AN INTEGRATED APPROACH TO COASTAL COMMUNITY'S VULNERABILITY ANALYSIS--- CASE STUDY IN TAMPA BAY REGION

By

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To my mom and dad

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LIST OF ABBREVIATIONS

GHG	Greenhouse Gas
GIS	Geographical Information System
GOM	Gulf of Mexico
GWR	Geographically Weighted Regression
NOAA	National Oceanic and Atmospheric Administration
OD	Origin Destination
SLR	Sea Level Rise
TAZ	Traffic analysis zone
TBRPM	Tampa Bay Regional Planning Model

Abstract of Dissertation Presented to the Graduate School
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The rise of sea level, as one of the most obvious and direct impacts of climate change in coastal areas, will cause more inundation and coastal flooding that may threaten the coastal communities. Analyzing coastal communities' vulnerability to sea level rise will provide guidance for adaptation planning. However, previous literature usually ignore the multidimensional nature of vulnerability (Yoon, 2012). This study tries to understand the multidimensional effects sea level rise may have on coastal community by answering the following research questions: How to determine the importance of different measures in integrated vulnerability index? How does coastal communities' overall vulnerability differ over the space and time? How do land use patterns, transportation network characteristics, and demographic factors influence transportation vulnerability to sea level rise? To answer these research questions, this study quantifies coastal community's vulnerability to sea level rise using economic, social, and infrastructure measures at the census block group level. Tampa Bay region in Florida is used as a case study considering data availability and its exposure to coastal disasters. The weight of each indicator in the overall vulnerability index is determined using an improved analytical hierarchy process (AHP) method and expert

ratings collected through surveys. A new trip-based vulnerability indexes are proposed to quantify the potential impacts of sea level rise on neighborhood accessibility at the traffic analysis zone level with consideration of trip production and attraction changes caused by sea level rise inundation. Regression models have been used to test the relationship between the accessibility based vulnerability index and local transportation network characteristics, land use pattern, and demographic factors. The vulnerability analyses have identified the most vulnerable census block groups in the region under different sea level rise scenarios. Although social, economic, and infrastructure vulnerabilities are weighted equally in the integrated vulnerability calculation, the influences of social, economic, and infrastructure to integrated vulnerability differ by location and time due to the differences in level of exposure and sensitivities. Risk assessment shows that the case study area should begin to make adaptation plans to help them prepare for significant vulnerability increases that will happen within 15 years (under medium and fast sea level rise scenario) to 25 years (under low sea level rise scenarios).

CHAPTER 1
INTRODUCTION

Climate change has become a popular research topic in recent years as more and more scientific evidences indicate that climate change is not a scientific fiction but phenomena that are happening and will continue to happen (IPCC, 2013). Due to urban infrastructure and transportation's great contributions to greenhouse gas emissions, many research focus on evaluating transportation and land use plan or policy's effects in greenhouse gas (GHG) mitigation. However, from another perspective, urban planning also plays a crucial role in adapting to climate change. For example, as acknowledged by Winkelman et al. (2010), transportation investments will not only affect GHG mitigations but also how communities adapt to the climate change. Since the National Research Council (2008) concluded that climate change would greatly affect the performance of transportation and urban infrastructures, many researchers have investigated the impacts of climate change on urban environment. Researchers conclude that rising sea levels, more frequent precipitation, and storms will challenge our current planning practice and call for more quantitative and localized research in this area (Olsen et al., 2005; Kirshen et al., 2004; Suarez et al., 2005; Sato and Robeson, 2006).

Among various climate change factors sea level rise is one of the most wide-spread and credibly predicted factors that caught many attention in recent years. Even if the greenhouse gases have no further increases, the accumulation of GHG emissions during the past centuries is enough to cause climate change that will quite likely change the sea levels in decades (National Research Council, 2008; EPA 2005). According to the IPCC (2001), since the peak of the last ice age, the average global sea level has risen more than 120 meters. Moreover, the global average rate of sea level rise in the 20th century was greater than that of the 19th century (IPCC, 2013). The IPCC Fourth Assessment Report (IPCC, 2013) projected that, using conservative estimates, average global sea levels will continue to rise by 0.18 to 0.59 meters before the year 2100.

Specifically, the case study area of this study, Gulf of Mexico area, is more vulnerable to sea level rise compared with other regions due to local subsidence and its extensive exposure to the ocean. According to Burkett (2002), the Gulf of Mexico is experiencing a significantly higher rate of sea level rise than other regions on the U.S. Pacific Coast, as the land surface of the Mississippi River Deltaic Plain is subsiding at a rate of 0.25 inch/year (10 mm/year). In addition, the Gulf of Mexico has a long coastline: states bordering the Gulf of Mexico have a total of 2610 km of open ocean coastline (Morton et al, 2004). The high rate of relative sea level rise will cause flooding that affects coastal and low lying areas and increasing coastal erosion, all of which are major challenges to urban infrastructures (US Climate Change Science Program, 2009).

Problem Statement

As sea level rise is such a continuous and severe threat to coastal communities, more and more planning scholars and professionals are taking sea level rise into consideration in the long range planning process, as necessary. Supported by the Gulf of Mexico Sea Grants and National Oceanic and Atmospheric Administration research project “Development of Sea Level Rise Adaptation Planning Procedures and Tools Using National Oceanic and Atmospheric Administration (NOAA) Sea Level Rise Impacts Viewer”, a survey that aims at understanding the current adaptation to sea level rise planning practice and research needs is being conducted in Tampa Bay region. The survey audiences are planning professionals, and respondents covering 18 important planning agencies within the region, including planners from four county level planning agencies, seven major city planning department, four regional planning department, and private planning consultant sectors. The survey results show that majority (over 90%) of the respondents believe sea level is rising. The survey asks audiences to list three most important agencies that should take primary responsibility in adaptation planning. The results show 77% respondents list county government as one of the agencies with primary responsibility, 59% of the respondents list city/town government as one of the agencies with primary responsibility, and 41% list state government. This emphasizes the importance of local planning in adaptation to sea level rise. However, more than 60% of the surveyed agencies do not have adaptation plan with a specific planning time range at the moment, and about 60% respondents think there is not adequate information and tools to support sea level rise planning and adaptation. All of these results show despite the significance of adaptation planning to coastal community the current adaptation planning practice at the local level is still limited due to the lack of information.

Regarding the information that may be useful to local adaptation planning, respondents identify water level maps, inundation maps, and flood frequency map as the most important ones, followed by identifying most vulnerable locations, showing integrated overall vulnerability, and providing adaptation suggestions. The water level map, inundation map, and flood frequency map have been generated by NOAA. Therefore, this study intends to develop a composite measure of overall vulnerability to reflect the multidimensional nature of vulnerability and potential conflicts of interest. The integrated vulnerability assessment includes assessments for social, economic and infrastructure sections. Especially, in terms of infrastructure, transportation infrastructure is rated as the most important infrastructures among other critical infrastructures (e.g. emergency operation centers, health care facilities) in the survey when considering cost, emergency function, and relocation difficulty perspectives. In addition, about half of the respondents who propose to add additional vulnerability measures to the existing NOAA study listed transportation infrastructure vulnerability as the measure that should be added. These emphasize that transportation planning is a critical part of adaptation planning, not only from transportation perspective but also from the general planning point of view. With the flooding and inundation maps generated by the NOAA coastal service center, this study aims at conducting local vulnerability analysis that could help local planners identify the most vulnerable places and provide corresponding adaptation strategies, especially for transportation planning. Factors causing the difference in vulnerability are analyzed and adaptation suggestions are evaluated for their effectiveness in reducing transportation system vulnerability.

Research Questions

The objective of the study is to quantify the spatial distribution of the overall vulnerability and transportation vulnerability and to understand the causes of such spatial disparity. For transportation, spatially related variables such as land use, network topology, and demographic factors' roles in shaping the spatial disparity of transportation vulnerability are analyzed. Better understanding the relationship between these factors and vulnerability provides better understanding of the causes of vulnerability and useful insights to assist planners in making corresponding adaptation strategies. This study proposes to measure and understand the spatial distribution of vulnerability through the following research questions:

1) How does overall vulnerability differ over the space at the census block group level? How does transportation vulnerability differ over the space at the traffic analysis zone level?

2) What are the effects of economic, social, and infrastructure vulnerability on overall vulnerability? How to determine the importance of different infrastructures in integrated vulnerability index? How does the integrated vulnerability changes over time under different sea level rising scenarios? Is current adaptation time frame adequate for adaptation planning?

3) Do land use patterns, transportation network characteristics, and demographic factors influence transportation vulnerability to sea level rise and to what degree? Do these factors have the same influential levels on transportation vulnerability across the study area or the influential levels differ by location? What adaptation strategies are effective to reduce the transportation vulnerability to sea level rise?

Answering these questions provides a comprehensive and quantitative way to understand the spatial and temporal distribution of coastal communities' vulnerability to sea level rise at the city and county level, which is an improvement from the previous generalized and qualitative vulnerability research. The methodology could be generalized to apply to other coastal regions, and the findings could help to prioritize the focus in adaptation planning. To answer these questions, the study first calculates integrated vulnerability to identify the most vulnerable places in the study region. Then a detailed transportation vulnerability assessment is conducted. Land use, transportation, and demographic factors are used to explore the underlying causes for the spatial heterogeneity in transportation vulnerability. Then adaptation strategies are evaluated for their effectiveness in reducing system level transportation degradation.

This dissertation includes six chapters. The first chapter provides an introduction to the research background and problem, and puts forward the research questions. Chapter 2 provides a review of the concepts and current knowledge related to general disruption studies and climate change/sea level rise vulnerability studies. Chapter 3 introduces the case study area, analysis time frame, and focused sea level rise scenario. Chapter 4 describes the research framework, procedures and data used in each step. Chapter 5 presents the results of integrated vulnerability analysis. Chapter 6 shows the findings of transportation vulnerability analysis. Chapter 7, in the end, summarizes the current status of the research, its significance to planning practice, and limitations that should be addressed in future study.

CHAPTER 2
LITERATURE REVIEW

Sea level rise's impact on urban planning and transportation planning is an interdisciplinary research topic that has evolved in the past years. Although it was until recent years vulnerability studies with a special focus on sea level rise have been developed, studies related to disaster disruption has already been conducted for decades. With more and more recognition of the impact sea level rise may have on our society, researchers begin to apply the general disaster study method to estimate the potential impacts of sea level rise on urban infrastructure and transportation system. This chapter provides a literature review regarding the relevant concepts and vulnerability studies specific related to climate change and sea level rise.

Vulnerability, Reliability, Robustness, and Resilience

In the literatures, there are four important and interrelated concepts related to disaster impacts: vulnerability, reliability, robustness, and resilience. This section provides a review of these concepts using the transportation system as an example.

Taylor and D'Este (2007) define reliability as the probability that a system will provide a required standard of performance. Generally speaking, reliability study is suitable for disruption events with high probability. Taking transportation system as an example, considering the difference in methodologies and measures, reliability could be further classified into connectivity reliability, capacity, and travel time reliability. At the early stage, connectivity, the physical topological relationship of the transportation network, is the only consideration in transportation reliability study. If a road with certain road type has met the criterion of level of service, it is defined as functional. Then for each pair of OD, a connectivity reliability index is calculated as the number of functional paths divided by number of all paths between this OD. For a large network with hundreds and thousands of nodes, however, it would not be possible to find all available paths between each OD pairs. This measure alone has soon been criticized for its simplification and unrealistic. Later, more consideration has been given the definition of “being connected”. For example, Zhang et al. (2009) established a level of service - based connectivity reliability index to evaluate dynamic transportation network. However, their methodology also has computation limitations when applied to large network. In addition, although adding travel time or level of service into the definition of connection improves the traditional connectivity study, it is still limited by considering connection as a dummy variable (either connected or not connected) and is challenged by the determination of the threshold.

To overcome the limitations of connectivity based reliability study, capacity based reliability and travel time based reliability is proposed. Travel time reliability is the probability that trip between certain origins and destinations can be completed within a specific time interval. Similarly but from the supply perspective, capacity reliability is the probability that the maximum network capacity exceeds a required demand level considering random variations. For example, Chen et al. (2002) introduced capacity reliability as an index to assess degradable road network performance. This index is defined as the probability of the network can accommodate a certain traffic demand at an acceptable level of service. However, in their study, travel time reliability and capacity reliability are two independent performance measures, which are in fact highly correlated. Leng et al. (2010) re-defined the capacity reliability and travel time reliability under ice and snow conditions. The link travel time model and path choice decision model were adjusted accordingly.

However, the probability in reliability study may overlook the impacts of low probability but high consequences events. Therefore, the concept of vulnerability is proposed as the severe consequences that a disaster may cause (Taylor and D'Este, 2007). Accessibility/mobility based vulnerability index has been developed to measure regional susceptibility under low probability disastrous circumstances. For example, Chang and Nojima (2001) proposed two accessibility indices (network coverage and transport accessibility) to assess the post-disaster transportation system condition. Their approach only requires data on network configuration, damage and pre-disaster OD matrix which could be easily implemented. However, they only measure the spatial separation of nodes without considering the difference in node size and volume of the network. Sohn (2006) provided a different accessibility index as a performance measure of network disruption due to flooding by incorporating population and traffic volume into original accessibility index. The critical limitation of their index is that by using average daily traffic on road link they assume the volume on each road segments will not change while shortest paths between origins and destinations will be affected under user equilibrium condition.

Similarly as reliability and vulnerability but from different perspectives, robustness is defined as the degree of functionality a system could sustain under various disruption levels. Findings related to robustness could help us to further understand the internal adaptive capability to disruptions. The methodologies could also be borrowed to conduct better vulnerability assessments. For instance, using two transportation system robustness indexes, Sullivan et al. (2010) found that completely removal of single link (100% disruption) on the network may create isolated sub-networks, significantly affecting accessibility. Thus, 16 levels of capacity disruption are tested for each links in three networks. Then they re-run the model to assess network performance measure to find the most critical links in the network. They found that the worst case performance occurs at 99% disruption level, not at 100% level, indicating that the no build may be better than building a vulnerable section. To taking spatial effects into consideration, Jenelius and Mattsson (2012) presented a grid-based approach to evaluate the robustness of transportation network under area-covering flooding scenario. The uniformly shaped and sized cells are used to represent the spatial location of the disruption events. All the roads intersect with the cell would be completely closed during the disruption events while other roads are unaffected. Their results indicated the factors that influence the vulnerability of network for area-covering disruptions are quite different from those with single link failure. Under area-covering disruptions, the local redundancy has much less impact on the robustness of transportation network. However, a great limitation of their study is that they assume the travel time outside the disruption area would not be affected by the change in traffic flows inside the disruption area which may not happen in reality. The disruption levels between events cells and surrounding cells are considered independent in their study, which may be highly correlated in reality. Furthermore, the impacts of cell size and form on the results are not studied.

Resilience is proposed to further take adaptation characteristics into account. There is a similarity between this definition and the vulnerability concept (Smit and

Wandel, 2006). Capacity to adapt to and recover from hazard is sometimes considered an aspect of vulnerability (Blaikie et al., 1994; Adger and Vincent, 2005), which is classified as “post adaptation vulnerability” by Smit and Wandel (2006). The relationship between such “post adaptation vulnerability” and resilience is dialectical (Aguirre, 2007). The study of resilience is still at the early stage, and there is no consensus reached toward the definition. Generally, it represents a system’s ability to maintain its demonstrated level of service or to restore itself to that level of service in a specified time frame. Resilience studies still have a lot of limitations. While resilience is a long term concept, some studies only evaluates the effect of short time passive adaptation (Murray-Tuite, 2006). Debates also exist in choosing resilience indicators. Serulle et al. (2011) provided a method to quantify the resilience of pre-event transportation system. Nine variables were considered in their research to calculate the base resiliency. Traffic engineering metrics in their study, e.g. road available capacity, average delay, are mainly based on empirical results. On the other hand, Freckleton et al. (2012) set up a method using four metric groups related to individual, community, economy and recovery are included, each supported by several attributes. The total resilience is calculated by weighted mean of four metric group values. There is no consensus in determining measures and indicators.

In summary, connectivity based and travel time/capacity based disruption analysis has obvious limitations due to their simplification of the problem. On the other hand, resilience studies are still at the early stage, and more quantitative studies are needed to give precise definition of the concept. Rather than focusing on specific low probability scenarios, the occurrence probabilities of various disruption levels in robustness studies are considered equal. As its focus is network characteristics, robustness study is not suitable for specific scenario based evaluation. Considering the uncertainty in future climate projection, the occurrence probability of sea level rise is increasing but unquantifiable. With the uncertain probability and high severity of potential consequences caused by sea level rise, scenario-based vulnerability study is more suitable than reliability, robustness, and resilience studies. The following section provides a review on recent vulnerability studies with a specific focus on climate change, especially sea level rise.

Climate Change and Sea Level Rise Related Vulnerability Study

Since the beginning of this century, the Center for Climate Change and Environmental Forecasting at U.S. Department of Transportation begin to pay attention to the issue of climate change on urban infrastructure. In 2002, it held the first workshop with the intent to explore the potential impacts of climate change on infrastructure and to delineate the research necessary to better understand these implications. Many studies have been conducted to evaluate the impacts of climate change on infrastructures and the urban environment (Burkett, 2002; Titus, 2002; Peterson et al, 2008; Suarez et al, 2005; Jacob, et al, 2007;Titus and Anderson; ICF International, 2007; U.S. Climate Change Program, 2008). These studies have addressed the many associated concerns, ranging from local sea level rise predictions to general conclusions about transportation facilities vulnerable to climate change and the associated economic costs, providing valuable information and instruction in how to adapt to climate change in coastal areas.

However, in spite of these studies that focus on estimating climate change’s impacts on urban environment, research in this area still have the following limitations. First, most of these studies focus on large scale, qualitative level analysis (ICF

International, 2007; U.S. Climate Change Science Program, 2008; Peterson et al, 2008; Jacob et al, 2007). Limited quantitative studies are not specific or accurate enough to assist local practitioners to develop local adaptation strategies to climate change (U.S. Climate Change Science Program, 2008; Suarez et al, 2005). Detailed impact assessments of climate change on urban environment and infrastructures are needed at the local level. Second, most previous studies use global average projections, rather than local projection to conduct impact assessments (Jerry et al, 2000; National Research Council, 2008; Peterson et al, 2008). As local sea level rise rate may differ significantly from the global average, studies based on the global average may generate misleading conclusions. Third, there is a lack of risk assessments to support decision making. Most previous studies typically concluded with recommendations for additional analysis of uncertainty, thresholds, and prioritization of actions, but little has been reported as to how planning should address the uncertainties (Kinsella and McGuire, 2005; National Assessment Synthesis Team, 2000; Entek UK Limited, 2004; Sato and Robeson, 2006; ABP Marine Environmental Research Ltd., 2004). Finally, most of the studies focus at the facility level, and few of them address the system-level impacts and overall strategies (Kirshen et al., 2004; Suarez et al., 2005), while the nature of vulnerability problem is multidimensional (Yoon, 2012). Yoon (2012) summarized that a composite vulnerability index is needed in order to analyze multiple dimensions of vulnerability otherwise it will be inadequate.

To overcome these limitations, in the past two years, several detailed and localized sea level rise vulnerability studies emerge (Blostcher et al., 2012; Lu and Peng, 2011; Wu et al., 2012). These recent studies focus on local or regional level, use local sea level rise projections, and start to discuss the underlying causes of vulnerability. Bloetscher et al. (2012) identified vulnerable Florida's state transportation infrastructure in Dania Beach and Punta Gorda under local sea level rise scenarios projected with Army Corps of Engineers' scenario-based methodology, using Florida Department of Transportation (FDOT) information system, satellite imagery, local roadway and hydrologic data. Wu et al. (2012) utilized the Analytic Hierarchy Process (AHP) to generate risk maps that could represent the integrated impacts of climate factors on vulnerability of the study region. However, their analyses only focus on the external vulnerability (i.e. climate), and did not include enough factors to represent internal vulnerability (i.e. infrastructure system, build environment, socio-economic factors). In reality, external factors are usually factors that can be hardly controlled or managed. As a result, adaptation often depends on thorough analyses of internal causes (socio-economic factors, land use patterns, network layout) of vulnerability. Therefore, while Wu et al. (2012) generated climate change risk map that could easily identifies places susceptible to multiple climate factors, it has limited ability in telling decision makers what aspects their adaptation should focus on. Lu and Peng (2012) assess Miami's transportation network's vulnerability to projected 2060 sea level rise scenarios using accessibility based index. The limitation is the lack of consideration of potential land use and analysis of the causes of the vulnerability. Despite there is very limited analysis of vulnerability causes (Jenelius, 2009), Hickman (2006)'s research indicates that flood vulnerable communities may have different causes: some may be caused by high economic costs of inundation, but less social costs; and some may show less economic vulnerability but more social exposure. However, their analyses only focus on socioeconomic aspects without consideration of urban infrastructures.

These sea level rise and flooding vulnerability studies follow similar procedure as general hazard (e.g. earthquake) vulnerability studies (Suarez et al., 2005; Lu and Peng, 2011; Jenelius and Mattsson, 2012; Sohn, 2006). However, sea level rise has a few distinctive characteristics from traditional hazards, which call for more comprehensive and integrated system analysis in its vulnerability study. First, despite tremendous efforts have been made to hazard prediction, prediction of earthquake, debris flow, hurricanes and other disasters usually have a high level of uncertainty. Sea level rise projection, on the other hand, is a trend based on historical data and is more credible, albeit debates exist regarding whether the rising rate is accelerating or constant (Donoghue, 2011). Second, due to the uncertainty in prediction it is very difficult to predict when and where general disasters (e.g. earthquake) will happen, and spatial randomness is usually an assumption for disaster attacks in traditional vulnerability assessment process. For sea level rise, it is easier to predict whether a location will be directly influenced by sea level rise or not as the level of influence is highly spatial-related. Third, as disasters such as earthquake usually have catastrophic consequences, their vulnerability studies often focus on identifying critical infrastructures that help to reduce system collapse effects under random attack scenarios (Nagurney, 2009; Sohn, 2006; Sullivan et al., 2010; Scott et al., 2006). Sea level rise and flooding has much less severe impacts but it will influence a wide range of infrastructures at the same time making project level priority and retrofit an inefficient adaptation strategy (Jenelius and Mattsson, 2012). Fourth, although sea level rise may not has direct catastrophic consequences as other disasters, sea level rise is a continuous process with slow but irreversible consequences while general disasters are often one-time events that may be recovered afterwards. As a result, the influence of sea level rise is more complicated than random one-time attacks, as its consequences include gradual influence on people’s behavior (e.g. land use change, travel pattern change) and chain reactions that need to be considered in the vulnerability assessment (Curtis and Schneider, 2011). Considering these differences between sea level rise and other disasters, the traditional vulnerability studies need to be modified to capture the spatial dependence and potential socioeconomic change when applied for sea level rise vulnerability analysis.

To overcome these research gaps, the study proposes 1) to develop an integrated vulnerability measure considering social, economic and infrastructure exposure and sensitivity to sea level rise; 2) to include potential land use change due to direct inundation of sea level rise in the vulnerability assessment process; 3) to analyze the influence of important factors (i.e. land use, transportation network characteristic, demographic factors) on transportation vulnerability to find the key factors for vulnerability reduction; and 4) to provide corresponding adaptation suggestions that will guide future development to assist local transportation planners with future long range plan update.

CHAPTER 3
CASE STUDY AREA AND ANALYSIS SCENARIOS

A case study is conducted to illustrate the implementation of proposed vulnerability analysis, and to generate conclusions that could guide adaptation planning in the case study area. The procedure and methodology used in the case study could be followed and applied by other coastal areas. Case study area is selected considering its susceptibility to sea level rise, development intensity, the availability of data (i.e. sea level rise projection, infrastructure data, socioeconomic data, etc.) and local support.

Case Study Area

Tampa Bay Region (Figure 3-1) is selected as the case study area considering its vulnerability to coastal disasters, intense transportation network, the availability of sufficient data, and local support from Tampa Bay Regional Planning Council for the ongoing NOAA sea level rise project. Tampa Bay region is located in the west central area of Florida, adjacent to Tampa Bay. The region has nearly 700 miles of coastline, making it very susceptible to potential sea level rise (Tampa Bay Regional Planning Council, 2005). It includes four counties—Hillsborough County, Manatee County, Pasco County, and Pinellas County, about 20 municipalities, and 43 local governments (Tampa Bay Regional Planning Council, 2005). It is home to more than 2.6 million residents based on 2003 population estimation and has a projected population of 4.1 million by the year 2035 (Tampa Bay Regional Planning Council, 2005). Because of this intense development and population density, Tampa-St Petersburg is ranked as the top 10 cities around the world that have the highest value of assets exposed to coastal flooding in 2005 (Nicholls et al., 2007). Although growth rate in the region has reduced since 1990s, there are still about an average of 26 thousand people moving into the region each year (Tampa Bay Regional Planning Council, 2005). As a result, it is especially important to guide future development in a way that is resilient to coastal flooding caused by sea level rise.

