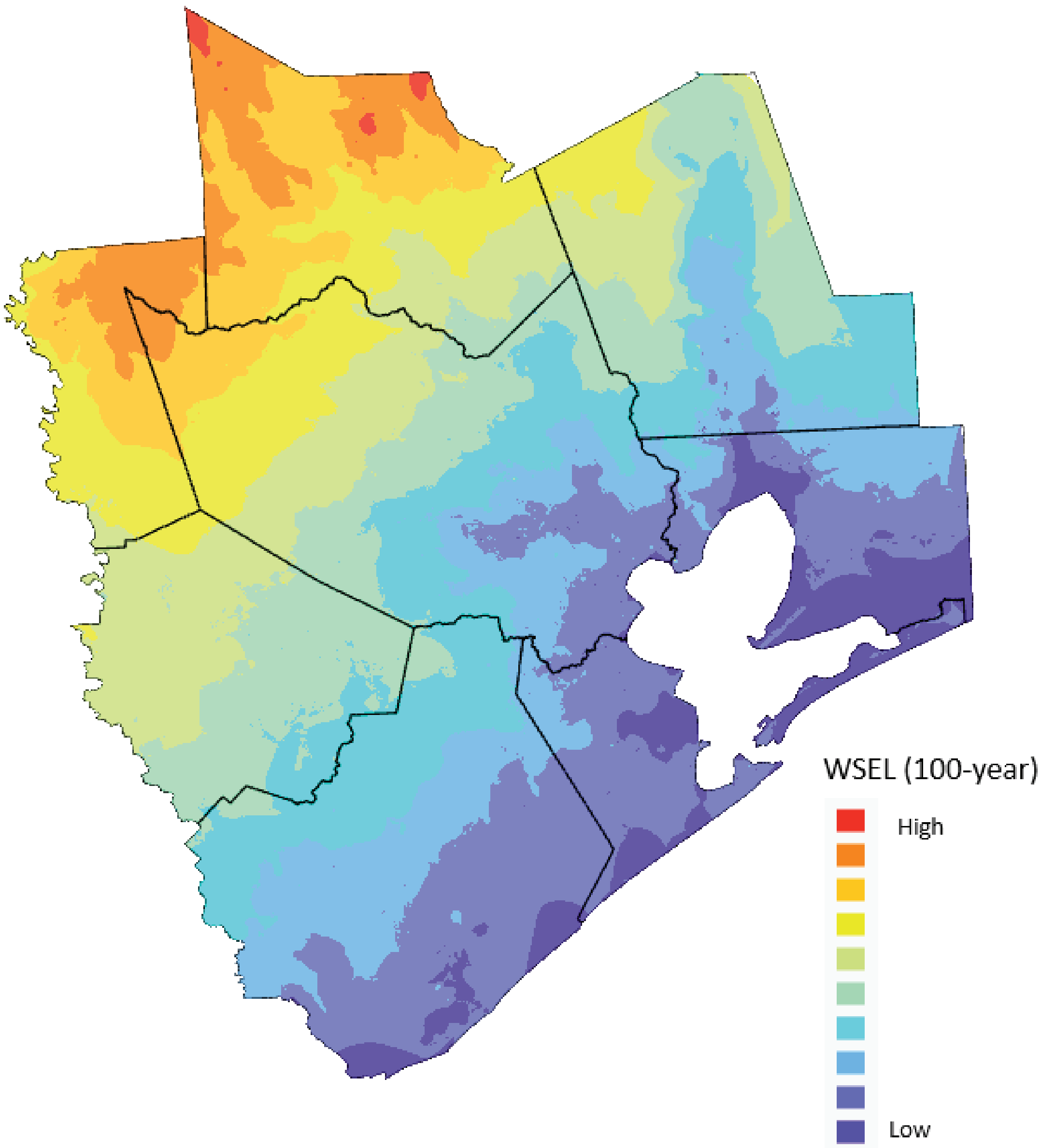


Figure 79 – 500-Year Flooding Water Surface Elevation Model (WSEL) Map for the region

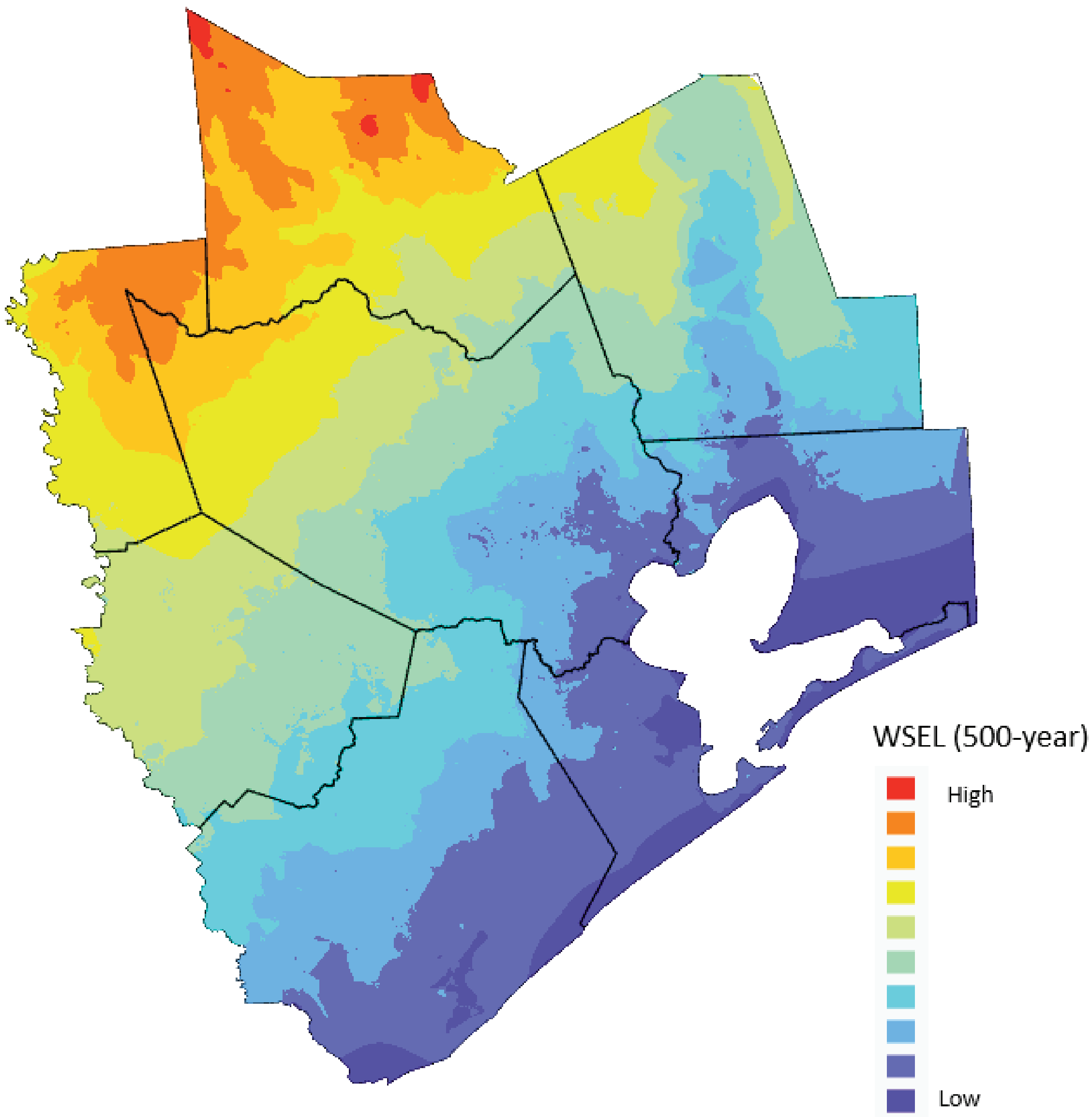


Figure 80 – 100-Year Flood Depth Grids Map for the region

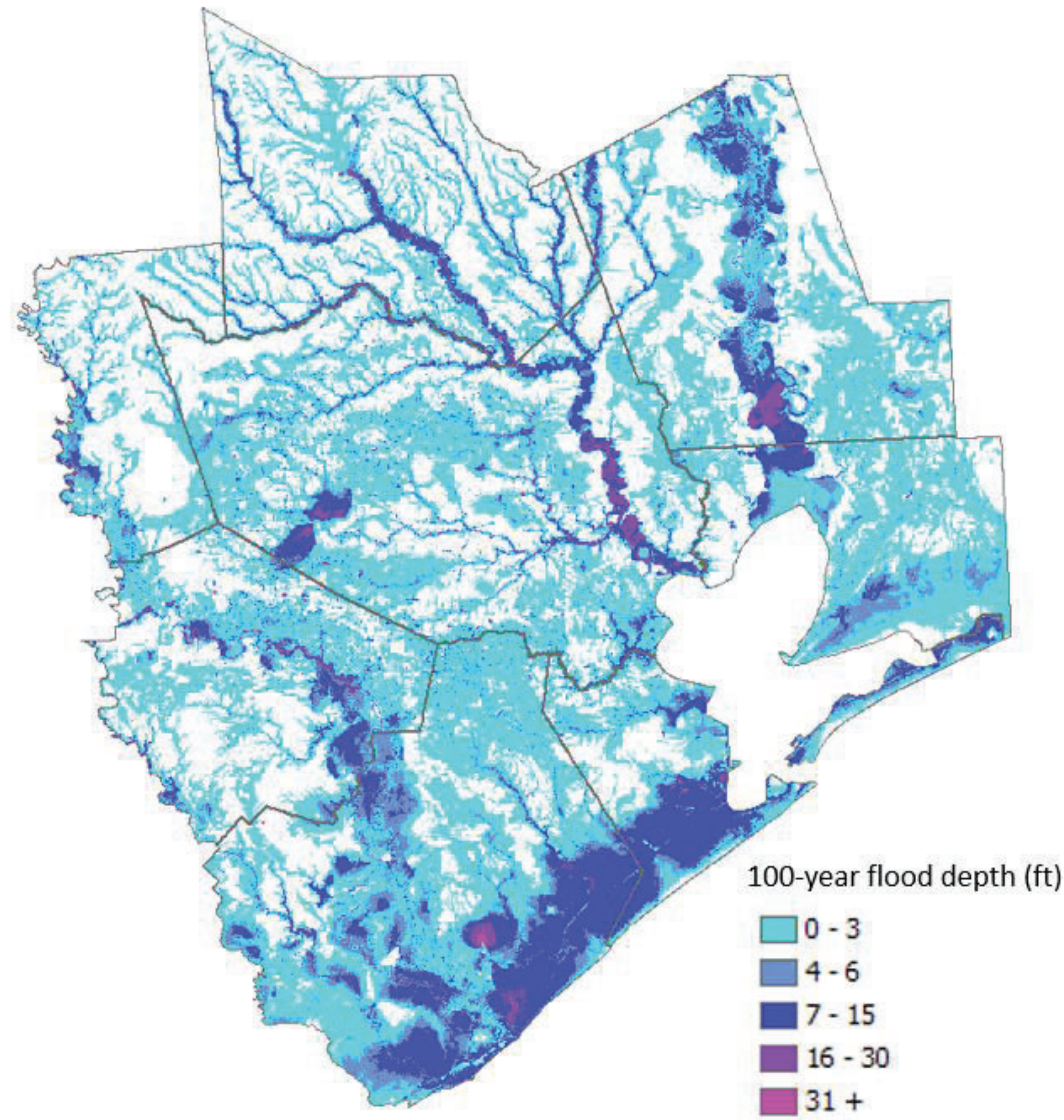
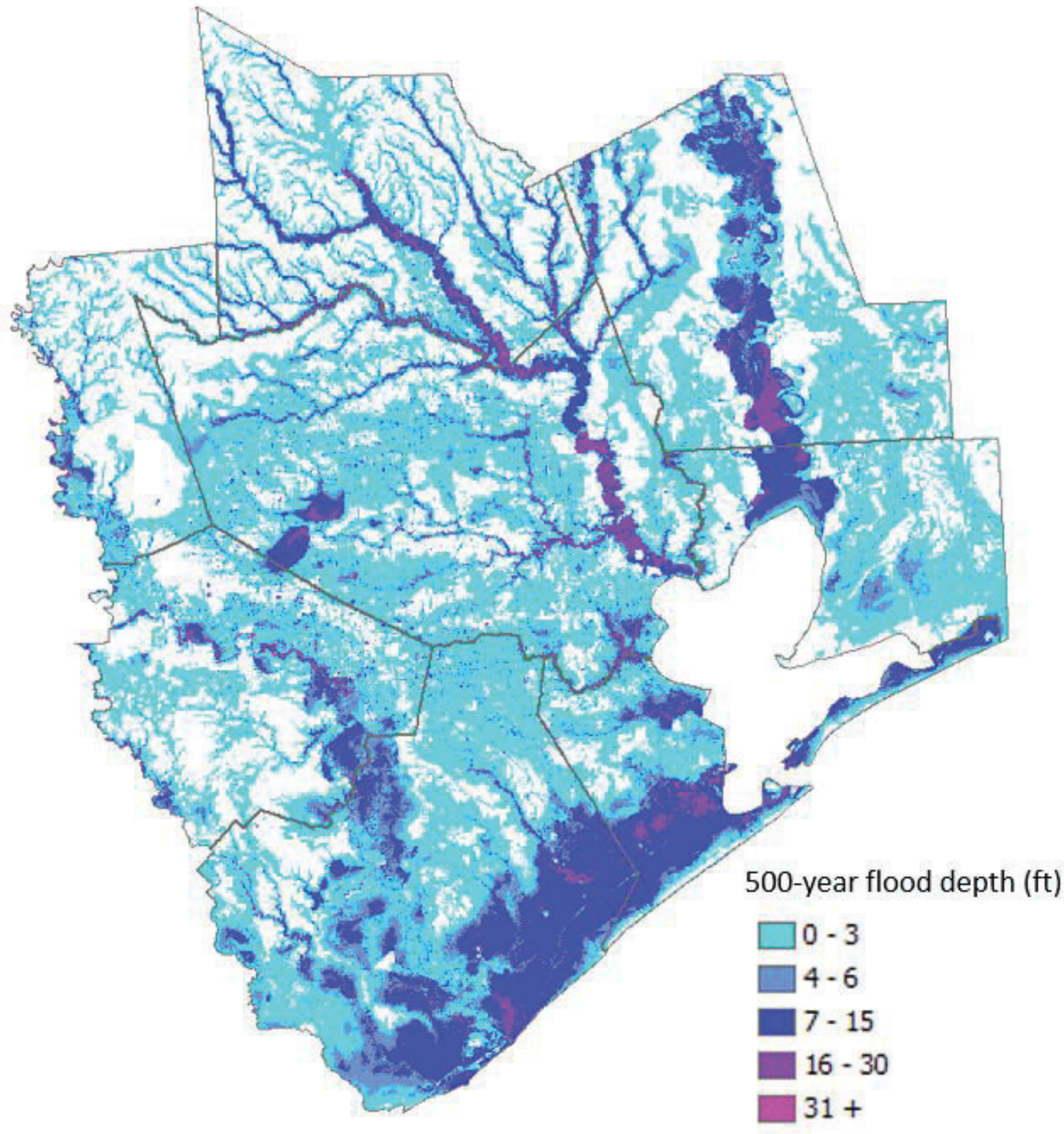


Figure 81 – 500-Year Flood Depth Grids Map for the region



Exposure Score

Exposure depth grid is a 5-by-5-meter raster grid representing flood level on top of a structure such as a roadway and bridge section. The value of exposure depth grid is equal to the difference between roadway/bridge surface elevation (DSM) and flood WSEL.

The scoring criteria for bridges are shown in Table 13. The same criteria applied to all climate stressors and scenarios. Also, the criteria apply to both grids and entire bridge structures. The scores for entire bridge segments are resulted from area-weighted summary. The results follow the same distribution and the risk classification.

Table 13 – Bridge Exposure Classification Criteria

Exposure Description	Exposure Category	Exposure Score
Water level 6+ feet below bridge deck	Not exposed/low risk	0
Water level 4-6 feet below bridge deck	Medium-low risk	1
Water level 2-4 feet below bridge deck	Medium risk	2
Water level within 2 feet below bridge deck	Medium-high risk	3
Water level above bridge deck	High risk	4

Unlike bridges, the exposure scoring criteria for roadway segments are different for different climate stressors (see Table 14 for inland flooding; coastal storm surge, Table 15 for sea-level rise). Sea level risk exposure has stricter criteria than inland flooding and coastal storm surge as it measures a permanent change in roadway functions. Also, for sea level rise, subsequent sensitivity assessment and adaptive capacity assessment are not performed as the exposed roads are likely to be permanently closed and replaced by other transportation infrastructures.

Table 14 – Roadway Exposure Classification Criteria (inland flooding; coastal storm surge)

Exposure Description	Exposure Category	Exposure Score
Not exposed/ Not flooded	Not exposed/low risk	0
0-1 foot of flood water	Medium-low risk	1
1-2 feet of flood water	Medium risk	2
2-3 feet of flood water	Medium-high risk	3
More than 3 feet of flood water	High risk	4

Table 15 – Roadway Exposure Classification Criteria (sea level rise)

Exposure Description	Exposure Category	Exposure Score
Not exposed/ Water level 3+ feet below	Not exposed/ low risk	0
Water level 2-3 feet below	Medium-low risk	1
Water level 1-2 feet below	Medium risk	2
Water level within 1 foot below	Medium-high risk	3
Water level above road	High risk	4

The aggregation procedure for roadway segments is different from that for bridges. Other than area-weighted aggregation, an additional centerline distance-based aggregation is conducted to address the issue associated with the length of the segments. The distance-based aggregation only captures the high-risk portions of a road segment (for freeways, high-risk portions of less than 300 feet are discarded and the aggregation scores are then rank-normalized to a 0-4 scale; for major roads, high-risk portions of less than 20 feet are discarded and the aggregation scores are normalized to a 0-4 scale, but not ranked). The final exposure score for road segments is the average of the area-weighted aggregation score and distance-weighted aggregation score. The final score ranges from 0 to 4 and follows the same risk classification criteria.

Sensitivity assessment

To assess the sensitivity of each transportation asset, the team selected a list of indicators related to assets' structure strength, maintenance conditions, and past closures and created a composite score. For bridges, four sensitivity indicators are selected and weights for these indicators are different for inland flooding and coastal storm surge, due to the different natures of the two climate exposures.

The data of all indicators come from the TxDOT Bridge Inventory database, in which evaluation and condition scores are already available (see Table 16).

