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Quantification of Multimodal Transportation Network Vulnerability: A Pilot Study in Mississippi

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1. Background and Project Description

Many factors influence vulnerability of urban coastal transportation network. Among them climate change, natural and incidental hazards, and the aging infrastructure are the most important factors. Thus it is crucial to understand how these factors impact multimodal transportation network sustainability and adapt solutions to cope with this.

Large scale transportation and infrastructure network include roads, railways, seaports and communication networks. These networks are subjected to threats from natural and man-made disasters as well as climate extremes. Hazards such as flooding and other disasters can cause significant disruption to transportation and infrastructure network. When parts of a linked transportation network are disrupted, the delay in commodity transport could cause significant economic losses. Development of a network based quantitative framework will be beneficial to interpret hazard responses as well as devise recovery strategies. Literature suggests that network science methods have resulted in actionable information on network vulnerabilities and fragility, especially in the context of response to disruptive events (Bhatia, 2015).

A growing number of populations now live in urban areas tend to be located near water. This trend is also a concern for increased risk associated with flooding especially in the urban coastal regions. Hurricane Katrina and Superstorm Sandy are two examples of why we need to enhance predictability and resiliency from flood risk in urban coastal areas in the context of changing climate. Due to anticipated sea level rise caused by climate change, flooding associated with coastal storms and hurricanes can have a devastating toll on the infrastructure system, especially on water, energy infrastructure and transportation networks. Impact depends on local conditions as well as projection of climate extremes. For example, individual coastal neighborhoods may encounter localized flooding, finding their drainage systems likely to be overloaded more frequently and severely, causing backups and street flooding, and impairing mobility of people and goods (IPCC, 2007). Responding to this multidimensional challenge requires dedicated research frameworks or centers (e.g., MarTREC Center) to investigate complex interdisciplinary science questions of critical importance. Department of Transportation's (DOT) Center for Climate Change is one of the leading research centers which was established in 1999 to conduct research to address these challenges. In 2008, funded by this center and several other organizations including the Transportation Research Board (TRB), Environmental Protection Agency (EPA), and the U.S. Army Corps of Engineers, the National Research Council (NRC) conducted a study to explore the potential impacts of climate change on US transportation and infrastructure (National Research Council, 2008). The NRC study report summarizes that *"the impacts of climate change will vary by region and it is certain that they will be widespread and costly in human and economic terms, and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems."*

In 2008, the Federal Highway Administration (FHWA) developed a conceptual model for the State Departments of Transportation (DOT) and Metropolitan Planning Organizations (MPOs) in order to assess risk and vulnerability of transportation infrastructure that will likely be impacted by climate change (http://www.climate.dot.gov/impacts-adaptations/forcasts.html). Based on this conceptual model, a number of pilot studies have been initiated (National Research Council, 2008; CCSP, 2009). Among them, the most pertinent one relevant to Mississippi is the Gulf Coast study titled "Impacts of Climate Change and Variability on Transportation Systems and Infrastructure" (CCSP, 2008, CCSP, 2009). It recognized the fact that transportation network and infrastructure along the three coastal counties of Mississippi (Hancock, Harrison and Jackson) where, hundreds of miles of coastal highways along with other infrastructures (ports, railways) are in immediate exposure to hazards from periodic and intense flooding. The consequence is, as National Research Council report (2008) summarizes, *"As climate changes induce new extremes, operational responses are likely to become more routine and proactive than today's approach of treating severe weather on an ad hoc, emergency basis. For example, if hurricanes increase in intensity, as is likely to be the case, establishment of evacuation routes and use of contra flow operations may become more frequent".* Thus it is critical, not only to systematically inventory multimodal transportation network and infrastructure in coastal Mississippi, but also to conceptualize a network based quantitative framework to explore vulnerability of transportation systems exposed to both natural and man-made hazards.

Water has historically played a central role in transportation systems. This is the primary reason that most urban developments are clustered along the coast and navigable rivers. However, the very reason that cities are located adjacent to water has led to increased vulnerability, as rivers flooding and coastal storm surge can temporarily halt land and water based transportation systems. While flooding is an obvious problem for land-based infrastructure, it also impacts shipping. For example, the Intracoastal Waterway (ICW) is a 3,000-mile (4,800 km) inland waterway along the Atlantic and Gulf of Mexico which provides the most economically significant navigable route in the United States. This pilot study is focused on transportation infrastructure along the Mississippi Gulf coast which is also a major hub of maritime transportation in Mississippi.

The objective of this exploratory study is to develop a conceptual framework to identify critical transportation infrastructure and their vulnerability to natural hazards based on existing and available data specific to the Mississippi Gulf Coast (Fig 1). This particular study area has been selected based on its robust transportation network (2 airports, approximately 340 miles of highways and navigable channels and ports) and intricate flood plain with barrier islands. As the Gulf coast had been impacted by three significant hurricanes in the past (Betsy in 1967, Camille in 1969 and Katrina in 2005), this particular area is ideal to explore future vulnerability.

The outcome of this exploratory study should help developing a comprehensive design, adaptation and mitigation framework for the State DOT and MPOs in order to address risk and vulnerability of Mississippi's transportation infrastructure when dealing with hazards. Present research findings are also aligned with the Maritime Transportation Research and Education Center (MarTREC) research interest in the area of "Multimodal Supply Chain Efficacy". More specifically, the objective of this pilot study is to address the following two scientific questions which are key to further explore the sustainability and effectiveness of multimodal transportation and infrastructure network under a wide variety of hazard conditions.

i. What are the possible scenarios of future climate changes with respect to projected sea level rise specific to the Mississippi coast?

ii. What are the multimodal transportation network and infrastructures that are vulnerable to natural hazards?