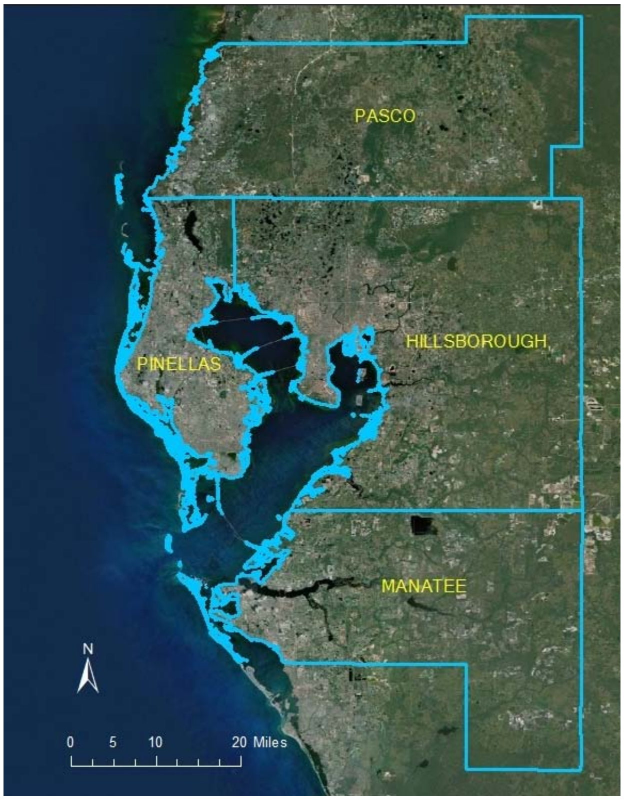


Figure 3-1. Case Study Area

Sea Level Rise in Tampa Bay Region and Analysis Scenarios

According to IPCC (2013) observation with high confidence, the sea level rising rate from the mid-19th to current is greater than the mean rate during the previous two millennia, and the global sea level has increased with a mean value of 0.19 m from 1901 to 2010. IPCC (2013) projects that the global mean sea level will continue to rise during this century at a rate which is very likely to exceed the observed rate (2.0 mm per year) between 1971 to 2010 because of the ocean thermal expansion and melting of glaciers and ice sheets. While global average sea level rise indicates a long-term acceleration trend, the rate of sea level rise differs significantly at the local level. At the local level, the relative sea level is influenced by a variety of factors, including the global average sea level (eustatic sea level), gradual uplift or subsidence of land elevation, abrupt changes due to a seismic event, gradual erosion, rapid bluff collapse, atmosphere pressure, weather systems as El Niño, and tides (California Coastal Commission, 2001). For instance, the historic rate of sea level rise in Gulf of Mexico is much higher than many other regions in the United States (IPCC, 2013).

According to the literature, although currently there is no consensus reached towards the future long term trend of sea level rise in Tampa Bay area (Cronin et al., 2007), the historical data collected from the St. Petersburg tide gauge station near Tampa Bay yield an average sea level growth rate of 2.4mm/year (Penland and Ramsey, 1990).

The analysis year for case study is determined according to preliminary results of the current NOAA research project “Development of Sea Level Rise Adaptation Planning Procedures and Tools Using NOAA Sea Level Rise Impacts Viewer”. The survey conducted in the project for understanding how sea level rise is addressed in the urban planning process within the Tampa Bay Region shows most of the respondents (about 70%) think sea level rise will start to have impacts in Tampa Bay region in no more than 25 years. It also found that among the agencies with adaptation plans the most common adaptation plan time range is 25 year, suggesting that the most useful adaptation support for the future plan development should be provided for the year range of 2040-2050. Also considering that the typical infrastructure planning horizon is

20 to 30 years, it is decided that vulnerability analysis and adaptation analysis will be conducted for planning year 2035.

The Climate Central (2013) recently published an estimation of annual flood risk for Tampa Bay region under low, medium, and fast sea level rise scenarios (Figure 3-2). 1ft, 2ft, 5ft flooding scenarios are analyzed as approximate representations for current annual, 10-year, and 100-year flood. A risk assessment is conducted for 2020, 2030, 2040, and 2050 considering the annual flood probability change for 1ft, 2ft, and 5ft flooding to determine the tipping point for integrated vulnerability change.

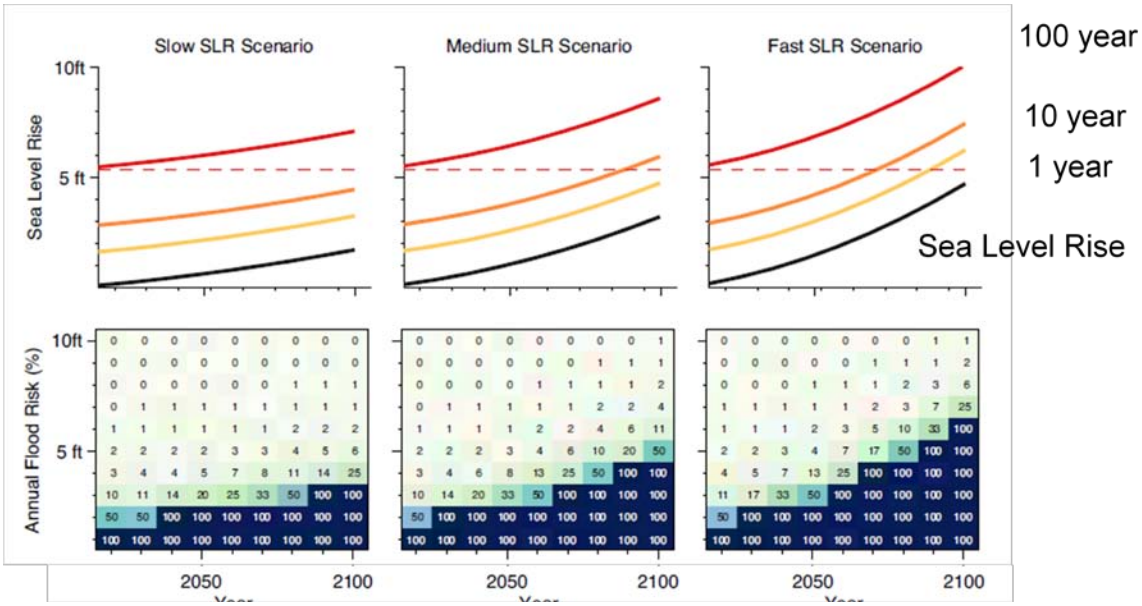


Figure 3-2. Sea level rise scenarios for St. Petersburg, Fl (Climate Central, 2013, pp. 41)

EPA (1995, pp. 144) provide a suggested formula for estimating sea level rise at a specific location using the formula: local(t)=normalized(t) + (t-1990)*trend, where local(t) representing the sea level by year t at a particular location, global (t) is the global rise in sea level projected in a scenario, and trend is the current rate of relative sea level rise at the particular location Currently the global sea level rise rate is 1.8mm/year, and sea level rise in the Tampa Bay region is rising at 2.3mm~2.4mm/yr. U.S. coast has a common historical rise rate of more than 2.5mm/year (Tampa Bay Regional Planning Council, 2006). Combined with global projections (IPCC, 2013), U.S. Environmental Protection Agency's suggested procedure for estimating sea level rise, and local planning agency's studies, the normalized sea level projection based on historical increase rates shows that the sea level at least will go up to 13cm, and at worst could go up to 49cm (approximately 2ft) by 2050 (Tampa Bay Regional Planning Council, 2006). According to this projection, the worst case is selected because the prediction is considered conservative even for the worst case as potential ice melt in Greenland and West Antarctic area and increase of storm surge due to rising sea levels is not considered (IPCC, 2013; Rosenzweig et al., 2011). According to recent Climate Central projection (2013), under all sea level rise scenarios (i.e. low, medium and fast), there will be 100% 2ft annual flood probability by year 2035. Therefore, 2ft coastal flooding scenario is selected to analyze the impact of sea level rise on transportation system by long range planning year 2035. The following assumptions are made for transportation network disruptions and land use changes:

1) The capacity reduction of flooded road is hard to determine because of its dependence on various factors such as flood depth, water speed, and the amount of debris. To simplify the problem, it is assumed that under all scenarios partially flooded roads and bridges (intersect with flood area) will have a 90% capacity reduction to represent the significant reduction of capacity. The road segments completely within the inundation area are removed to represent 100% disruptions.

2) Although centroid connectors are virtual representations of TAZ internal accessibility, it is assumed that centroid connectors represent the location internal connectivity to some extent. The closer the centroid connectors are to the inundation area, the more capacity reduction they will have. Therefore, it is assumed that under all scenarios centroid connectors completely within inundation area have higher accessibility loss (assumed to be 95% loss) than centroid connectors intersect with inundation area (assumed to be 90% loss). Centroid connectors do not have a

physical relationship with flood area but within partially inundated TAZ will have a capacity loss proportion to the inundation percentage of that TAZ.

3) Under freeway and bridges protection scenarios, important bridges and interstate freeways are assumed to be built above ground and will be easier to be protected against flood than local roads. The bridges and interstate freeways that assumed to remain fully functional include I275, I75, I4, Gulf to Bay Blvd, Gandy Blvd, S 22nd street, Clearwater Memorial Causeway, and Bayside Bridge.

4) For land use change, it is assumed that new residential and business development will be prohibited in the inundation area but will be allowed in the nearest suitable coastal area within the same traffic analysis zone. No hard structure protection will be provided for the existing developments. Existing housing, population, business, hotel/motel, and school once get inundated will move out of the region and will not contribute to the travel demand within the study area.

CHAPTER 4
DATA AND METHODOLOGY

Data is obtained from National Oceanic and Atmospheric Administration sea level rise viewer (http://www.csc.noaa.gov/digitalcoast/tools/slrviewer) to generate inundation maps using Digital Elevation Model and Mean Higher High Water surface data. As the National Oceanic and Atmospheric Administration provides estimations with one foot increments from zero to six feet above Mean Higher High Water surface, the selected sea level rise scenarios are rounded to the nearest foot integer (1ft, 2ft, 5ft) to match with the inundation scenarios in NOAA sea level rise viewer. The direct inundation map is created to identify the locations where its elevation value in Digital Elevation Model is lower or equal to the elevation of the water surface and it is immediately adjacent to other direct inundation locations in 8 direction raster connectivity analysis.

As measures from different perspective (e.g. social, economic) may result in different vulnerability index values, it is hard for decision maker to identify the most vulnerable places without an integrated vulnerability index. For example, the most socially vulnerable places in Figure 4-1(data source: social vulnerability produced by the Hazards and Vulnerability Research Institute, 2011) are not the most vulnerable places using economic indicators in Figure 4-2 (total employment by census block group from the Bureau of Labor Statistics' Quarterly Census of Employment and Wages information). This paper proposes an integrated vulnerability index for general planning purpose and a vulnerability analysis specifically focusing on transportation (Figure 4-3). The integrated vulnerability assessment helps to identify the most susceptible places that need adaptation attention. The integrated infrastructure vulnerability analysis also emphasizes the importance of transportation planning, and a detailed transportation vulnerability analysis is conducted afterwards.

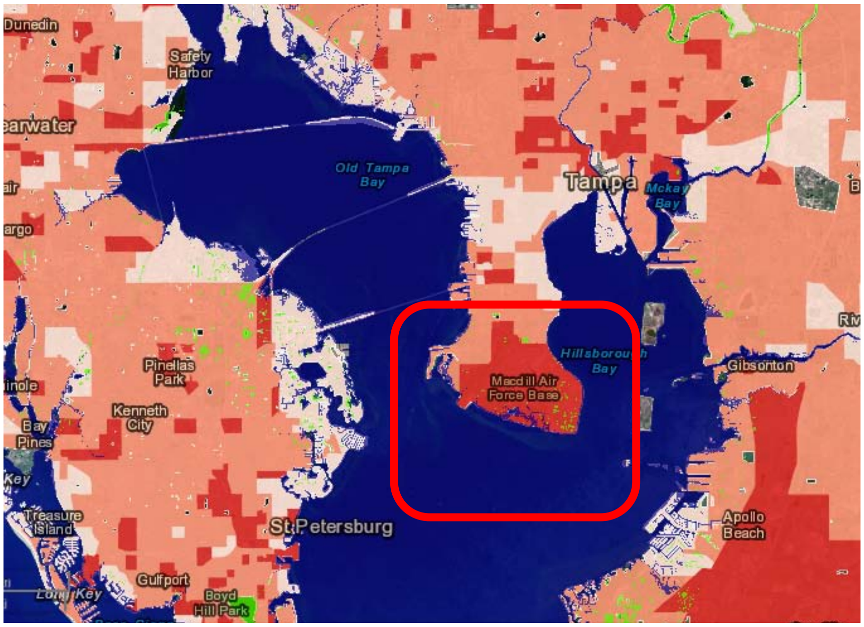


Figure 4-1. Social Vulnerability for Tampa Bay Area (Data Source: NOAA, Sea Level Rise and Coastal Flooding Impacts, available at http://www.csc.noaa.gov/slr/viewer/#, accessed January, 2014)

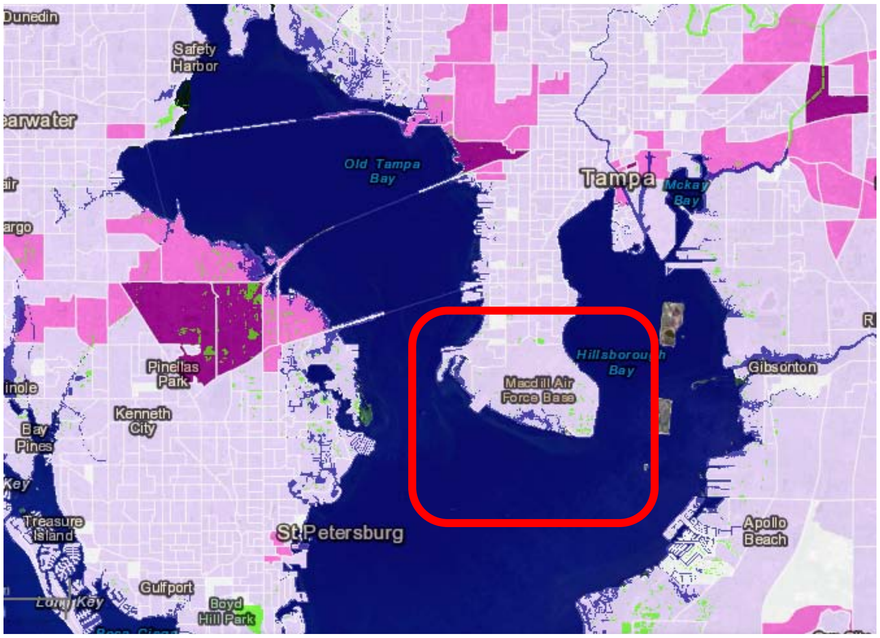


Figure 4-2. Business Vulnerability for Tampa Bay Area (Data Source: NOAA, Sea Level Rise and Coastal Flooding Impacts, available at http://www.csc.noaa.gov/slr/viewer/#, accessed January, 2014)

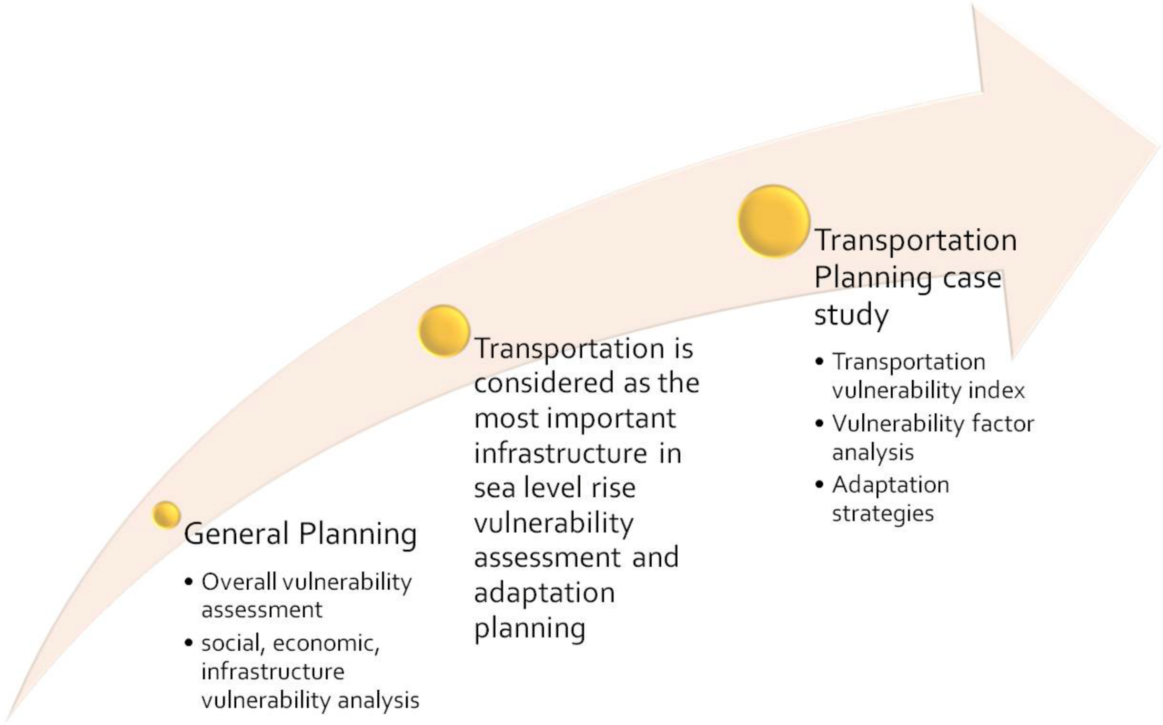


Figure 4-3. Research Components

The transportation vulnerability analysis includes two components: transportation network vulnerability assessment and analysis, and adaptation planning suggestions (Figure 4-4). Long range transportation demand forecasting model is used to conduct the transportation network impact assessment under selected sea level rise scenarios. In order to find key planning factors that influence the transportation vulnerability, Global ordinary least square model and geographical weighted regression (GWR) are used to test the relationship between transportation vulnerability and network characteristics, land use pattern, and demographic factors.. Then in the adaptation analysis part, three adaptation strategies are evaluated using system degradation measures.

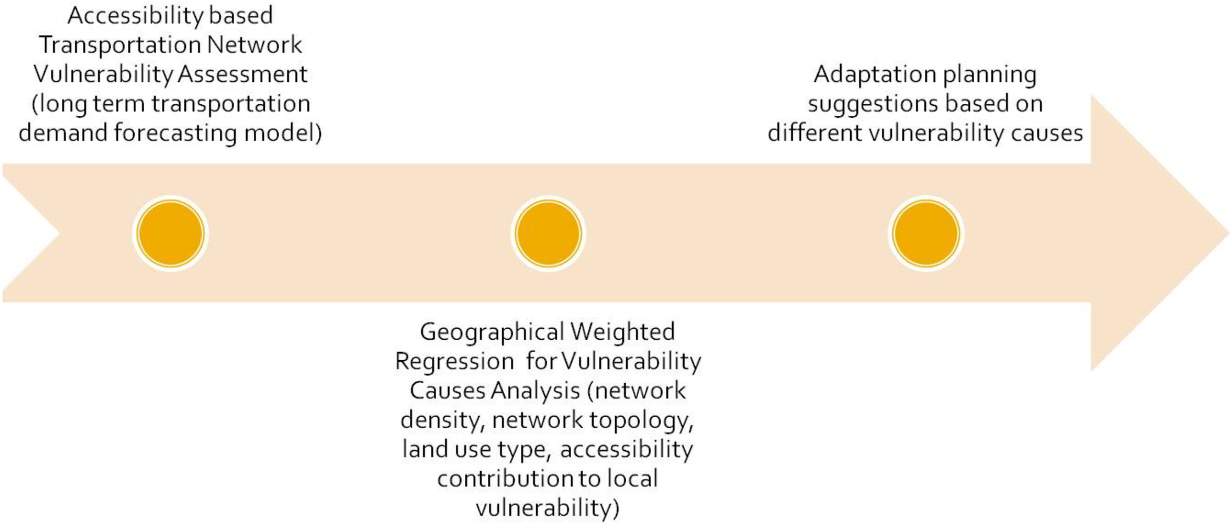


Figure 4-4. Transportation Vulnerability Analysis Framework

Integrated Vulnerability Assessment

The measures considered in the integrated assessment are generated using the following data: social vulnerability index produced by the Hazards and Vulnerability Research Institute (2011) at the University of South Carolina at the census block group level (Figure 4-1); total business establishments, employment, and quarterly wages information from the Bureau of Labor Statistics' Quarterly Census of Employment and Wages information; critical infrastructures in critical facility inventory, which include emergency operation center, health care facilities, principal transportation facilities, fuel distribution centers, police and fire department (Florida Division of Emergency Management, 2012). A survey is conducted in the study area to get planners' ratings on the relative importance of the three perspectives (i.e. social, economic, and infrastructure) and the importance of different measures in each perspective in adaptation planning process (Appendix A). The ratings are used 1) to compare the relative importance of different types of infrastructures (i.e. emergency operation center, health care facilities, principal transportation facilities, fuel distribution centers, police and fire department) in the infrastructure vulnerability assessment, 2) to compare the relative importance of business establishment, employment, and quarterly wages, and to select the most important measures to calculate the economic vulnerability, 3) to compare the relative importance between infrastructure vulnerability, social vulnerability, and economic vulnerability in the overall adaptation planning, and to determine the relative weight for each of these indicators to generate an integrated system vulnerability index. Analytic Hierarchy Processes (AHP) is used in infrastructure vulnerability analysis to consider different criteria of importance including facility cost, easiness to reallocate, emergency priorities (Figure 4-5). The ratings are then processed with statistic tests to generate pairwise average rating comparison matrix ([A]), based on which the relative weights of these indicators are calculated.

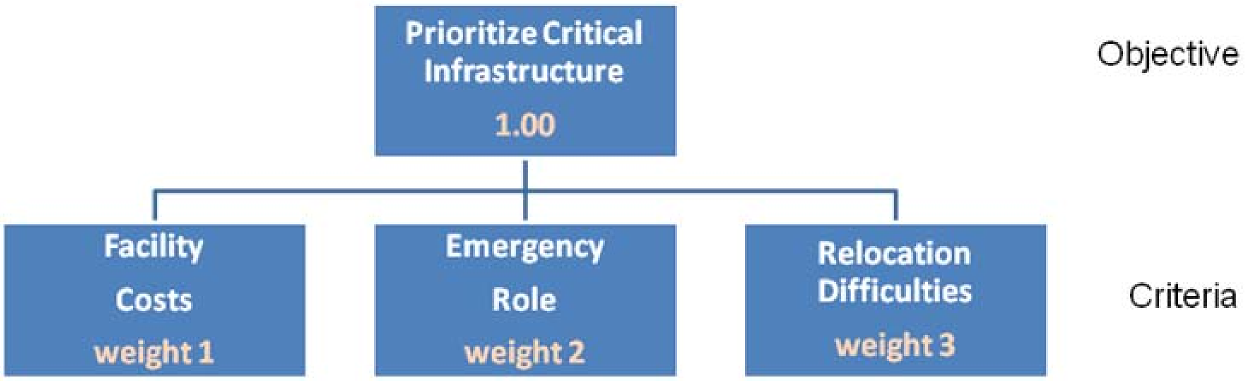


Figure 4-5. Analytical Hierarchy Process in Infrastructure Vulnerability Assessment

After selecting indicators and determining the weight for each indicator, indicators vulnerable to sea level rise inundation are calculated under 1ft, 2ft, and 5ft SLR scenarios respectively. For point data, total number of vulnerable units is calculated for each census block group. For linear data, total length of vulnerable segments is calculated for each census block group. For polygon data, total area of vulnerable places is calculated for each census block group. The measures are then normalized using percentage (relevant to total number of units in the region) to eliminate the difference in measuring units, and density to eliminate the difference in census block group size. Min-max normalization is performed to scale economic, social, and infrastructure vulnerabilities in the range [0,1] to calculate the final integrated vulnerability score, using the following formula:

$$\mathrm{X_{new}} = \frac{\mathrm{X - X_{min}}}{\mathrm{X_{max} - X_{min}}} \tag{4-1}$$

The integrated vulnerability score is mapped by standard deviation to identify the places with extreme vulnerability. The process is illustrated in Figure 4-6.

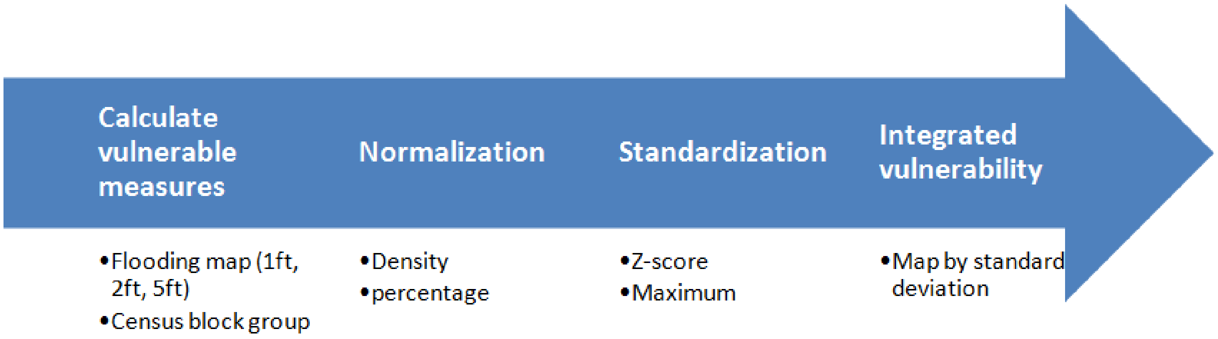


Figure 4-6. Integrated Vulnerability Calculation Process

Risk assessment is conducted using the probability information provided by Climate Central (Figure 3-2). The overall vulnerability for each census block is calculated as sum of $\mathrm{Integrated\ Vulnerability}_{\mathrm{i\ ft}} * \mathrm{Annual\ Flooding\ Probability}_{\mathrm{i\ ft}}, \mathrm{i} = 1, 2, 5$. The overall vulnerabilities for year 2020, 2030, 2040, 2050 are mapped by standard deviation for low SLR, medium SLR, and fast SLR scenarios as well.

Survey results show that transportation infrastructure (in terms of principal highway network) are important component in the general adaptation planning process.

As a result, a specific transportation vulnerability analysis is conducted to explore the relationship between planning factors and transportation vulnerability so as to propose detailed adaptation suggestions. The following paragraph will provide detailed explanation of the data and methodology used for transportation vulnerability analysis.