Table 16 – Bridge Sensitivity Indicators and Scoring Criteria

Indicator	Weight (Inland Flooding)	Weight (Storm Surge)	Sensitivity Classification	Criteria	Sensitivity Score	Data Source	Criteria Justification
Bridge Age	5%	10%	Low	Age 1-10	0	TxDOT Bridge Inventory	TxDOT Texas Transportation Asset Management Plan
			Medium-Low	Age 11-25	1		
			Medium	Age 26-40	2		
			Medium-High	Age 41-60	3		
			High	Age 61+	4		
Structural Evaluation	30%	35%	Low	Score=9 Superior condition	0		
			Medium-Low	Score in (7, 8) Desirable condition	1		
			Medium	Score in (5, 6) - min satisfying condition	2		
			Medium-High	Score=4 Meets criteria	3		
			High	Score < 4 - condition below standard	4		
Channel Conditions	35%	20%	Low	Score in (8, 9) - good condition, well-protected	0		
			Medium-Low	Score = 7 minor repairs needed	1		

			Medium	Score in (5, 6) - minimum satisfying condition	2		
			Medium-High	Score = 4 protection is severely undermined	3		
			High	Score < 4 bank protection has failed	4		
Scour Ratings	30%	35%	Low	Score in (8, 9) - good condition	0		TxDOT Texas Transportation Asset Management Plan
			Medium-Low	Score=7 Countermeasure	1		
			Medium	Score in (5, 6) - minimum satisfying condition	2		
			Medium-High	Score = 4 action required to protect exposed foundation	3		
			High	Score < 4 - scour critical bridges	4		

For road segments, weights are the same across all exposure categories (see Table 17). Both indicators are rom TxDOT, yet they are only available to a subset of road segments (TxDOT OnSystem Roadway). For the remaining road segments, sensitivity assessment is skipped and not included in the final vulnerability score calculation.

Table 17 – Road Sensitivity Indicators and Scoring Criteria

Indicator	Weight	Sensitivity Classification	Criteria	Sensitivity Score	Data Source
Pavement Condition	40%	Low	Pavement condition score: [90, 100]	0	TxDOT Pavement Condition Information System
		Medium-Low	Pavement condition score: [75, 90)	1	
		Medium	Pavement condition score: [50, 75)	2	
		Medium-High	Pavement condition score: [35, 50)	3	
		High	Pavement condition score: [0, 35)	4	
Past Closure	60%	Low (Never Closed)	Never Closed	0	TxDOT DriveTexas Transportation Record System
		Medium-Low	Single record of closure due to flooding	1	
		Medium	2-5 times of closure	2	
		Medium-High	6-9 times of closure	3	
		High	10+ times of closure	4	

Adaptive Capacity Assessment

Adaptive capacity indicates how well the regional transportation system can weather or recover from the service disruption. Two main aspects of adaptive capacity are examined in the analysis: network redundancy and repair cost. Since adaptive capacity is assessed in a post-disruption situation, the criteria are the same for all climate stressors and scenarios. Table 18 shows the adaptive capacity indicators and scoring criteria for bridges. Table 19 shows the adaptive capacity indicators and scoring criteria for road segments.

Table 18 – Bridge Adaptive Capacity Indicators and Scoring Criteria

Indicator	Weight	Criteria	Score	Data source
Detour Length	80%	1-2 miles	4	TxDOT Bridge Inventory
		3-4 miles	3	
		5-7 miles	2	
		7-10 miles	1	
		10+ miles/No detour	0	
Repair Cost	20%	Scored as low repair cost TxDOT	4	Expert opinions from TxDOT engineers
		Scored as medium repair cost by TxDOT	2	
		Scored as high repair cost by TxDOT	0	

Table 19 – Road Segment Adaptive Capacity Indicators and Scoring Criteria

Indicator	Weight	Criteria	Score	Data source
Detour Length	80%	1st ratio category in criticality results	4	GIS transportation network analysis by the team
		2nd ratio category in criticality results	3	
		3rd ratio category in criticality results	2	
		4th ratio category in criticality results	1	
		No detour (for major roads only)	0	
Repair Cost	20%	Scored as low repair cost by TxDOT	4	Expert opinions from TxDOT engineers
		Scored as medium repair cost by TxDOT	2	
		Scored as high repair cost by TxDOT	0	

Vulnerability assessment

The vulnerability score is a weighted summary of exposure score, sensitivity score, and adaptive capacity score (see Table 20). Different weights are given to different components of vulnerability based on importance and data availability.

Table 20 – Vulnerability Score Weighting Criteria

Asset Type	Climate Stressor	Exposure	Sensitivity*	Adaptive capacity¶
Bridge	Inland flooding	70%	20%	10%
Bridge	Storm surge	70%	25%	5%
Freeway	Inland flooding	80%	5%	15%
Freeway	Storm surge	80%	5%	15%
Major road	Inland flooding	80%	5%	15%
Major road	Inland flooding	80%	N/A	20%
Major road	Storm surge	80%	5%	15%
Major road	Storm surge	80%	N/A	20%

**For most major road segments sensitivity indicators are not provided by TxDOT, consequently the sensitivity scores are not applicable. Scores are applied for the major roads with sensitivity indicator information.*

¶Adaptive capacity scores need to be reversed as a low adaptive capacity contributes to a higher vulnerability.

Since scores of each category are scaled from 0 to 4, the aggregated vulnerability score would also range from 0 to 4. For each asset type, the team cumulatively normalized the score into a scale of 0 to 1, with 1 indicating the highest vulnerability.

In the assessment of vulnerability to sea level rise, exposure scores are directly used to represent overall vulnerability. Unlike roads exposed to inland flooding and coastal storm surge that can recover from the disruptions, roads exposed to sea level rise are more likely to be permanently dysfunctional. Therefore, if an asset is inundated by rising sea water, subsequent assessments on its sensitivity and adaptive capacity are no longer meaningful.

Some additional adjustments are applied to the calculation of vulnerability score. Since most inland transportation assets are not exposed to coastal storm surge, their vulnerability index would remain zero for coastal storm surge exposures, regardless of their sensitivity and adaptive capacity attributes. Figures 82 - 90 show flood risk for transportation assets in multiple event types.