2. Methodology and Approach

To explore the possible scenarios of future climate changes with respect to projected sea level rise specific to the Mississippi coast, an extensive literature review has been conducted. Changes in the future climate in different US regions have been documented by many researchers (IPCC, 2007; National Research Council, 2008). For example, the study conducted by Federal Highway Administration (FHWA, 2009, 2010) presented a regional scale picture of how the climate might change over the near term (2010-2040), and long term (2040-2100) (http://www.fhwa.dot.gov/hep/climate/climate_effects/effects01.cfm#content). The Gulf Coast Phase1 study (CCSP, 2008, 2009) identified change scenarios specific to the central Gulf Coast. This published report was valuable to the present study. However, the climate change information must be downscaled for our pilot project located in the Gulf coast. In order to develop future climate data with respect to projected sea level rise, a suite of computational and visualization tools (NOAA Digital Coast, EPA and USGS web based software) are used. Results are presented in Section 3.0.

To understand the impact of hazards on multimodal transportation network, a detailed inventory specific to the project area has been done through extensive literature survey. For inventory of critical infrastructure, primarily NOAA Digital Coast web based program has been used. As our study area is on an urban coastal setting, we concentrated only on the critical infrastructures such as railroads, evacuation roads, schools, ports, maritime transport and health care and emergency facilities. Examples of transportation and infrastructure inventory data are presented in the following section.

3. Findings

Research findings summarizing primary goals and objectives are described below:

3.1 Scenario for Site Specific Climate Related Forcing

As stated above, one of the objectives of this study is to explore risk and vulnerability of coastal Mississippi's multimodal transportation infrastructures due to climate changes. Mainly three factors of climate change (i.e., changes in temperature, changes in rainfall and storm events, and sea-level rise) and projected sea level rise specific to the Gulf coast are considered. Figure 2 shows the downscaled projection of maximum temperature for the Mississippi Coast. This is developed using Department of Interior, USGS Climate Projection tool. As shown in Figure 2, an increase of 3 to 4 degree Fahrenheit in maximum temperature for the next century is projected for Mississippi. Fig 3 shows downscaled projection of Mean Annual Precipitation for the study area. No significant change in the Mean Annual Precipitation is noticeable in the next century. This is an interesting observation as flash flood due to extreme rainfall and associated vulnerability of transportation infrastructure in the study area may remain unchanged in near future. However, increasing destructiveness of tropical cyclones over the past 30 years, suggests possible intensification of hurricanes in the near future (Emanuel, K., 2005, Webster, 2005). Further research is needed to address this issue.

Later, NOAA long term tide and current records are used to determine downscaled sea level rise scenario for the study area (https://tidesandcurrents.noaa.gov/). Figure 4 shows a map demonstrating available tidal stations near Mississippi Gulf coast which are operated by NOAA. Figure 5 shows mean sea level trend for Bay Waveland (Station No. 87437). This plot shows monthly Mean Sea Level (MSL) without regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95% confidence interval. The calculated trends show about 0.3 meter or about 1.0 feet of sea level rise in the study area per century. This is also shown in Figure 6 where at the 99% confidence level (blue line), the Mean Higher High Water (MHHW) sea level rise is projected to rise about 0.3 meter (about 1 foot) in all but one year by next century although it could be exceeded more than once in other years. Based on these long term records and downscaled climate projections, a 0.3 meter (1.0 foot) sea level rise scenario is adopted for the pilot project for future vulnerability analyses.

Figure 7(a) shows existing FEMA flood zone along the Mississippi coast with 1% probability of chance (100 year return period) without considering sea level rise. This map has been developed using NOAA Digital Coast web based application. Figure 7(b) shows the zoomed Mississippi Gulf Coast area considering 1 foot sea level rise scenario. Notice that Highway 90 which is one of the main highways in the study area is anticipated to flood considering 1 foot sea level rise scenario. Figure 8 shows storm surge flooding from different categories of hurricanes with 1 foot sea level rise scenario. Here red color shows the inundation from relatively weak category 1 hurricanes; whereas, yellow color shows the inundation from the strongest category 5 hurricanes. Widespread flooding on road and infrastructures is noticeable with this scenario run. All of these maps are developed using NOAA Digital Coast web based application. These maps are used to identify multimodal transportation network vulnerable to present and future climate related hazards.

3.2 Inventory of Critical Infrastructure Exposed to Hazard Condition

As described in Section 3.1, extreme storm surge and flooding condition along with a 1 foot sea level rise scenario has been used in this study to identify critical infrastructures that are vulnerable. A suit of software and tools (NOAA digital coast, USGS Infrastructure Resilience, FEMA HAZUS) are used to identify critical infrastructure located in the project area. Figure 9(a) and 9(b) shows maps of critical facilities (coastal roads, schools, fire station, railroad, maritime transportation) located in the study area. These sites are geo-referenced and populated into a database to be used later for the multimodal network vulnerability analyses. Moreover, projected population growth in this area also increases the dimension of future vulnerability. Figure 10(a) shows a map of current population. Dark brown color adjacent to highway 90 represents population density of more than 45,000 per square mile. Figure 10(b) shows the population projection developed using USGS tool. Data shows an average 2.5% growth per year (Blue shade) along the narrow coastal fringe where storm surge vulnerability is the highest. Figure 10(c) shows high intensity development within the vicinity of the study area. These figures demonstrate socioeconomic and demographic importances which are critical to quantify future hazard condition and transportation network vulnerability. Figure 11 shows the vulnerability of critical facilitates under combined effect of sea level rise and storm surge. This is developed using Digital coast tool developed by NOAA. Note that with 1 foot sea level rise along with a modest synthetic hurricane scenario (Cat 3), most of the critical facilitates and transportation network are exposed to significant flooding considering current land use condition.

A thematic map illustrating combined infrastructure vulnerability is shown in Figure 12. This map is developed using socioeconomic variables (Fig 9, 10) and flood inundation using 1 foot sea level rise scenario (Fig 11). The interpretation of the thematic map is that, during a flood event, red or dark brown-colored area are at higher risk than the area shown in light colors. In this particular case, there are seven census blocks which are found to be very highly vulnerable (Z-score ≥ 1.5), whereas 20 blocks are found to be highly vulnerable (0.5 ≤ Z-score <1.5). The majority of the blocks (32) are in the intermediate vulnerability group (−0.5 ≤ Z-score > 0.5), 16 blocks are in low vulnerability group (–1.5 ≤ Z-score < –0.5) and the rest of 16 blocks are in very low vulnerability group (Z-score < −1.5). Relevant transportation infrastructures grouped by the vulnerability index are then georeferenced and organized into a database. This database will be the key element to conceptualize and explore future vulnerability and sustainability of multimodal transportation and infrastructure network under a wide variety of hazard conditions.