Transportation Vulnerability Assessment

Vulnerability of transportation system is affected by multiple factors: transportation network topology, operational characteristics, infrastructure locations, land use patterns, as well as social and institutional structures. The location and geographical characteristics of infrastructure and land use development to some degree determine their exposure and susceptibility to flooding caused by sea level rise. The characteristics of the transportation network and the associated land use play a crucial role in shaping travel demand. Operational attributes (e.g. capacity) and network topology will then determine the end users' accessibility and the system's mobility. The conceptual model is illustrated in Figure 4-7. The accessibility based vulnerability measures are adopted in transportation vulnerability assessment. It takes transportation network supply, capacity, land use, and travel demand into consideration in the evaluation process. It is also a good indicator to measure local susceptibility, making it suitable for identifying vulnerable locations in planning process.

To estimate the system performance change, links susceptible to inundation are identified in sea level rise inundation maps. Spatial analysis in Geographical Information System (GIS) is performed to assess the impacts of sea level rise on 2035 transportation highway network, identifying vulnerable links that intersect with or complete within the inundation area. Direct inundation of land use in 2035 long range plan is estimated based on the proportion of inundation area.

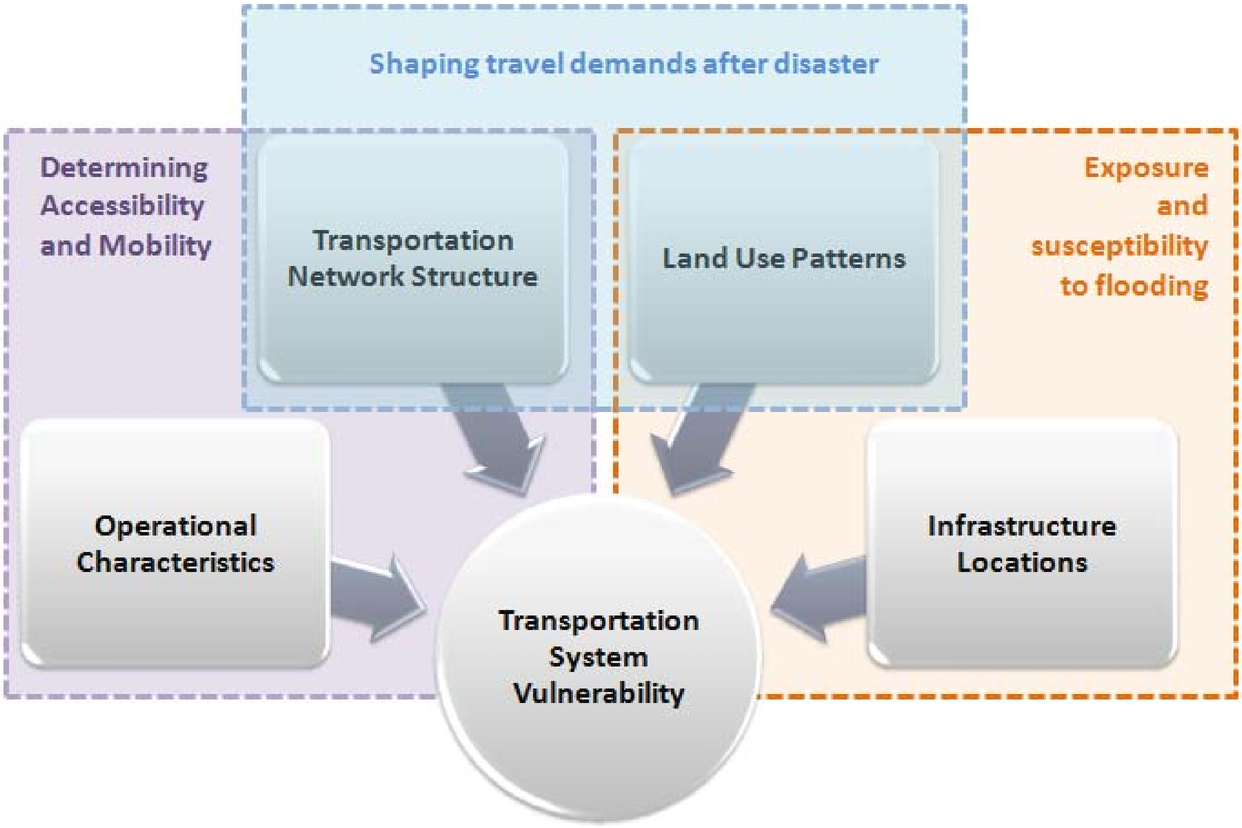


Figure 4-7. Transportation Network Vulnerability Assessment Inputs

The 2035 cost feasible scenario in Tampa Bay Regional Planning Model (TBRPM) version 7.1 is used to estimate the change in transportation system performance for the chosen sea level rise scenario. The model includes 2253 internal traffic analysis zones, 26 external zones, 12,300 highway links with a total of 12,400 lane miles for Tampa Bay region. The long range transportation planning model is rerun with link disruptions. Congested travel time table and origin destination distribution matrix are obtained to calculate the total travel time, system travel time, and zonal vulnerabilities (Figure 4-8). Total travel time is calculated as:

$$T = \sum_{i=1}^{N} \sum_{j=1}^{N} t_{ij} , \qquad (4\text{-}2)$$

where t_{ij} represents the shortest congested travel time from traffic analysis zone i to traffic analysis zone j, which means the shortest driving time considers the volume and capacity of the road segment and is calculated based on a shortest-routes-finding algorithm, Both the travel time and number of trips will change after the network inundation, therefore two important measures for transportation vulnerability are travel time change $\sum_{j=1}^{N}\frac{t_{ji}^{*}}{t_{ji}}$ (Figure 4-8) and number of trips changes (Figure 4-9)

$$(\sum_{j=1}^{N} T_{ji}^{*} - \sum_{j=1}^{N} T_{ji}) / \sum_{j=1}^{N} T_{ji} \ , \tag{4-3}$$

where $\frac{t_{ji}^{*}}{t_{ji}}$ represents the percentage of travel time increase from zone j to zone i after the network inundation, and $(\sum_{j=1}^{N} T_{ji}^{*} - \sum_{j=1}^{N} T_{ji}) / \sum_{j=1}^{N} T_{ji}$ represents percentage of attraction changes. T_{ji} is the number of trips attracted from TAZ j to TAZ i before the network inundation, and T_{ji}^{*} is the number of trips attracted from TAZ j to TAZ i after the network inundation. Previous population weighted Hansen-type Vulnerability Index (e.g. Lu and Peng, 2012) could only represents the travel time changes but not the number of trip changes. This is because the previous studies assume that only the shortest trip routes between TAZs will change but the trip distribution among TAZs will remain the same, which is not the case as shown in Figure 4-9. As a result, an improved accessibility based zonal vulnerability index is proposed as

$$VA_i = (\sum_{j=1}^{N} \frac{t_{ji}^{*}}{t_{ji}} * T_{ji} + 1) \frac{1}{T_{.i}^{*} + 1} \tag{4-4}$$

to represent the increase of level of difficulty that a traffic analysis zone can be reached by travelers in all the other traffic analysis zones across the region after the network inundation, where $T_{.i}^{*} = \sum_{j=1}^{N} T_{ji}^{*}$, and T_{ji}^{*} is the number of trips attracted from TAZ j to TAZ i after the network inundation.

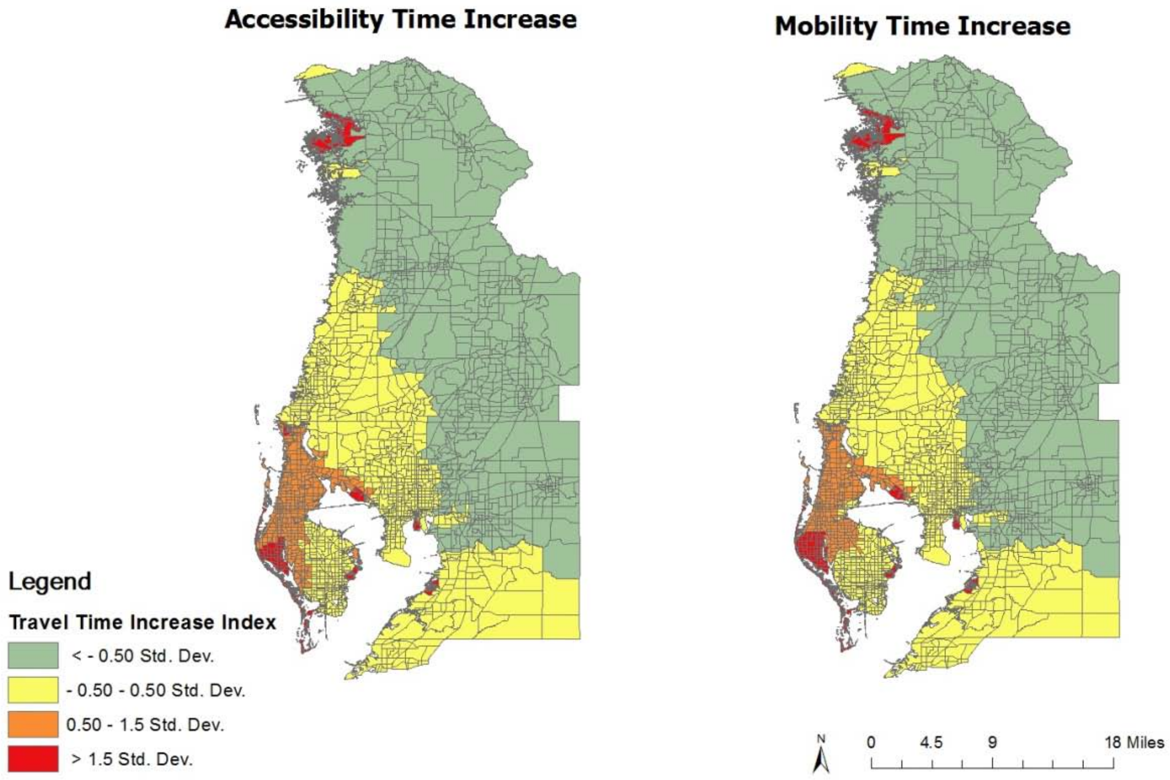


Figure 4-8. Travel Time Increase after Inundation

Similarly, mobility based zonal vulnerability represents the increase of difficulty that travelers in the traffic analysis zone have in order to go to other traffic analysis zones in the region, as is defined by:

$$VM_{i} = \left(\sum_{j=1}^{N} \frac{t_{ij}^{*}}{t_{ij}} * T_{ij} + 1\right) \frac{1}{T_{i.}^{*} + 1}. \qquad (4\text{-}5)$$

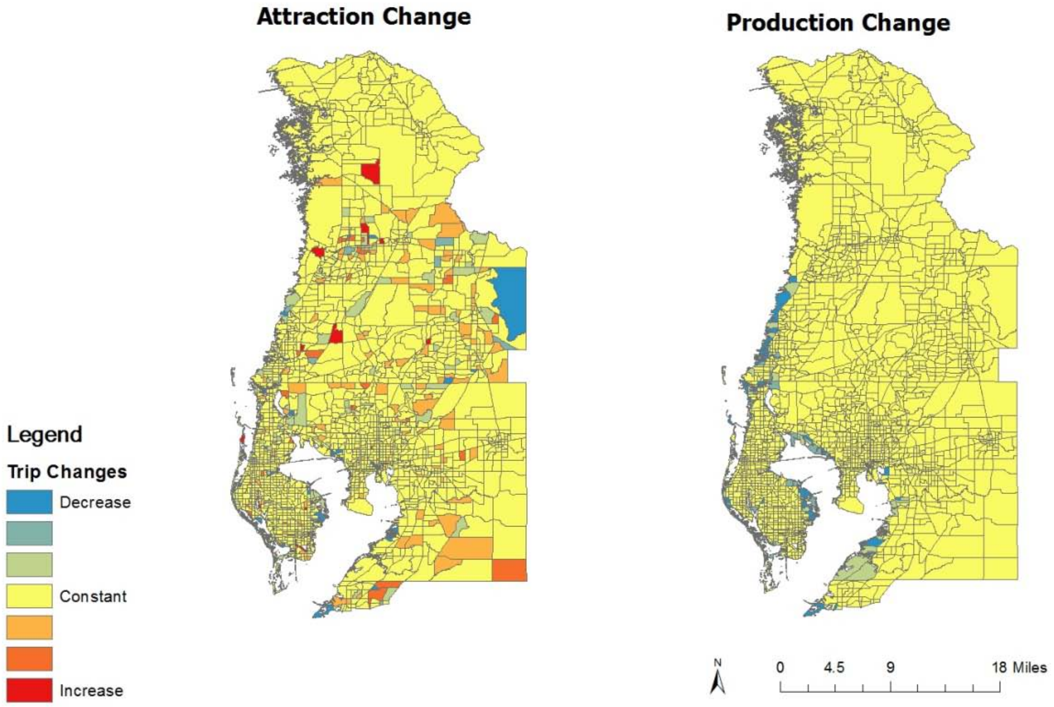


Figure 4-9. Trip Production and Attraction Changes after Inundation

Both indexes have values greater than zero. If the value of the index is less than 1, it represents the increase of attractiveness or reduction of travel time. The larger the value is, the more vulnerable the traffic analysis zone is to sea level rise.To test the validity of the proposed transportation vulnerability index, a regression model is developed between the proposed vulnerability index and the travel time change index, travel time change $\sum_{j=1}^{N}\frac{t_{ji}^{*}}{t_{ji}}$ and number of trips changes $(\sum_{j=1}^{N}T_{ji}^{*}-\sum_{j=1}^{N}T_{ji})/\sum_{j=1}^{N}T_{ji}$ for the study region. The regression results are shown in Table 4-1. The results show that as the travel time increases and number of attraction decreases due to inundation, the vulnerability increases. The adjusted R squared of the model is 0.66, indicating high correlation between the proposed vulnerability index andtravel time and number of trip changes. The same regression is conducted using a population weighted Hansen type accessibility vulnerability index

$$A_i = w_i^p \sum_{j=1}^{n-1} w_j^r \left(\frac{t_{ij}^*}{t_{ij}} \right). \tag{4-6}$$

The adjusted R squared of the model is only 0.12. Therefore, the proposed index has better internal validity in representing the travel time change and attraction changes caused by the inundation compared with population weighted index. To test the hypothesis whether transportation network, local land use pattern, and demographic characteristics affect transportation vulnerability, regression models are used. A Global Ordinary Least Square Model is established as

$$Y = \beta X + \varepsilon . \tag{4-7}$$

The dependent variable Y is the calculated transportation vulnerability index for each traffic analysis zone, and the independent variables X include transportation factors (e.g., road density, capacity reduction, average free flow travel time per mile, TAZ internal capacity reduction ratio), land use factors (population, employment, population/employment ratio, TAZ size, population/employment density, local employment ratio, school enrollment), and demographic characteristics (percentage of retired household, percentage of household with children, and average car ownership) (Figure 4-11). All of the variables are calculated at the traffic analysis zone level. To test the spatial effect, geographically weighted regression model is applied to explore the relationship between different land use and network factors and transportation vulnerability, and to identify influential planning factors for transportation vulnerability reduction purpose. In geographically weighted regression (GWR) models, the coefficient β are determined by the set of points within a defined neighborhood (radius r) of each of the sample point, and are allowed to vary spatially. The regression model form is

$$Y = X\beta(t) + \varepsilon \, . \tag{4-8}$$

Instead of setting a fixed radius r for defining the neighborhood for sample collection, a distance-decay function $f(d)$ is used. $(1-d^2/h^2)^2(d<r)$ is an example form of $f(d)$. d in the function represents distance from the sample point, h is a parameter called bandwidth, which determines the way of the weighting schemes. Considering the size of the TAZ is different, a specific number of neighbors is set in the GWR model so that in dense area the spatial context is smaller and in sparse area the spatial context is larger. The results of GWR are compared with a global regression model in the study area for the variance in variables, coefficient β, and goodness of fit.

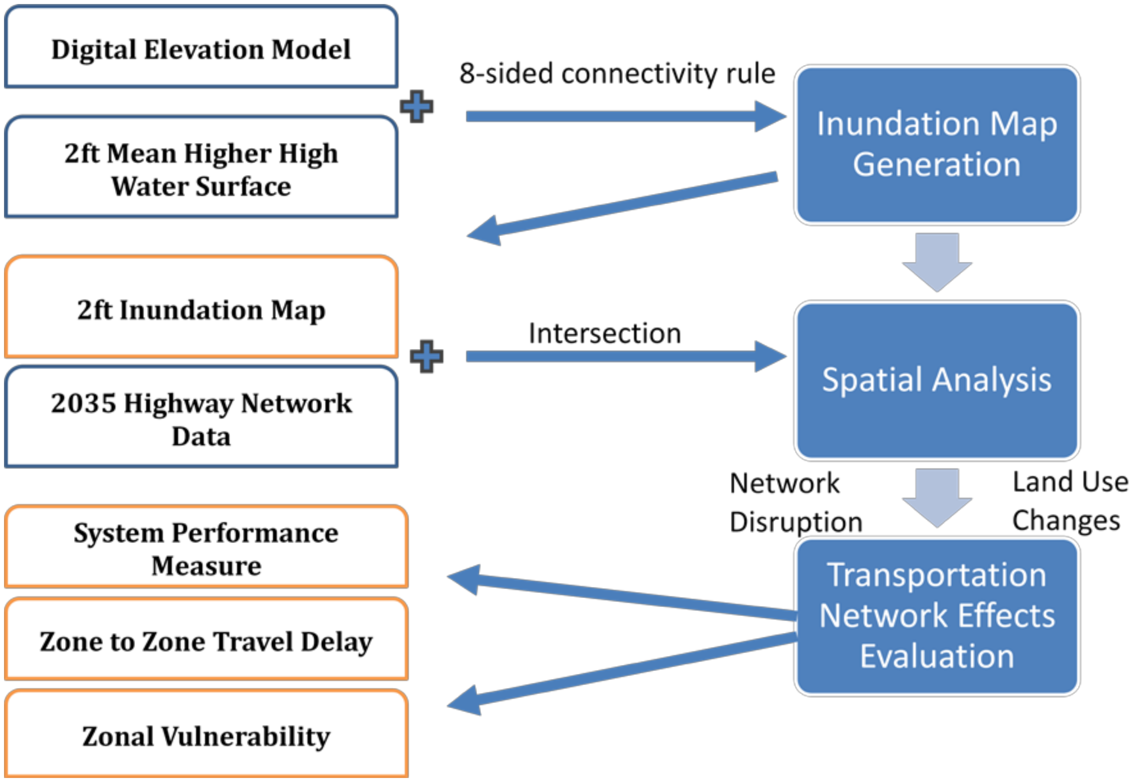


Figure 4-10. Transportation Network Vulnerability Assessment Process

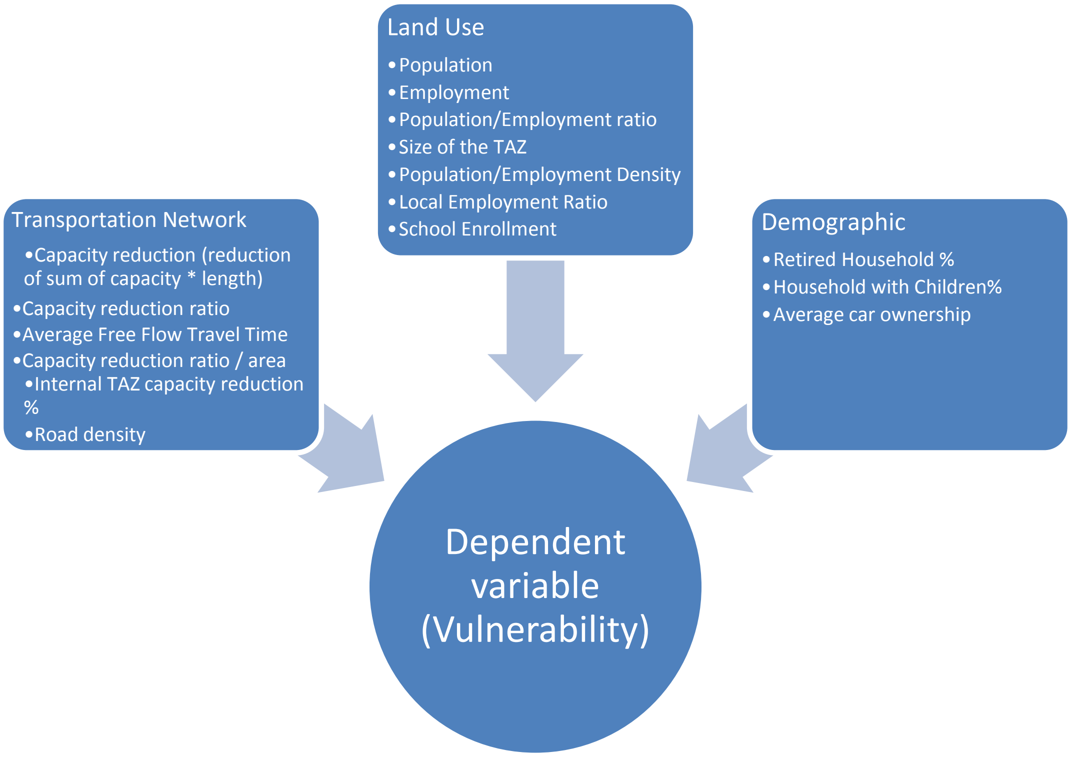


Figure 4-11. Regression model structure

Adaptation Analysis

According to the overall vulnerability assessment and risk assessment, the changes of vulnerability as sea level rises over time are mapped for the study area. To understand where economic adaptation and infrastructure protection should be implemented, census block groups, whose economic vulnerability or infrastructure vulnerability change dramatically as sea level rises, are identified. Under low, medium, and fast sea level rising scenarios, the overall vulnerability of the region are mapped by each census block group per decade until 2050. To understand the appropriate time scale for adaptation, and the time period during which the region's overall vulnerability significantly increases, are identified.

For transportation sector three adaptation strategies are proposed and evaluated. To compare the impacts of different adaptation strategies (hard structure protection, accommodation, and planned retreat) in reducing transportation system vulnerability to sea level rise, three adaptation strategies' (protection, accommodation, and planned retreat) impacts on transportation system performance are analyzed. Under protection strategy, important bridges and interstate freeways in low-lying areas will be elevated through addition of asphalt layers or protected by building walls, including part of I275, I75, I4, Gulf to Bay Blvd, Gandy Blvd, S 22nd street, Clearwater Memorial Causeway, and Bayside Bridge. Under accommodation scenario, access roads within local community (traffic analysis zone) will be prepared against flood through strategies such as ecological buffer zones and storm water management to insure the internal connectivity within the low-lying TAZs are not reduced. Under planned retreat scenario, no hard structure protection will be provided for the existing developments. Existing housing and business within the inundation zone once inundated will be moved out of the region. Socioeconomic data and network data under different adaptation scenarios are then input into the 2035 Tampa Bay Regional Planning Model to compare the before and after system performance measures.

CHAPTER 5
INTEGRATED VULNERABILITY ANALYSIS

This chapter shows the results of the integrated vulnerability analysis with two parts. The first part explains how the expert ratings are processed with statistic tests to compare the difference in expert ratings considering their response variances so as to determine the weight of each indicator in the overall vulnerability index. The second part demonstrates the calculated economic vulnerability, infrastructure vulnerability, and overall vulnerability for the case study area, using the weight determined in the first part.

Weight Determination

Social and economic vulnerability data have been collected from NOAA Coastal Service Center, as shown by Figure 4-1 and Figure 4-2 in Chapter 4. A survey is conducted to understand the importance of different perspectives in adaptation planning decision making process in the Tampa Bay Region. The survey was distributed with the help of Tampa Bay Regional Planning Council to local planning professional network. Survey targets include planners, city managers, council members, and planning and engineering professionals in the four counties and twenty municipalities in Tampa Bay Region. The survey has 49 respondents and 24 effective ones from different agencies, including seven municipal planning agencies, four county agencies, state and regional environmental protection agencies and department of transportation, and private planning and engineering companies. Some municipal agencies did not provide an effective response because they are small municipals who do not have specialized planning staff and their planning work are done by the county planning agencies, from whom we already got effective responses. Survey data regarding weight of different measures in integrated vulnerability assessment has been processed using statistic tests following the procedure shown in Figure 5-1.

Survey respondents have been asked to rate different sectors in adaptation planning on a scale of 1 to 9 with 1 being least important and 9 being most important (see Appendix A). The result shows social vulnerability gets an average rating of 6.75, economic vulnerability gets an average rating of 7.5, and infrastructure rating gets an average rating of 7.08. Shapiro-Wilk test shows non-normal distribution (test score for social rating is 0.786, test score for economic rating is 0.864, test score for infrastructure rating is 0.914). As the survey data is not normally distributed, Friedman's test is performed to test the true difference in ratings. The Friedman's test result shows that at 95% confidence level, social, economic, and infrastructure aspects could be weighted equally in the integrated assessment.