Figure 82 – Flooding risk: 500-year flooding event - Roads

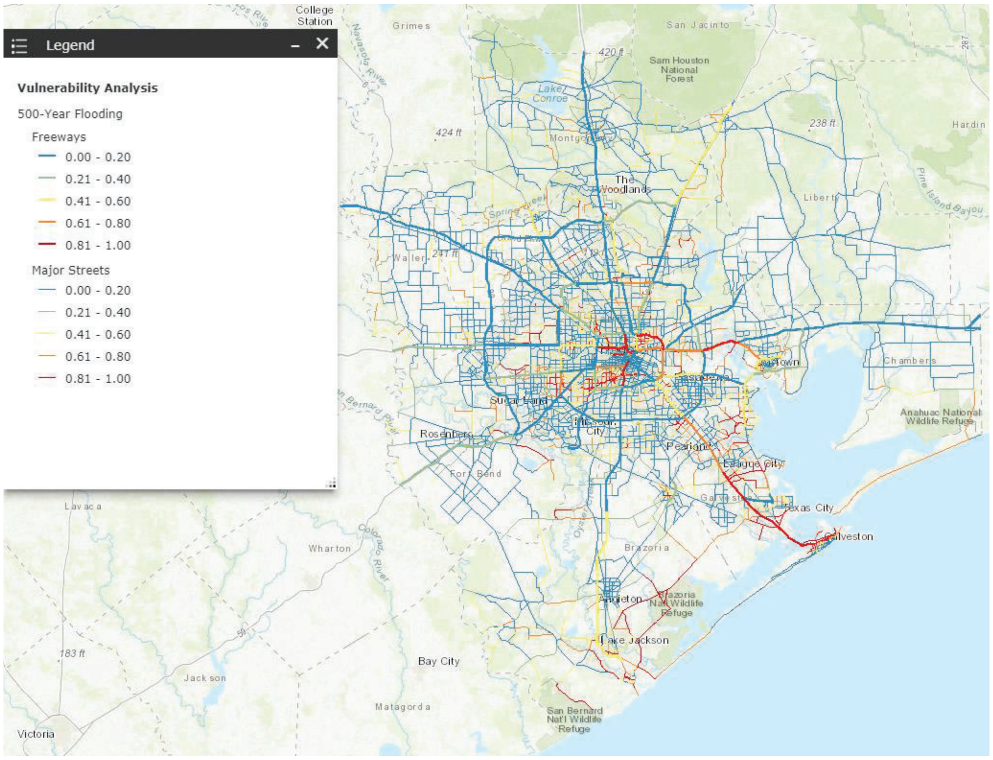


Figure 83 – Flooding risk: 500-year flooding event - Bridges

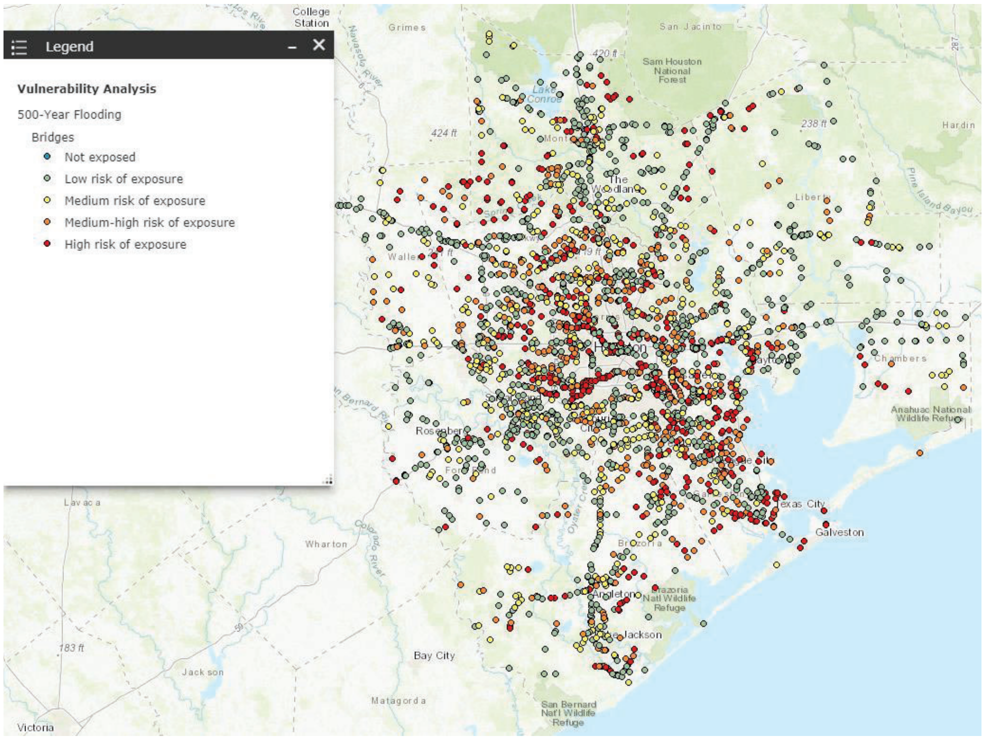


Figure 84 – Flooding risk: Hurricane Harvey -Roads

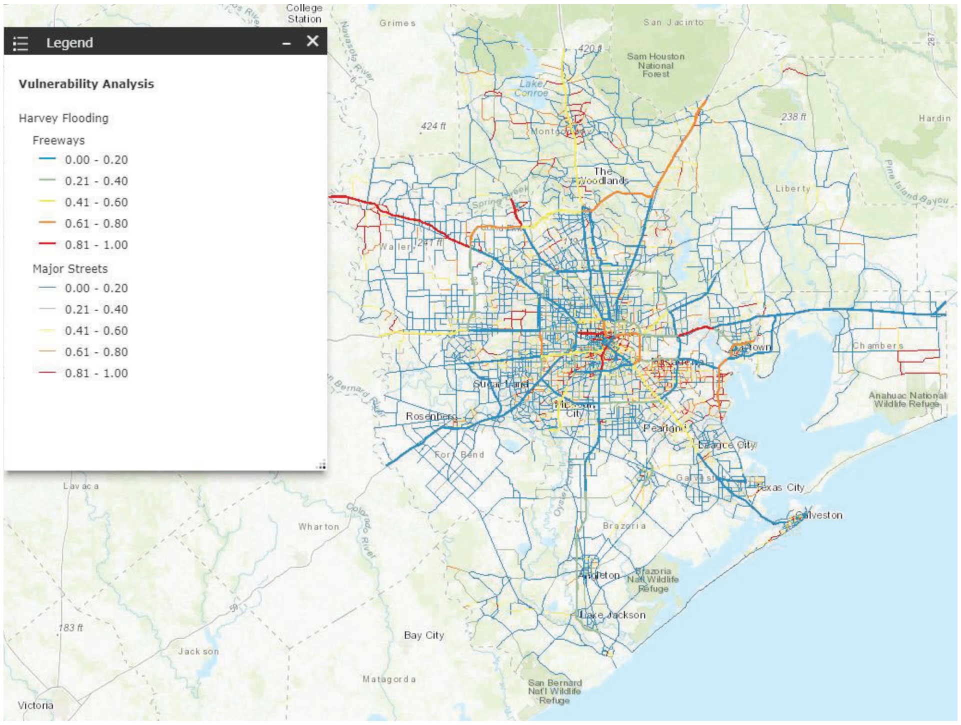


Figure 85 – Flooding risk: Hurricane Harvey -Bridges

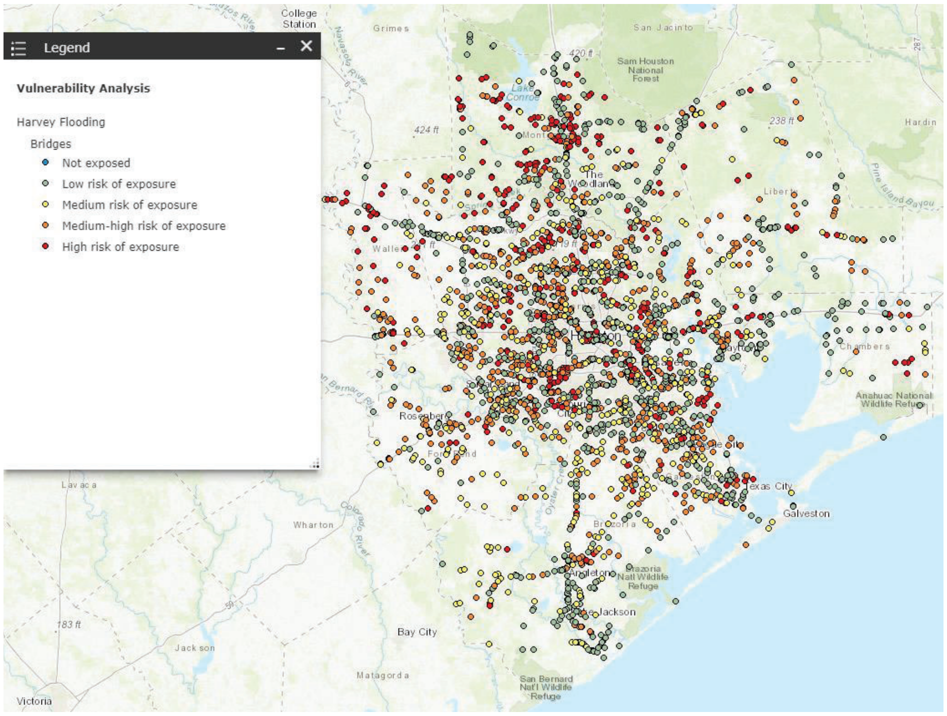


Figure 86 – Storm surge risk: Category 4 storm - Roads

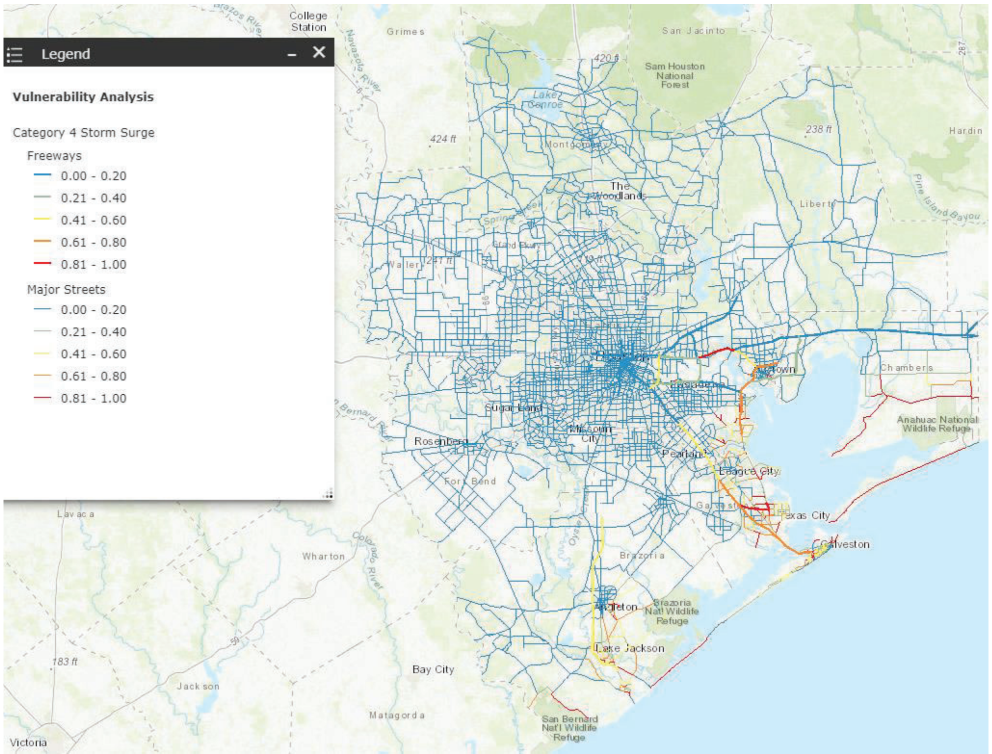


Figure 87 – Storm surge risk: Category 4 storm - Bridges

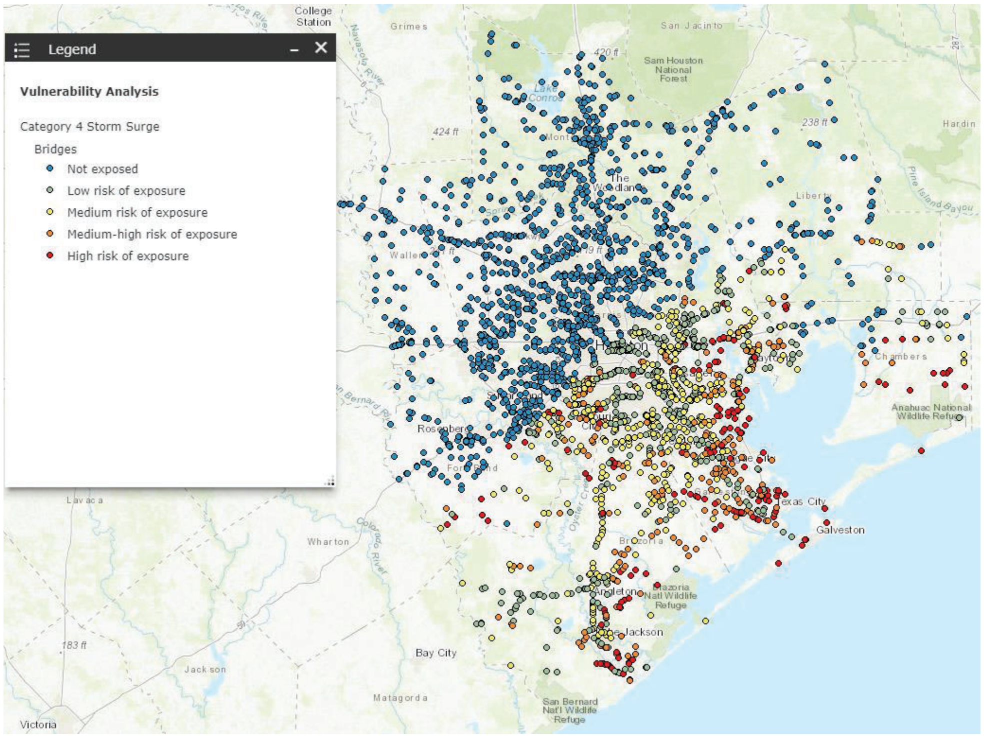


Figure 88 - Storm surge risk: Hurricane Ike - Roads

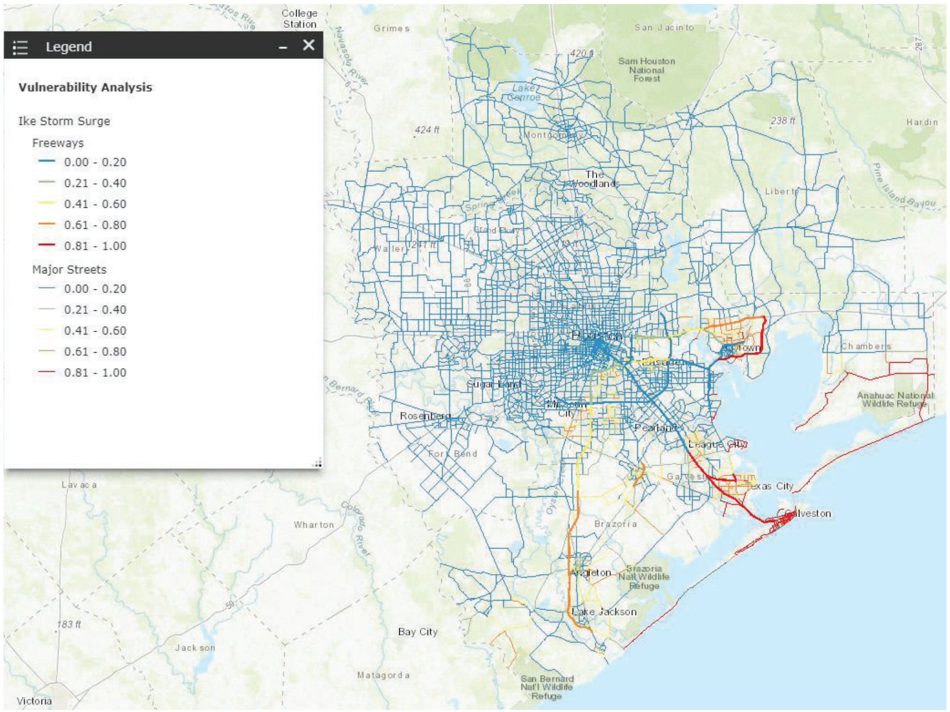


Figure 89 – Storm surge risk: Hurricane Ike - Bridge

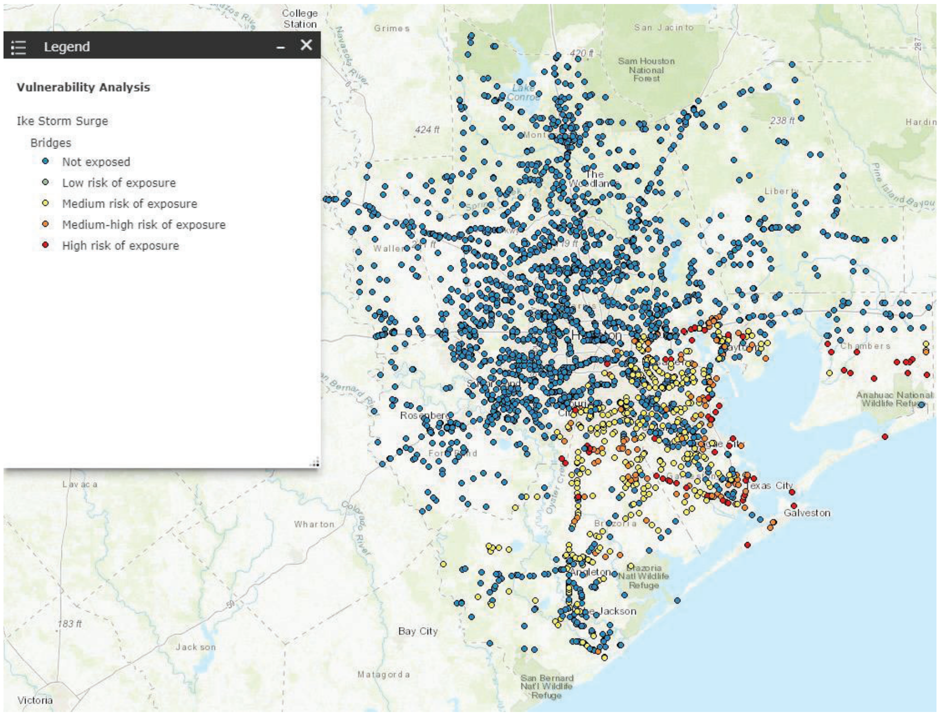
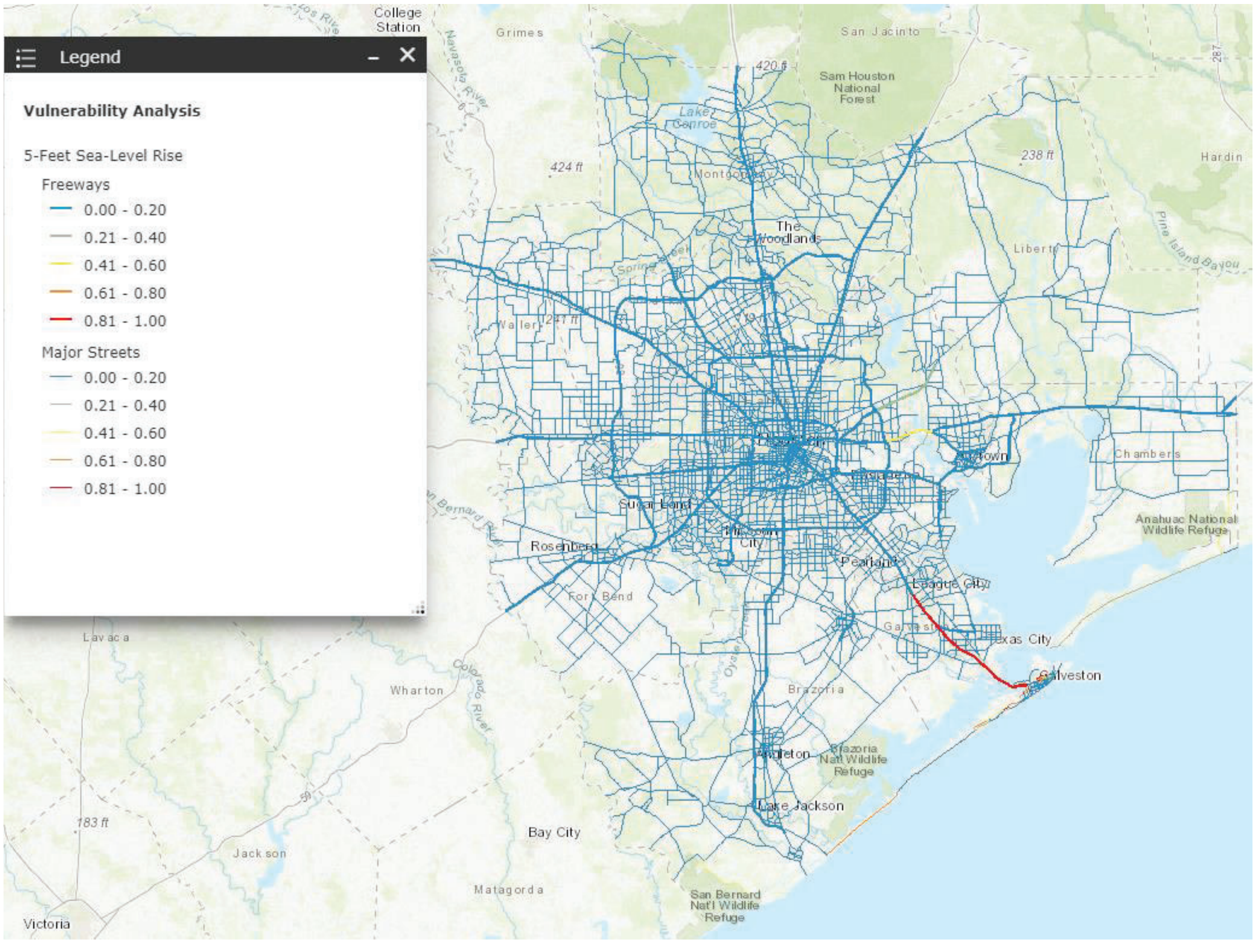


Figure 90 – Sea level rise risk: 5-feet sea level rise - Roads



APPENDIX C: ECONOMIC IMPACT ANALYSIS SCENARIO SELECTION PROCESS

Economic Impact Analysis Scenario 1: Interstate 10 San Jacinto Bridge

The segment is between Magnolia Street and Independence Parkway/S Main Street in the northeast Harris County. This segment is highly vulnerable to flooding and storm surge exposures. The segment is also highly critical to the region's transportation system as it holds a large amount of the region's truck traffic, supporting the Houston Ship Channel freight network. It is also part of the evacuation route and the national strategic highway system. Around 38% of freeway segment is highly vulnerable to Category 4 storm surge, and 45% is highly vulnerable to Category 5 storm surge.

Figures 91 – 94 present various flooding scenarios for the segments specified above. Figure 95 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 91 – Economic Impact Analysis Scenario 1-Hurricane Harvey Flooding

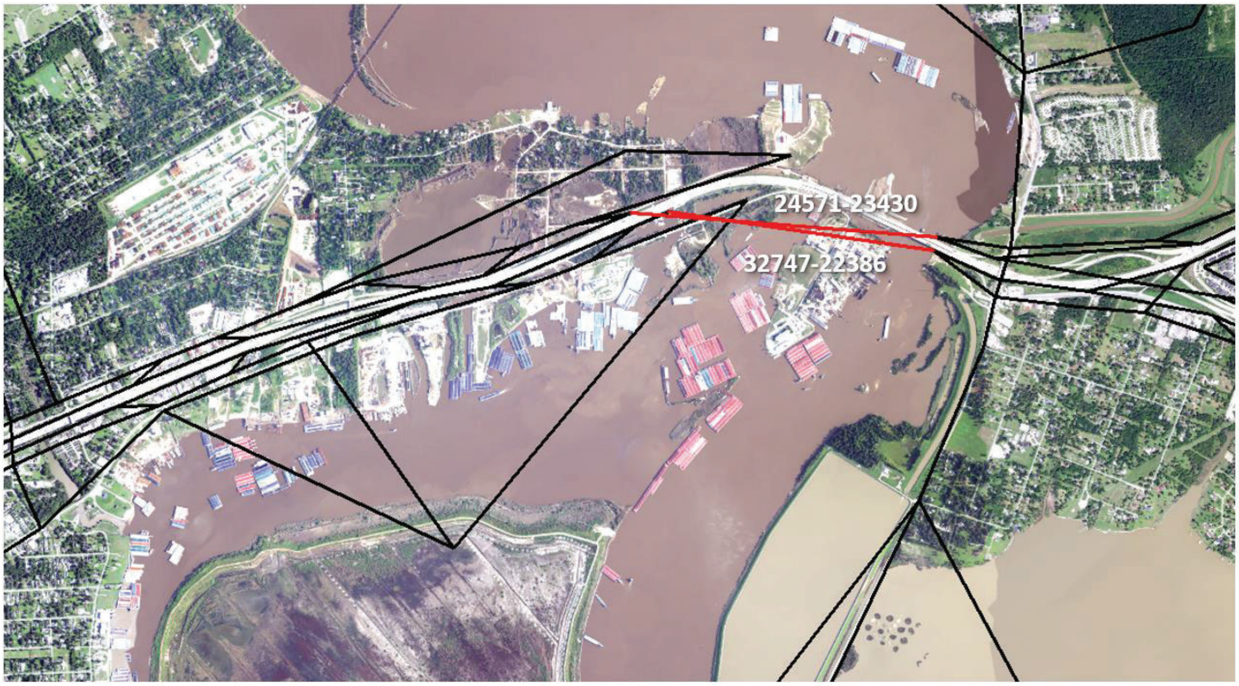
Figure 92 – Economic Impact Analysis Scenario 1-500-Year Flooding

Figure 93 –Economic Impact Analysis Scenario 1-Hurricane Ike Storm Surge

Figure 94 – Economic Impact Analysis Scenario 1-Category 4 Hurricane Surge

Figure 95 – Economic Impact Analysis Scenario 1-TDM Network

Link ID: 24571-23430 & 32747-22386



Economic Impact Analysis Scenario 2: Gulf Freeway (South and North Access to Galveston Causeway)

Gulf Freeway marks the southern end of Interstate 45 and provides access to the Galveston Island. Although the bridge segment (i.e., Causeway Bridge) is not vulnerable to climate stressors, roads at both ends of the bridge are highly vulnerable to flooding, especially to coastal storm surge. This segment has an extremely low adaptive capacity as there are no immediate alternative roads once the asset is disrupted or closed. Around 53% of miles in this segment are highly vulnerable to Category 4 storm surge; for Category 5, the percentage is 75%.

Figures 96 – 100 present various flooding scenarios for the segments specified above. Figure 101 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 96 – Economic Impact Analysis Scenario 2-Hurricane Harvey Flooding

Figure 97 – Economic Impact Analysis Scenario 2-500-Year Flooding

Figure 98 – Economic Impact Analysis Scenario 2-Hurricane Ike Storm Surge

Figure 99 – Economic Impact Analysis Scenario 2-Category 4 Hurricane Storm Surge

Figure 100 – Economic Impact Analysis Scenario 2-5-Feet Sea-Level Rise

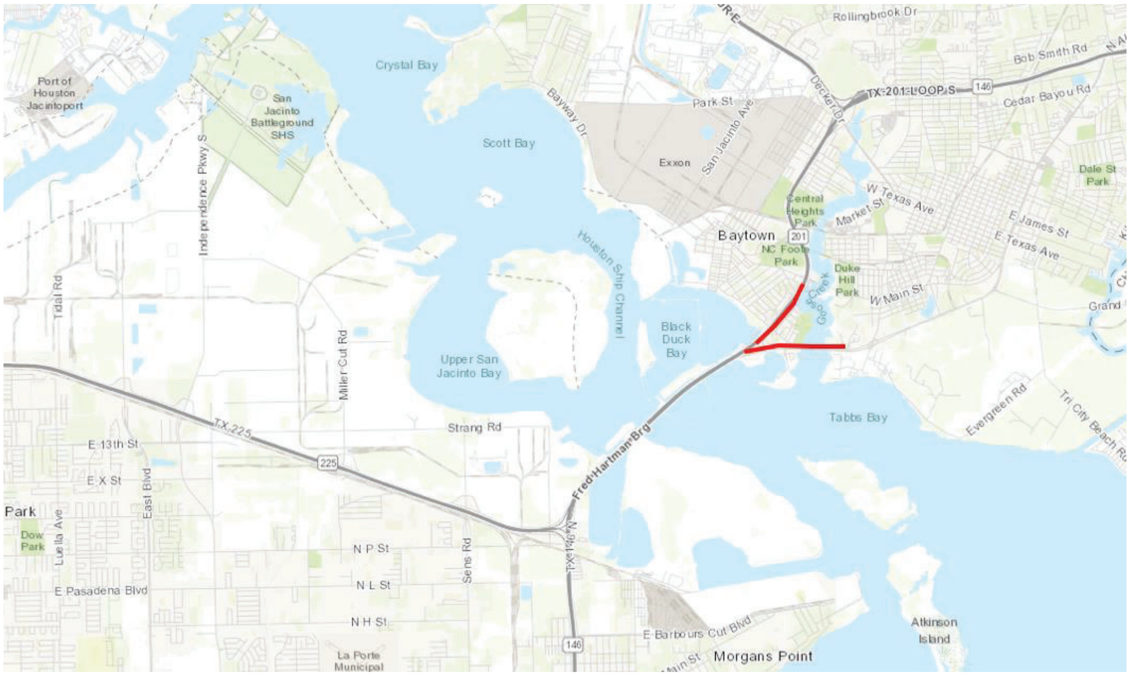
Figure 101 – Economic Impact Analysis Scenario 2-TDM Network

Link ID: 26499-37019, 29438-26498, 29734-29905, 29734-29925, 29735-37020, 29906-26499, 29924-29735, 29926-29735, 37019-29734, 37020-29438

Economic Impact Analysis Scenario 3: State Highway 146 (North Access to Fred Hartman Bridge)

State Highway 146 and State Highway 146B, providing access to Fred Hartman Bridge are highly vulnerable to 500-year flooding events and to Category 4 storm surge. The segments provide vital access and linkage to several industrial facilities. For the State Highway 146 segment, around 23% of miles are highly vulnerable to Hurricane Harvey flooding and 45% are highly vulnerable to Category 5 storm surge. Figure 102 shows Segment 3.