4. Project Impacts

- Accomplished key project goals by identifying future climate scenarios and inventory of critical infrastructure and transportation data specific to the Mississippi Gulf Coast project area.
- Based on the long term records and downscaled climate projections, a 0.3 meter (1.0 foot) sea level rise scenario is projected for the Gulf coast pilot project for future vulnerability analyses.
- From our findings, although extreme rainfall within the study area may remain unchanged, possible intensification of hurricanes in future may need to be explored while addressing storm surge vulnerability.
- Critical infrastructures vulnerable to future climate condition and storm surge scenario are identified, and then organized into a database.
- This database will be helpful to conceptualize and explore future vulnerability and sustainability of multimodal transportation and infrastructure network under a wide variety of hazard conditions.
- Although not funded through the project, a graduate student named Neha Sinha worked on this project. Ms. Neha Sinha successfully defended her MS thesis with a concentration in coastal engineering. She graduated in May, 2017.
- Graduate Student Marvin Thomas and Lei Bu also worked on this project. Both of them were primarily mentored by Dr. Feng Wang with support from the PI of this project. Their work generated a peer reviewed publication as cited:

  Marvin Thomas, Lei Bu, Himangshu Das and Feng Wang, "Analyses of Storm Surge Induced Flood Risk in Coastal Areas of Mississippi", Invited Student Paper, TRB 96th Annual Meeting at Washington DC, January 8-12, 2017

5. Recommendations

We have developed a conceptual quantitative framework and database identifying critical transportation infrastructure and their vulnerability to natural hazards using existing data, modeling while incorporating downscaled climate scenario specific to the Mississippi

Gulf Coast. It is recommended that the current inventory database should be supplemented with other critical transportation assets managed by state and MPO(s). This enhanced database will be helpful to explore future vulnerability and sustainability of multimodal transportation and infrastructure network under a wide variety of hazard conditions. It is recommended that the inventory of critical transportation infrastructures that has already been developed must be linked into a network algorithm. Later response and recovery of the perturbed network must be quantified through what-if scenarios. Recently the Principal Investigator of this study submitted a proposal to MarTREC illustrating this concept while seeking additional funding to support a Ph.D level graduate student to continue working on this project. If funded, this network based quantitative framework will be instrumental to broadly understand vulnerability of transportation systems exposed to both natural and man-made hazards.

6. List of Figures

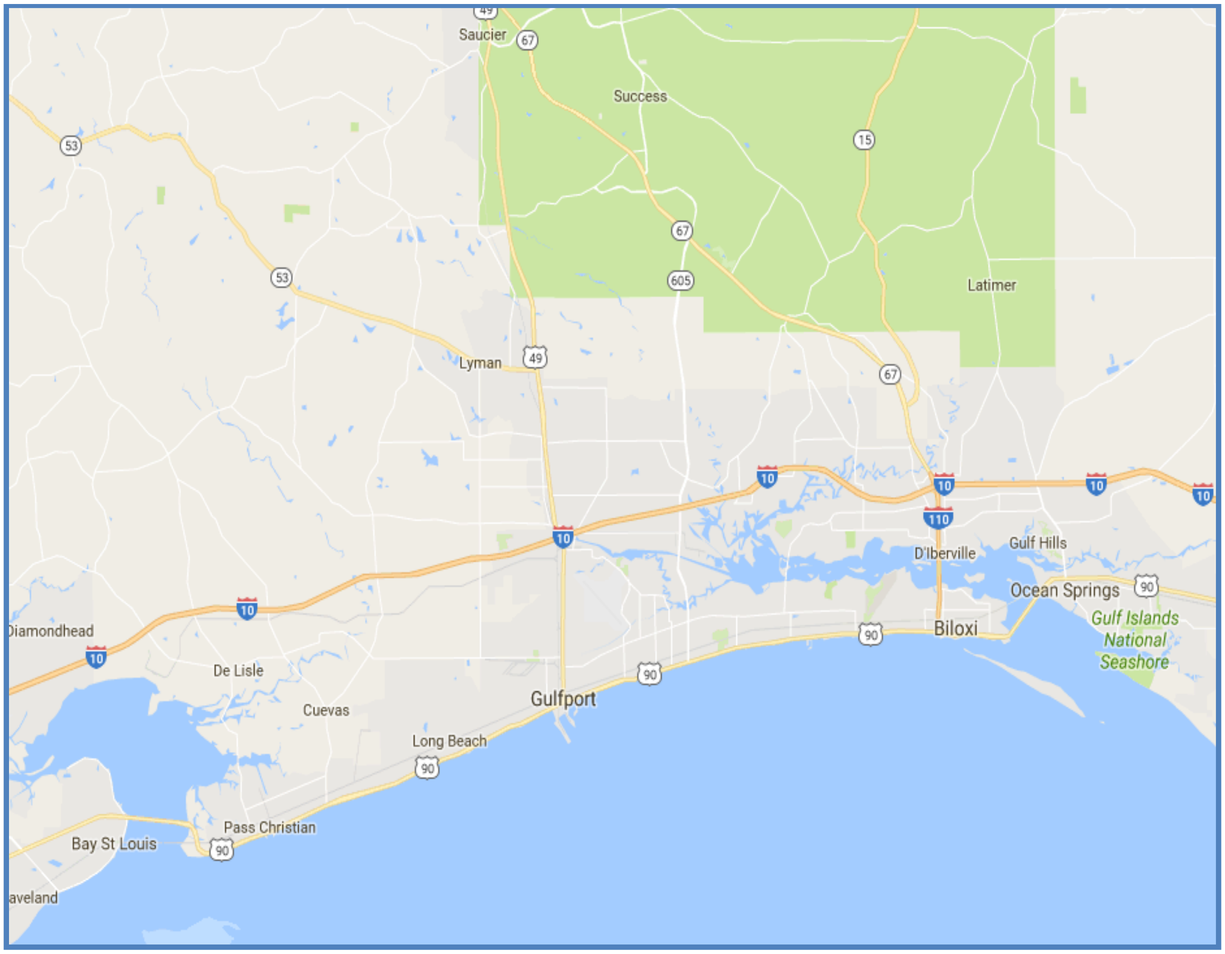
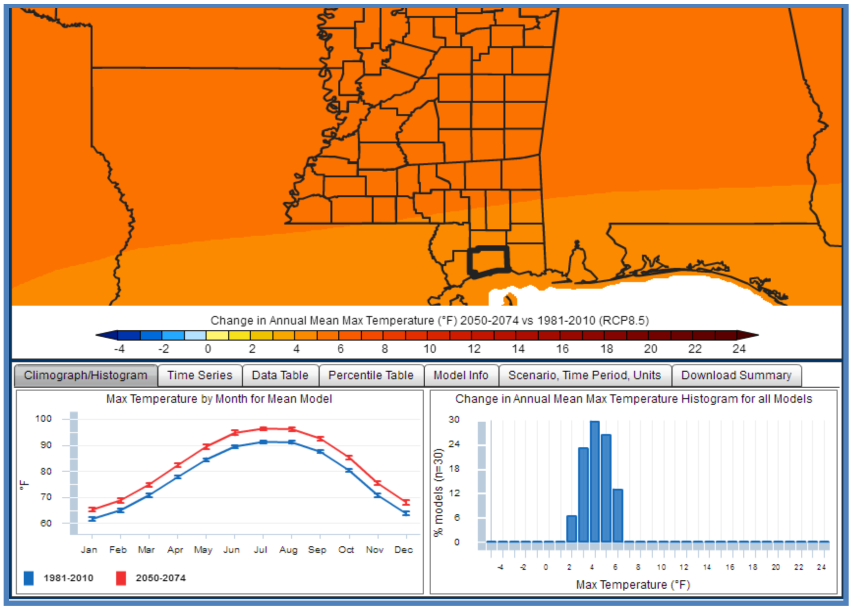