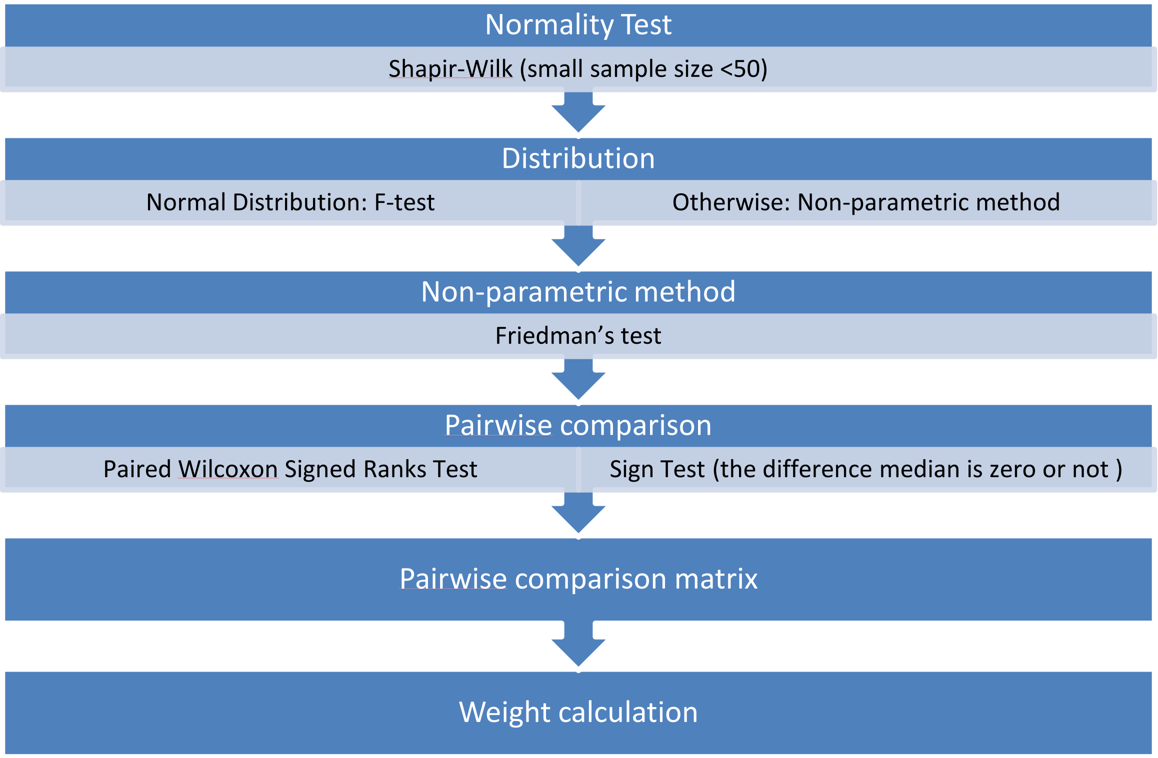


Figure 5-1. Statistic Test Procedure

Similarly, the same procedure is applied to evaluate the importance of three economic indicators in economic vulnerability assessment. Employment indicator got an average rating of 7.2 out of 9, business indicator has an average rating of 6.8, and wages indicator has an average rating of 6.2. Shapiro-Wilk test shows non-normal distribution. Friedman's test is performed to test whether difference exists in ratings and the null hypothesis that the three indicators are considered equally important is rejected at 95% confidence level. Paired Wilcoxon signed ranks test demonstrates that employment is valued as significantly more important than wages and business indicators in economic vulnerability assessment. Therefore, number of employment is selected as economic indicator for planning purpose. Economic vulnerability to sea level rise is calculated as the density of inundated employments for each census block group.

Analytical hierarchy process (AHP) is used to compare different critical infrastructures (i.e. emergency operation center, health care facilities, principal transportation facilities, fuel distribution centers, police and fire department) from three perspectives (cost, facilities' function under emergency situations, and relocation difficulties). According to the survey results, the cost perspective got a 7.833 out 9 average rating of importance. The facilities' function under emergency situations got an average rating of 7.1667. Relocation difficulties got an average rating of 6.6250. Shapiro-Wilk test shows non-normal distribution. Friedman's test is applied, showing the three perspectives are not rated equally at 95% confidence level. Paired Wilcoxon signed ranks test shows that there is no significant difference between the importance of relocation difficulty and emergency function, and between the importance of emergency role and cost at 95% confidence level. But there is significant difference between the importance of relocation difficulty and the importance of cost. Using average rating and the test results, a pairwise comparison matrix is composed to compare the importance of different criteria (Table 5-1). The Maximum Eigen Value of Table 5-1 is 3.00312, and the consistency index is 0.00155995, which is far less than 0.1. This justifies the consistency of the pairwise comparison. The eigenvector x of Table 5-1 is calculated by Gaussian Elimination using equation $(A - \lambda I)x = 0$ to determine the weights for the three criteria. The results are shown in Figure 5-2.

Table 5-1. Pairwise comparison matrix for different criteria in infrastructure vulnerability assessment

	Facility Cost	Emergency function	Relocation Difficulties
Facility Cost	1	1	1.1824
Emergency Role	1	1	1
Relocation Difficulties	0.8457	1	1

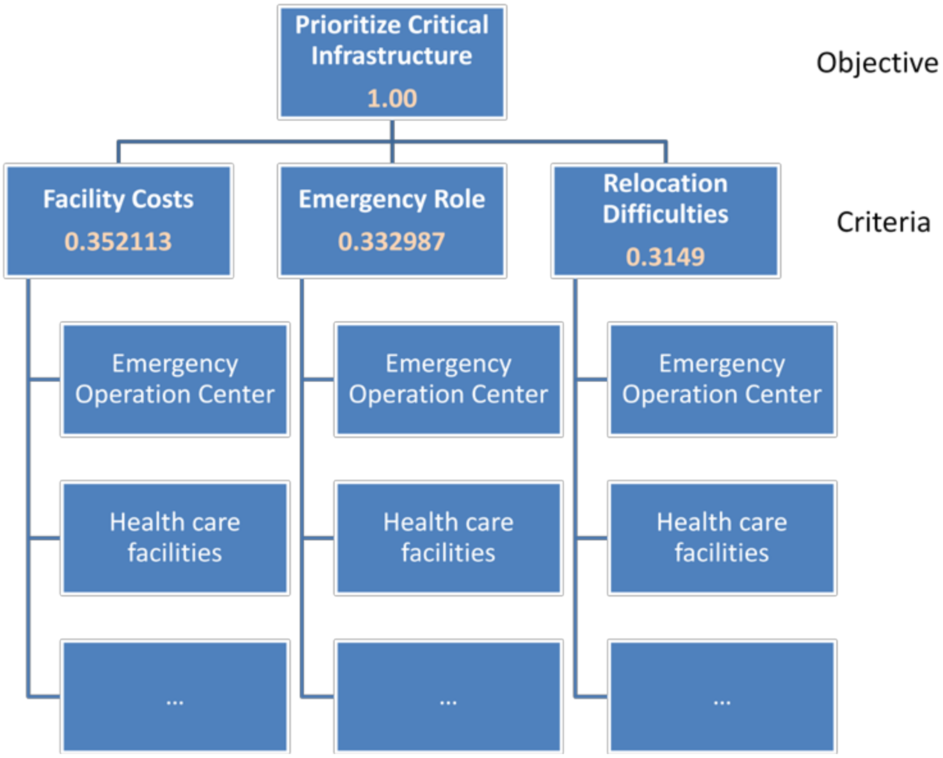


Figure 5-2. Weights of different criteria in infrastructure vulnerability assessment

Following the same process, the weight for different critical infrastructure under each criterion is determined. The descriptive statistics of the rating under each criterion are summarized in Table 5-2. Using cost criterion, Shapiro-Wilk test shows non-normal distribution of the rating for different infrastructures. Friedman's test demonstrates the rejection of the hypothesis that all infrastructures cost equally at 95% confidence level. Paired Wilcoxon signed ranks test shows that transportation infrastructures are considered significantly more costly than most of the other infrastructures except police and fire station at 95% confidence level. Using average rating and the test results, a pairwise comparison matrix is composed to compare the importance of different infrastructures under the cost perspective (Table 5-3). The Maximum Eigen Value of Table 5-3 is 5.00735, and the consistency index is 0.00183755, which is far less than 0.1. This justifies the consistency of the pairwise comparison.

Under emergency role criterion, Shapiro-Wilk test shows non-normal distribution of the rating for different infrastructures. Friedman's test fails to reject the hypothesis

Table 5-2. Descriptive statistics for ratings under different criteria in infrastructure vulnerability assessment

Criterion	Infrastructure Type	Mean	Standard Deviation
Facility Cost	Emergency operation center	5.7917	2.51913
	Health care facility	5.8750	2.25181
	Transportation	7.3333	1.88049
	Distribution center	5.5833	2.06243
	Police and fire station	6.4583	2.08471
Emergency Role	Emergency operation center	7.4348	1.90278
	Health care facility	7.3913	1.37309
	Transportation	7.6522	1.58426
	Distribution center	6.5652	2.06323
	Police and fire station	7.0435	1.96511
Relocation Difficulties	Emergency operation center	5.3478	2.16603
	Health care facility	6.5652	1.44052
	Transportation	7.5652	1.44052
	Distribution center	6.4783	1.75472
	Police and fire station	5.3478	2.32787

Table 5-3. Pairwise comparison matrix for different infrastructures under cost perspective

	Emergency Operation Center	Health care facilities	Principal transportation facilities	Distribution centers	Police and fire department
Emergency Operation Center	1	1	0.7897	1	1
Health care facilities	1	1	0.8011	1	1
Principal transportation facilities	1.2662	1.2482	1	1.3134	1
Distribution centers	1	1	0.7614	1	1
Police and fire department	1	1	1	1	1

that all infrastructures cost equally at 95% confidence level. All infrastructures are considered equally important from the emergency role perspective.

Considering relocation difficulties, Shapiro-Wilk test shows non-normal distribution of the rating for different infrastructures. Friedman’s test demonstrates the rejection of the hypothesis that all infrastructures cost equally at 95% confidence level. Paired Wilcoxon signed ranks test shows differences exist between the following infrastructures at 95% confidence level: distribution center and emergency operation center, distribution center and police and fire station, transportation and emergency operation center, transportation and police and fire station, health care facility and transportation. Using average rating and the test results, a pairwise comparison matrix is composed to compare the importance of different infrastructures under the cost perspective (Table 5-4). The Maximum Eigen Value of Table 5-4 is 5.00274, and the consistency index is 0.000686163, which is far less than 0.1. This justifies the consistency of the pairwise comparison.

Considering relocation difficulties, Shapiro-Wilk test shows non-normal distribution of the rating for different infrastructures. Friedman's test demonstrates the rejection of the hypothesis that all infrastructures cost equally at 95% confidence level. Paired Wilcoxon signed ranks test shows differences exist between the following infrastructures at 95% confidence level: distribution center and emergency operation center, distribution center and police and fire station, transportation and emergency operation center, transportation and police and fire station, health care facility and transportation. Using average rating and the test results, a pairwise comparison matrix is composed to compare the importance of different infrastructures under the cost perspective (Table 5-4). The Maximum Eigen Value of Table 5-4 is 5.00274, and the consistency index is 0.000686163, which is far less than 0.1. This justifies the consistency of the pairwise comparison.

Table 5-4. Pairwise comparison matrix for different infrastructures from relocation difficulty perspective

	Emergency Operation Center	Health care facilities	Principal transportation facilities	Distribution centers	Police and fire department
Emergency Operation Center	1	0.8146	0.7069	0.8255	1
Health care facilities	1.2276	1	0.8678	1	1.2276
Principal transportation facilities	1.4146	1.1523	1	1	1.4146
Distribution centers	1.2114	1	1	1	1.2114
Police and fire department	1	0.8146	0.7069	0.8255	1

The eigenvector of Table 5-3 and Table 5-4 are calculated to generate the weights for different infrastructures considering the three criteria. The results are shown in Table 5-5. The overall weight of each infrastructure is used to calculate the infrastructure vulnerability. Then the infrastructure vulnerability, social vulnerability, and economic vulnerability are used to calculate the integrated vulnerability as shown in Figure 5-3.

Table 5-5. Weights of different infrastructures in infrastructure vulnerability

Infrastructure /Criterion	Facility Cost 0.352113	Emergency Role 0.332987	Relocation Difficulties 0.3149	Overall Weight
Emergency Operation Center	0.186574	0.20	0.170915	0.1861
Health care facilities	0.18926	0.20	0.209243	0.1991
Principal transportation facilities	0.236247	0.20	0.234592	0.2237
Distribution centers	0.179868	0.20	0.214335	0.1974
Police and fire department	0.208051	0.20	0.170916	0.1937

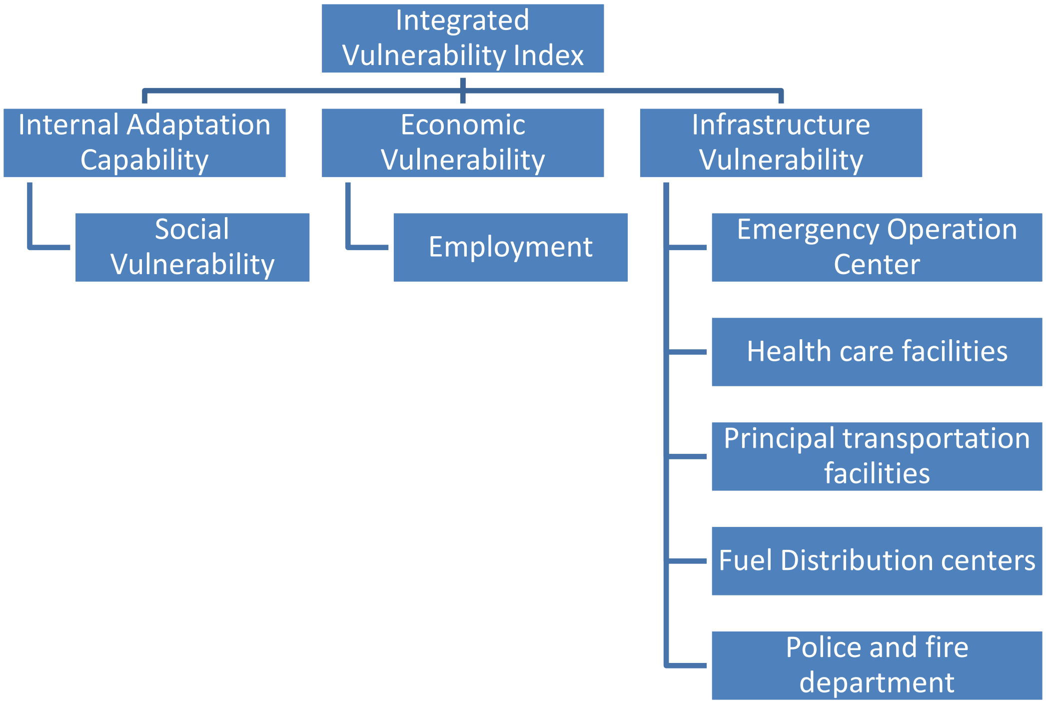


Figure 5-3. Integrated vulnerability index component

Vulnerability Analysis

Using the data and methodology described in Chapter 4 and the above calculated weights, the economic vulnerability, infrastructure vulnerability, and integrated vulnerability are generated for each census block group under 1ft, 2ft, and 5ft inundation scenarios. Social Vulnerability produced by the Hazards and Vulnerability Research Institute(2011) at the University of South Carolina are mapped in Figure 5-4 using standard deviation from the mean. Highly social vulnerable census block groups are defined as those census block group with social vulnerability scores greater than 2.5 standard deviations from the mean. The social characteristics of the population are assumed to be unchanged as sea level rises, and the social vulnerability representing adaptability are constant under all scenarios. Highly socially vulnerable places are census block group with clustering of low income population and disadvantage groups (e.g. minority, elderly). Economic vulnerability for each census block group is mapped by standard deviation under 1ft, 2ft, 5ft inundation scenarios in Figure 5-5, Figure 5-6, and Figure 5-7. Census block group with economic vulnerability scores greater than 2.5 standard deviations from the mean are considered to be highly economically vulnerable census block groups.

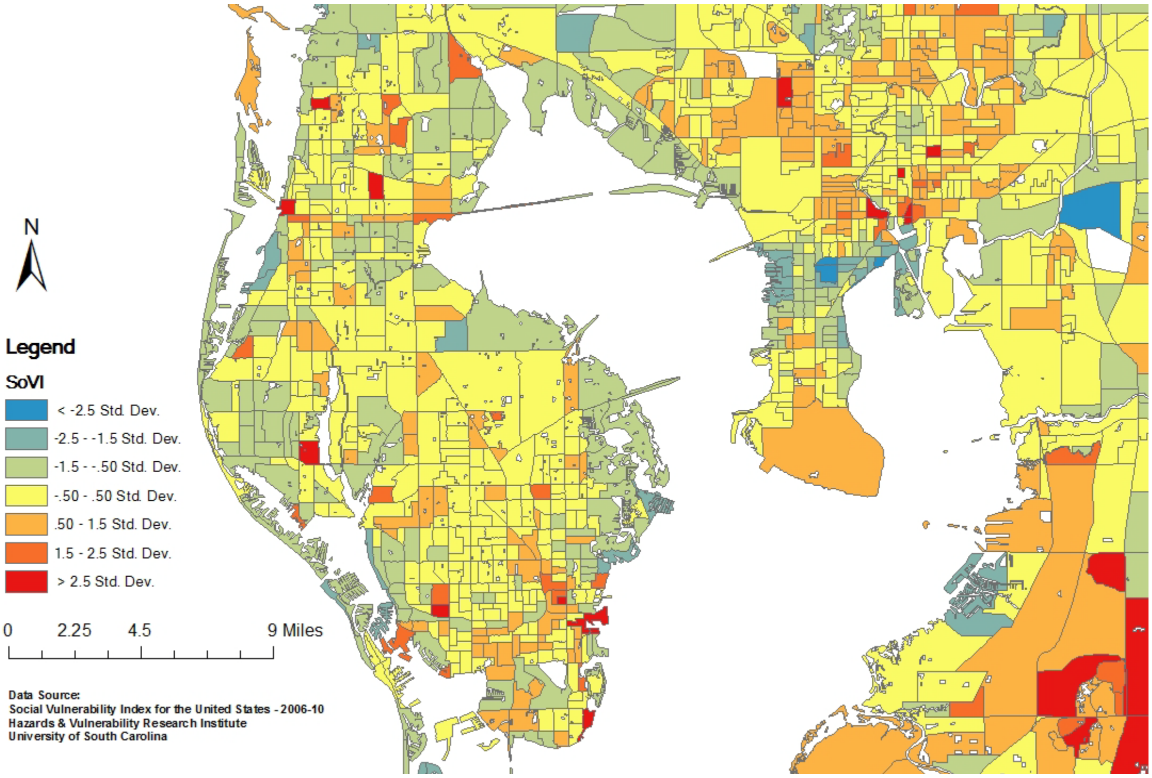
Percentages of inundated critical infrastructures by different category are calculated (Figure 5-8). Figure 5-8 shows that intermodal distribution centers are the most vulnerable critical infrastructure under all inundation scenarios. Transportation facilities are the second most vulnerable infrastructures. Infrastructure vulnerability for each census block group is mapped by standard deviation under 1ft, 2ft, 5ft inundation scenarios in Figure 5-9, Figure 5-10, and Figure 5-11. Census block group with infrastructure vulnerability scores greater than 2.5 standard deviations from the mean are considered to be infrastructure vulnerable census block groups.

Similarly, integrated vulnerability for each census block group is mapped by standard deviation under 1ft, 2ft, 5ft inundation scenarios (Figure 5-12, Figure 5-13, Figure 5-14). Census block group with integrated vulnerability scores greater than 2.5 standard deviations from the mean are considered to be highly vulnerable census block groups.

The social, economic, infrastructure, and integrated vulnerability maps show that with no sea level rise or low sea level rise, the integrated vulnerability pattern is very similar to social vulnerability pattern, indicating that social vulnerability is the most influential components in determining the integrated vulnerability under these scenarios. However, as sea level rises, the integrated vulnerability distribution pattern changes as infrastructure and employment become sensitive to the changes in sea levels. Therefore, as sea level rises, the influence of employment and infrastructure on integrated vulnerability will become more significant. These findings indicate that although social, economic, and infrastructure vulnerabilities are weighted equally in the integrated vulnerability calculation, the influences of social, economic, and infrastructure to integrated vulnerability differ by location and time due to the difference in level of exposure and sensitivities.

Using annual flooding probability information provided in Figure 3-2, the overall vulnerability is calculated and mapped by standard deviation for each census block group per decade from year 2020 to year 2050. The results are shown in Appendix B. The maps demonstrate that under low sea level rise scenario, by year 2040, the overall vulnerability to sea level rise in the region will increase significantly from the mean value of 0.2757 in year 2030 to 0.3665. Under medium and fast sea level rise scenarios, by year 2030, the overall vulnerability to sea level rise in the region will increase significantly from the mean value of 0.2757 in year 2020 to 0.3665 (Table 5-6).

As indicated by the infrastructure vulnerability assessment (Figure 5-8), transportation infrastructures are one of the most vulnerable infrastructure in the region. According to the planners' rating, transportation infrastructures are rated as the most important critical infrastructures (Table 5-5). Therefore, a detailed transportation vulnerability analysis is conducted in the following chapter so as to better understand the socioeconomic impacts of the disruption of the infrastructure.



Data Source:
Social Vulnerability Index for the United States - 2006-10
Hazards & Vulnerability Research Institute
University of South Carolina