Figure 102 – State Highway 146 (North Access to Fred Hartman Bridge)



Figures 103 – 106 present various flooding scenarios for the segments specified above. Figure 107 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 103 – Economic Impact Analysis Scenario 3-Hurricane Harvey Flooding

Figure 104 – Economic Impact Analysis Scenario 3-500-Year Flooding

Figure 105 – Economic Impact Analysis Scenario 3-Category 4 Hurricane Storm Surge

Figure 106 – Economic Impact Analysis Scenario 3-Hurricane Ike Storm Surge

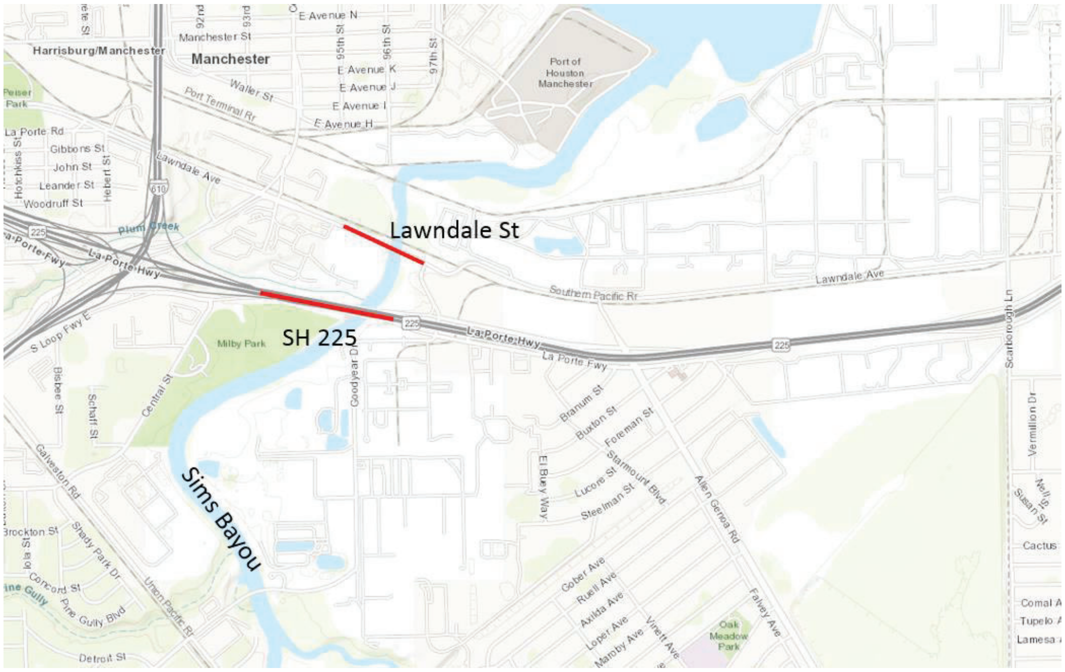
Figure 107 – Economic Impact Analysis Scenario 3-TDM Network

Link ID: 22383-20784 & 27244-22382

Economic Impact Analysis Scenario 4: State Highway 225 (Pasadena Freeway)/Lawndale Street

State Highway 225 (Pasadena Freeway) and Lawndale Street between Allen Genoa and Interstate 610 over Sims Bayou are high-risk. Given the segment's proximity to Sims Bayou and Buffalo Bayou, the segment is highly vulnerable to flooding and storm surge. The segment provides important linkage to industrial sites in southeastern Houston and several cities in the Houston metropolitan area. Only 8% of this road segment is highly vulnerable to Hurricane Harvey flooding and 15% is vulnerable to Category 5 storm surge. However, for the Lawndale Street segment, 57% is highly vulnerable to 500-year flooding event and 76% to Category 5 storm surge. Figure 108 shows Segment 4.

Figure 108 – State Highway 225 (Pasadena Freeway)/Lawndale Street



Figures 109 – 111 present various flooding scenarios for the segments specified above. Figure 112 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 109 – Economic Impact Analysis Scenario 4-Hurricane Harvey Flooding

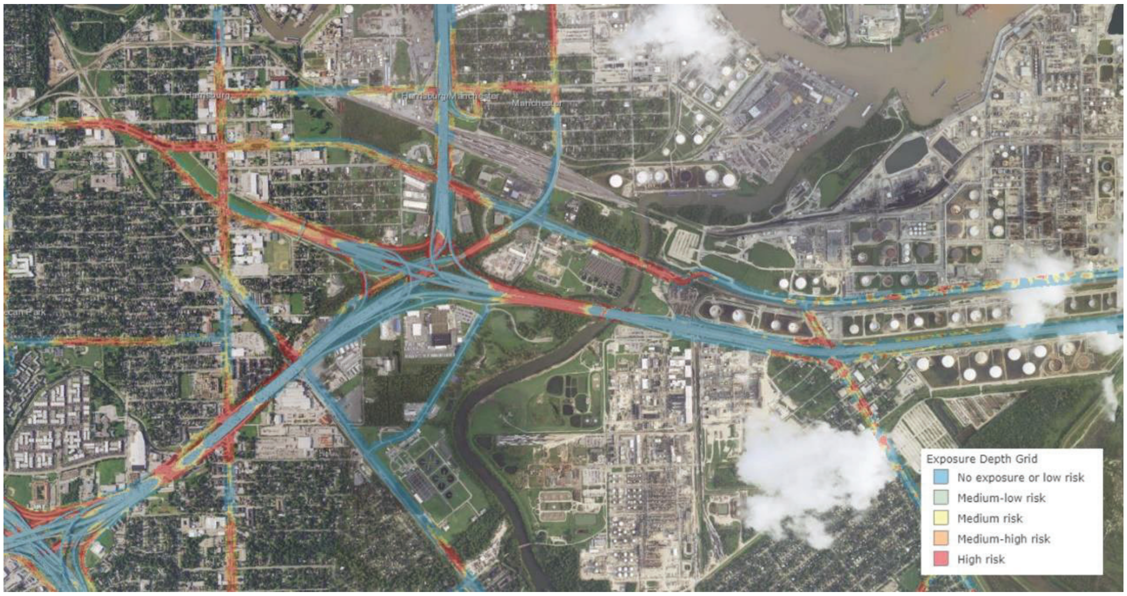


Figure 110 – Economic Impact Analysis Scenario 4-500-Year Flooding

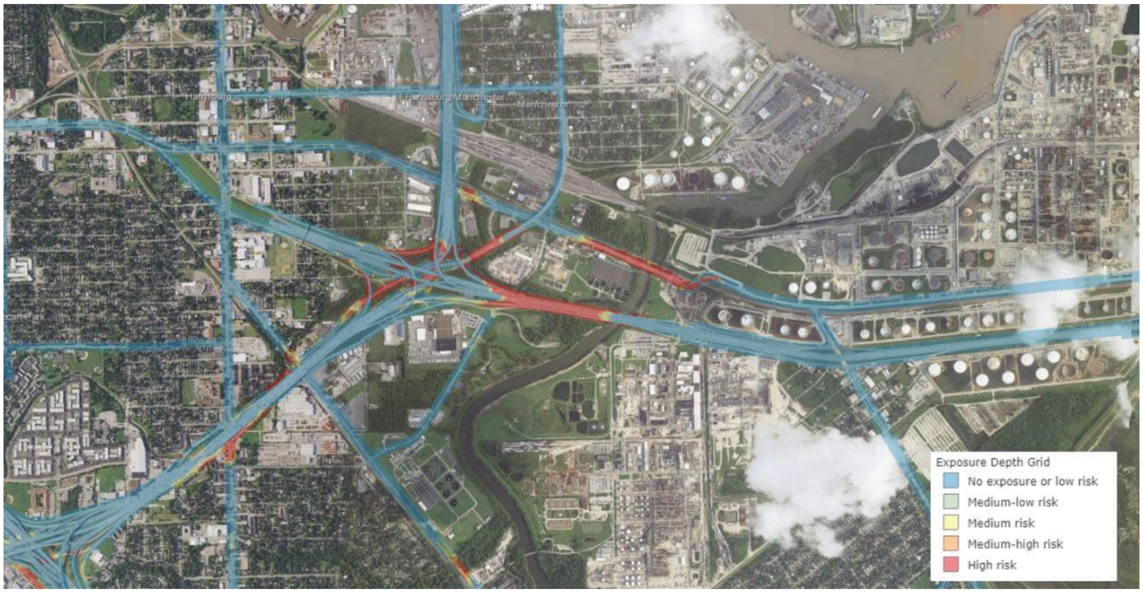


Figure 111 – Economic Impact Analysis Scenario 4-Category 4 Hurricane Storm Surge

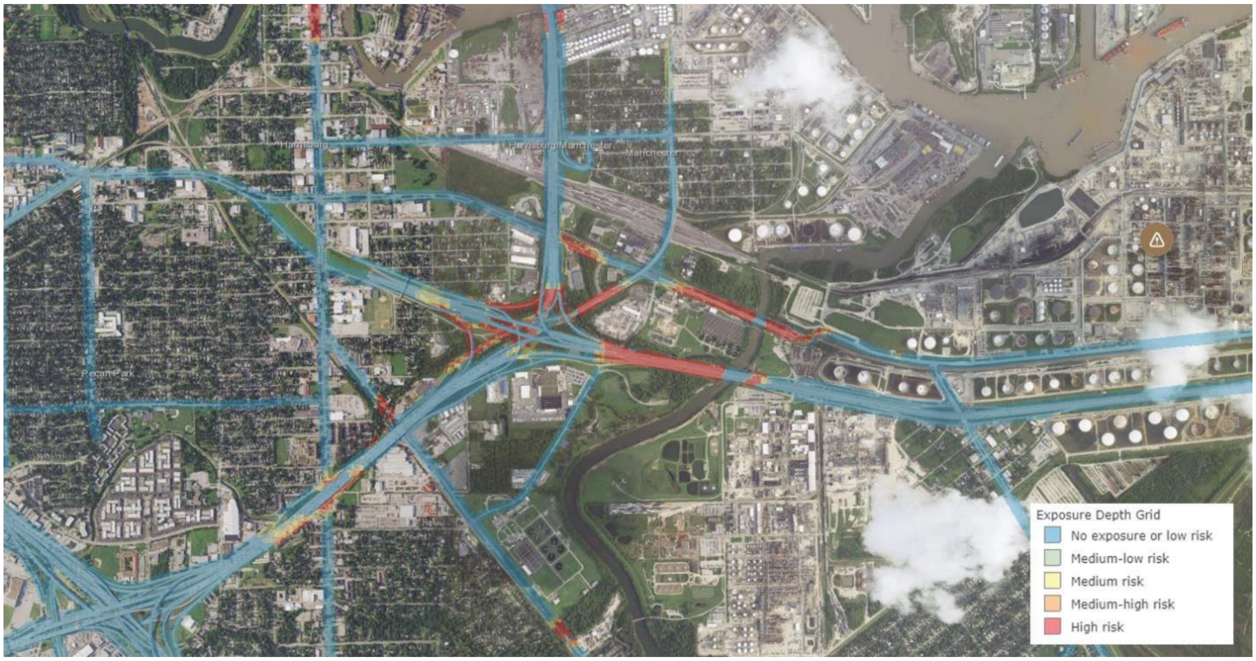
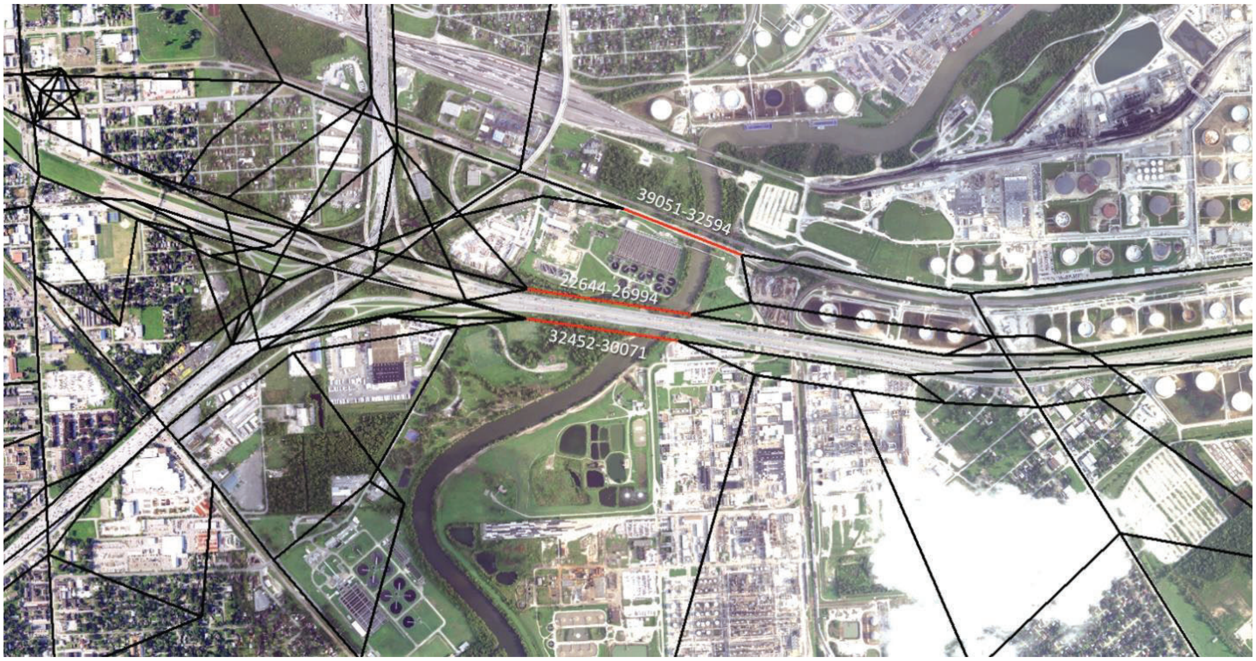


Figure 112 – Economic Impact Analysis Scenario 4-TDM Network

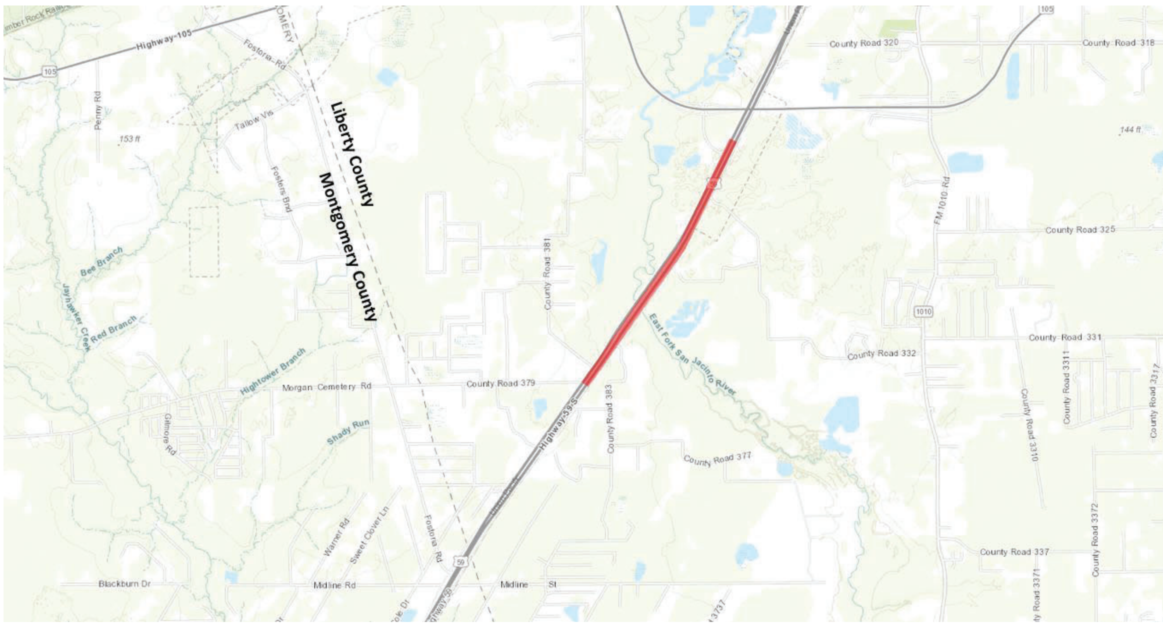
Link ID: 22644-26994, 32452-30071, & 39051-32594



Economic Impact Analysis Scenario 5: US Highway 59

US Highway 59 (Interstate 69) between Morgan Cemetery Road/County Road 379 and State Highway105 Bypass over East Fork San Jacinto River is high-risk as it was completely inundated during Hurricane Harvey. Around 24% of the highway segment miles are highly vulnerable to Hurricane Harvey flooding. Figure 113 shows Segment 5.

Figure 113 – US Highway 59 between County Road 379 and State Highway 105 Bypass



Figures 114 – 115 present various flooding scenarios for the segments specified above. Figure 116 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 114 – Economic Impact Analysis Scenario 5-Hurricane Harvey Flooding

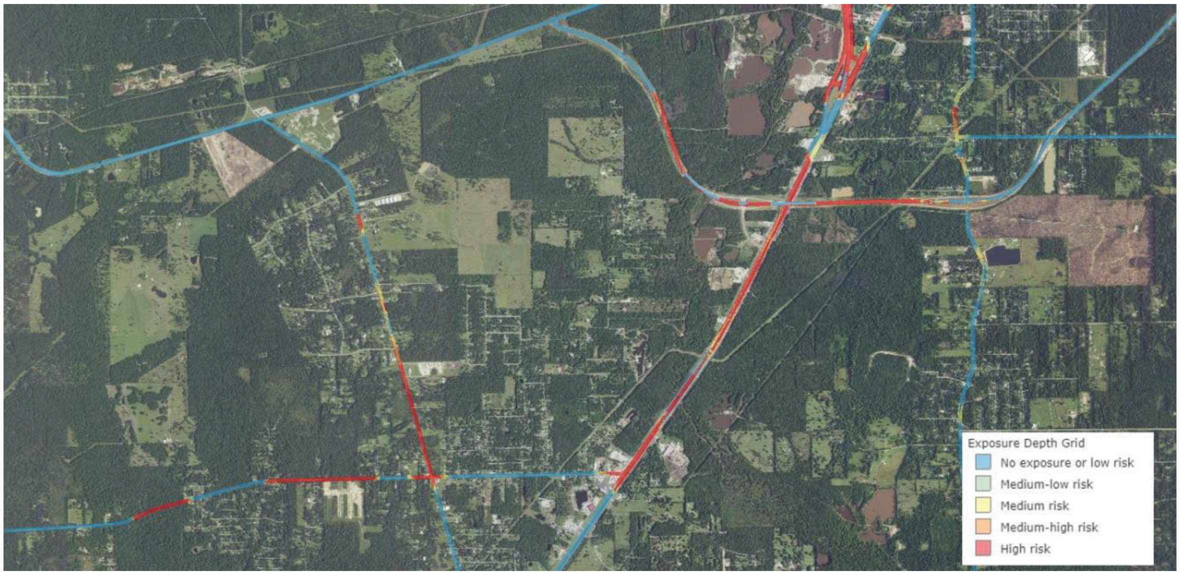
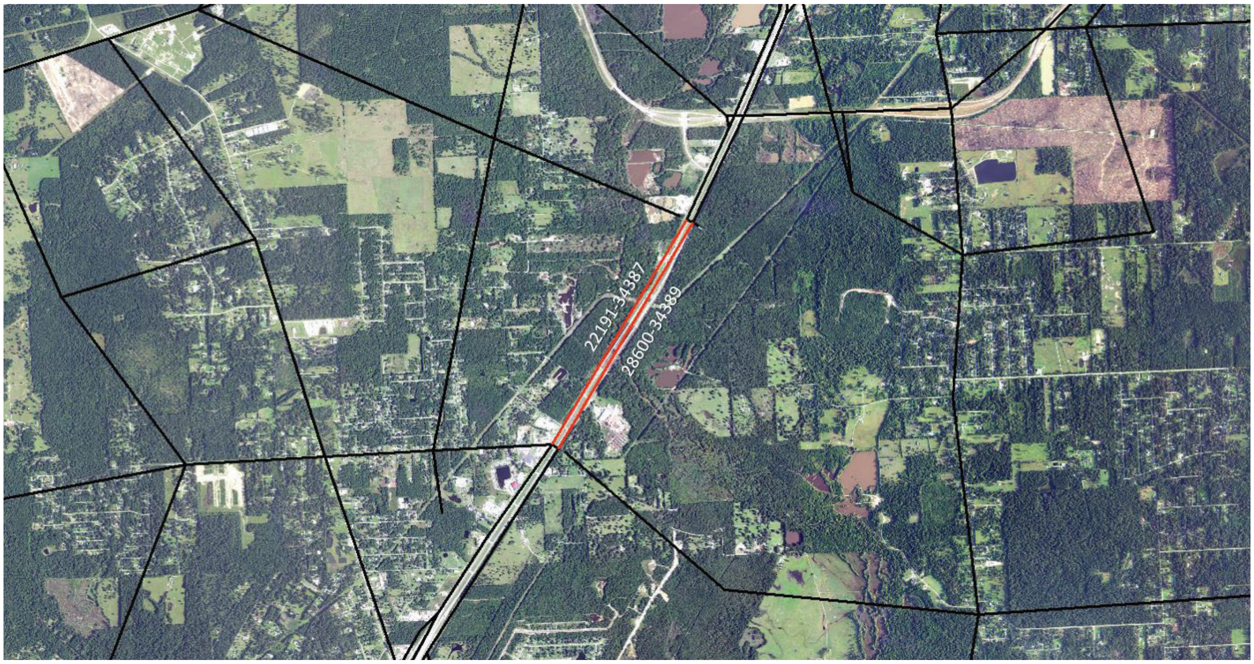