Figure 1: Study Area (Mississippi Gulf Coast)



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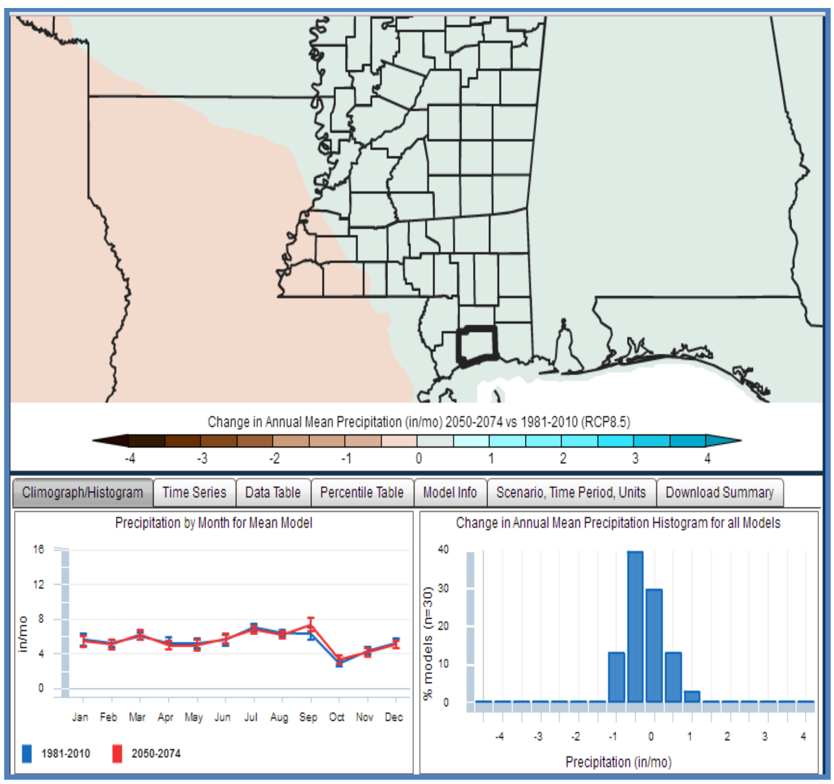


Fig 3: Downscaled projection of Mean Annual Precipitation specific to Mississippi Coast [Developed using Department of Interior, USGS Climate Projection Tool]