Figure 5-4. Social vulnerability under all scenarios

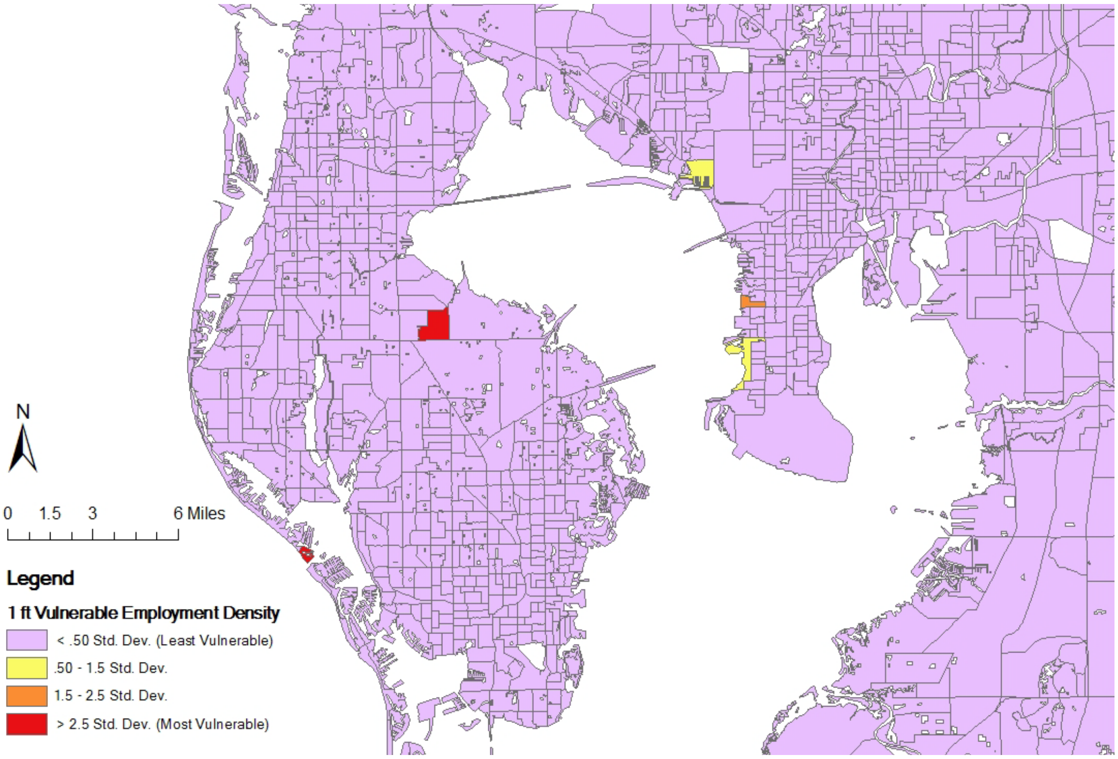


Figure 5-5. Economic vulnerability under 1ft coastal inundation scenario

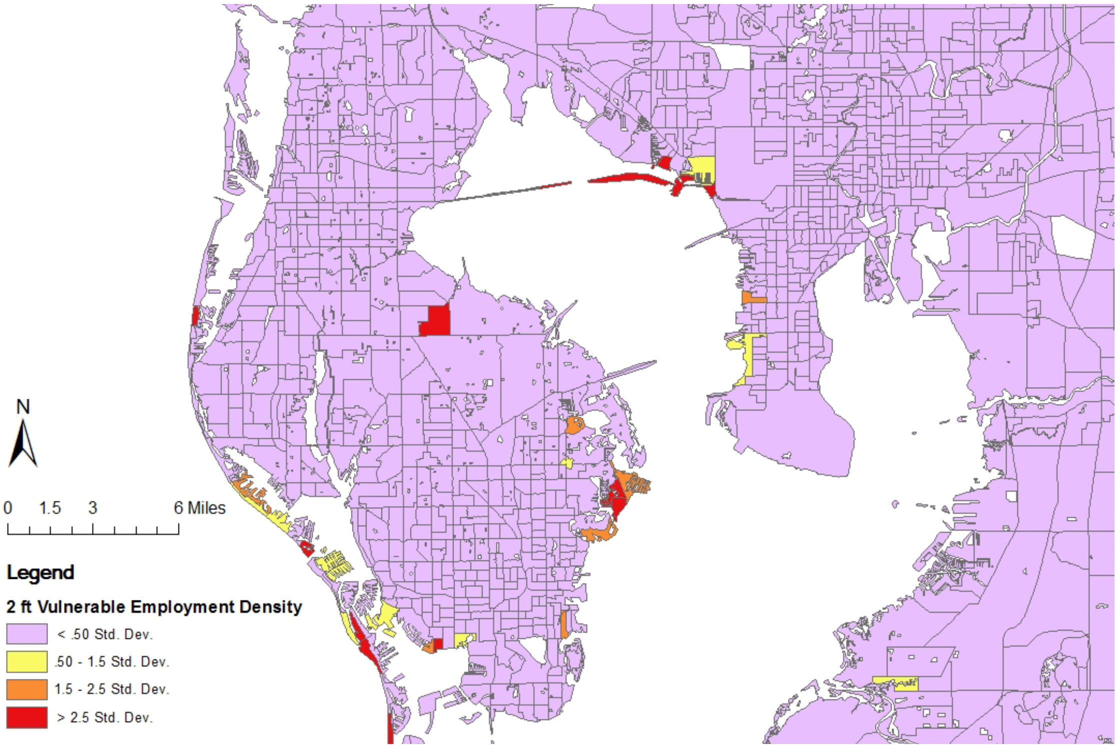


Figure 5-6. Economic vulnerability under 2ft coastal inundation scenario

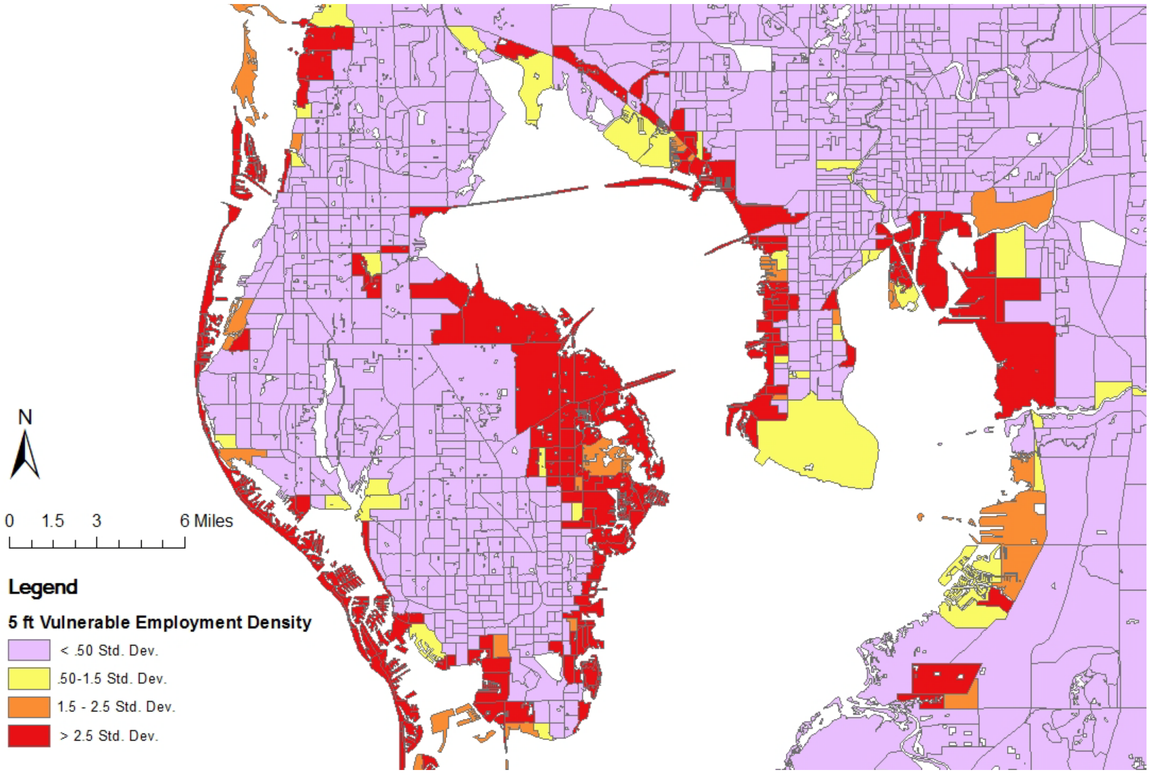


Figure 5-7. Economic vulnerability under 5ft coastal inundation scenario

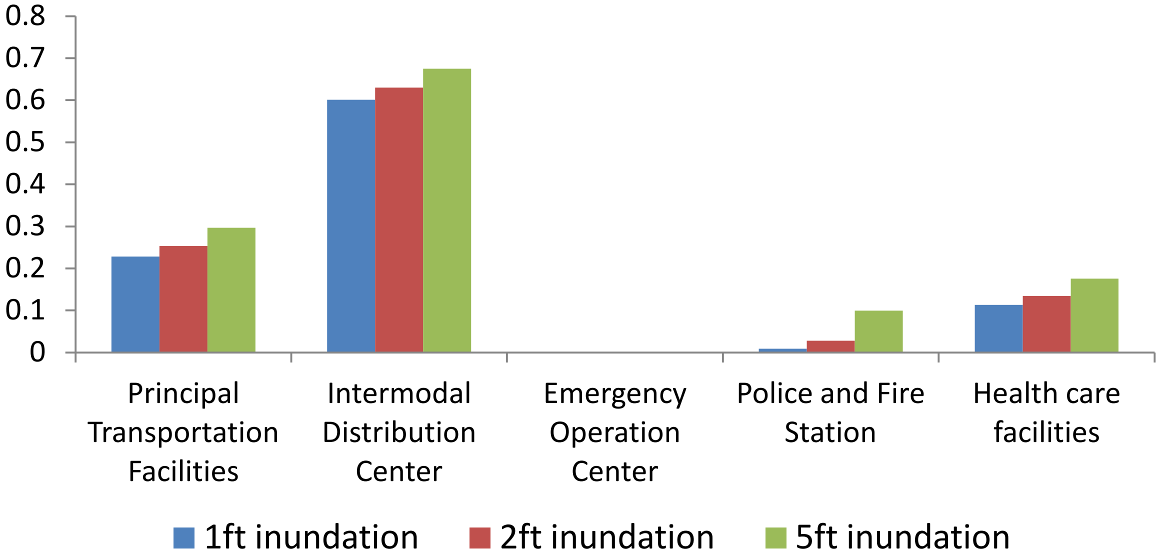


Figure 5-8. Most vulnerable infrastructures by type

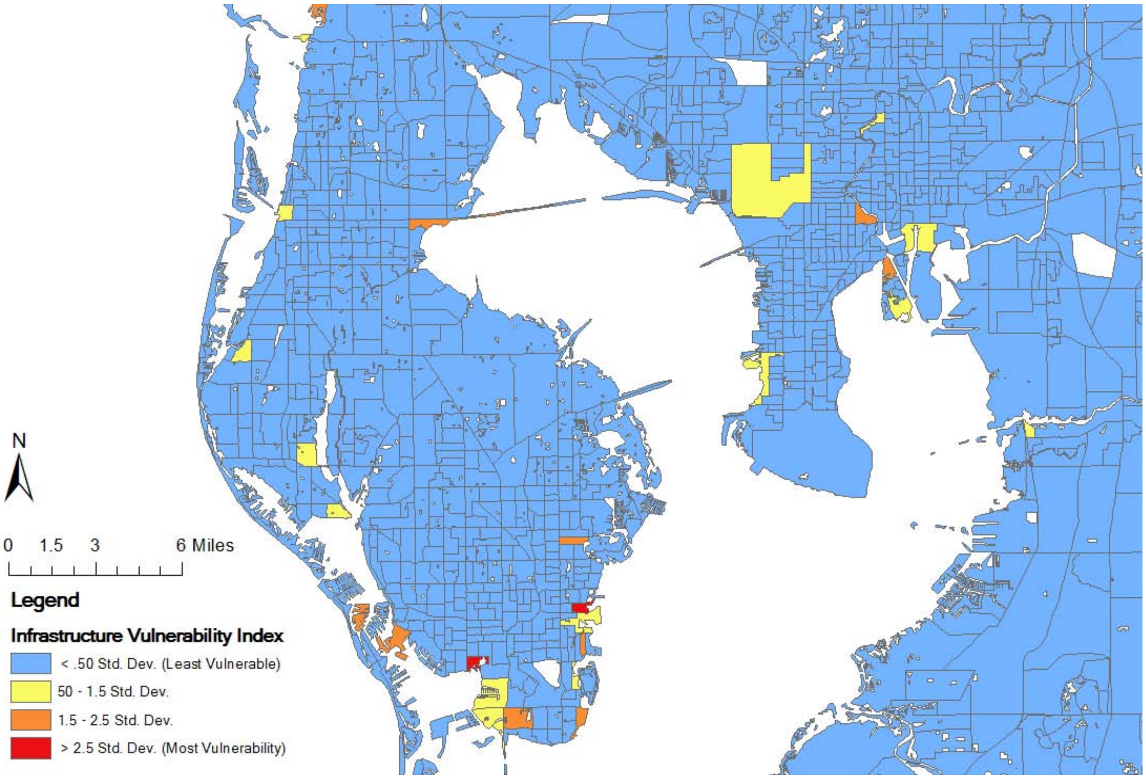


Figure 5-9. Infrastructure vulnerability under 1ft coastal inundation scenario

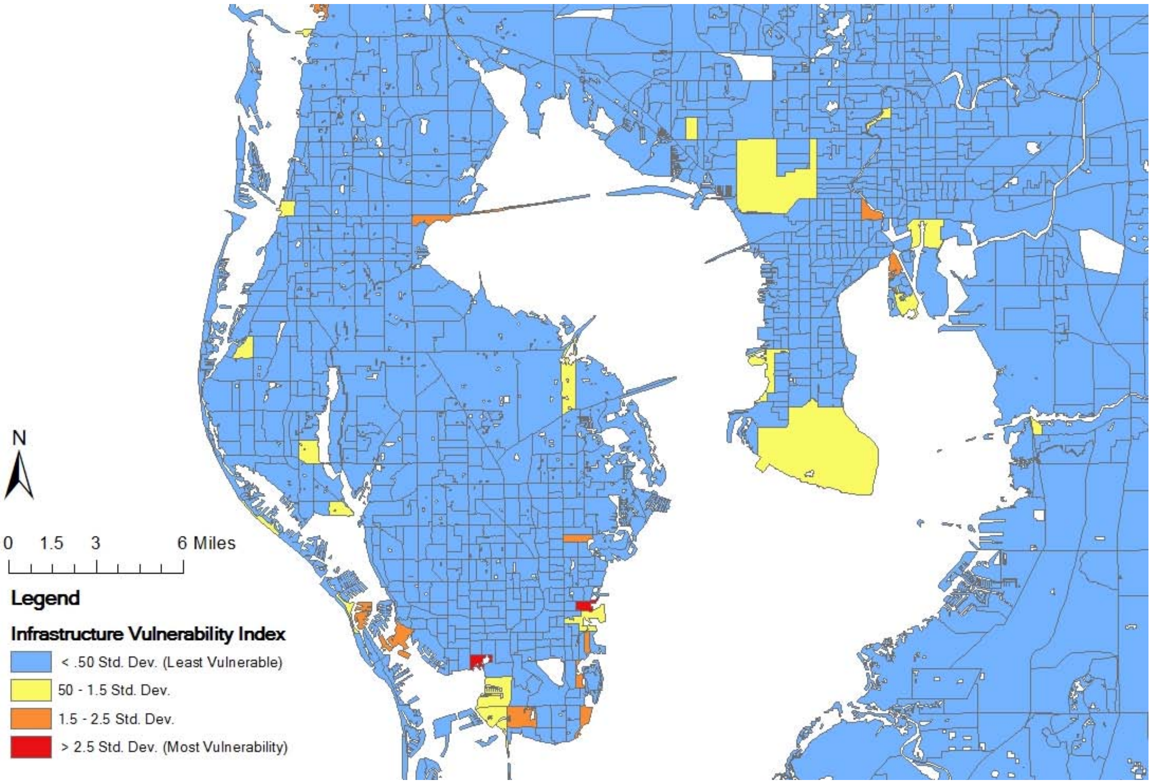


Figure 5-10. Infrastructure vulnerability under 2ft coastal inundation scenario

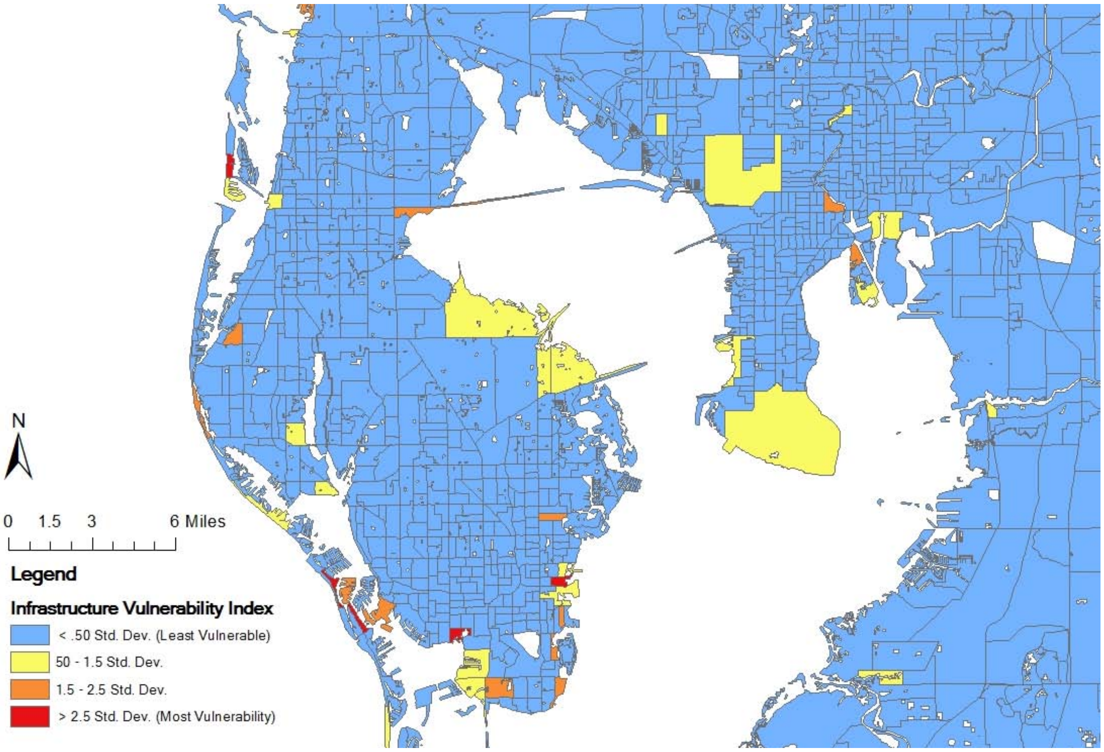


Figure 5-11. Infrastructure vulnerability under 5ft coastal inundation scenario

Table 5-6. Change of average integrated vulnerability by time under different sea level rise scenarios

	Integrated Vulnerability Index (Mean)		
Year	Low Sea Level Rise Scenario	Median Sea Level Rise Scenario	High Sea Level Rise Scenario
2020	0.2757	0.2757	0.2757
2030	0.2757	0.3665	0.3665
2040	0.3665	0.3665	0.3684
2050	0.3665	0.3684	0.3703

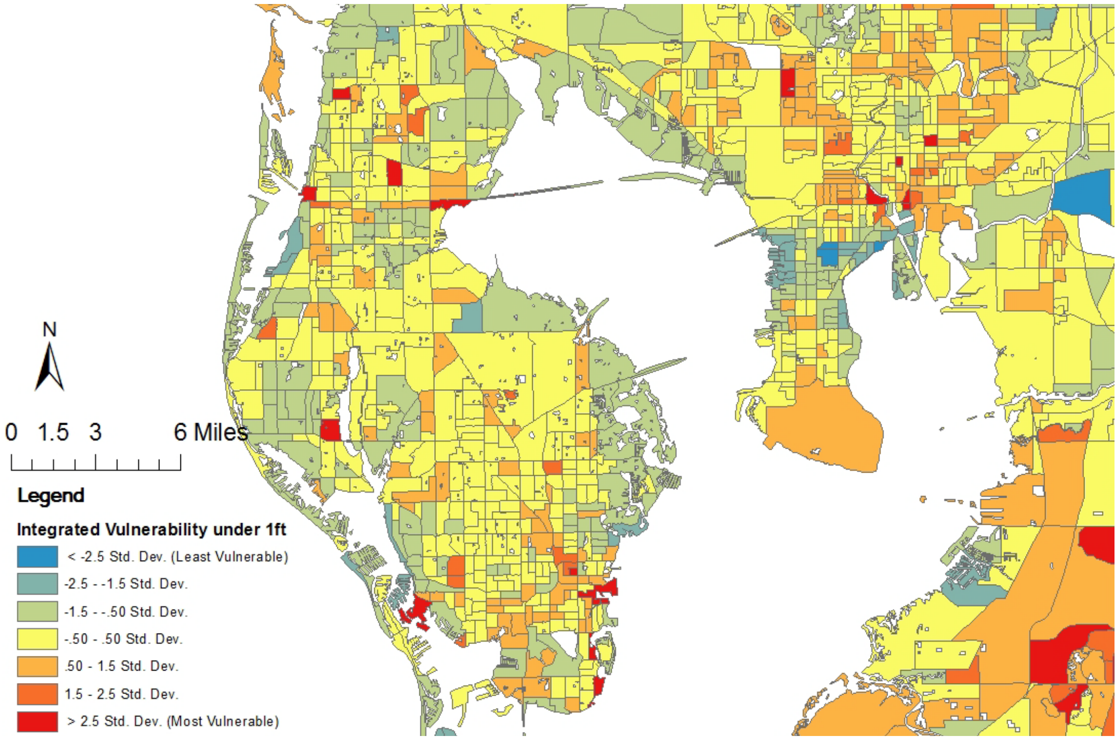


Figure 5-12. Integrated vulnerability under 1ft coastal inundation scenario

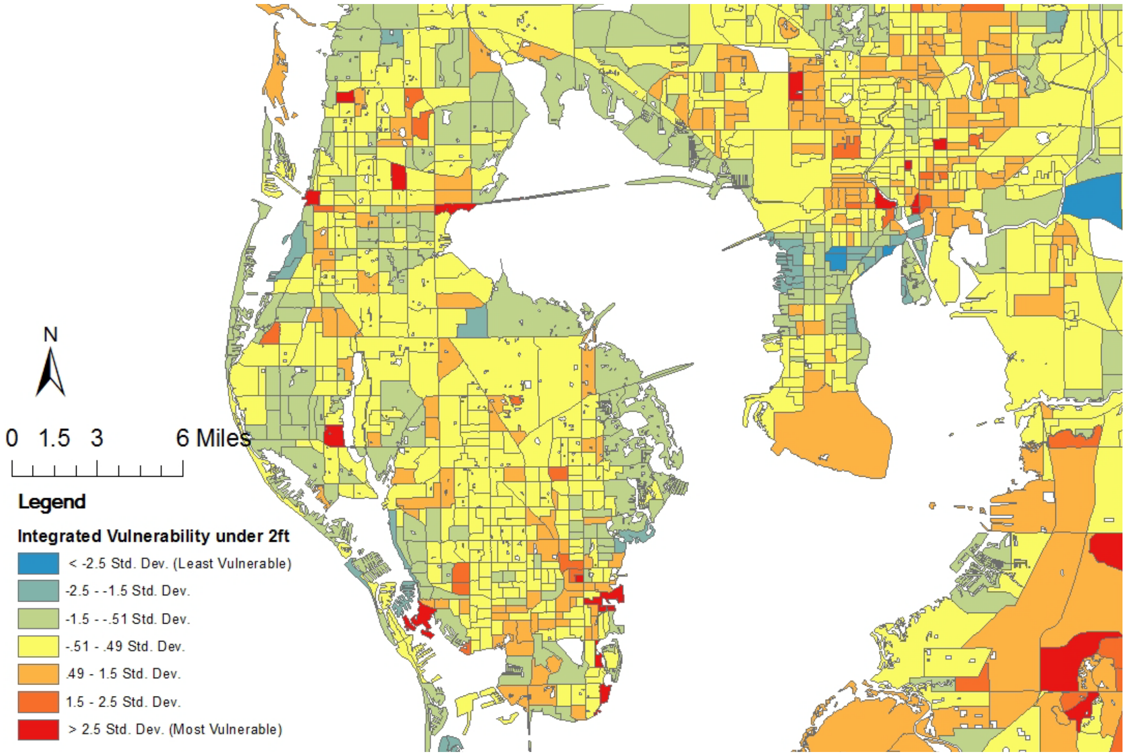


Figure 5-13. Integrated vulnerability under 2ft coastal inundation scenario

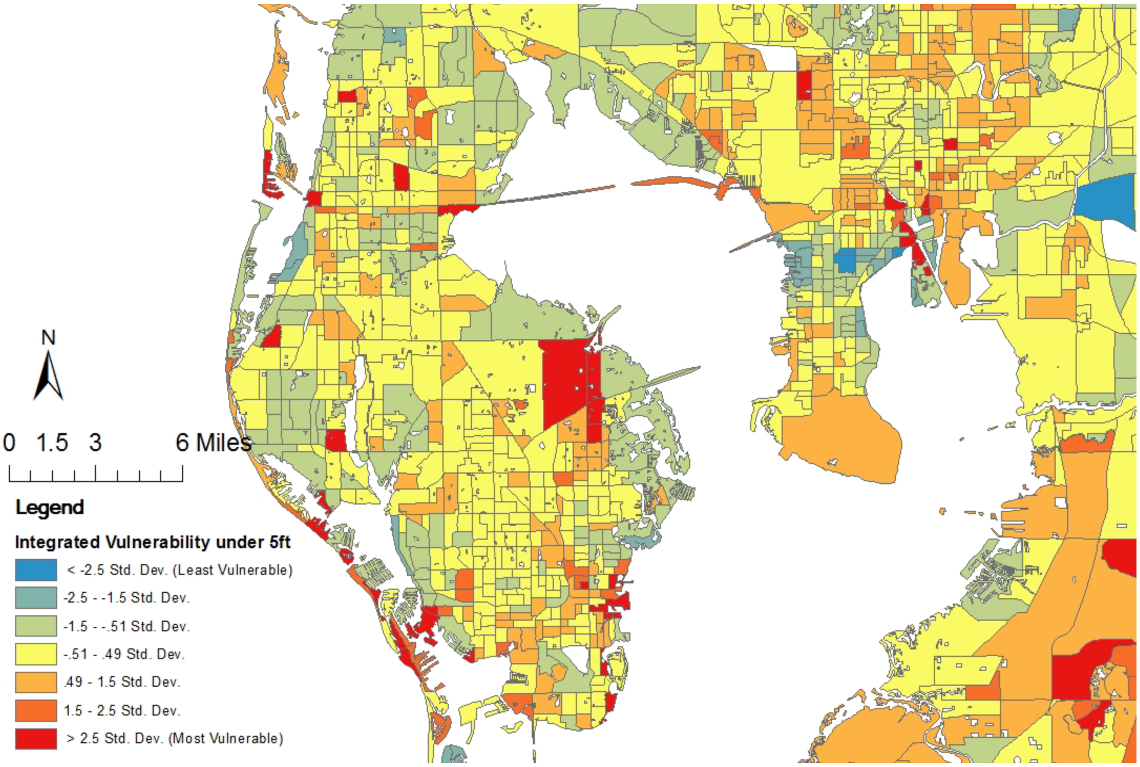


Figure 5-14. Integrated vulnerability under 5ft coastal inundation scenario

CHAPTER 6
TRANSPORTATION VULNERABILITY AND ADAPTATION ANALYSIS

In this chapter, the results of the transportation vulnerability analysis are presented in three sections. First, the characteristic of proposed transportation vulnerability index is illustrated through a simplified numerical example to show how the index's sensitivity to travel time changes and attraction changes. Second, the proposed transportation vulnerability index is applied to the case study area and calculated for each of the traffic analysis zones. Then analysis is conducted to explore the relationship between transportation vulnerability and local land use and network characteristics. Third, to assist adaptation decision making, three adaptation strategies are evaluated using transportation system performance measures.

Transportation Vulnerability Index Sensitivity Analysis

To illustrate the sensitivity of proposed transportation vulnerability index to travel time changes and number of incoming trip changes, two sensitivity analysis are conducted, First, to evaluate how the value of the vulnerability index changes in response to travel time changes between the target TAZ and other TAZs, the number of attractions are kept constant. Second, to evaluate how the value of the vulnerability index changes in response to number of attraction changes between the target TAZ and other TAZs, the travel time are kept constant. In order to perform these two analyses, a simplified numerical example is used.

$$V_i = \left(\sum_{j=1}^{N} \frac{t_{ji}^*}{t_{ji}} * T_{ji} + 1\right) \frac{1}{T_{.i}^* + 1} \qquad (6\text{-}1)$$

In the example, there are three zones (Figure 6-1). Their travel time to zone 1 and number of trips attracted to zone1 are listed in Table 6-1. The internal trips of zone 1 are

10 trips. There are 30 trips coming from zone 2 to zone 1, and 60 trips coming from zone 3 to zone 1. As there are less trips coming from zone 2 than zone 3, zone 2 is identified as a small (contribution) zone to zone 1's total attraction and zone 3 is identified as a big (contribution) zone to zone 1's total attraction.

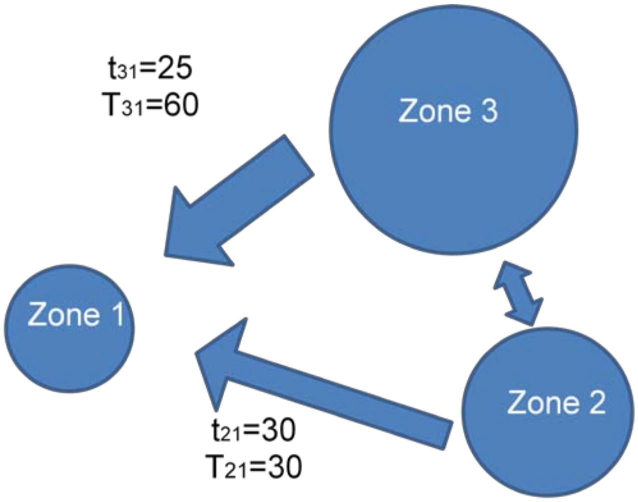


Figure 6-1. Numerical example traffic analysis zones

Table 6-1. Original travel time and number of trips to zone 1

	Zone 1 to Zone 1	Zone 2 to Zone 1	Zone 3 to Zone 1
Original Travel Time	5	30	25
Original Trips	10	30	60

Suppose after a disruption event, there is only one travel time between TAZ j to TAZ 1 is affected. t_{11}^*, t_{21}^*, t_{31}^* changes one at a time. t_{j1}^* changes as a proportion to the origin travel time. Other variables remain constant. Figure 6-1 shows how the changes of t_{11}^*, t_{21}^*, t_{31}^* affect V_1. Figure 6-1 indicates that the vulnerability index is always positive. When there is no change, the ideal value of the index is 1. The larger the index is, there is more delay/increase in travel time. The smaller the index is, there is more savings in travel time. It also shows that same proportion of travel time changes,

changes between zone 3 and 1 creates the highest vulnerability, and changes in internal travel time creates the lowest vulnerability. This means that differences in number of trips are the decisive factor for vulnerability. Changes in routes connecting big (contribution) zones will generate more vulnerability than changes in routes connecting small (contribution) zones despite their distance to the targeted zone.