Figure 115 – Economic Impact Analysis Scenario 5-500-year Flooding

Figure 116 – Economic Impact Analysis Scenario 5-TDM Network

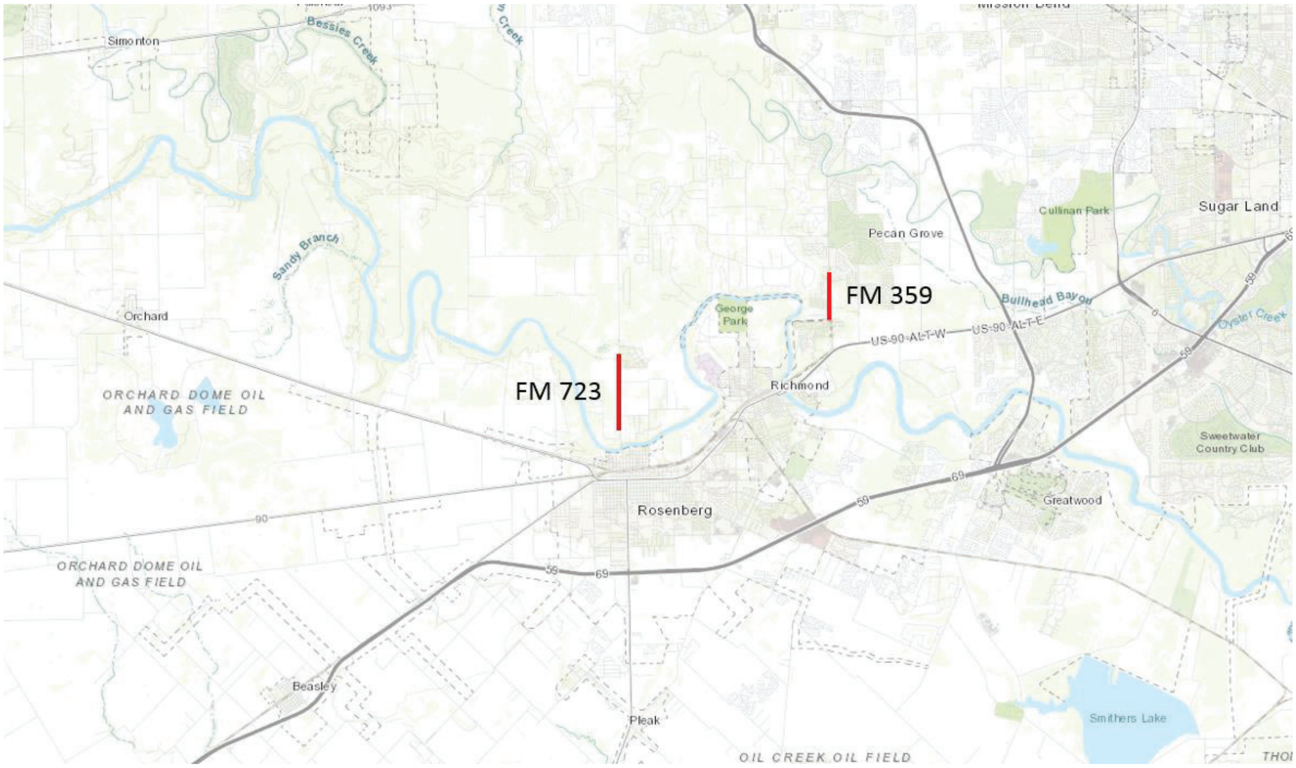
Link ID: 22191-34387 & 28600-34389



Economic Impact Analysis Scenario 6: Farm-to-Market Roads 723 and 359

Farm-to-Market Road 723 between US Highway 90A and Beadle Road and Farm-to-Market Road 359 between US Highway 90A and Farmer/Mason over the Brazos River are high-risk. Both road segments were fully inundated during Hurricane Harvey and are projected to be severely impacted by 500-year flooding events. These segments provide essential transportation support to several suburban neighborhoods in Fort Bend County and there are no alternative routes and limited redundancy to them. Figure 117 shows Segment 6.

Figure 117 – Farm-to-Market Roads 723 and 359 Segments



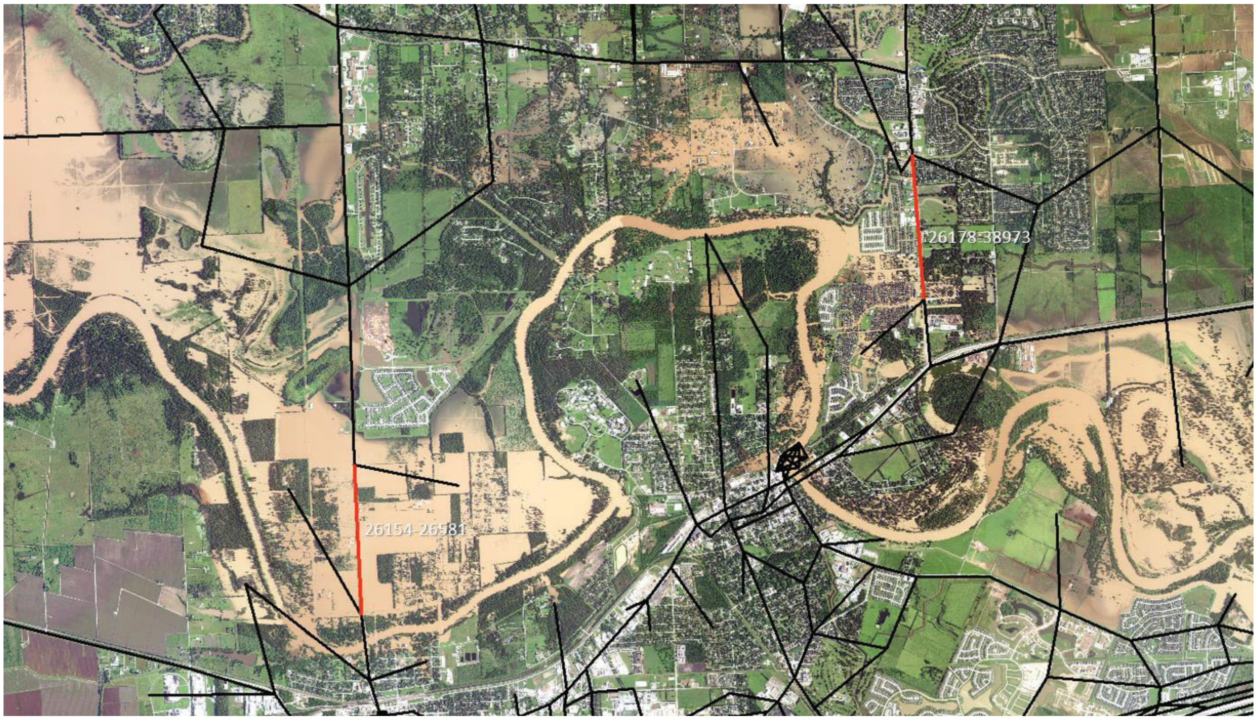
Figures 118 – 129 present various flooding scenarios for the segments specified above. Figure 120 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 118 – Economic Impact Analysis Scenario 6-Hurricane Harvey Flooding

Figure 119 – Economic Impact Analysis Scenario 6-500-Year Flooding

Figure 120 – Economic Impact Analysis Scenario 6-TDM Network

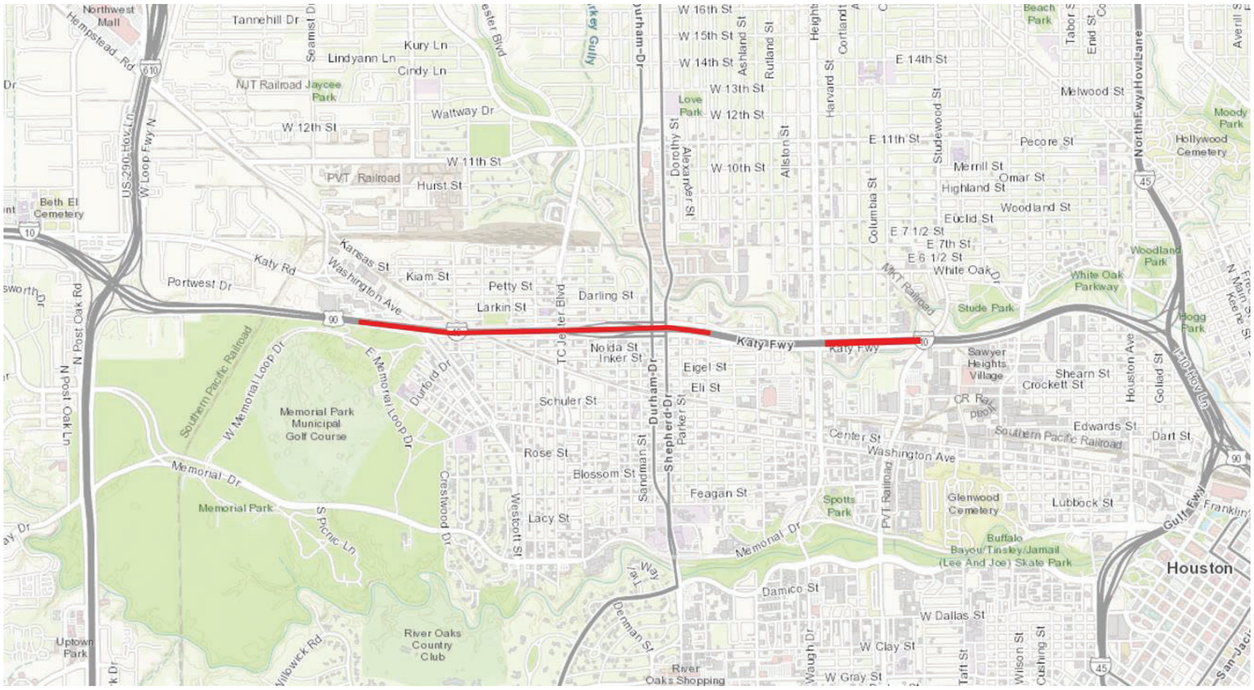
Link ID: 26154-26581 & 26178-38973



Economic Impact Analysis Scenario 7: Interstate 10

Interstate 10 between Shepherd Drive and Washington Avenue and between Heights Boulevard and Studemont Street is modeled to be highly vulnerable to flooding events. Located over Buffalo Bayou, these segments were severely flooded during Hurricane Harvey and are projected to be undergoing similar disruption during 500-year flooding events. This segment provides vital connections to major employment centers such as Galleria and Houston downtown area, as well as to several major residential communities. Around 32% of the segment are highly vulnerable to a 500-year flooding event and 40% are to Hurricane Harvey flooding. Figure 121 shows Segment 7.

Figure 121 – Interstate 10 Segments



Figures 122 – 123 present various flooding scenarios for the segments specified above. Figure 124 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 122 –Economic Impact Analysis Scenario 7-Hurricane Harvey Flooding

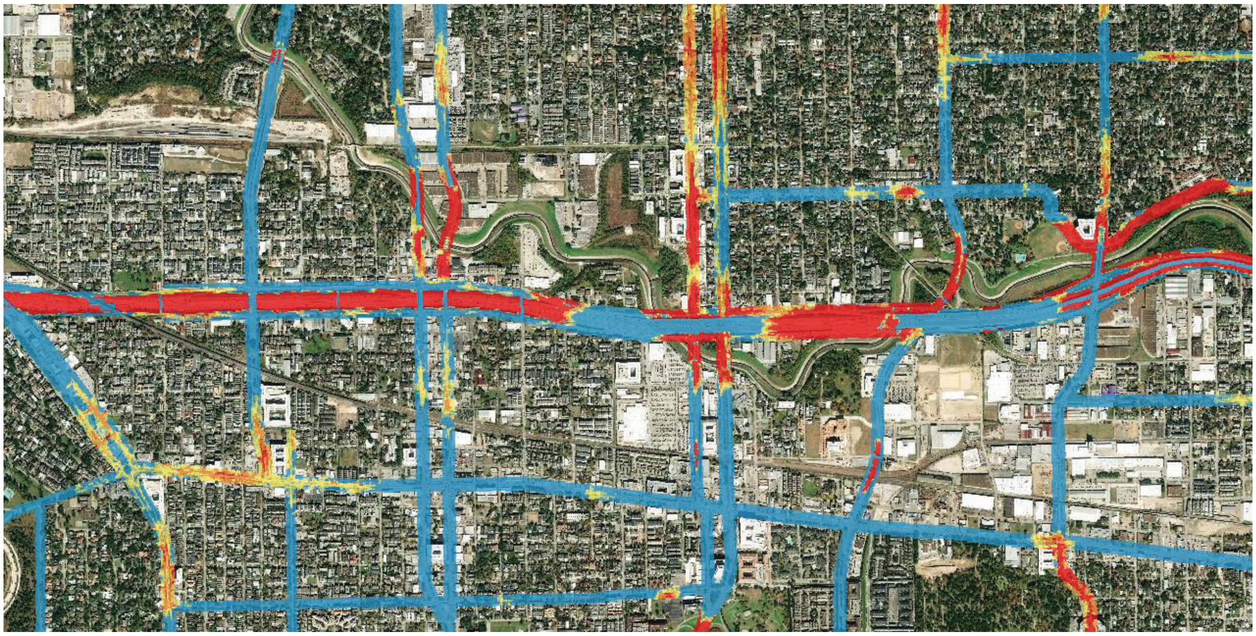


Figure 123 – Economic Impact Analysis Scenario 7-500-Year Flooding

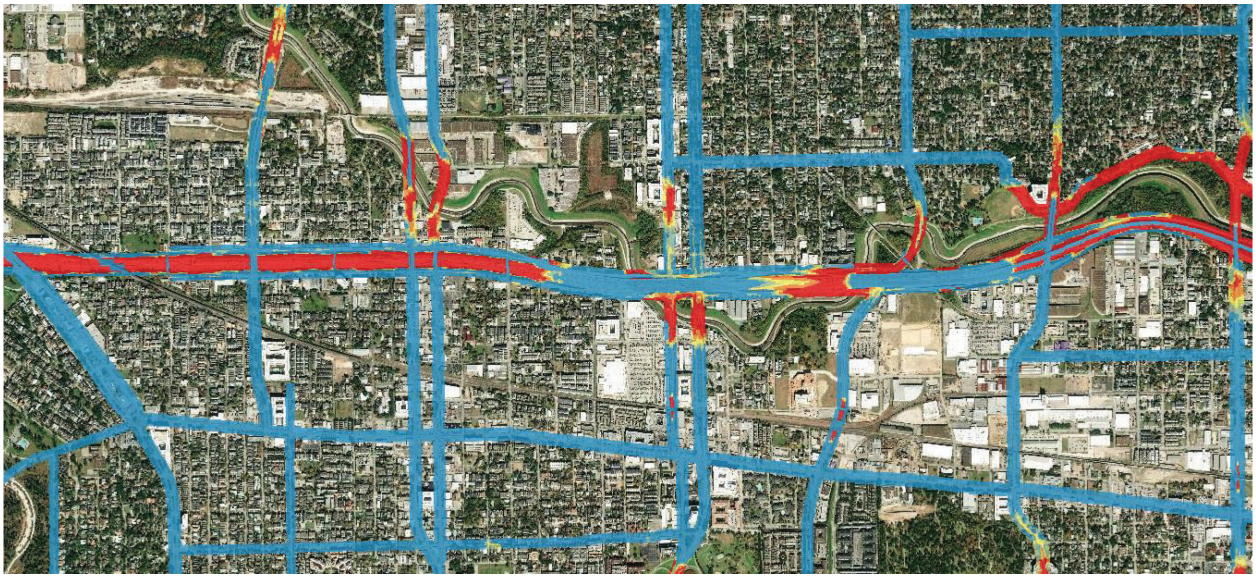
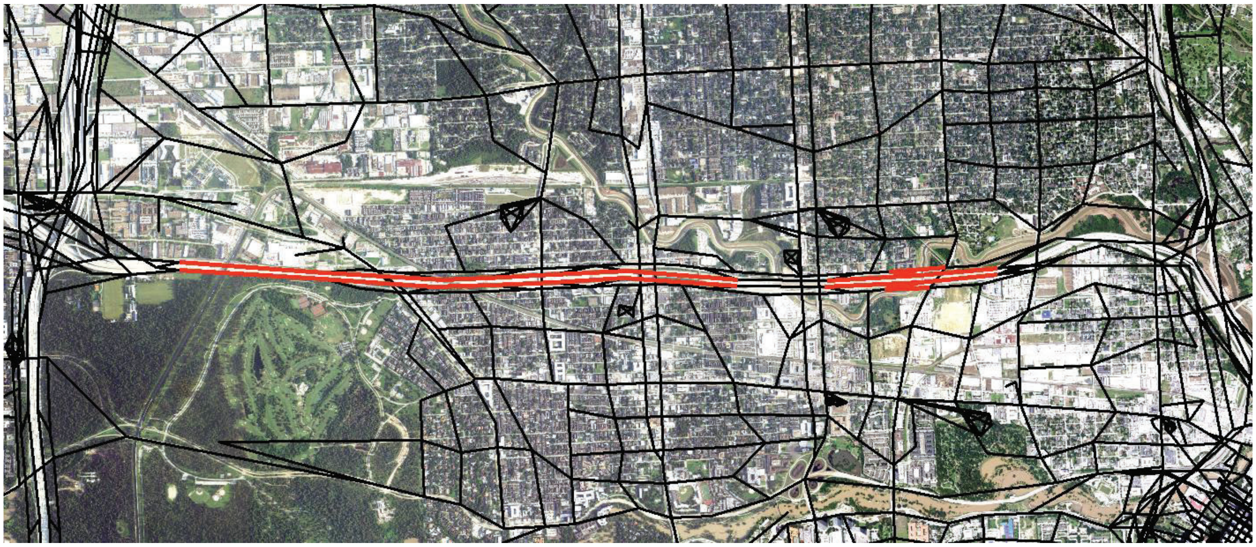