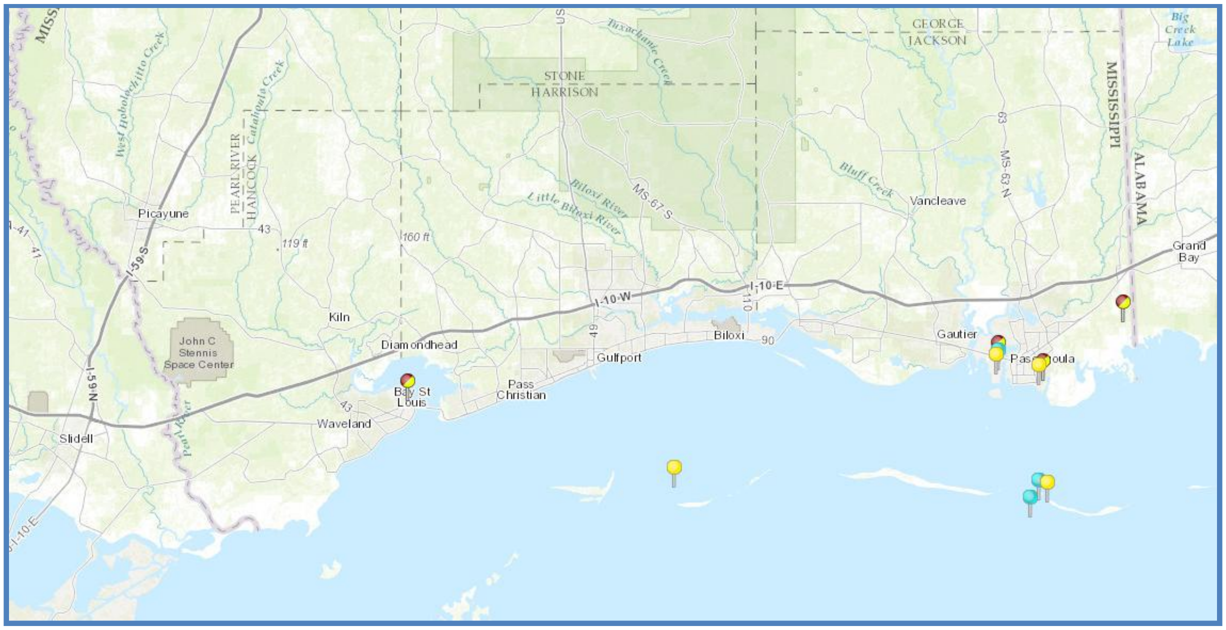
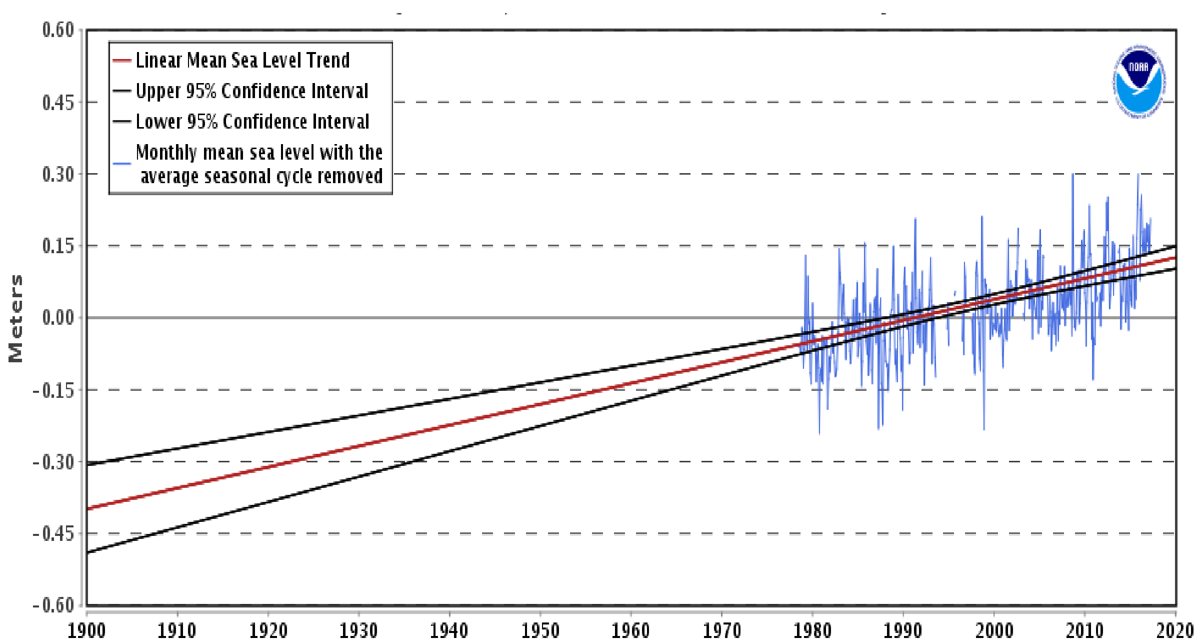


Figure 4: Map of available tidal stations near the Mississippi Gulf coast managed by NOAA.



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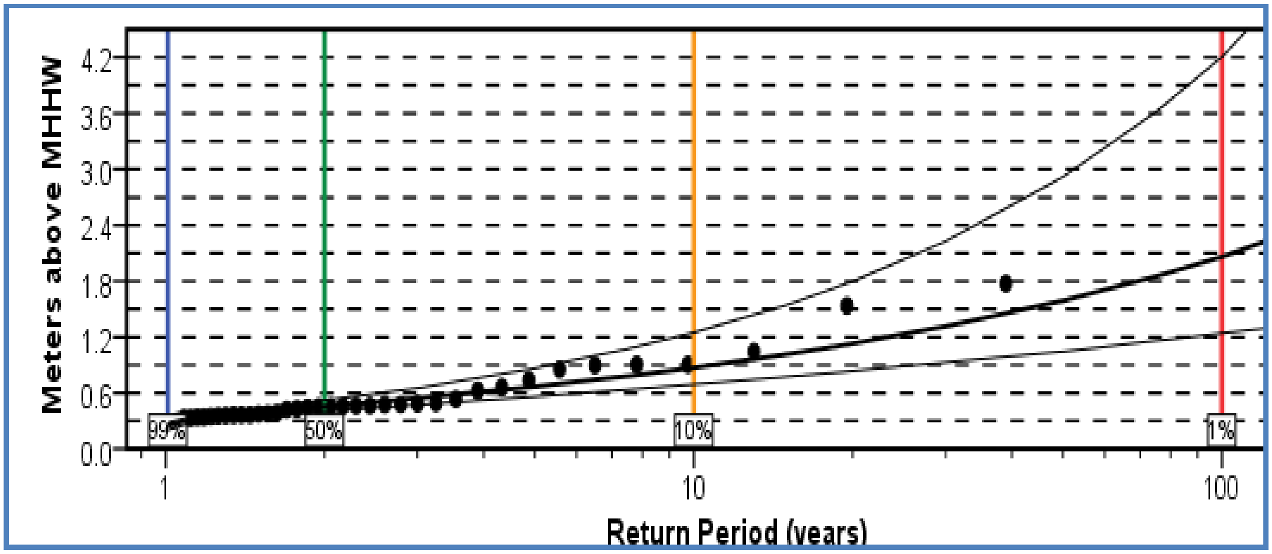