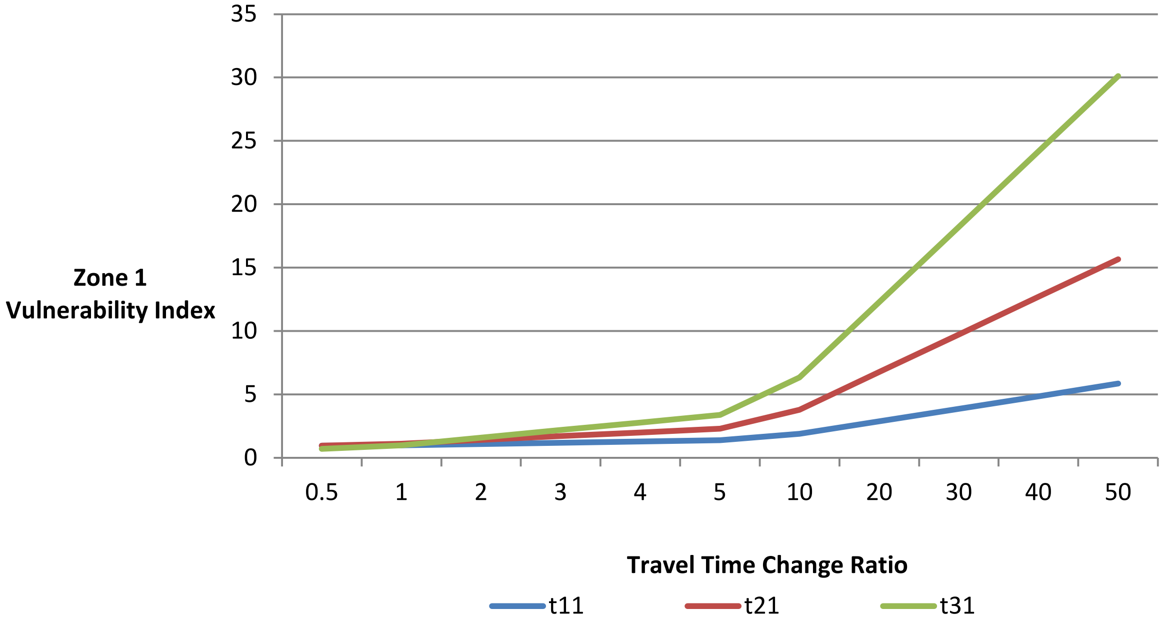


Figure 6-2. Vulnerability sensitivity to travel time changes

Suppose travel time remain constant, T_{11}^{*}, T_{21}^{*}, T_{31}^{*} changes one at a time. T_{j1}^{*} changes as a proportion to the origin trips. Other variables remain constant. Figure 6-2 shows how the changes of T_{11}^{*}, T_{21}^{*}, T_{31}^{*} affect V_1. With the increase of number of trips, the zone become more attractive and the vulnerability index will be small and close to 0. When there is no change, the ideal value of the index is 1. With the decrease of number of trips, the zone becomes less attractive and the vulnerability index will be large, which considers its potential trip loss as an increase of vulnerability. With same proportion of changes, changes in number of trips between zone 3 and 1 creates the highest vulnerability, and changes in internal trips creates the lowest vulnerability. The index is proportional to the difference in number of trips.

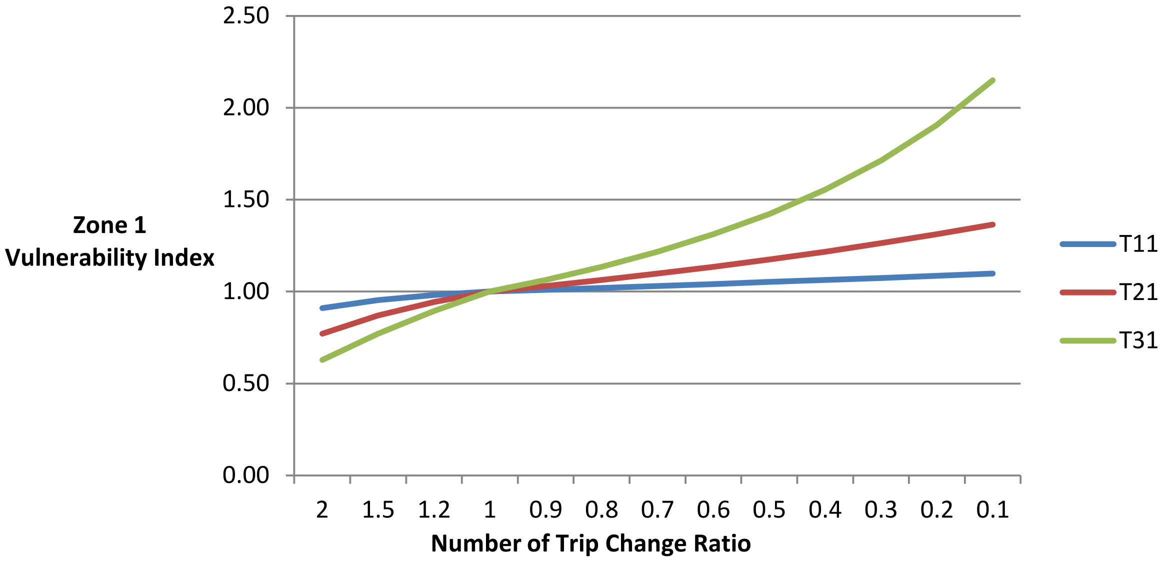


Figure 6-3. Vulnerability sensitivity to changes of number of trips

Vulnerability Analysis

The study region has a total area of 2,073,578 acres of land and 22,321 acres will be inundated by 2 feet sea level rise. Out of the total 33,681 network links (13,009 miles) there will be 577 road or bridge segments (316.93 miles) and 680 centroid connectors (269.05 miles) directly within or across inundation areas. In addition, there will be 1596 centroid connectors (610.31 miles) within partially inundated TAZs. According to the spatial analysis, there will be 148 bridges in the region at inundation risk. However, due to the limitation of LiDAR data in extracting transportation features (Csanyi, 2006), field examinations or target ground control are needed to confirm these conclusions. Table 1 provides the summary of inundated transportation infrastructures by functional class, indicating collector roads are most vulnerable to inundation, followed by divided arterials. A large amount of centroid connectors are shown to be affected. As centroid connectors are virtual representations of internal accessibility rather than actual roads, it indicates that TAZ internal accessibility may be significantly reduced.

Table 6-2. Transportation network inundation spatial analysis summary

Spatial Relationship with inundation area	Facility Type	Number of Segments	Length (miles)
Intersect (across) with the inundation area	Freeways and Expressways	42	64.70
	Divided Arterials	193	93.15
	Undivided Arterials	50	15.53
	Collectors	212	101.41
	Centroid Connectors	106	245.36
	One-way Facilities	14	2.70
	Ramps	27	9.47
	Toll Facilities	31	28.47
	TOTAL	675	560.79
Completely within the inundation area	Divided Arterials	2	0.06
	Collectors	6	1.45
	Centroid Connectors	574	50.69
	TOTAL	582	52.19
No spatial interaction with inundation area according to the virtual shape but within TAZs that are partial inundated	Centroid Connectors	1596	610.31
	TOTAL	1596	610.31

To estimate the inundated land use changes, data from different sources are obtained. 2010 census blocks data from U.S. Census Bureau is obtained to estimate the number of population and housing will be inundated in each TAZ. Lodging facilities in Florida 2011 dataset from Florida Geographic Data Library (FGDL) and Florida parcel data 2010 from the Florida Department of Revenue's tax database are obtained to estimate the inundated hotel and motel units. If a hotel/motel parcel is affected by inundation zone, the point lodging facilities data (100 feet buffer applied to resolve data inconsistency) within that parcel will be identified as being inundated. Similarly, for school enrollment estimation, Florida public and private schools in 2012 from FGDL and Florida parcel data in 2010 from the Florida Department of Revenue's tax database are used to estimate the impacts on school enrollment. If a school parcel is affected by inundation, the point school facilities data (100 feet buffer applied to resolve data inconsistency) within that parcel will be identified as being inundated. For employment estimation, 2010 point employment data by category are obtained from Florida Department of Transportation Central office. Table 6-3 gives a summary of the socioeconomic changes under scenario 6. It is assumed that those inundated residents and businesses will move out of the region and will not contribute to the travel demand within the study area.

Table 6-3. Inundated land use data

Variable	Number of Inundation Units	Regional Total	Inundation Percentage
Total dwelling units	16,883	2,034,630	0.83%
Permanent dwelling unit population	27,106	4,130,170	0.66%
Number of business hotel/motel units (rooms)	901	19,121	4.71%
Number of economy hotel/motel units (rooms)	222	27,451	0.81%
Number of resort hotel/motel units (rooms)	1,571	17,500	8.98%
Industrial employment	201	419,656	0.05%
Regional commercial employment	191	227,097	0.08%
Local commercial employment	412	300,418	0.14%
Regional service employment	1,160	1,111,330	0.10%
Local service employment	87	277,850	0.03%
Total employment	2,051	2,336,350	0.09%
School enrollment from kindergarten to grade 12	7,995	619,938	1.29%

The network and land use data are input into the 2035 Tampa Bay long range transportation model. Before and after travel time matrix and trip distribution matrix are obtained to construct the the vulnerability indexes:

$$VA_i = \left(\sum_{j=1}^{N} \frac{t_{ji}^*}{t_{ji}} * T_{ji} + 1\right) \frac{1}{T_{.i}^* + 1}, \tag{6-2}$$

$$VM_i = \left(\sum_{j=1}^{N} \frac{t_{ij}^*}{t_{ij}} * T_{ij} + 1\right) \frac{1}{T_{i.}^* + 1} \tag{6-3}$$

The indexes are calculated for each traffic analysis zone. The indexes represent the increase of difficulty for the TAZ to be reached by traveler in other TAZs or the difficulty for travelers within a TAZ to travel to other TAZs. The vulnerability indexes are mapped by standard deviation as shown in Figure 6-3. The green areas are TAZs that have attracted more trips or have less travel time because of the disruption in coastal area. Figure 6-3 also confirms that the index could reflect the trend that the vulnerability of accessibility and mobility in coastal areas are higher than inland areas. With the network disruption caused by sea level rise, the mobility (i.e. people’s easiness to travel around) will reduce for all of the traffic analysis zones. However, as the disruption caused by sea level rise happen in the coastal area, the attractiveness of coastal zones may reduce while the attractiveness of inland zones may increase relatively as shown in the left map in Figure 6-3.

To understand the effects of different land use, network, and demographic factors’ influence on zonal accessibility based vulnerability, an ordinary least square model is built. The dependent variable is zonal accessibility based vulnerability, and the independent variables include transportation network characteristics, local land use patterns, and demographic factors (Figure 4-11). With 2078 samples, the dependent and independent variables’ descriptive statistics are shown in Table 6-4. After testing the multicollinearity and removing insignificant variables, the model is finalized as Table 6-5. The adjusted R-squared of the model of the model is 0.4214.

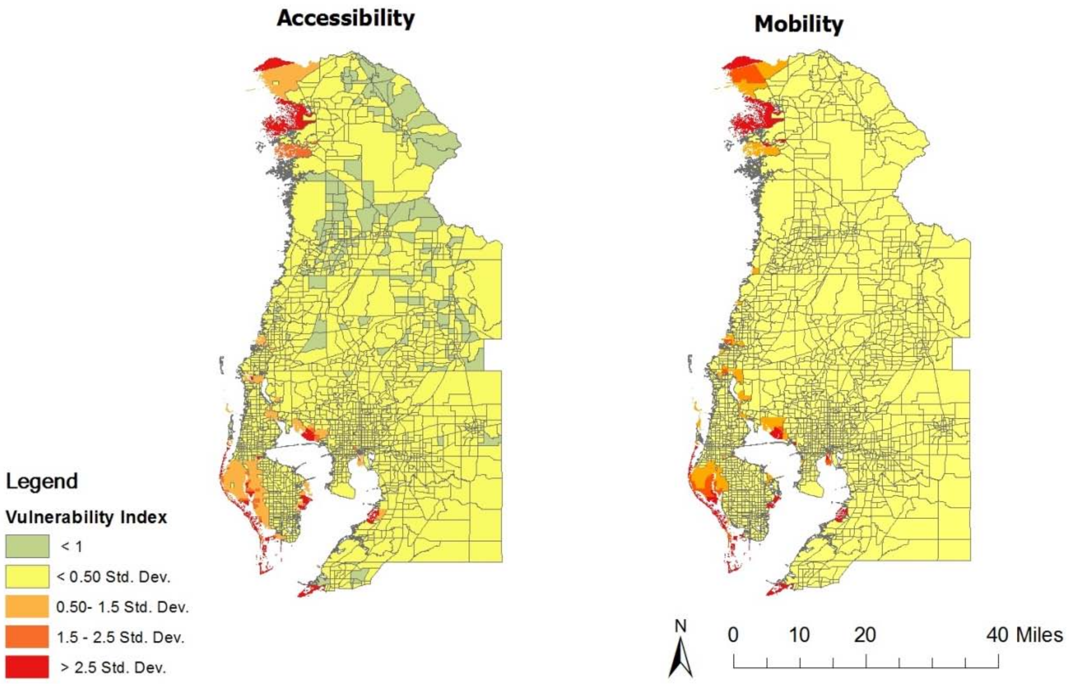


Figure 6-4. Zonal vulnerability

The model indicates positive correlation between transportation vulnerability and average household automobile ownership, TAZ internal capacity reduction, inundated population percentage, inundated employment percentage, hotel motel units, and capacity reduction. There are negative correlations between transportation vulnerability and inundation area percentage, number of employment, employment density, percentage of retired household, percentage of household with children, average household size, average surrounding highway capacity, average free flow travel time, and average travel time increase (neighborhood/local ratio). Variables that are not significant include population, population density, local employment, employment and population balance, road density, and school enrollment. The results show that automobile dependence (high automobile ownership) and exposures to inundation (high inundation population percentage, high inundation employment percentage and

Table 6-4. Descriptive statistics

Variable	Min	Max	Mean	Standard Deviation
zonal vulnerability	0.89	7.09	1.240	0.4010
Population density	0	121187.43	4183.48	7422.53
Inundated population ratio	0	1	0.0063	0.0376
Inundation area ratio	0	0.4518	0.0070	0.0305
Dwelling units	0	5427	849.35	758.58
Inundated dwelling units ratio	0	0.6383	0.0061	0.0322
Population	0	12049	1826.50	1594.83
Hotel/motel units	0	1739	26.79	102.37
Inundated hotel/motel ratio	0	1	0.0049	0.0613
Employment	0	14896	1046.67	1272.03
Employment density	0	823175.58	6612.01	33482.96
Inundated employment ratio	0	0.4475	0.0009	0.0128
Local employment	0	4606	254.95	311.36
Local employment ratio	0	1	0.2658	0.2031
Inundated local employment ratio	0	0.90	0.0015	0.0266
TAZ area	0.0058	75.71	1.45	3.76
Employment population balance	0.00032	3268	6.71	101.29
Road density	0.0059	75.3988	6.6498	7.0536
Average capacity (distance weighted)	385.85	1888.70	827.03	210.26
Highway capacity reduction ratio	0	0.90	0.0277	0.1231
Surrounding highway total length (miles)	0.0439	43.32	3.352	3.24
Average free flow travel time per mile (min)	0.07	6.75	0.81	0.65
TAZ internal connector total length (miles)	0.07	55.98	2.19	2.46
TAZ internal average free flow travel time per mile (min)	0.15	18.84	1.77	1.30
Internal average capacity	9995.33	10005.42	10000.00	0.4366
Internal capacity reduction percentage	0	0.90	0.0088	0.0484
Average travel time increase neighborhood to local ratio	0	1.26	0.99	0.0579
Retired household %	0	89	28.92	14.77
Household with child %	0	100	28.94	12.39
Average household vehicle ownership	0.41	2.23	1.51	0.30
School enrollment	0	5256	279.60	686.11
Average household size	0	3.69	1.9698	0.5172

high highway capacity reduction) are the two primary causes of transportation vulnerability to sea level rise at the TAZ level. It is also found that demographic characteristics (e.g retirement, child presence, household size, and automobile ownership) are important in determining the TAZ's vulnerability considering their influence in shaping trip generation and distribution patterns. Employment and population balance at the TAZ level does not have a significant impact on the vulnerability indicates that internal capture of trips does not have a significant impacts in reducing the region’s vulnerability to sea level rise.

Global ordinary least square model assumes spatial independence of the residuals. Spatial autocorrelation is tested to justify this assumption (Figure 6-5). Given the z-score of 51.78, there is a less than 1% likelihood that spatial autocorrelation does not exist. To overcome this limitation, geographically weighted regression is performed and the results are shown in table 6-6 Number of neighbors of the GWR model has been set from 20 up to 100 with ten increments, and from 100 to1000 with 100 increments. Small sample size could potential improve the local goodness of fit, but have the local multicollinearity problem and could only include very limited number of independent variables. As a result, 1000 is selected as the number of neighbors to eliminate the local multicollinearity problem. After removing the variables with local multicollinearity, eleven independent variables are included in the GWR model. Their coefficient ranges are summarized in Table 6-6. The table shows that the highway capacity reduction caused by sea level rise inundation has positive correlation with the transportation vulnerability across the region, which is consistent with the global ordinary least square model results. However, all the other variables have both negative and positive correlation with transportation vulnerability depending on their geographical location, which make it questionable whether the global model findings are applicable across the whole region. The mean value of local R squared is 0.2828. The minimum local R-squared is 0.1145, and the maximum R-squared is 0.4377. Figure 6-6

Table 6-5. Ordinary least square model

Variable (17)	Coefficient	StdError	t-Statistic	Probability	VIF
Intercept	3.4763	0.1394	24.9287	0.0000*	--------
Inundation Area %	-2.3350	0.3091	-7.5542	0.0000*	1.9842
No. of Employment	0.0000	0.0000	-2.3902	0.0169*	1.2640
Employment Density	0.0000	0.0000	-2.4559	0.0141*	1.2884
Retired Population %	-0.0033	0.0007	-4.6874	0.0000*	2.3839
Working with Children Household %	-0.0078	0.0009	-8.3955	0.0000*	2.9369
Average Household Size	-0.0548	0.0146	-3.7549	0.0001*	1.2705
Average Automobile Ownership	0.0777	0.0312	2.4876	0.0129*	2.0026
Average Capacity (distance weighted)	-0.0001	0.0000	-3.4522	0.0005*	1.0813
Average Free Flow Travel Time (distance weighted)	-0.0750	0.0137	-5.4680	0.0000*	1.7974
Size of the TAZ (sq miles)	0.0058	0.0025	2.2927	0.0219*	2.0109
Average Internal Free Flow Travel Time	-0.0376	0.0080	-4.6754	0.0000*	2.4586
Internal Capacity Reduction %	3.4674	0.1786	19.4170	0.0000*	1.6707
Average Travel Time Change Neighborhood/local ratio	-1.7446	0.1210	-14.4205	0.0000*	1.0950
Inundated Population %	0.4568	0.2027	2.2537	0.0243*	1.2990
Inundated Employment %	4.0484	0.5485	7.3809	0.0000*	1.1042
Hotel Motel Units	0.0003	0.0001	4.2635	0.0000*	1.1036
Capacity Reduction %	0.6069	0.0631	9.6241	0.0000*	1.3437
Dependent variable	Accessibility based transportation vulnerability index				
Sample size (N)	2078				
R squared	0.4261				
Adjusted R squared	0.4214				

demonstrates the spatial distribution of the GWR model residuals, showing that inland area are best estimated and majority of the coastal areas are either underestimated or overestimated. This distribution of residuals indicates that inundated coastal areas may have different causes of vulnerability compared with inland areas. However, as geographically weighted regression model choose the neighbors only based on their distance, it fails to distinguish coastal TAZs from the inland TAZs, which may be

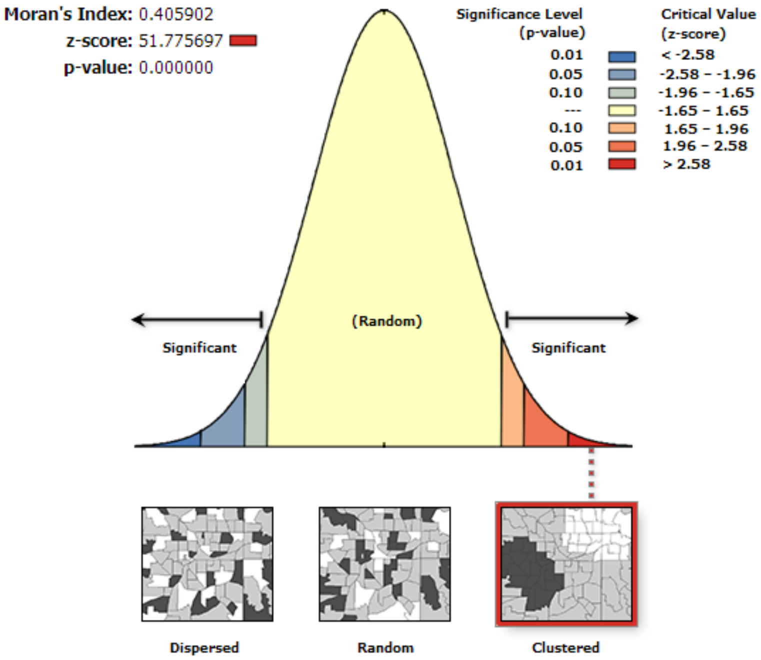


Figure 6-5. Spatial autocorrelation of the residual of global regression model

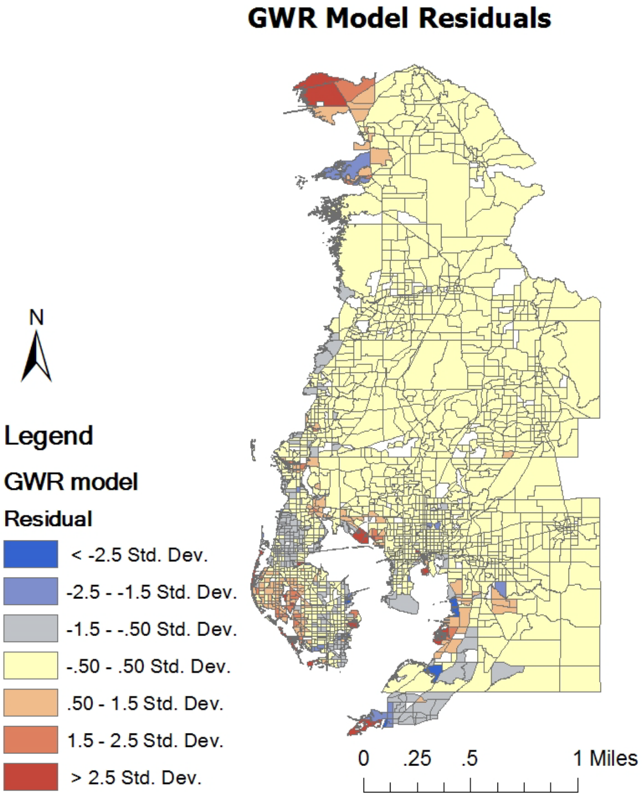


Figure 6-6. Spatial distribution of geographically weighted regression residuals

the underlying reason for such disparity. Furthermore, even using geographically weighted regression model, the spatial autocorrelation of residuals still exist. The Moran's index of GWR model residuals is 0.2715, and the z-score is 35.4643, indicating spatial cluster of residuals exist at the 99% confidence level.