Figure 124 – Economic Impact Analysis Scenario 7-TDM Network

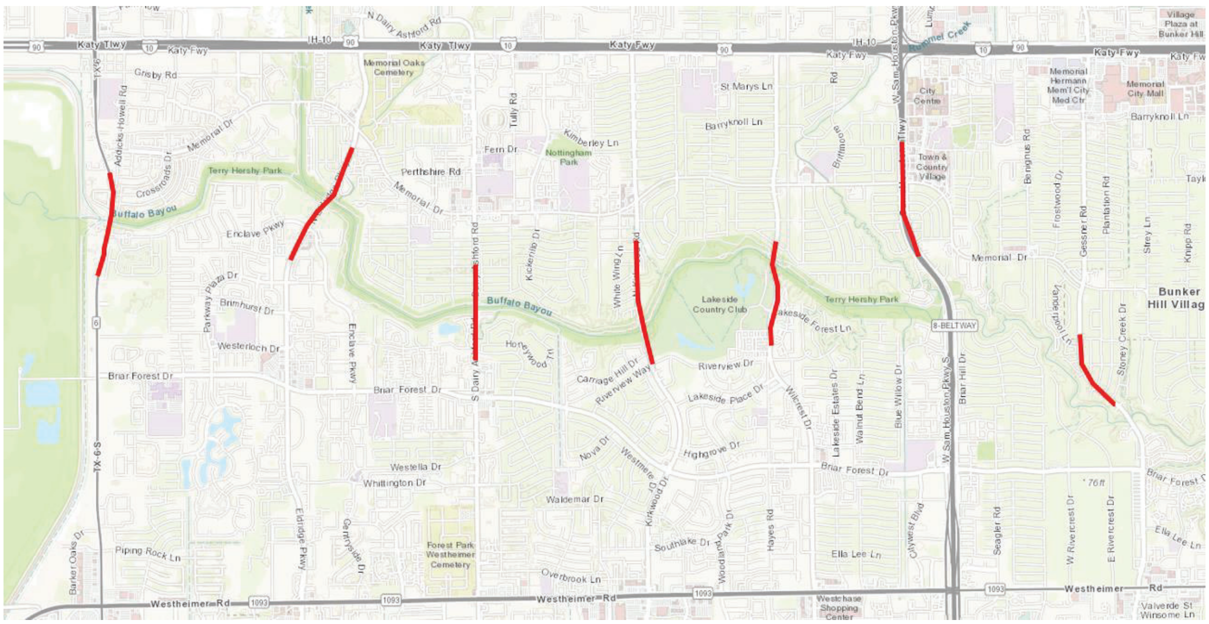
Link ID: 22232-30175, 23354-24091, 24078-28811, 24091-30169, 24092-31312, 25659-26837, 25661-31543, 25676-30178, 25687-25676, 25821-24091, 25821-25824, 25823-25822, 26837-25815, 28811-25661, 30175-24078, 30178-25659, 31312-25822, 31312-30312, 24076-25687, 31543-33517



Economic Impact Analysis Scenario 8: North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest

The scenario includes sections of State Highway 6, North Eldridge Parkway, Dairy Ashford Road, North Kirkwood Road, Wilcrest Drive, Beltway 8, and Gessner Road crossing the Buffalo Bayou. They were severely impacted during Hurricane Harvey and significantly impacted residents of Memorial-Energy Corridor area. These segments provide vital connections to Interstate 10, which is highly critical to the region's economic and social functioning. For beltway 8, 25% of the highway segment is highly vulnerable to Hurricane Harvey flooding. For all the major roads in the scenario, around 23% are highly vulnerable to Hurricane Harvey flooding. Figure 125 shows Segment 8.

Figure 125 – North-South Connecters along Buffalo Bayou between Memorial Drive and Briar Forest



Figures 126 – 127 present various flooding scenarios for the segments specified above. Figure 128 identifies the Travel Demand Modeling Network IDs for the above specified segments.

Figure 126 – Economic Impact Analysis Scenario 8-Hurricane Harvey Flooding

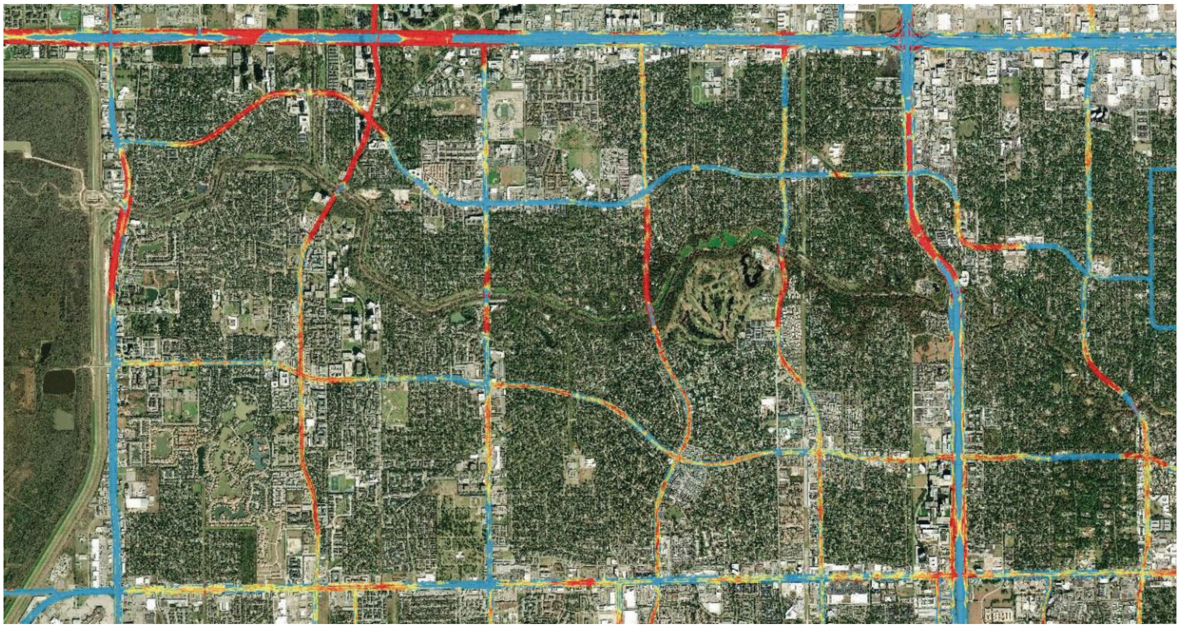


Figure 127 – Economic Impact Analysis Scenario 8-500-Year Flooding

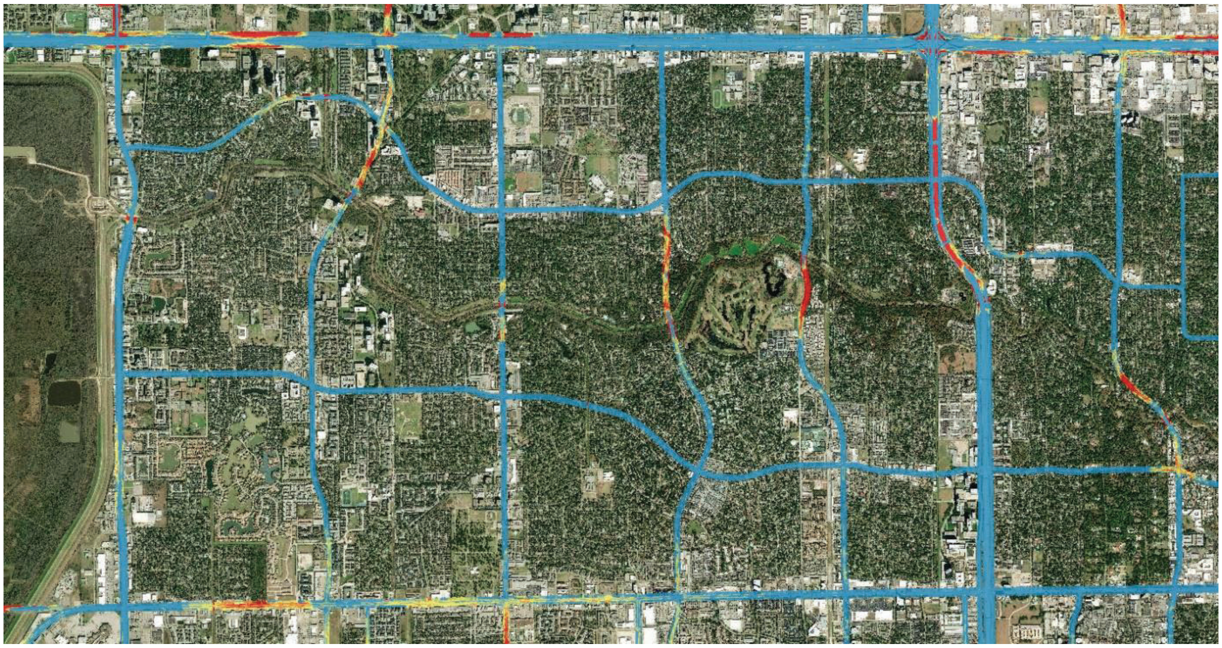
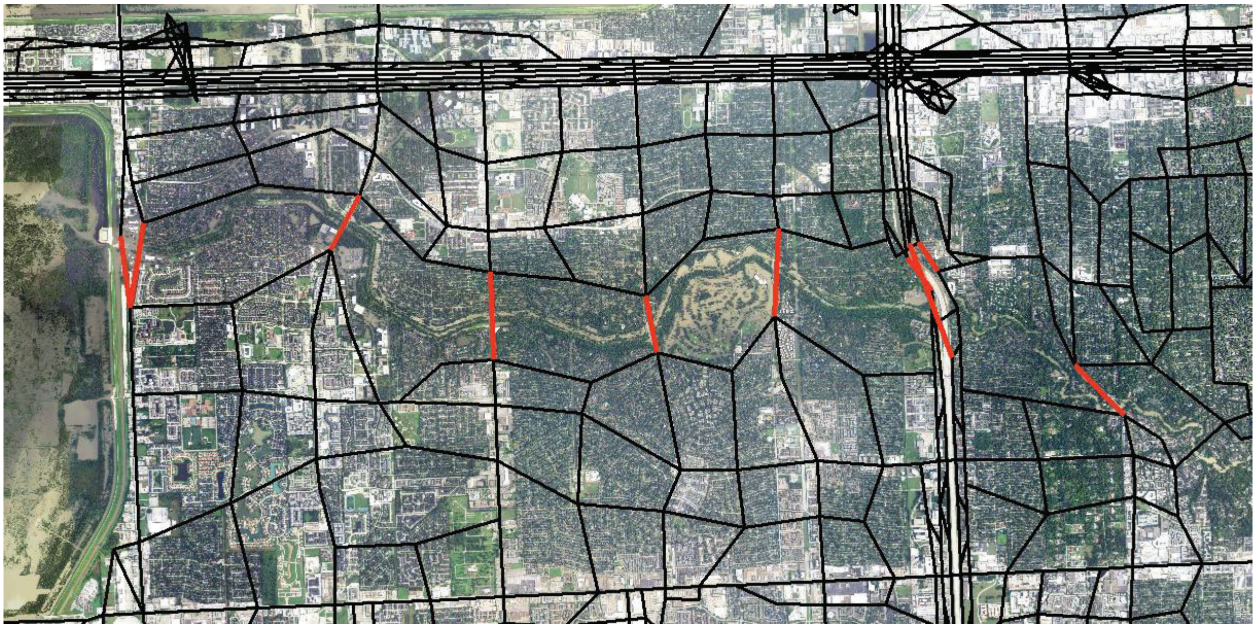


Figure 128 – Economic Impact Analysis Scenario 8-TDM Network

Link ID: 31840-22492, 23046-24736, 23109-32131, 24422-24423, 23046-24736, 31840-22492, 41043-31934, 39965-31949, 31951-31952, 31956-32105, 32055-32056, 31956-32105, 39965-31949, 41043-31934



APPENDIX D: GLOSSARY AND ACRONYMS

Overview

Language used in resiliency work is very important. In everyday speech, it's common for words like "risk" and "vulnerability" to be used interchangeably. However, for this Pilot Program and for technical discussions, sharing a common understanding of terms is essential. Many of these definitions are taken from FHWA's most recent Hydraulic Engineering Circular HEC-17[13i]. Definitions from other sources are cited.

Glossary Definitions

ADAPTATION: Preparing for the effects of extreme events and climate change on the transportation infrastructure and systems. Adaptation refers to the planning, designing, constructing, operating, or maintaining transportation infrastructure while incorporating consideration of extreme events and climate change.

ADAPTIVE CAPACITY: The degree to which the system containing the asset (road, bridge, etc.) can adjust or mitigate the potential for damage or service interruption by climatic hazards.

ANNUAL EXCEEDANCE PROBABILITY (AEP): The probability that the magnitude of the random variable (e.g. annual maximum flood peak) will be equaled or exceeded each year.

BASE FLOOD: The flood having a 1% chance of being equaled or exceeded in any given year.

BASE FLOODPLAIN: The area subject to flooding by the base flood.

CENTERLINE MILE: Centerline miles measure the length of a road or highway regardless of how many lanes it has. Because of divergences and curves, centerline miles can vary slightly between the two sides of a divided highway. Centerline miles are a more intuitive measurement of the overall length of roads than lane miles. (For instance, if there are only 10 centerline miles of roadway in each city but it all consists of five-lane highway, it would measure 50 lane miles.)

CLIMATE CHANGE: 1) A significant and lasting shift in the statistical distribution of weather patterns around the average conditions (e.g., more or fewer extreme weather events) over periods ranging from decades to millions of years. 2) Any significant shift in the measures of climate lasting for an extended period, including major alterations in temperature, precipitation, coastal storms, or wind patterns, among others, that occur over several decades or longer. 3) A non-random shift in climate that is measured over

[13]https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf

several decades or longer. The change may result from natural or human-induced causes.

CLIMATE: The characteristic weather of a region, particularly regarding temperature and precipitation, averaged over some significant interval of time (minimum 20 years).

COLLECTOR: Provides both land access service and traffic circulation within residential neighborhoods, and commercial and industrial areas. A collector may penetrate residential neighborhoods, distributing trips from the arterials through the area to the ultimate destination. The collector street also collects traffic from local streets in residential neighborhoods and channels it into the arterial system. In the central business district and in other areas of like development and traffic density, the collector system may include the street grid which forms a logical entity for traffic circulation.

DISCHARGE: Volume of water passing a given point per unit of time. Also known as flow.

EXPOSURE: The frequency, nature, and degree to which a transportation asset (road, bridge, etc.) will experience a climatic hazard.

EXTREME EVENT: Severe and rare natural occurrence that may pose significant risks for damage, destruction, or loss of life. Per Order 5520 and for the purposes of this report "extreme event" refers to risks posed by climate change and extreme weather events (FHWA 2014).

EXTREME FLOOD EVENT: Specific type of extreme weather event that is manifested as flooding.

EXTREME WEATHER EVENT: Significant anomalies in temperature, precipitation, and winds that may manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms (including tornados and tropical storms). They are rarely occurring, weather-induced events that usually cause damage, destruction, or severe economic loss.

FLOOD: A general and temporary condition of partial or complete inundation of normally dry land areas resulting from the overflow of inland or tidal waters.

FLOODPLAIN: The land area susceptible to being inundated by flood waters.

FLOW: Volume of water passing a given point per unit time. Also known as discharge.

HAZARD: Something that is potentially dangerous or harmful, often the root cause of an unwanted outcome.

HYDROLOGY: The earth science that considers the occurrence, distribution, and movement of water in the atmosphere, between the atmosphere and the earth's surface, and in the earth.

IMPERMEABLE: not permitting passage (as of a fluid) through its substance.[14]

MINOR ARTERIAL: Inter-connects with and augments the principal arterial system and provides service to trips of moderate length at somewhat lower of travel mobility than principal arterials. Ideally, they should not penetrate identifiable neighborhoods. The spacing of minor arterial streets should normally be not more than 1 mile in fully developed areas.

NATURE-BASED INFRASTRUCTURE: healthy ecosystems, including forests, wetlands, floodplains, dune systems, and reefs, which provide multiple benefits to communities, including storm protection through wave attenuation or flood storage capacity and enhanced water services and security.[15]

PERMEABLE: capable of being permeated: penetrable especially having pores or openings that permit liquids or gases to pass through a permeable membrane permeable limestone.[16]

POLYLINE: a connected series of line segments.

PRECIPITATION: Water in the form of rain, hail, sleet, or snow that forms in the atmosphere and falls to the earth’s surface.

RESILIENCE: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.

RETURN PERIOD: The average length of time between occurrences in which the value of a random variable (e.g. flood magnitude) is equaled or exceeded. Actual times between occurrences may be longer or shorter, but the return period represents the average interval. The return period is the inverse of the Annual Exceedance Probability (AEP). For example, if the AEP equals 0.01 (or 1%) the return period is 100 years.

RISK: The consequences associated with hazards (including climatic) considering the probabilities of those hazards. More specifically for this report, risks are the consequences associated with the probability of flooding attributable to an encroachment. It shall include the potential for property loss and hazard to life during the service life of the highway (23 CFR 650 A).

[14] https://www.merriam-webster.com/dictionary/impermeable
[15] https://coast.noaa.gov/states/fast-facts/natural-infrastructure.html
[16] https://www.merriam-webster.com/dictionary/permeable

RUNOFF: The portion of a rainfall event discharged from a watershed into the stream network during and immediately following the rainfall.

SENSITIVITY: The degree to which an asset is damaged, or service is interrupted by a climatic hazard.

VULNERABILITY: The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.

Acronym Definitions

AADT: Annually Averaged Daily Traffic

AADTT: Annually Averaged Daily Truck Traffic

AEP: Annual Exceedance Probability

BMP: Best Management Practice

CVM: Criticality-Vulnerability Matrix

DEM: Digital Elevation Model

DSM: Digital Surface Model

EMS: Emergency Management Services

EOC: Emergency Operations Center

FEMA: Federal Emergency Management Agency

FHWA: Federal Highway Administration

FHWA: U.S. Federal Highway Administration

GDP: Gross Domestic Product

GIS: Geographic Information System

GRID: Geospatial Roadway Inventory Database

H-GAC Region Resilience Pilot Program: Resiliency and Durability to Extreme Weather in the H-GAC Area Region Pilot Program

H-GAC: Houston-Galveston Area Council

HOU: William Hobby Airport

IAH: Bush Intercontinental Airport

LiDAR: Light Detection and Ranging

LiDAR: Light Detection and Ranging

MHHW: Mean Higher High Water

MOM: Maximum of Maximums

MPO: Metropolitan Planning Organization

NOAA: National Oceanic and Atmospheric Administration

NPDES: National Pollutant Discharge Elimination System

Pilot Program : Resiliency and Durability to Extreme Weather in the H-GAC Area Region Pilot Program

REMI: Regional Economic Models, Inc.

SWPPP: Stormwater Pollution Prevention Plans

TDM: Travel Demand Modeling

The team: Pilot Program team

TMA: Transportation Management Area

TNRIS: Texas Natural Resources Information System

TxDOT: Texas Department of Transportation

U.S.: United States

USACE: United States Army Corps of Engineers

VAST: Vulnerability Assessment Scoring Tool

VHT: Vehicle Hours Travelled

VMS: Variable Messaging Signs

VMT: Vehicle Miles Travelled

WAD: Wave Attenuation Devices

WSEL: Water Surface Elevation Model

APPENDIX E: ADAPTATION STRATEGIES

A detailed overview of the 25 strategies is provided on the pages that follow. All images in this Appendix provided courtesy of the Texas A&M Transportation Institute.