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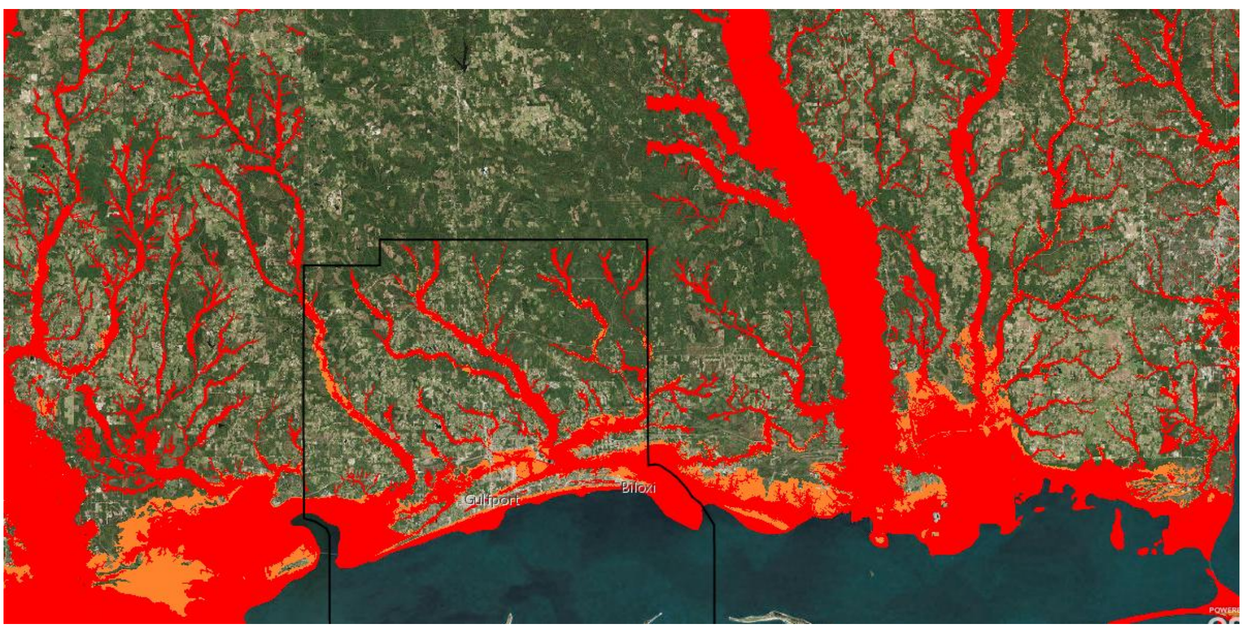


Figure 7(a): Existing FEMA Flood Zone with 1% probability (100 year return period) without Sea Level Rise [Map developed using NOAA web based software)

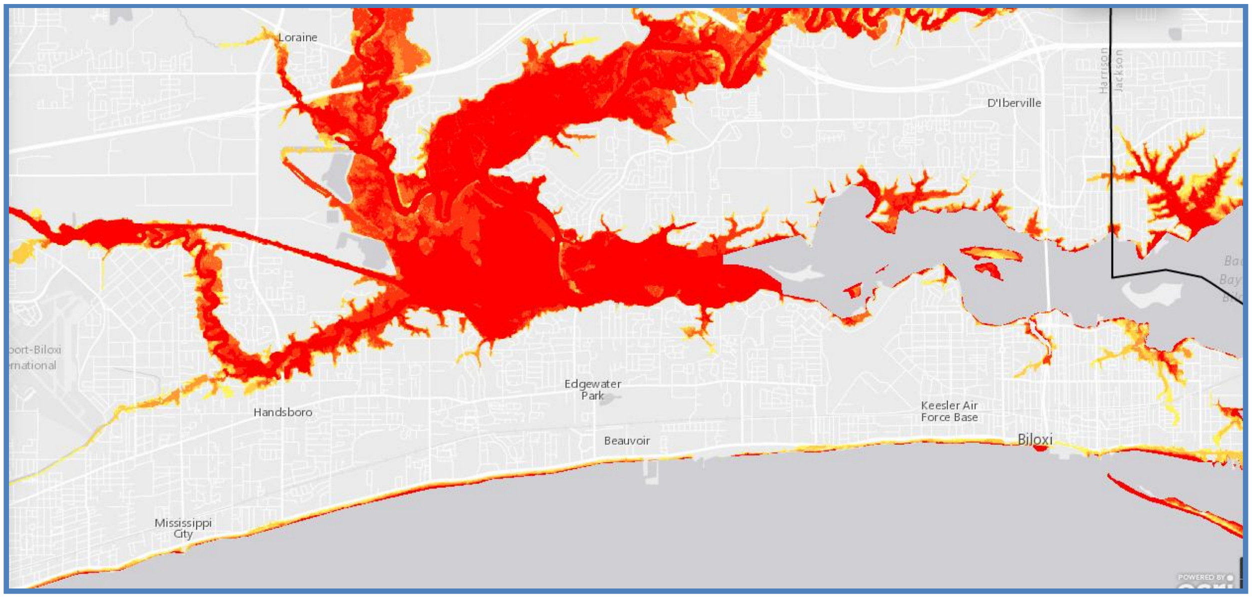


Figure 7(b): Mississippi Gulf Coast Area flooding considering 1 foot Sea Level Rise scenario