Table 6-6. Geographically weighted regression model coefficients summary

Variable (12)	Coefficient min	Coefficient max	Coefficient mean	Coefficient std
Intercept	0.9930	1.7770	1.2800	0.2306
Inundation Area %	-0.1790	2.6792	1.0938	0.5175
No. of Employment	-0.000047	0.000019	0.0000	0.000012
Hotel/Motel Units	-0.000103	0.000676	0.000186	0.000234
Employment Density	-0.000008	0.000003	-0.000001	0.000002
Retired Population %	-0.001972	0.006895	0.001254	0.001852
Average Capacity (distance weighted)	-0.000379	0.000106	-0.000088	0.000128
Average Free Flow Travel Time (distance weighted)	-0.117362	0.103744	0.001006	0.038852
Size of the TAZ (sq miles)	-0.03746	0.03496	-0.0022	0.0115
Average Internal Free Flow Travel Time	-0.08317	0.1126	-0.0275	0.0266
Inundated Population %	-0.06396	9.2344	0.7499	1.2723
Inundated Employment %	-25.4656	12.0287	2.9202	2.9190
Capacity Reduction %	0.1393	1.6739	0.6870	0.2935
Dependent variable	Accessibility based transportation vulnerability index			
Maximum local R squared	0.4377			
Minimum local R squared	0.1145			
Mean local R squared	0.2828			
Sample size (N)	2078			

Based on the findings of geographically weighted regression that inundated coastal zones have different patterns with inland areas, a regression model with a dummy variable that identifies the inundated coastal zones is constructed. The inundation dummy variable has a value of 1 if the TAZ is affected by sea level rise inundation, and 0 if not. There are 385 TAZs in the region being inundated, and the mean value of the dummy variable for the 2078 TAZs across the region is 0.1853.The

63 independent variables are tested in the new model, including the dummy variable, 31 independent variables in Table 6-4 and 31 interactive variables (the dummy variable multiplied by other independent variables). Testing the significance of the interactive variables could test the hypothesis whether the vulnerability pattern in inundation area differs from the inland areas. The results of the model with location dummy variables are shown in Table 6-7. There are fifteen significant variables in the model, twelve of which are interactive variables (variables that interact the dummy variables), indicating significant differences exist between the vulnerability pattern within the inundation TAZs and the pattern in the other TAZs. The model has an adjusted R-squared value of 0.4902, which is better than the R-squared of the global regression model without the location dummy variable (0.4214) and the best local R-squared of the geographically weighted regression model (0.4377). The model indicates within the inundated TAZs, inundated employment percentage, hotel/motel units, employment density, internal capacity reduction percentage, surrounding highway capacity reduction percentage, average vehicle ownership, and average capacity have positive correlation with the accessibility based transportation vulnerability. This confirms that business development within inundation area, high automobile dependency, and high level of exposure of transportation network (high percentage of capacity reduction) will make the coastal inundated TAZs more difficulty to be accessed by travelers from other TAZs. The model shows average free flow travel time per mile, and average internal free flow travel time per mile within the TAZ have a negative correlation with transportation vulnerability across the study area, including both the inundated TAZs and the inland TAZs. Less free flow travel time per mile within and near the TAZ indicates higher capacity and

potential higher loss of capacity within inundation area. Less free flow travel time per mile within and near the TAZ outside the inundation area demonstrates that TAZs adjacent to freeways or arterial roads are more vulnerable due to the increase of congestion caused by network disruption. Across the study region, demographic variable percentage of household without children also shows a positive correlation with the transportation vulnerability. This may be caused by their relative high work-related trip rates. Population density, within TAZ population employment ratio, TAZ size, road density, and school enrollment are proved to be insignificant for transportation vulnerability.

Table 6-7. Regression model with dummy variable identifying the inundation area

Variable (15)	Coefficient	StdError	t-Statistic	Probability
Intercept	1.307	0.020	65.914	0.0000*
Inundation Area %	-3.006	0.289	-10.393	0.0000*
Work household with children %	-0.002	0.001	-3.449	0.0006*
Average Free Flow Travel Time (distance weighted)	-0.069	0.012	-5.608	0.0000*
Average Internal Free Flow Travel Time	-0.019	0.007	-2.924	0.0035*
Internal Capacity Reduction %	3.202	0.175	18.280	0.0000*
Inundated Employment %	3.850	0.511	7.539	0.0000*
Surrounding Highway Capacity Reduction %	0.322	0.064	5.053	0.0000*
Inundation Dummy	2.012	0.169	11.924	0.0000*
Hotel/motel Unit (*Dummy)	0.001	0.000	6.159	0.0000*
Employment Density (*Dummy)	0.000	0.000	-3.862	0.0001*
Work household with children % (*Dummy)	-0.013	0.002	-8.655	0.0000*
Average Vehicle Ownership (*Dummy)	0.354	0.067	5.302	0.0000*
Average Capacity (* Dummy)	0.000	0.000	-2.018	0.0437*
Average Internal Free Flow Travel Time (*Dummy)	-0.052	0.016	-3.267	0.0011*
Neighbor Travel Time increase/Local Travel Time Increase (Dummy)	-1.721	0.116	-14.842	0.0000*
Dependent variable	Accessibility based transportation vulnerability index			
Sample size (N)	2078			
R squared	0.4902			
Adjusted R squared	0.4865			

Adaptation Analysis

By the year 2035, there will 100% risk for Tampa Bay region to have 2ft annual flood under low, median, and high sea level rise scenarios. Therefore, 2ft inundation scenario is selected for adaptation analysis to help the region prepare for the potential annual flood risk by year 2035. Three transportation adaptation scenarios are tested and compared under 2ft inundation scenario, including hard structure protection, accommodation, and planned retreat. With hard structure protection strategy, it is assumed that important bridges and interstate freeways in low-lying areas will be elevated in part through addition of asphalt layers. The bridges and interstate freeways that may remain fully functional include I275, I75, I4, Gulf to Bay Blvd, Gandy Blvd, S 22nd street, Clearwater Memorial Causeway, and Bayside Bridge. With accommodation strategy, it is assumed that access roads within local community (traffic analysis zone) will be prepared against flood using ecological buffer zones and improvements of storm water management. The internal accessibility of 472 traffic analysis zone with a total of 345,173 acres will not be reduced under this scenario. With planned retreat strategy, it is assumed that new residential and business development between now and 2035 will be restricted in the coastal inundation zones. These developments will occur in the nearest suitable coastal area outside the inundation zone. No hard structure protection will be provided for the existing developments. To estimate the maximum effect population relocation can have in reducing the system congestion levels, it is assumed that existing housing, population, business, hotel/motel, and school within the inundation zone will be moved out of the region and will not contribute to the travel demand within the study area.

These scenarios are tested in the Tampa Bay long range transportation model for the year 2035 and evaluation results are compared with base scenario 2035 and no-action scenario. There are three categories of performance measures to be compared, including congestion measures, energy and emission consumption, and system costs. These performance measures are generated by TBRPM model or are post processed in cube voyager software. Specifically, the energy consumption and emission totals are calculated based on estimated link attributes (volume, distance, travel time, speed) and their projected 2020 emission rates in the highway evaluation module (HEVAL) process within TBRPM (Fleming, 2010). The accident costs are calculated based on standard accident rate, injury rate, and fatality rate parameters in the HEVAL process (Fleming, 2010). Total fuel consumption are calculated based on vehicle miles travelled (VMT) with assumed gas price of $6.55 per gallon by year 2035. Total delay due to congestion is calculated based on vehicle hours travelled (VHT).

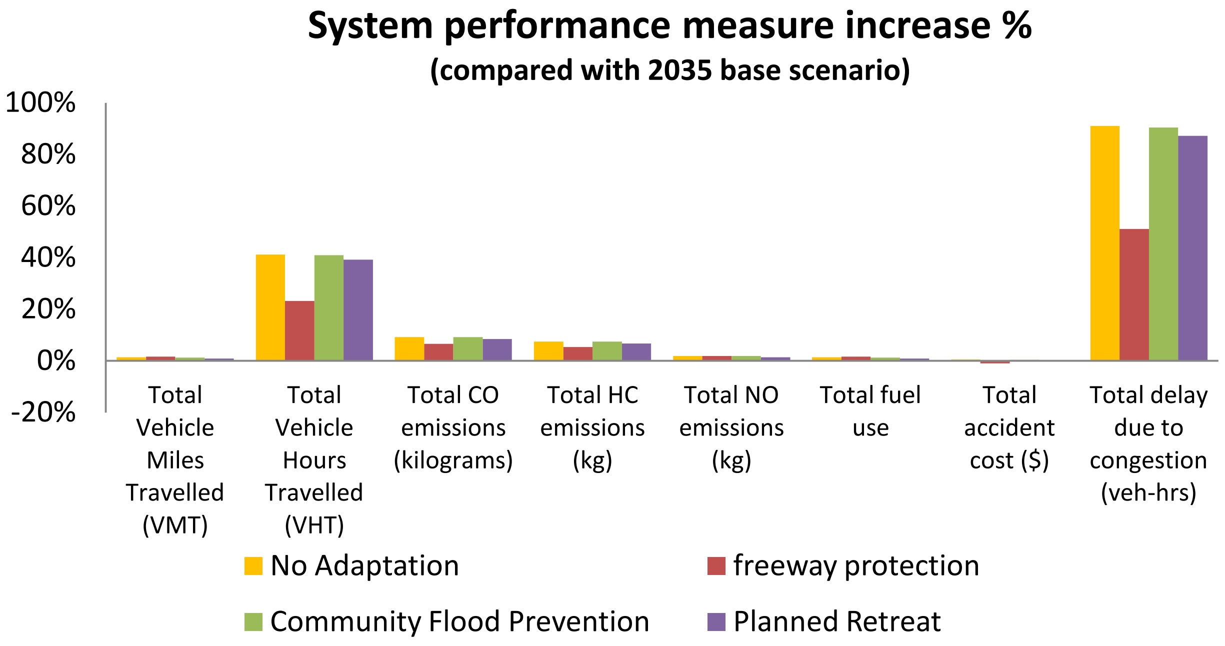


Figure 6-7. Evaluation of three adaptation strategies

Without any adaptation strategies, the regional transportation system in Tampa Bay could have almost 50% of vehicle hours travelled increase and a nearly double of congestion delay under 2ft sea level rise scenario. Among the three adaptation strategies, elevating freeways has the most significant transportation system vulnerability reduction effects but will with some negative effects. Up to 108.78 miles of freeway and bridge network protection could contribute to 948,228 VHT savings, 78,807 CO emission reductions, 4,111 HC emission reduction, $187,893 accident cost savings, and $936,899 delay cost saving. The reductions may be caused by high speed travel on interstate highways. However, 291,859 more VMT and thus $119,662 more fuel use and total user costs indicate the detours made by travelers in order to travel on interstate freeways. Overall protecting the 108.78 miles of freeway will results in $1,124,792 system savings per day for the study region. Taking elevating roads strategy as an example, it costs about $2 million/mile to increase road elevation by 1 meter (Stanton et al., 2007). Considering the system benefits from the hard structure protection, it takes about half a year for the regional accrued benefits to exceed the estimated costs.

CHAPTER 7
CONCLUSIONS

In conclusion, the study has made both methodological and substantive contribution to the literature from the following aspects. First, using local sea level rise projection the study has conducted localized and quantitative vulnerability assessments, which is an improvement from the previous generalized, large scale assessment (ICF International, 2007; U.S. Climate Change Science Program, 2008; Peterson et al, 2008; Jacob et al, 2007). Second, in the assessment, rather than focusing on a specific sector, a composite vulnerability index that integrates social, economic, and infrastructure vulnerabilities is developed to address the multidimensional nature of vulnerability as emphasized by Yoon (2012). Using statistic tests to compare the pairwise median ratings, an improved analytical hierarchy process (AHP) method is developed for the integrated index composition to overcome the limitation in tradition AHP methods which overlooks the variances between different survey respondents. Third, for detailed transportation vulnerability analysis, new trip-based vulnerability indexes are proposed to quantify the potential impacts of sea level rise on neighborhood accessibility and mobility at the traffic analysis zone level. The index is an improvement to previous population-weighted Hansen-type vulnerability index as it could capture the potential changes of trip production and attraction caused by sea level rise inundation. Using the new index, trip loss increases the value of the vulnerability index, while with previous population-weighted Hasen-type vulnerability index trip loss has no effects in the value of the vulnerability index (Lu and Peng, 2012). In addition, with the travel time changes caused by sea level rise disruptions, some inland TAZs compared with coastal TAZs will have relative less travel time increase thus attract more trips than without sea level rise disruptions. The index could capture this trip redistribution effects as well. A linear regression model has been established between the index and travel time increase, percentage of trip changes, the adjusted R^2 of the model is 0.66. A similar linear regression model using previous population weighted vulnerability index results in an adjusted R^2 of 0.12. This verifies the newly proposed transportation vulnerability index has better explanatory power for travel time changes and number of trip changes compared with previous ones.

The substantive findings of the study include visualization of spatial and temporal distribution of community's overall vulnerability, identification of most vulnerable places, evaluation of current adaptation plan time frame, analyzing the relationship between transportation vulnerability and land use, network, demographic factors, and evaluation of potential transportation adaptation strategies. The results could be used by the decision makers of the study region to assist their adaptation planning in several ways. First, the study results provide a visualization of the spatial and temporal distributions of communities' vulnerability to sea level rise as shown in Appendix B. The visualization shows where the most susceptible places to sea level rise are, and where infrastructure and employment are most vulnerable under different inundation levels. Second, to identify the vulnerable places where adaption strategies should be considered, the study identified the places with significant increase (larger than 2.5 standard deviations) of economic vulnerability and infrastructure vulnerability as sea level rises. Their vulnerability increases are mapped by standard deviation (Figure 7-1, Figure 7-2, Figure 7-3, and Figure 7-4). Census block groups whose economic vulnerabilities increase larger than 2.5 standard deviations are identified as the places where the economic adaptation strategies should be implemented (Figure 7-1 and Figure 7-2). Census block groups whose infrastructure vulnerabilities increase larger than 2.5 standard deviations are the places where infrastructure protection and relocation strategy should be implemented (Figure 7-3 and Figure 7-4). Third, according to the proposed composite vulnerability index, risk assessment is conducted with annual flood probability projection (Climate Central, 2013) to evaluate the appropriateness of the time frame of current adaptation plan in study region. Through the risk analysis of integrated vulnerability per decade, the study identifies the crucial time period during which the region's integrated vulnerability will increase significantly. According to the changes of integrated vulnerability (Appendix B), it is found that under low sea level rise scenario, the region's vulnerability to coastal flooding caused by sea level rise will increase significantly during 2030-2040. Under medium and high sea level rise scenario, the region's vulnerability to coastal flooding caused by sea level rise will increase most between 2020 and 2030. The results of the survey (Appendix A) shows that majority (64%) of the planning agencies in Tampa Bay region do not have adaptation plan with a specific planning time range at the moment. Among the agencies with adaptation plans, the most common (50%) adaptation plan time range is 25 years (Figure 7-5). This shows that the current adaptation planning time frame is only consistent with slow sea level rising scenario, and is not prepared for the changes under medium and fast sea level rising scenario. Considering the current sea level rise projection is conservative, it is suggested that adaptation plan should be made with a 10 to 15 year time frame and be implemented between year 2020 and 2030.

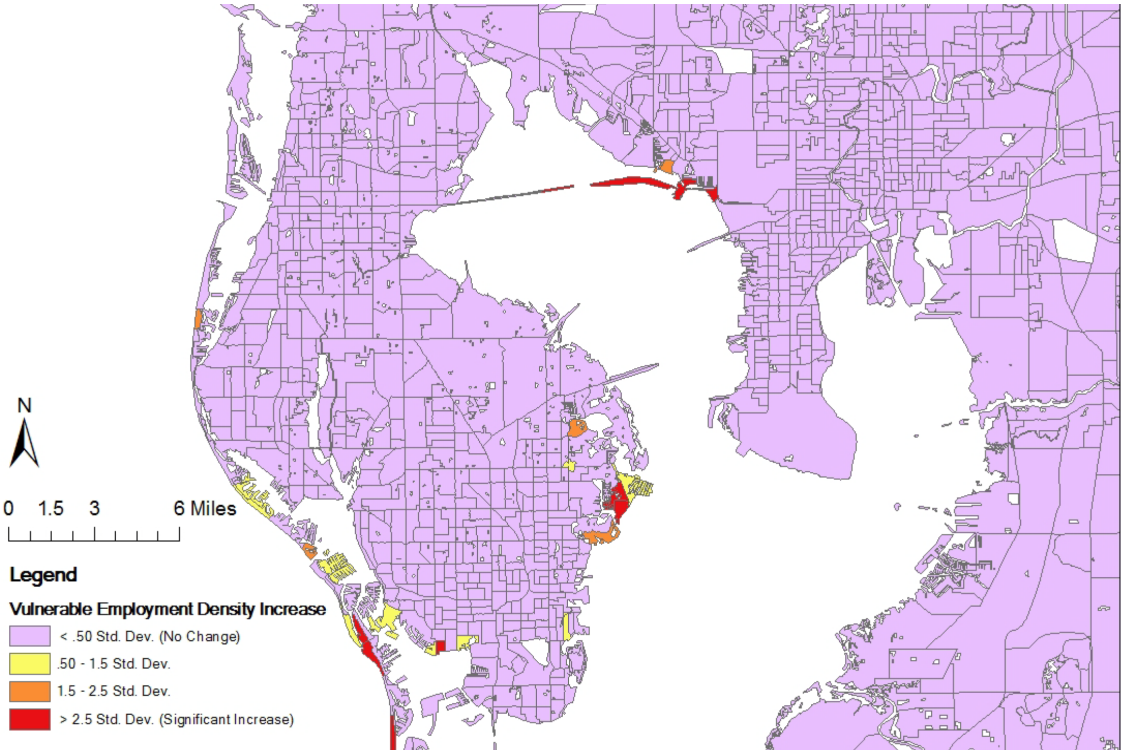


Figure 7-1. Economic vulnerability increase as sea level rises from 1ft to 2ft

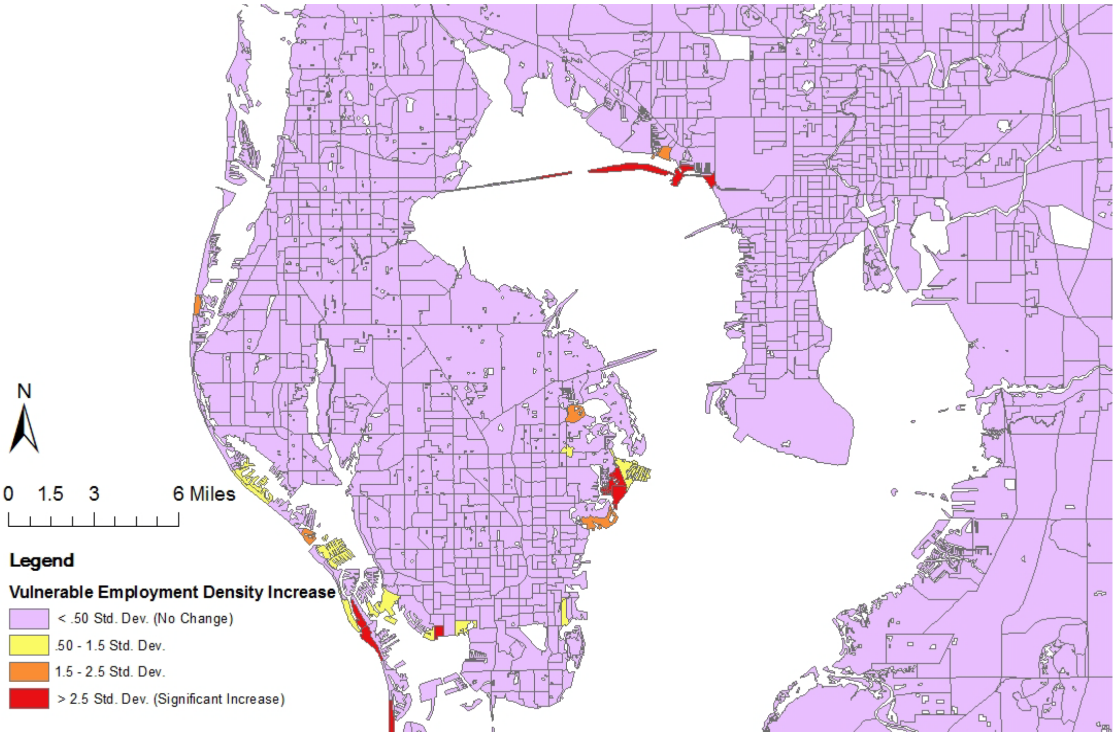


Figure 7-2. Economic vulnerability increase as sea level rises from 2ft to 5ft

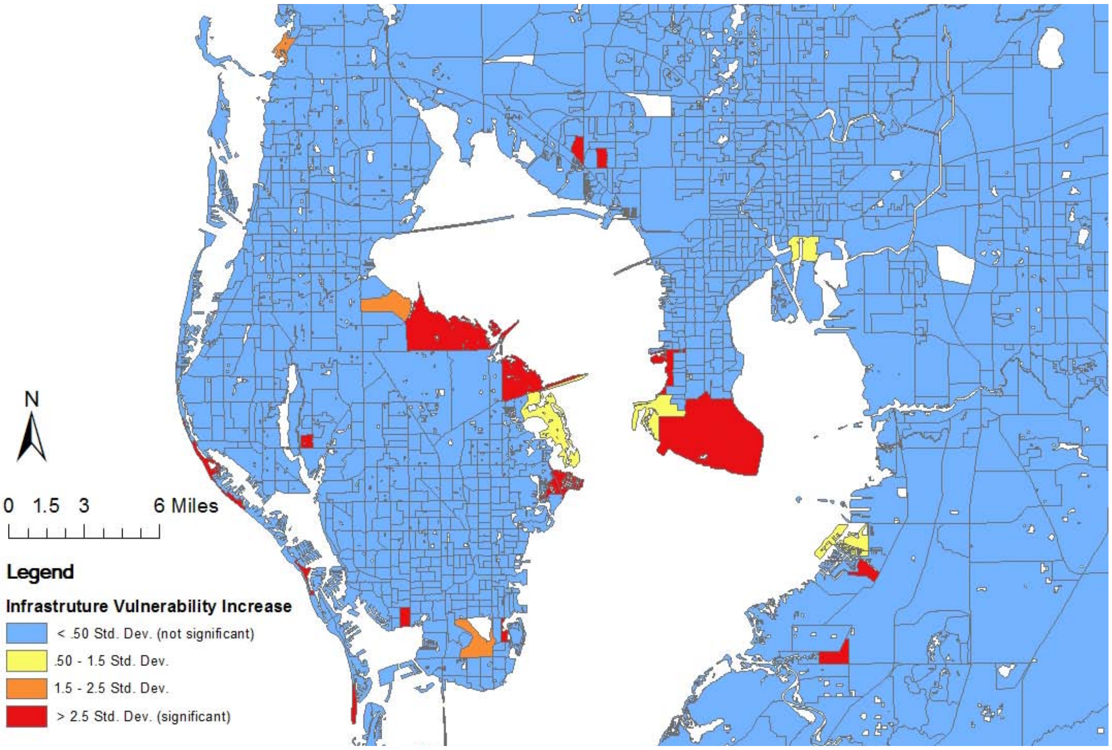


Figure 7-3. Infrastructure vulnerability increase as sea level rises from 1ft to 2ft

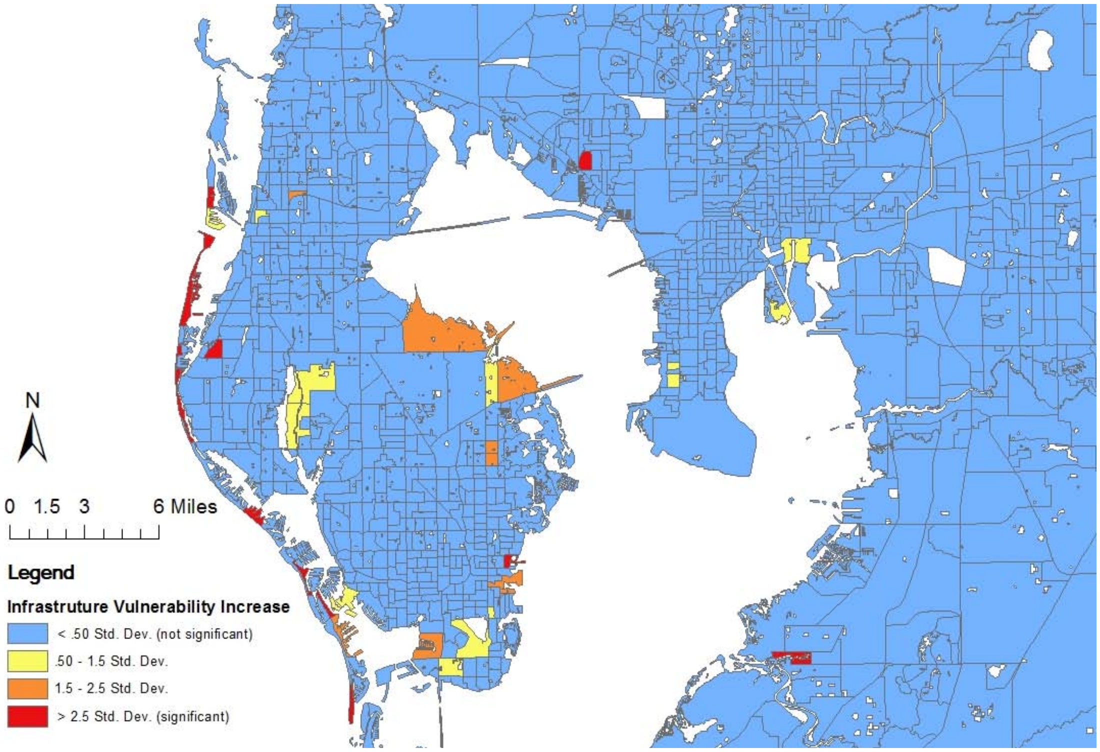


Figure 7-4. Infrastructure vulnerability increase as sea level rises from 2ft to 5ft

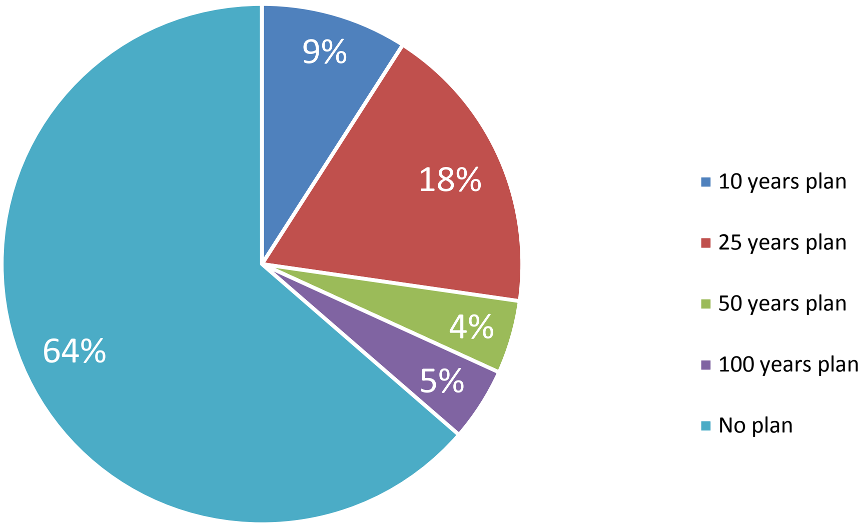


Figure 7-5. Current adaptation plan time frame

Especially, according to the survey results, transportation infrastructure is considered as the most vital critical infrastructure considering its cost, role in emergency situations, and relocation difficulties (Table 5-5). Analysis of transportation system under 2ft inundation scenario shows that even with less than 5% of the road segments being directly inundated in Tampa Bay region, system performance measure in terms of congestion delay could double. The proposed accessibility-based vulnerability index is calculated for each traffic analysis zone within the study area. Three regression models have been used to test the relationship between the accessibility based vulnerability index and local transportation network characteristics, land use pattern, and demographic factors. The global regression model shows spatial autocorrelation exists. Geographically weighted regression model is applied to overcome this limitation, and shows slightly improved local R-squared for several coastal TAZs, where local R-square is larger than R squared of global regression model 0.4214 (Figure 7-6). However, test of residuals show spatial clustering, and indicates that coast inundated TAZs have different vulnerability patterns compared with inland TAZs (Figure 6-6). Geographically weighted regression model could not separate the coastal TAZs from inland TAZs in neighbor selection, therefore majority of the TAZs do not have an improved local R-squared. Finally, a regression model with a location dummy variable that identifies the inundated coastal TAZs is proposed. The regression model shows an improved adjusted R-squared of 0.4865 compared with the regression model without dummy variable and the geographically weighted regression model. The model results indicates that intense business development, high automobile dependency, and high level of exposure of transportation network in terms of capacity reduction are the causes for increased level of accessibility based vulnerability. TAZs near freeways and arterials with higher capacity would be more likely to experience increased level of congestions caused by network disruption. In addition, demographic characteristics such as working without children could influence the regional vulnerability through its impacts on trip generation patterns. These findings help to better understand the factors causing transportation vulnerability to sea level rise and make corresponding integrated land use and transportation system adaptation plans. According to the findings, future adaptation planning could focus on restricting intensive business development in potential inundation areas, reduce automobile dependency, and reduce the level of infrastructure exposure through hard structure protection.