Strategy 1: Increase Number of Swales and Ditches

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

Swales and ditches are a stormwater best management practice (BMP) that helps drain stormwater away from road infrastructure toward larger stormwater facilities (e.g., channels, detention/retention ponds, permanent water bodies).

As is the case for many hydraulic design best practices, ditches and swales should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and retention ponds. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events, when implemented as part of a broader hydraulic system, they represent a low-cost method for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Rural roads (i.e., no hard sidewalks) • Component of general regional BMP for hydraulic design	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

When sized, located, and maintained properly, swales and ditches can help reduce flooding during severe rainstorm events, but also play a role in preventing water from damaging pavement substructures. Swales and ditches also:

- Improve the recovery time (return to use rate) of inundated roads following heavy storms
- Improve functionality of other hydraulic design features (culverts, channels)
- Reduce subsurface damage following chronic, acute flooding.

OTHER BENEFITS

Swales and ditches can play a role in preventing chronic damage from repeated smaller flood events.

LIMITATIONS / CONSIDERATIONS

Swales and ditches require preventative maintenance (e.g., need to be cleared of debris) to ensure that they continue to drain stormwater at their designed capacity. There is, therefore, a need to re-establish swales and ditches (vegetation, concrete, riprap). Swales and ditches can also affect driveway access.

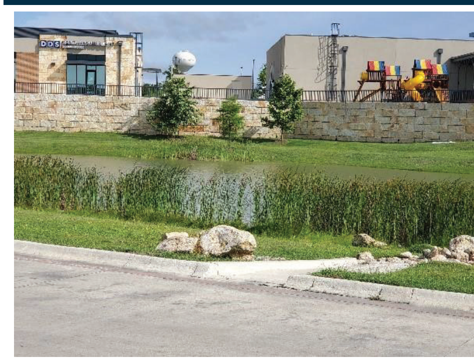
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Temporary drainage easements. Keep roadway clear of stormwater by conveying excess stormwater to outfall structure.	Effective with formal preventative maintenance strategy and allocated resources.	Easy	Typically included in construction costs.	Low

Strategy 2: Retention and Detention Ponds

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION



Creating retention and detention ponds is an effective method for managing stormwater by collecting stormwater and releasing it at a rate that prevents flooding or erosion. The main difference between the two is that retention ponds hold water indefinitely, while detention ponds act as a temporary area for storing stormwater. Often, detention ponds are smaller than retention ponds.

As is the case for many hydraulic design best practices, retention/detention ponds should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, their utility and effectiveness depend, in part, on their inclusion in broader scale hydraulic system designs. When retention and detention ponds are implemented in transportation corridors, safety issues such as clear site lines (vegetation) and vehicle interaction must be considered.

APPLICATION	CLIMATE STRESSORS
• Urban locations • Residential locations	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

When properly designed and maintained, retention and detention ponds can help reduce flooding during severe rainfall events. These ponds also improve the functionality of other hydraulic design features (culverts, swales/ditches, etc.).

OTHER BENEFITS

By collecting sediment-laden stormwater, these ponds capture heavier contaminants, such as solids and metals from roadways, as well as other pollutants. Retained water and associated vegetation naturally filter these contaminants and return clean water downstream.

LIMITATION S / CONSIDERATIONS

Location

- Sufficient space is required for the construction and to provide maintenance access for these ponds.
- Topography should ensure surrounding area drains to the pond.

Maintenance

- Since these ponds are designed to collect sediment, it is important to regularly remove sediment buildup to ensure their holding capacity is not reduced.

Soil type/structure

- Soil type/structure must be considered to ensure effective stormwater storage by limiting infiltration.

Safety

- Prohibit public access to address safety concerns.

DECISION CRITERIA				
Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Improves water quality.	Available space (square feet), soil type, topography must be considered.	Moderate	Moderate	Low

Strategy 3: Bioswales (Biofiltration Swales)

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

A bioswale is a narrow strip of vegetation that redirects and filters stormwater. It is used to collect runoff stormwater from non-porous surfaces such as roads, parking lots, and rooftops. Bioswales improve water quality by infiltrating the first flush of stormwater and filtering secondary runoff.

As is the case for many hydraulic design best practices, bioswales should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, they are low-cost methods for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Implemented in and adjacent to areas requiring stormwater conveyance	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Mitigate flooding potential and diverts stormwater away from critical infrastructure.
- Decreases runoff peak flow rates and volumes.

OTHER BENEFITS

- Aesthetically pleasing
- Improves water quality
- Improves biodiversity
- Groundwater recharge

LIMITATION S / CONSIDERATIONS

- Bioswale design considerations include climate, precipitation patterns, available space/location, budget, and vegetation suitability.
- They should be sized to convey a 10-year storm minimum.
- A bioswale typically comprises four different layers:
    - Planting soil bed for vegetation
    - Sand layer for infiltration
    - Gravel layer for storage

Infiltration pipe/drain tube for conveyance

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Improves stormwater quality	Climate, site size/location, budget, and vegetation suitability	Low	Low	Low

Strategy 4: Depressed and Raised Medians

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

Raised medians are curbed sections that typically occupy the center of the roadway. Depressed medians have a common ditch or swale between divided roadways.

APPLICATION	CLIMATE STRESSORS
• Urban locations • Residential locations	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

Raised medians allow curb inlets that convey stormwater away from roadway. They create positive drainage in super elevation conditions.

In addition, depressed medians hold/convey stormwater away from the roadway protecting the pavement structure.

OTHER BENEFITS

- Reduced motor vehicle crashes
- Increased roadway capacity
- Decreased delays for motorists
- Snow storage in colder climates

LIMITATION S / CONSIDERATIONS

If width allows, medians can potentially use unused space to provide stormwater conveyance and storage. Underground utilities may limit the use of medians.

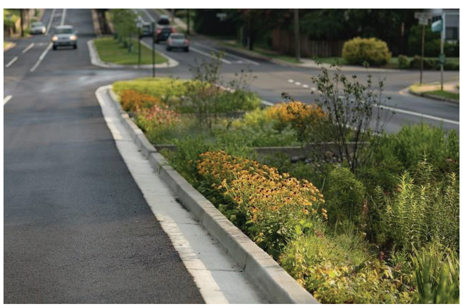
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control.	Sufficient width between travel lanes	Moderate	Low	Low

Strategy 5: Green Infrastructure

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION



Impervious streets, parking lots, and sidewalks increase peak flow and reduce the time between storm occurrence and peak flow rate. Both factors result in increased localized flooding. Green infrastructure is a stormwater management approach that incorporates vegetation, soil, and engineered systems (e.g., tree wells and biofiltration gardens) to slow, filter, and clean stormwater.

Typical green infrastructure stormwater control applications include:

- Green parking/streets/roofs
- Bioretention filters
- Rainwater harvesting
- Urban tree canopy

As is the case for many hydraulic design best practices, green infrastructure should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, it is a low-cost method for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Urban areas to reduce stormwater runoff	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Decreases the volume of water that enters waterways as direct runoff through a combination of planned practices and engineered devices.

OTHER BENEFITS

- Improves air quality
- Reduces urban heat islands

LIMITATIONS / CONSIDERATIONS

- Easy to implement during new construction
- Maintenance is required for aesthetic and functional purposes
- Must meet local landscape, stormwater, and public ordinances and policies

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Collects and improves stormwater.	Public works coordination—maintenance plan.	Moderate - Technical guidance and standard drawings are available to assist in the development of green infrastructure plans.	Moderate	Low

Strategy 6: Culvert Cleaning/Maintenance

STRATEGY CATEGORY	Maintenance (Primary) & Stormwater Management (Secondary)

DESCRIPTION

A culvert "conveys surface water through a roadway embankment or away from the highway right-of-way (ROW) or into a channel along the ROW."[ii] Cleaning and regular maintenance of culverts ensures optimal flow of water through the stormwater management system. A proactive culvert maintenance strategy is effective in helping protect road infrastructure in a flooding event.

APPLICATION	CLIMATE STRESSORS
• Allows the movement of water under a road, bridge, or railway without disrupting traffic	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Reduces the risk of flooding if adequately designed to move large volumes of water at a reasonable speed through the drainage system.

OTHER BENEFITS

- Can serve as specialized wildlife crossings and generally improve wildlife habitat connectivity.

LIMITATION S / CONSIDERATIONS

A typical regional culvert network is very large, and many culverts are undocumented. Developing a culvert inventory in a geo-referenced format may help plan and prioritize culvert maintenance. A more feasible option could be to prioritize maintenance based on known local flooding.

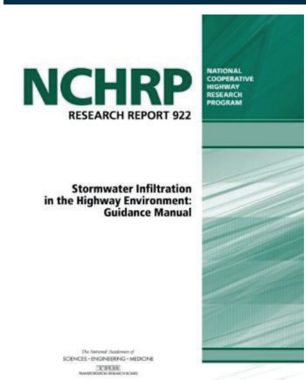
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Require culvert inventory, routine inspections, and maintenance strategy.	Routine inspections to identify sedimentation and erosion on the outfall. Clear debris.	Can be expensive. Extensive resource requirements to develop comprehensive culvert inventory.	Relatively low.

Strategy 7: Stormwater Management Plan

STRATEGY CATEGORY	Planning (Primary) & Stormwater Management (Secondary)

DESCRIPTION



A stormwater management plan is a functional plan addressing existing stormwater system conditions, the operation and maintenance of existing facilities, and the required capacity for new facilities.

When stormwater is unable to infiltrate into the ground because of impervious surfaces (such as roads, parking lots, and roofs), it flows across the surfaces until it encounters a collection system (e.g., storm drainage), surface water body, or other points of discharge. As impervious surfaces increase with development, stormwater runoff occurs more quickly and with increased volume, meaning peak flows in a watershed occur quicker and at an increased rate. This increase in peak flow rate increases the frequency of flooding downstream.

APPLICATION	CLIMATE STRESSORS
• A Stormwater Management Plan should include the development and enforcement of the following: o Stormwater Pollution Prevention Plans o Municipal Separate Storm Sewer System o BMPs o Response Actions (if available)	• Local Flooding • Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

An up-to-date Stormwater Management Plan is critical to repair a system after weather-related disaster events (e.g., flooding, sea-level rise, storm surge, or a combination of these events).

OTHER BENEFITS

- Stormwater management is important to maintain the ecological integrity, quality, and quantity of water resources.
- Stormwater management can result in reduced costs and/or fees for remediation of adverse impacts on the environment.

LIMITATION S / CONSIDERATIONS

Local permitting agencies may determine the development and implementation of a Stormwater Management Plan. The plan must include monitoring and evaluation.

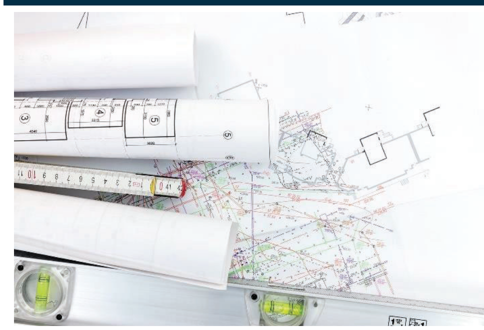
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
A Stormwater Management Plan is important to prevent physical damage to persons and property from flooding or other weather-related disasters.	Understanding of National Pollutant Discharge Elimination System is required.	Moderate - Fiscal and operational constraints must be considered during implementation.	Low	Low

Strategy 8: Land Use Planning/Climate Justice

STRATEGY CATEGORY	Planning

DESCRIPTION



Land use planning refers to planning the physical layout of communities and cities. Land use planning determines where development occurs (i.e., the built environment)[iii] and identifies open space or land for preservation (i.e., the natural environment). Land use planning aimed at increasing resiliency includes adopting land-use codes and zoning regulations that avoid development in flood-prone areas (thereby reserving open space to enhance drainage) and the development and adoption of development standards and building codes and incentive/disincentive programs to avoid development in vulnerable areas (such as low income and minority housing areas). Incentivizing innovative construction techniques also allows communities to recover quickly after catastrophic weather-related events.

APPLICATION	CLIMATE STRESSORS
• Cities • Communities	• Local Flooding • Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- More resilient communities.
- Open space to enhance drainage. Open spaces slow the flow of floodwater and reduce potential damage and erosion.

OTHER BENEFITS

- Conserve vulnerable natural resources, such as wetlands, watersheds, groundwater, and tidal basins. If impact fees are levied as part of a comprehensive land-land use planning policy, the revenue can be used to invest in further resilience adaptation strategies, such as stormwater management and flood control improvements associated with the new developments.

LIMITATION S / CONSIDERATIONS

Adaptation strategies often focus on infrastructure and stormwater management with less emphasis on local land use planning or p

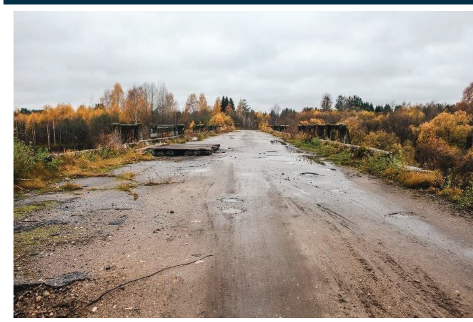
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Comprehensive planning Land use codes Zoning regulations Development standards/Building codes Incentive programs Broad community stakeholder and decision-maker buy-in	Risk of private property owners challenging land-use policy as infringing on property rights.	Dependent on community and stakeholder support but tend to be lower with new construction/ development.	Low

Strategy 9: Relocate or Abandon Roads

STRATEGY CATEGORY	Planning (Primary) & Infrastructure (Secondary)

DESCRIPTION



Relocate or abandon roads that have experienced repeated damage or inundation in the past. Abandoning can also entail converting roads to gravel or other low maintenance materials

APPLICATION

- Typically used for lower functional classes of roads
- Serving small communities with one or more viable alternative roads
- Coastal roads inundated by sea level rise
- Costs of raising road profile or maintaining a road has become excessive

CLIMATE STRESSORS

- Local Flooding
- Sea Level Rise

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Enhance resiliency by mitigating future risks and damage to the road.

OTHER BENEFITS

- Reduced cost over the life of the asset.

LIMITATION S / CONSIDERATIONS

- Abandoning a road can only be considered if a community has a viable alternative mode of access available.
- Hydrologists and engineers need to map the floodplain and restructure the roadways for the post-flood environment.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Community must have access to a viable alternative mode/road.	Easy	Low to high (if an alternative road needs to be constructed)	Can potentially be lower than with the existing road.

Strategy 10: Shelter-in-Place

STRATEGY CATEGORY	Planning

DESCRIPTION

The term "shelter-in-place" was originally used to describe an emergency response to nuclear or biological hazards. It describes a situation where residents are advised or lawfully ordered to remain in place during a threat to mitigate the damage caused by an ongoing hazard. The strategy is essentially the opposite of an evacuation.

APPLICATION

Guidance, advice, incentives, or lawful orders are given to sections of a population to prevent or minimize the use of road networks during floods while inundation is present." Shelter-in-place in this context is used broadly to describe various strategies to temporarily reduce road use with the goal of improving safety and reducing the long-term economic costs of flooding (e.g., damage to pavements). This shelter in place strategy is comprised of two connected components: 1) a cost-benefit analysis of the safety and infrastructure benefits of reduced travel versus the social and economic cost of this reduced travel, and 2) communications (guidance, advisories, or orders) designed to temporarily reduce or prevent road use.

To be successful, shelter in place strategies should be developed proactively and as part of a broad, cross-disciplinary approach for managing the impacts of flooding.

ADAPTION RESPONSE	CLIMATE STRESSORS
• Protect • Recovery	• Local Flooding

RESILIENCE BENEFITS

- Acknowledges that flooding will inevitably occur, but that damage and impacts of flooding can be reduced through potentially simple, low-cost social strategies.
- Encourages stakeholders to develop a systems approach to flood mitigation and to organize knowledge and information on flood hazards and impacts.

OTHER BENEFITS

- Shelter-in-place strategies can be adapted to preparing for and mitigating other hazards (e.g., infectious diseases, such as the COVID-19 response).

LIMITATION S / CONSIDERATIONS

Shelter-in-place may be perceived to be a last resort, alarmist, autocratic, and possibly a failure of traditional engineering approaches. Effective communication and proactive planning are required to change this perception.

The term "shelter in place" may also cause negative perceptions. Concepts such as "flood day" (akin to snow days often used in northern states) may be more effective terms for positively affecting behavior.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Potentially effective, but unproven	Robust planning and organization	Difficult	Medium. However, costs could be offset by maintaining strategies and using the planning process to design and review other resilience strategies. Indirect costs, such as economic loss.	Medium. Similar to implementation costs.

Strategy 11: Evacuation Route Identification and Planning

STRATEGY CATEGORY	Planning

DESCRIPTION

When extreme weather events require evacuation, it is essential that evacuation and rescue routes are identified and designated in advance. It is also critical that the public is informed and provided information about designated evacuation and rescue routes. Information can be shared through various methods, including published guidelines/information, automated calling systems (texts and phone calls), variable messaging signs, and live radio announcements.

APPLICATION	CLIMATE STRESSORS
• Urban and rural locations	• Storm Surge • Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Effective strategy to provide public with a safe route to evacuate from a potentially impacted area in advance of an extreme weather event.

OTHER BENEFITS

- Improves community participation/safety during planning process.

LIMITATION S / CONSIDERATIONS

- Evacuations can be a complex process. Careful planning will minimize risks associated with evacuation during emergency situations.
- A key consideration in the planning and use of evacuation routes is the vulnerability and mobility of the potential users of the routes. Options are needed for vulnerable populations (disabled or the elderly) to safely use the routes.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Highly effective strategy to protect public.	Can be complex process. Requires extensive agency coordination.	Moderate	Moderate	Moderate

Strategy 12: Prohibiting Overweight / Oversize Vehicles

STRATEGY CATEGORY	Planning (Primary) & Infrastructure (Secondary)

DESCRIPTION

Flooding and the inundation of the pavement structure reduce pavement layer stiffness and have the potential to cause substantial damage to pavement structures. Heavy loads on weakened pavements in the immediate aftermath of a flooding event can lead to sudden failure or severe damage, such as severe cracking, ruts, and potholes. This strategy prohibits oversize/overweight vehicles on inundated pavements or pavement structures until flood water has drained from base layers.

APPLICATION	CLIMATE STRESSORS
• Pavement structures vulnerable to flooding/inundation and failure or severe damage	• Local Flooding

ADAPTION RESPONSE

- Protect
- Recovery

RESILIENCE BENEFITS

- Reduce the risk of failure or damage to the pavement structure.

OTHER BENEFITS

- Increase the service life of the impacted roads.

LIMITATION S / CONSIDERATIONS

Might impact recovery strategies and might not be well received by the trucking industry.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Support from decision-makers	Potentially challenging	Low, but requires enforcement	Wil reduce maintenance costs over the life of impacted roads.