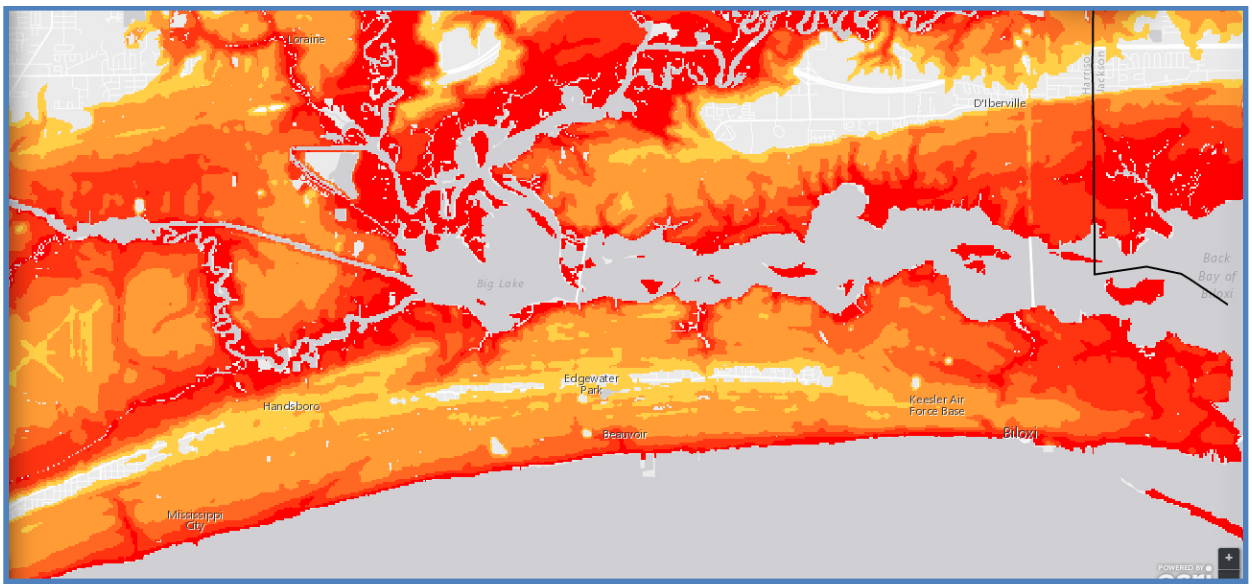


Figure 8: Inundation from storm surge (Red Color: Category 1 storm; Yellow Color, Category 5 storm)

Figure 9 (a): Critical infrastructure facilities located in the study area (Developed using Dept of Interior, USGS Tool)

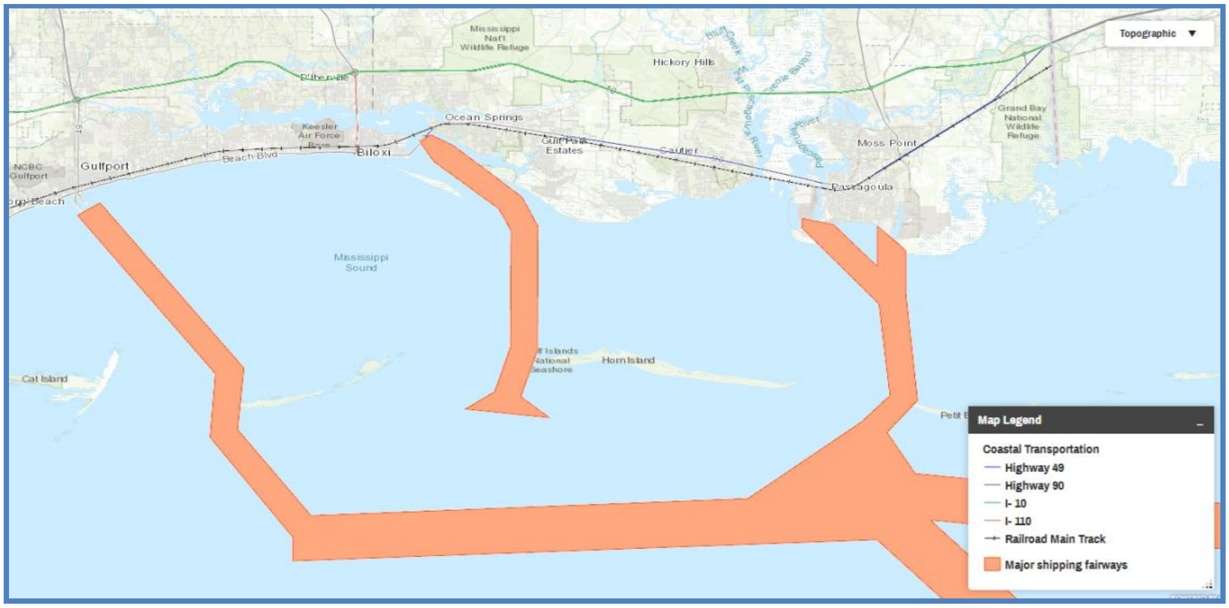
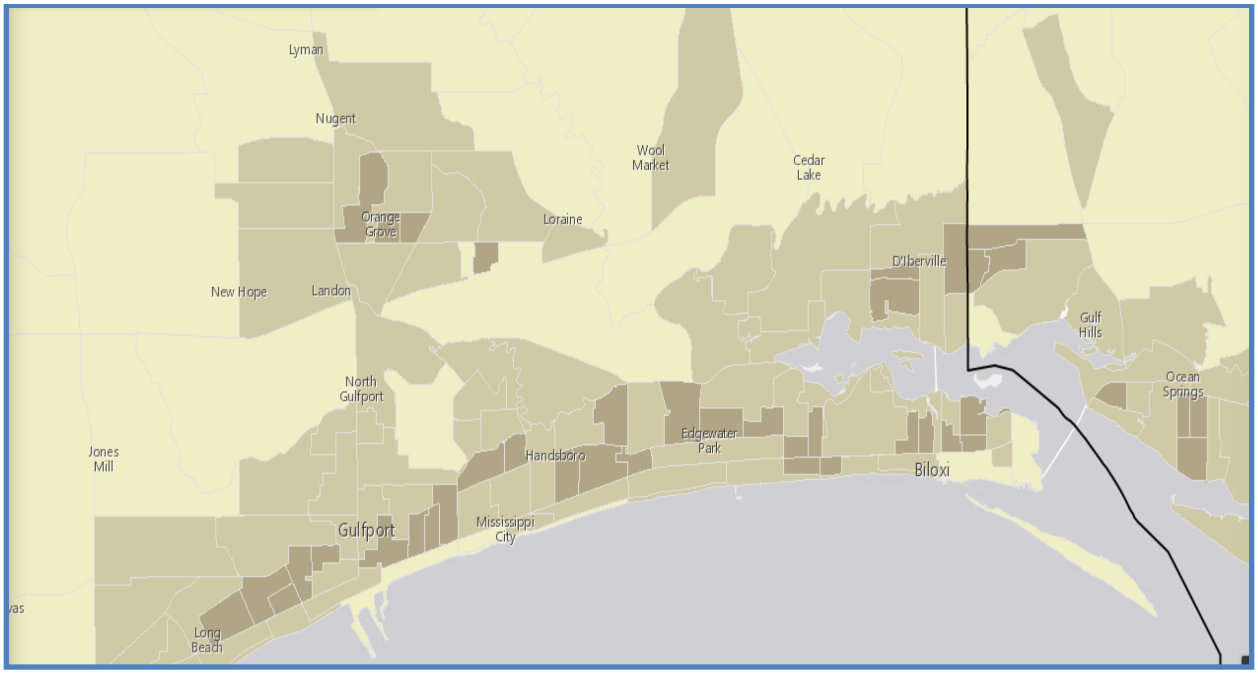