Strategy 13: Sensor Technologies and Monitoring Programs

STRATEGY CATEGORY	Planning

DESCRIPTION

Stormwater system design is based on the concept of risk. Infrastructure is engineered to accommodate rainfall events up to a limit (e.g., a 100-year storm) determined by analyzing a history of local rainfall events. When these design intensities or durations are exceeded, the structure will temporarily fail (i.e., prevent drainage), and flooding will inevitably occur. In extreme cases, the hydraulic pressures associated with flooding can cause infrastructure to catastrophically fail, causing damage to roadway infrastructure and affecting the safety and mobility of travelers. This family of strategies includes employing sensors to monitor rainfall, runoff, water levels, and the general condition of the stormwater system.

Examples include:

- Water flow and level sensors on stormwater management systems
- Spatial databases of stormwater management infrastructure (e.g., sizing, location, age, design, construction material, condition)
- Real-time decision warning systems to help predict floods and flood impacts
- Decision support tools to identify weaknesses in the stormwater system and identify and prioritize remedial actions

APPLICATION

- System-wide or targeted to vulnerable portions of the system (acknowledging either a higher cost or a reduction in the resolution of data and decision-making tools)
- Used in conjunction with other planning strategies

ADAPTION RESPONSE	CLIMATE STRESSORS
• Prepare • Protect • Recovery	• Local Flooding

RESILIENCE BENEFITS

- Provides data essential for a system-wide approach to resilience planning.
- A connected network of sensing devices can operate continuously and provide a detailed, real-time view of system performance.
- Potential for data to prevent/reduce flooding (e.g., detecting critical infrastructure or malfunctions).
- Potential for data to reduce flooding impacts (e.g., issuing local flood alerts and travel advisories).
- Potential for forensically examining flood events, identifying problem infrastructure, and prioritizing engineering solutions.

OTHER BENEFITS

- Encourages a system-wide approach to stormwater management.
- Potential to improve collaboration and information sharing among stakeholders (e.g., transportation planners, urban planners, hydrologists / hydraulic engineers, and natural resource managers).

LIMITATION S / CONSIDERATIONS

- Various organizations monitor water level gauges in key drainage channels. The national bridge inventory maintains a database of larger culverts but does not include smaller culverts, culverts not associated with roadways, or other infrastructure critical for local flood prevention. Nevertheless, both initiatives provide a starting point useful for developing more detailed, systemic monitoring programs.
- Local standards and best practices exist for determining the frequency and duration of rainfall events (based on local rainfall data).
- These standards directly influence the design specification of the existing stormwater infrastructure. A historical view of such standards could be used for identifying critical infrastructure.
- Culvert designs and tolerances are typically available in engineering plans. However, considerable work may be required to locate and digitize historical plans.

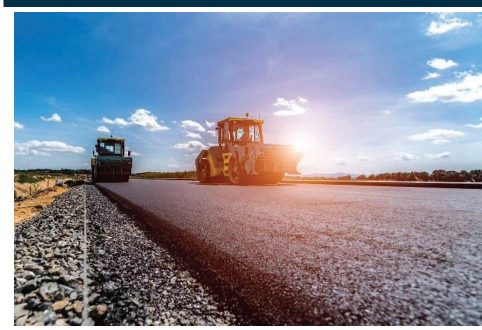
- Stormwater structures are usually designed using specialized stormwater engineering, computer-aided design software. Over the long-term, programs could be developed to inform these designs at a lower cost and ensure consistent, electronic formats more useful for analysis.

DECISION CRITERIA				
Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Untested. But could potentially include prevention of flooding, effective planning, and mitigating the impacts of flooding.	Cross agency coordination.	Moderate. Depending on spatial scale, resolution, and stakeholder buy-in.	Medium – especially considering the benefits of successful implementation.	Potentially low if programs are designed to efficiently collect and curate data.

Strategy 14: Enhanced Road Surface

STRATEGY CATEGORY	Infrastructure

DESCRIPTION



Enhancing the surface of a roadway typically involves additional thickness of the surface course (e.g., 6-inch asphalt layer as opposed to a 4-inch asphalt layer).

APPLICATION

- Pavement structures vulnerable to flooding and failure or severe damage
- Raising the road profile is not a feasible solution

CLIMATE STRESSORS

- Local Flooding
- Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Protect against damage caused by water flowing over the surface of the pavement.

OTHER BENEFITS

- Increase pavement service life.
- Reduces adverse impacts of water standing on road surface,

LIMITATION S / CONSIDERATIONS

Enhancing the road surface can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes vulnerable to flooding.

Information on the pavement structure, pavement work history, and the actual age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

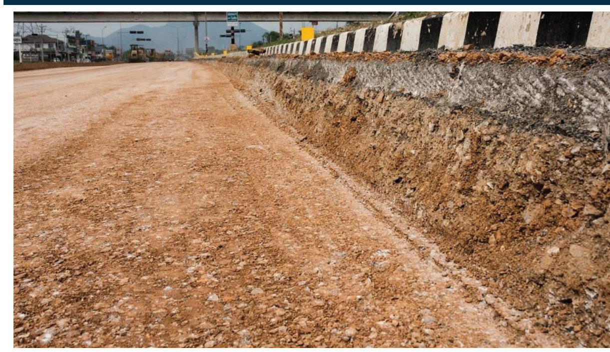
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Pavement structure information to determine which road surfaces to enhance. Typically done through non-destructive testing.	Well established engineering and construction methods are available and must be adhered to.	Cost is very high (construction as well as user cost)	No additional maintenance costs. Maintenance costs of enhanced surface might be lower than before.

Strategy 15: Enhanced Sub-Grade

STRATEGY CATEGORY	Infrastructure

DESCRIPTION



Flooding has the potential to cause significant damage to pavement structures. The structural capacity of pavements can be affected by flooding mainly due to the inundation of unbound layers (i.e., base course and sub-base course) and the period of inundation (e.g., the time it takes for the water to dissipate). A subgrade's performance depends on two interrelated characteristics: load-bearing capacity and volume changes. Both are negatively affected by excessive moisture. An increase in the moisture content of unbound layers can notably reduce layer stiffness and result in sudden failure or severe damage. Cement treated bases and lime traded sub-bases are two options to enhance and harden the pavement structure.

APPLICATION	CLIMATE STRESSORS
• Pavement structures vulnerable to flooding/inundation and failure or severe damage	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Reduce the risk of failure or damage to the pavement from flooding and other water-related damage.

OTHER BENEFITS

- Increase pavement service life.

LIMITATION S / CONSIDERATIONS

The first step in evaluating the potential benefits of an enhanced sub-grade strategy to enhance resiliency is to identify and assess the structure of the pavements that are vulnerable to flooding/inundation. Information on the pavement structure, pavement work history, and age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Perform pavement forensics in vulnerable areas. Strengthen sub-grade in the event of erodible soils.	Well established engineering and construction methods are available and must be adhered to.	High. Upfront capital cost and cost to user (construction zones).	No additional maintenance costs

Strategy 16: Hardened Shoulders

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Enhancing or hardening (i.e., providing additional lateral support for) paved shoulders can reduce the damage to the pavements and roads from inundation and storm surge in some circumstances.

APPLICATION

- Roadways directly exposed to coastal waves
- Inland roads requiring protection from flooding

CLIMATE STRESSORS

- Local Flooding
- Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Protect main lanes from damage from flooding and storm surge.
- Can be used as an extra lane and used in evacuations/recovery.

OTHER BENEFITS

- Improve the edge conditions of pavements and reduce damage to main lanes.
- Provide additional safety benefits at a low cost if the strategy can be implemented in the existing ROW.

LIMITATION S / CONSIDERATIONS

May require additional right-of-way to construct.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Adequate ROW	Well established engineering and construction methods are available and must be adhered to.	Moderate	Moderate

Strategy 17: Raised Road Profile

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Roads can be raised to remain passable in the event of flooding, sea-level rise, and storm surge. Raising/elevating roads is a well-established strategy and has been implemented in many coastal communities. Adequately designed culverts are needed to facilitate the drainage of water under the raised/elevated roads.

APPLICATION	CLIMATE STRESSORS
• Roadways directly exposed to coastal waves • Inland roads requiring protection from flooding	• Local Flooding • Sea Level Rise • Storm Surge

ADAPTION RESPONSE

• Prepare • Protect	• Recovery

RESILIENCE BENEFITS

- Road segments that are vulnerable to inundation.
- Stormwater management (e.g., drainage) strategies are considered less effective.

OTHER BENEFITS

- May eliminate persistent maintenance difficulties and associated costs.
- May improve motorist's visibility.

LIMITATION S / CONSIDERATIONS

- Raising the profile of a road can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes considered vulnerable to inundation.
- Additional ROW may need to be acquired to allow for increased side slopes.
- Road signs, guardrails, and other appurtenances may be affected.
- Potential impacts to adjoining homes or businesses since these properties tend to remain at a lower elevation.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective.	Needs to be complemented with adequately designed culverts to facilitate drainage. Consider inundation depth and length of inundation (period of inundation considering different scenarios)	Well established engineering and construction methods are available and must be adhered to.	High initial costs associated with road reconstruction, additional ROW purchases (if required), and given impacts on appurtenances.	No additional maintenance costs after raising the road.

Strategy 18: Geosynthetics / Geo Textiles

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Geosynthetics/geotextiles (such as green mats) are increasingly used in strengthening or enhancing the resiliency of transportation infrastructure. Geotextiles/Geonets are used to enhance drainage, Geogrids and geotextiles are typically used on embankments and to strengthen pavement layers, and geotubes and erosion control mats are used effectively to mitigate beach erosion.

APPLICATION	CLIMATE STRESSORS
• In coastal regions and areas where drainage issues are prevalent, as well as where erodible soils, like silts and sands, are applicable	• Local Flooding • Storm Surge

ADAPTION RESPONSE

• Prepare • Protect	• Recovery

RESILIENCE BENEFITS

- Enhance or strengthen the base of pavement structures.
- Provide a moisture barrier that prevents water infiltrating into the base and weakening sub-layers.
- Prevent erosion.

OTHER BENEFITS

- Increase the service life of the road.

LIMITATION S / CONSIDERATIONS

- Initial costs and design guidance available for some applications, while in other cases, the available information is largely empirical.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective and well-established case studies and guidelines in some cases.	Requires moderate to specialized construction equipment (infrastructure specific)	Location-specific	Moderate to high initial costs	Low maintenance costs

Strategy 19: Permeable Pavement

STRATEGY CATEGORY	Infrastructure (Primary) & Stormwater Management (Secondary)

DESCRIPTION

Permeable pavements have porous surfaces that slow, filter, and clean stormwater runoff.

APPLICATION	CLIMATE STRESSORS
• Appropriate for highways with low traffic volumes, axle loads, and travel speeds • Parking areas • Bridge decks	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Help to reduce runoff and mitigate flooding.
- Facilitate greater drainage into the soil.

OTHER BENEFITS

- Reduce particulates and clean runoff.
- Reduce erosion.

LIMITATION S / CONSIDERATIONS

- The open pores can become clogged if not installed properly or not well maintained.
- Only appropriate on gentle slopes.
- Not as strong as conventional pavements, therefore potentially shorter service life.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective in applicable location and if well maintained.	Location-specific	Location-specific	Moderate	Low

Strategy 20: Maintain and Restore Wetlands

STRATEGY CATEGORY	Other

DESCRIPTION

A wetland is an area of land where freshwater or saltwater covers the soil or is present either at or near the surface of the soil all year or for varying periods of time during the year. Wetland ecosystems are critical buffers against extreme climatic events. Wetlands reduce erosion and flooding, store water during droughts, and act as a natural barrier to the spread of fires. Wetlands can also minimize the impacts of storms by slowing the speed and reducing the height and force of waves.

Wetlands are diverse and delicate ecosystems that are ecologically and economically valuable. The extent to which a wetland ecosystem can buffer against extreme events depends on the ecosystem's health and the intensity of the event.

APPLICATION	CLIMATE STRESSORS
• Inundated coastal or inland ecosystems that protect against extreme climatic events	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Absorb floodwaters and minimize the negative impacts of storms.

OTHER BENEFITS

- Carbon sequestration through photosynthesis.
- Increase biodiversity.
- Create space for education and recreation.

LIMITATION S / CONSIDERATIONS

- Wetlands are not able to treat highly toxic modern wastewater.
- Constructed wetlands are land-intensive undertakings

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Wetland conservation and restoration helps protect against the adverse ecological impacts of a changing climate (flooding and negative impacts of storms).	Hydrology, vegetation type, and soil type must be considered for effective wetland implementation	Difficult	Moderate	Low

Strategy 21: Beach Nourishment and Dune Restoration

STRATEGY CATEGORY	Other

DESCRIPTION

Beaches reduce the destructive impact from coastal storms by acting as a buffer along the coastal edge and absorbing and dissipating the energy of breaking waves. Beach nourishment and dune restoration are soft engineering alternatives to hard shoreline structures.

Beach nourishment is the process of adding sand to replace beach material lost through erosion. A wide beach can reduce storm damage to coastal structures by dissipating a storm's energy and protect structures from storm surges and rising tides.

Beach dunes act as natural fences and provide erosion, flood, and storm protection by acting as a buffer against the high wind and waves of powerful storms. Without them, a tropical storm surge would flow unimpeded over the coast causing major damage to property and communities.

APPLICATION	CLIMATE STRESSORS
• Coastal communities	• Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Provides resilience against storms and sea-level rise.
- Protects salt marshes and seagrass beds.

OTHER BENEFITS

- Dunes provide habitat for plants and animals, including rare and endangered species.
- Beach nourishment enhances the recreational value of a beach.

LIMITATION S / CONSIDERATIONS

- Sand used for replenishment must be compatible with existing sand on the beach.
- The public will not have access to the beach during beach nourishment and dune restoration activities.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Reduce coastal storm risk and enhance coastal community resilience.	May need to be implemented with other structures to provide more capacity to absorb induced wave energy.	Moderate	Moderate	Low

Strategy 22: Vegetation (as Erosion Control)

STRATEGY CATEGORY	Other

DESCRIPTION

Vegetation cover is the most effective and practical means of preventing loss of sediment. The roots of vegetation bind soil particles together to resist erosion from runoff rainwater. Vegetation also absorbs the impact of raindrops to prevent the detachment of soil particles and reduces the velocity of runoff, which allows water to infiltrate.

APPLICATION	CLIMATE STRESSORS
• Slope and channel protection • Dune protection • Aquatic vegetation	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Reduces sediment loss.
- Increases biodiversity.

OTHER BENEFITS

- Unlike pavements, vegetation “cools” the air by eliminating heat energy.
- Vegetation acts as a carbon sink by absorbing more carbon dioxide than it releases.
- Vegetation significantly reduces noise pollution, particularly in urban areas, through sound attenuation.

LIMITATION S / CONSIDERATIONS

Not applicable.

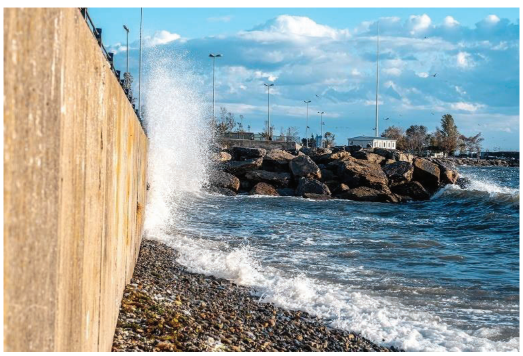
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Protects against erosion and sediment loss.	Maintenance program must be developed during installation.	Easy - Methods of implementation include sodding, hydroseeding, hydro-mulching, drill seeding.	Low	Low

Strategy 23: Seawalls and Revetments

STRATEGY CATEGORY	Other

DESCRIPTION



Seawalls and revetments are shore parallel structures at the transition between the low-lying beach and the higher mainland or dune line. Seawalls and revetments effectively act as a form of coastal defense by redirecting the energy of a wave (caused by storm surge) back to the ocean water, protecting the coastline from flooding and reducing erosion of the beachfront. A revetment has a distinct slope (e.g., 2:1 to 4:1), while a seawall is vertical. It is important to note that while seawalls and revetments protect the properties behind them from storm surge and sea-level rise, they also cause a high degree of turbulence in front of them, which often scours the beach material.

APPLICATION	CLIMATE STRESSORS
• Coastal shorelines and communities	• Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Provides opportunities for sightseeing and recreation.

LIMITATION S / CONSIDERATIONS

- Seawall/revetment construction is expensive.
- Offers a long-term solution.
- Should be implemented as part of a larger coastal region management plan.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Protects shoreline by redirecting wave energy back to the ocean	Large space required for construction	Difficult - Requires professional engineering/construction services	High	Low

Strategy 24: Wave Attenuation Devices

STRATEGY CATEGORY	Other

DESCRIPTION

Storm surge is often the greatest threat to coastal life and property from a tropical storm or hurricane. When a storm surge approaches, marshes are often the first line of defense. However, the effectiveness of marshes is reduced with the increased wave action of a storm surge. Wave Attenuation Devices protect shorelines by reducing and reflecting the energy of waves while allowing water to pass through. It is important to note that they are not wave eliminators.

APPLICATION	CLIMATE STRESSORS
• Coastal area and shoreline	• Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Can support sea life when vegetation and bivalves are established, which attract fish.
- Allow boat mooring.

LIMITATION S / CONSIDERATIONS

- Performance of a WAD is a function of depth and width.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Provides protection from destructive wave energy.	Specialized equipment required for safe implementation.	Difficult	Moderate	Low

Strategy 25: Debris Deflectors for Bridge Protection

STRATEGY CATEGORY	Other

DESCRIPTION

Debris accumulating around bridge columns after a storm event can cause damage or failure of a bridge structure. It can also result in increased scour and backwater buildup. Removal of the debris is difficult, time-consuming, and an expensive part of maintenance programs. Debris deflectors are placed immediately upstream of the structure and are oriented in the direction of the flow so that the debris does not make direct contact with the bridge structure, reducing the impacts.

APPLICATION	CLIMATE STRESSORS
• In waterways that have bridge structures that are subject to debris accumulation	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Protects structures (bridge piers, beams, etc.) during and after storm events.
- Prevents debris from damaging drainage structures.

OTHER BENEFITS

- Increasing the service life of the bridge.

LIMITATION S / CONSIDERATIONS

- Prior to design or implementation of debris deflectors, a field investigation should be completed to determine flow characteristics, sediment and potential future changes in the watershed.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective at reducing damage from debris accumulating on bridge structures.	Field investigation and engineering study required. Access to structure.	Moderate	Moderate	Low

---

[ii] Texas Department of Transportation. 2019. Hydraulic Design Manual. September 12. Available at: http://onlinemanuals.txdot.gov/txdotmanuals/hyd/culverts.htm

[iii] Pace, N.L. N.D. "Resilient Coastal Development Through Land Use Planning: Tools and Management Techniques in the Gulf of Mexico", University of Mississippi School of Law. Available at http://www.gulfofmexicoalliance.org/files/projects/files/79ResilientLandUse.pdf