Figure 9 (b): Critical maritime infrastructure facilities located in the study area (Developed using Dept of Interior, USGS Tool)



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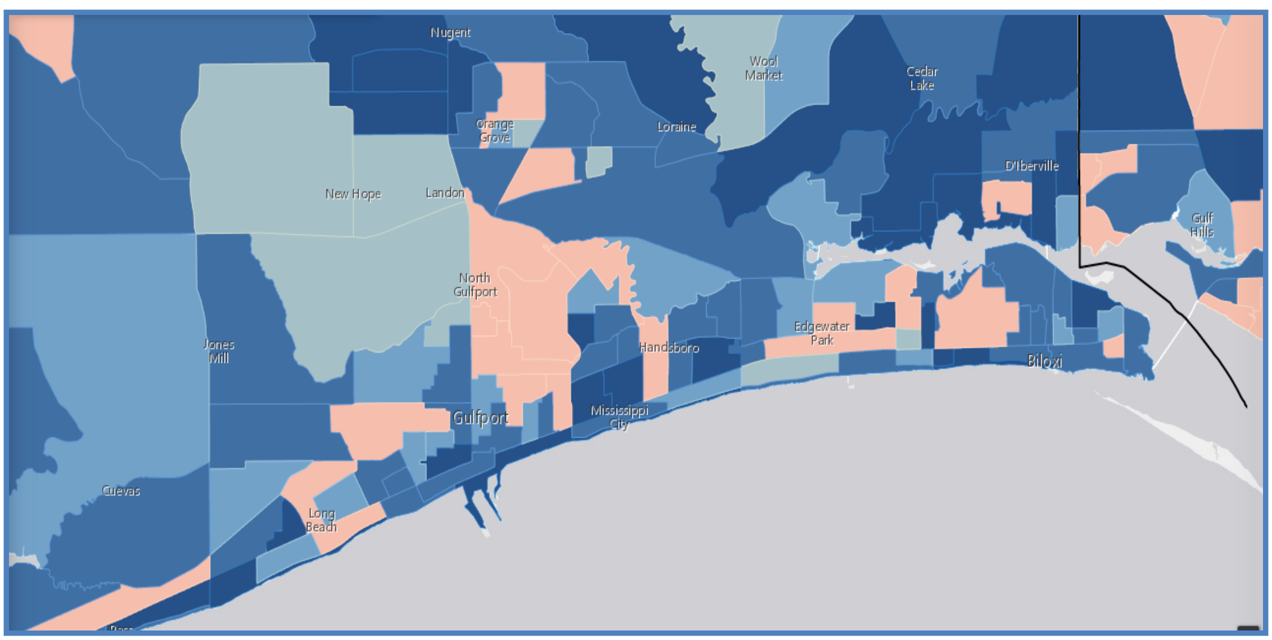

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Figure 11: Vulnerability of critical facility under combined effect of Sea Level Rise and Storm Surge (Developed using NOAA Digital Coast Tool)

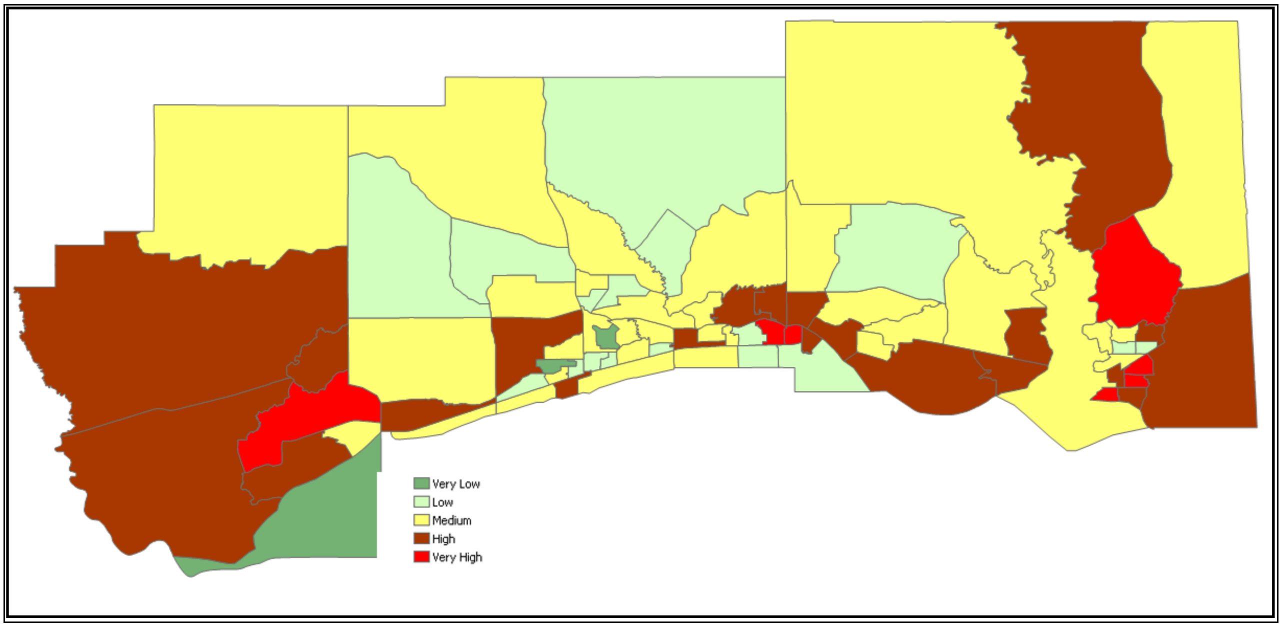

Figure 12. Combined surge and socioeconomic vulnerability in the study area developed using normalized Z-score approach

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