To further assist the decision making in transportation adaptation planning, three adaptation strategies are tested for year 2035, including protection, neighborhood accommodation, and relocation. The results show protecting the freeways and important bridges are the most effective strategy among the three to reduce the system transportation vulnerability. Protecting 108 miles of freeway and important bridges could generate a net system savings of $1,124,792 per day for the study region. Assuming the cost of protection is $2 million per mile, it will take only 194 days for the accrued benefits to exceed the costs.

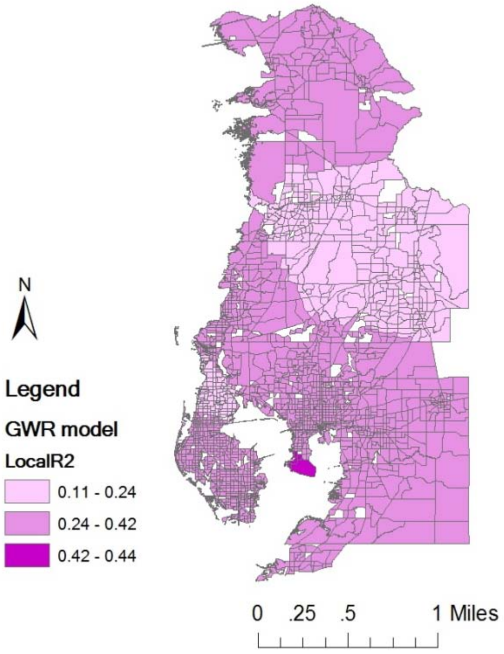


Figure 7-6. Local R-squared distribution of GWR model

CHAPTER 8
DISCUSSIONS

This section discusses several important assumptions the research and its findings rely on, the limitations of these assumptions, and potential improvement in future research. First, to determine the weight of different indicators in the integrated vulnerability index, expert opinions are collected through surveys. There are 24 effective survey respondents representing major planning agencies in the case study area, including seven municipal planning agencies, four county agencies, state and regional environmental protection agencies and department of transportation, and private planning and engineering companies. The sample size is relative small, but it covers all the county level planning agencies, and majority of the regional planning agencies (e.g. regional environmental protection agencies, state department of transportation). If more respondents from the local planning agencies at the city level are collected, the ratings of different indicators in adaptation planning may change. For example, at the county and regional level, social, economic, and infrastructure are considered equally important. For small cities, some of them may focus more on economic sector and some may focus more on social aspects. Therefore, the variances of ratings will increase with the increase of sample size, and more attention will be paid to problems at smaller scale.

Second, the social vulnerability is included in the integrated vulnerability as a representation of social capability to adapt to changes, which is only related to the demographic characteristics of the population in spite of the population size and property values. However, in reality, the vulnerable population size and the amount of property values do affect the adaptation decision making. More improvements are needed in future to take the vulnerable number of population and property values into account. The exposure of population and property to sea level rise and flooding should also be considered. In addition, the demographic characteristics of the population are assumed to remain unchanged over the time, which may not be the case with the threat of sea level rise, Data regarding people's relocation behaviors needs to be collected in future in order to estimate the change of demographic structure with sea level rise.

Third, analysis indicates that demographic characteristic is a factor influencing transportation vulnerability. Assuming demographic characteristics of the population unchanged with sea level rise can affect the estimation of transportation vulnerability. With more data regarding people's relocation behavior obtained in future, this limitation could be overcome.

Fourth, transportation demand forecasting model is used to estimate the transportation vulnerability at the traffic analysis zone level. The region's travel demand forecasting model is a traditional four step model. Using the model assumes that with sea level rise travel behavior in coastal area will be the same as usual. However, people with different demographic characteristics may make different adjustments to their trips when sea level rise happens. More travel behavior data under inundation scenarios are needed to test these hypotheses. The traditional four step model may need to be recalibrated to take these behavior changes into account.

In summary, this research contributes to the integration of multidimensional aspects of vulnerability to sea level rise, and the results could be used to promote conflict resolution in adaptation planning. The detailed transportation sector vulnerability analysis provides a method to estimate the increase of difficulty travelers in other traffic analysis zones may have to reach the target traffic analysis zone with sea level rise, and gives insights into the factors that may influence such transportation vulnerability.

However, more expert inputs will further enhance the integrated vulnerability analysis, especially for small cities in the case study area. Future research could be devoted to comparison studies between different sample size and different regions. Furthermore, more research regarding people’s relocation and travel behavior changes in response to sea level rise is needed in future. Behavioral data collection will be the fundamental step of future research. The potential limitations in the assumptions could be tested and improved with such data. Future research regarding people’s response behaviors to sea level rise will be conducted and the impacts of such behavior on adaptation planning will be estimated.

APPENDIX A
SURVEY FORM

The following survey collects primary data for a research project which is supported by Gulf of Mexico Sea Grant and lead by University of Florida. It is designed to understand how sea level rise is addressed in the urban planning process within the Tampa Bay Region. The results of the survey will help to capture the research needs, prepare adaptation plans, and improve the corresponding decision support tools (NOAA sea level rise viewer). The survey will take about 40 minutes.

You will answer questions based on your opinion towards the existing NOAA sea level rise viewer's role in sea level rise adaptation planning. It would be better if you could take a few minutes to explore the tool before filling out the survey. NOAA sea level rise can be accessed at: http://www.csc.noaa.gov/digitalcoast/tools/slrviewer/index.html.

Agency:______________________________________

Number of Planning Employees: __________________

Position: ____________________________________

Section 1 Focus Area in Planning Practice

This section will ask your opinion towards the importance of different sectors in general planning practice. It will help us to evaluate the relative importance of social factors, economic factors, and infrastructure factors in overall vulnerability assessment.

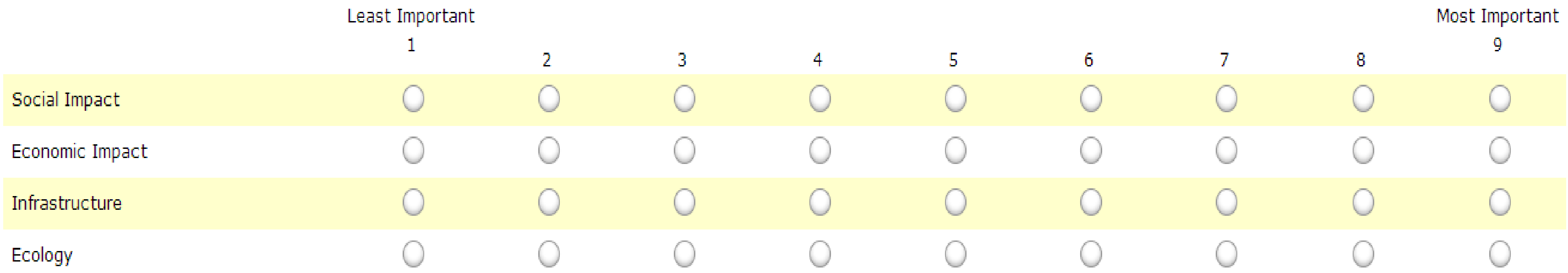
1.1 Comparing different sectors in overall planning

On a scale of 1 to 9 with 1 being least important and 9 being most important, please compare the following sector's importance in your planning practice. If two are considered equally important, use the same number for the two.

Social impacts: human vulnerability to hazards, based on population attributes (e.g., age and poverty) and the built environment, measured by The Social Vulnerability Index (SoVI®) 2005-09, including about 30 socioeconomic variables representing income, age, urban and rural, special needs, race, gender, employment, and migration, etc.

Economic impact: Employment, wages, and the number of establishments (or businesses) exposed to a hazard are strong indicators of a community's overall economic impact.

Infrastructure: critical infrastructure and key resources (CI/KR).



	Least Important 1	2	3	4	5	6	7	8	Most Important 9
Social Impact	○	○	○	○	○	○	○	○	○
Economic Impact	○	○	○	○	○	○	○	○	○
Infrastructure	○	○	○	○	○	○	○	○	○
Ecology	○	○	○	○	○	○	○	○	○

1.2 Comparing economic indicators

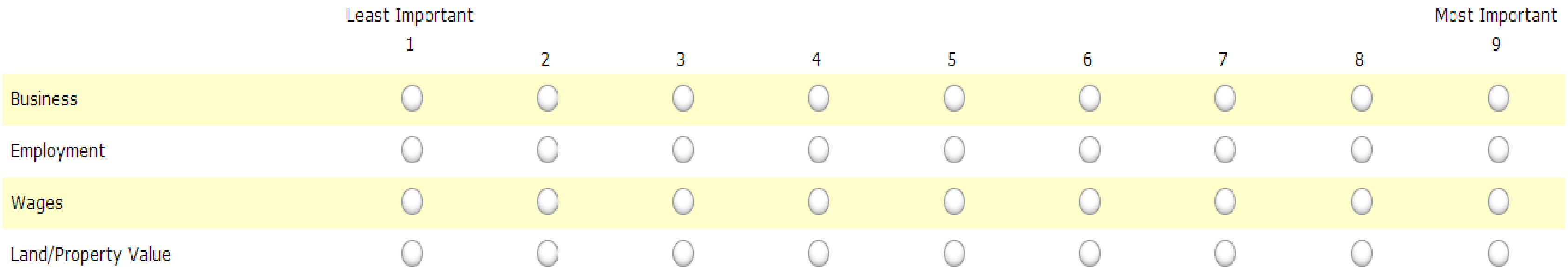
On a scale of 1 to 9 with 1 being least important and 9 being most important, please compare the following indicator’s importance within economic sector in your practice.

Business: number of businesses within the area.

Employment: number of employment within the area.

Wages: the total amount of quarterly wages within the area.

Land/Property Value: monetary value of the land or property within planning area.



	Least Important 1	2	3	4	5	6	7	8	Most Important 9
Business	○	○	○	○	○	○	○	○	○
Employment	○	○	○	○	○	○	○	○	○
Wages	○	○	○	○	○	○	○	○	○
Land/Property Value	○	○	○	○	○	○	○	○	○

1.3 (a) Comparing costs of infrastructure

On a scale of 1 to 9 with 1 being least expensive and 9 being most expensive, please compare and rate the cost of the following infrastructure. If two are considered equally, using the same number for the two.

Emergency operations centers include county and city's emergency operation center, emergency alert system stations, U.S. national weather service, primary hurricane shelters, designated regional recovery centers, and disaster recovery centers.

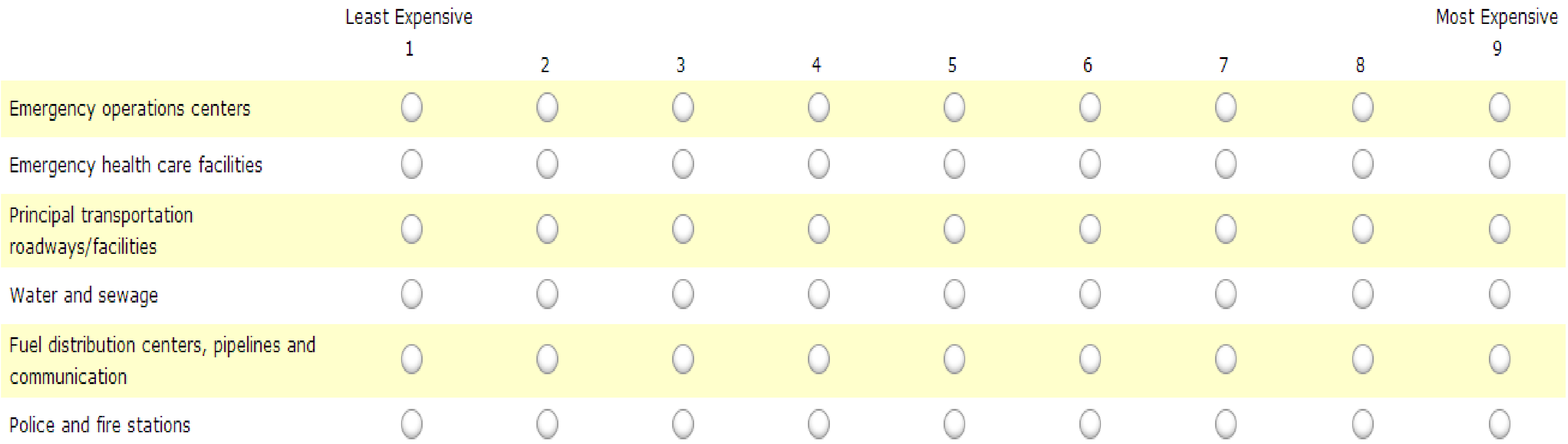
Emergency health care facilities include American Red Cross operations center and emergency medical services.

Principal transportation roadways/facilities include Interstate system, US highway system, and major county collectors, high-risk intersections/critical links/bridges/waterways.

Water and Sewage include water plant, major water processing facilities, and water and sanity sewer systems.

Fuel distribution centers, pipelines and communication include communication towers, information dissemination offices, telephone system switching stations and land lines, principal gas and electrical transmission lines, and fuel distribution network and pipelines.

Police and fire stations include fire protection agencies and essential public offices.



	Least Expensive 1	2	3	4	5	6	7	8	Most Expensive 9
Emergency operations centers	○	○	○	○	○	○	○	○	○
Emergency health care facilities	○	○	○	○	○	○	○	○	○
Principal transportation roadways/facilities	○	○	○	○	○	○	○	○	○
Water and sewage	○	○	○	○	○	○	○	○	○
Fuel distribution centers, pipelines and communication	○	○	○	○	○	○	○	○	○
Police and fire stations	○	○	○	○	○	○	○	○	○

1.3 (b) Comparing facilities importance in emergency situations

On a scale of 1 to 9 with 1 being least important and 9 being most important, please compare and rate the importance of facilities in emergency situations (as hurricane and flood situations). If two are considered equally, using the same number for the two.

Emergency operations centers include county and city's emergency operation center, emergency alert system stations, U.S. national weather service, primary hurricane shelters, designated regional recovery centers, and disaster recovery centers.

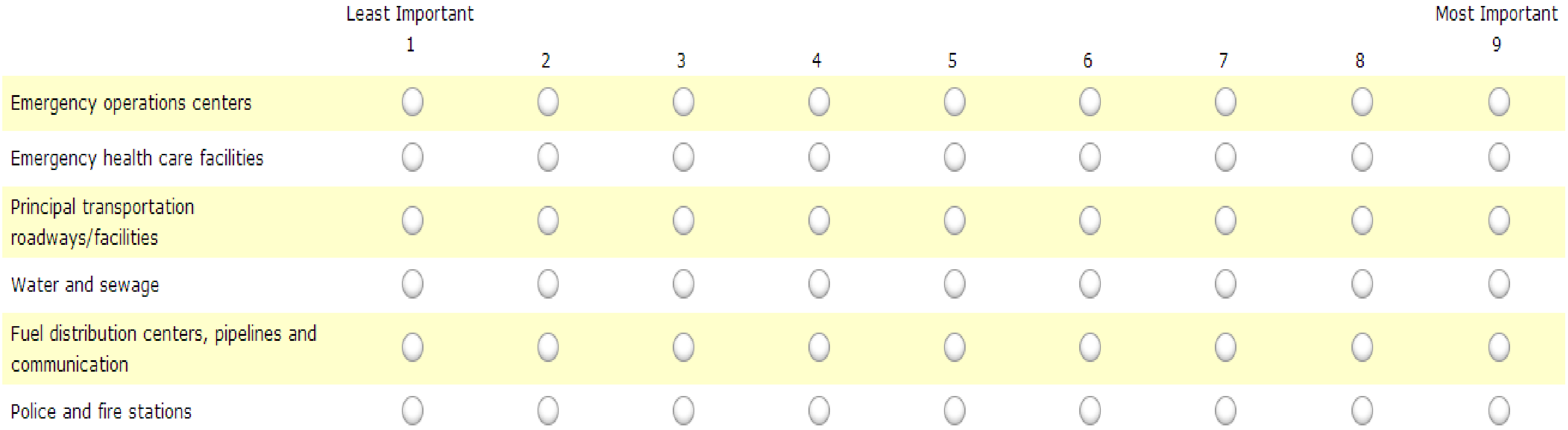
Emergency health care facilities include American Red Cross operations center and emergency medical services.

Principal transportation roadways/facilities include Interstate system, US highway system, and major county collectors, high-risk intersections/critical links/bridges/waterways.

Water and Sewage include water plant, major water processing facilities, and water and sanity sewer systems.

Fuel distribution centers, pipelines and communication include communication towers, information dissemination offices, telephone system switching stations and land lines, principal gas and electrical transmission lines, and fuel distribution network and pipelines.

Police and fire stations include fire protection agencies and essential public offices.



	Least Important 1	2	3	4	5	6	7	8	Most Important 9
Emergency operations centers	○	○	○	○	○	○	○	○	○
Emergency health care facilities	○	○	○	○	○	○	○	○	○
Principal transportation roadways/facilities	○	○	○	○	○	○	○	○	○
Water and sewage	○	○	○	○	○	○	○	○	○
Fuel distribution centers, pipelines and communication	○	○	○	○	○	○	○	○	○
Police and fire stations	○	○	○	○	○	○	○	○	○

1.3 (c) Comparing relocation difficulties of infrastructure

On a scale of 1 to 9 with 1 being easiest and 9 being most difficult, please compare and rate the relocation difficulties of facilities. If two are considered equally, using the same number for the two.

Emergency operations centers include county and city’s emergency operation center, emergency alert system stations, U.S. national weather service, primary hurricane shelters, designated regional recovery centers, and disaster recovery centers.

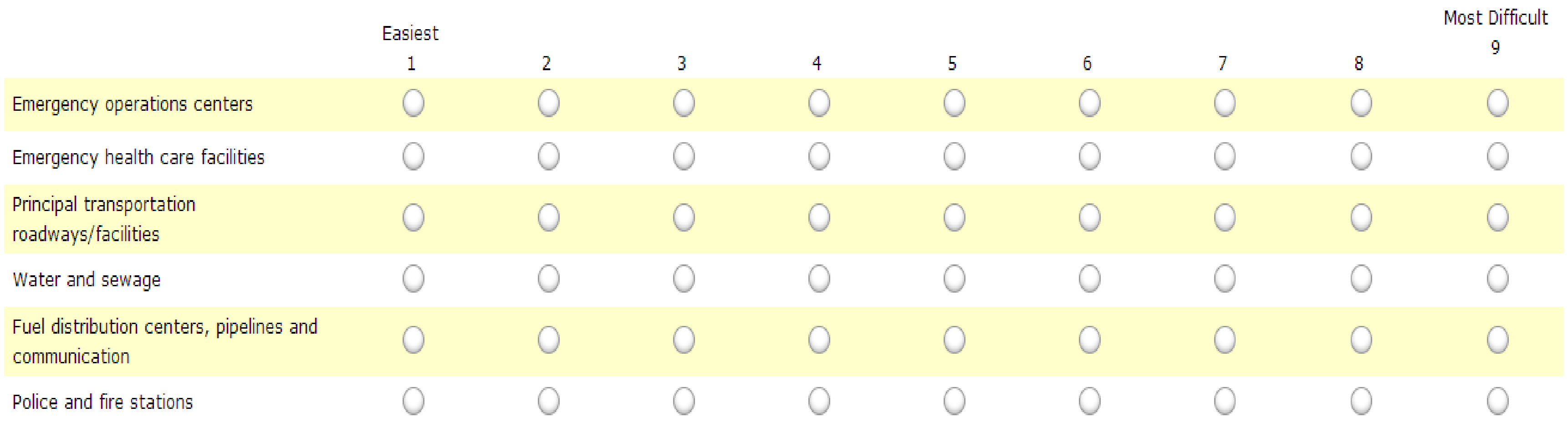
Emergency health care facilities include American Red Cross operations center and emergency medical services.

Principal transportation roadways/facilities include Interstate system, US highway system, and major county collectors, high-risk intersections/critical links/bridges/waterways.

Water and Sewage include water plant, major water processing facilities, and water and sanity sewer systems.

Fuel distribution centers, pipelines and communication include communication towers, information dissemination offices, telephone system switching stations and land lines, principal gas and electrical transmission lines, and fuel distribution network and pipelines.

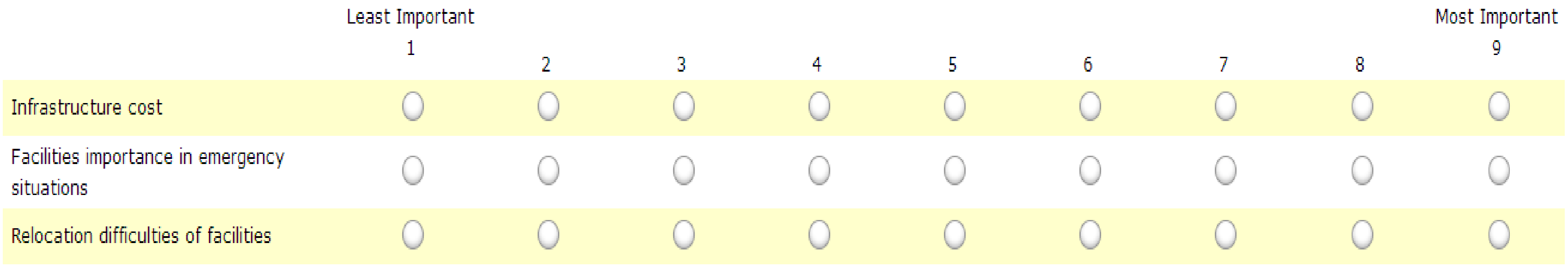
Police and fire stations include fire protection agencies and essential public offices.



	Easiest 1	2	3	4	5	6	7	8	Most Difficult 9
Emergency operations centers	○	○	○	○	○	○	○	○	○
Emergency health care facilities	○	○	○	○	○	○	○	○	○
Principal transportation roadways/facilities	○	○	○	○	○	○	○	○	○
Water and sewage	○	○	○	○	○	○	○	○	○
Fuel distribution centers, pipelines and communication	○	○	○	○	○	○	○	○	○
Police and fire stations	○	○	○	○	○	○	○	○	○

1.3 (d) Comparing importance of perspectives in overall planning

On a scale of 1 to 9 with 1 being least important and 9 being most important, please compare each of the perspectives considering their importance in overall planning practice. If two are considered equally, using the same number for the two.



	Least Important 1	2	3	4	5	6	7	8	Most Important 9
Infrastructure cost	○	○	○	○	○	○	○	○	○
Facilities importance in emergency situations	○	○	○	○	○	○	○	○	○
Relocation difficulties of facilities	○	○	○	○	○	○	○	○	○

Section 2 Suggestions for Sea Level Rise Viewer

Please take a few minutes to explore the NOAA sea level rise tool before filling out the following questions. NOAA sea level rise can be accessed at: http://www.csc.noaa.gov/digitalcoast/tools/slrviewer/index.html.

2.1 What do you think of the viewer's interface? Please rate using a number between 1 to 10. ___

1: not easy to use at all.

10: very friendly user interface.

What are your suggestions for improvement?

What do you think of Google Map interface (https://maps.google.com/maps?hl=en)? Please rate using a number between 1 to 10.

1: not easy to use at all.

10: very friendly user interface.

Do you think it is more convenient if the tool has the same interface as google map?

___Yes   ___No

2.2 Which of the following functionality do you think is most important for assisting sea level rise planning? Please check three(3) most important ones.

__water level map

__inundation map with confidence level

__flood frequency map

__marsh impact maps

__other ecology impact maps

__highlight most vulnerable locations

__show socio-economic vulnerability

__show integrated overall vulnerability

__adaptation strategies evaluation

__others (please specify below)

If you think additional functionality should be added to the impact viewer, please specify and briefly state the reason.___

2.3 Besides existing socio-economic vulnerability and mash impacts in the tool, is there additional vulnerability measurements do you think should be mapped? If yes, please specify _____

2.4 Other suggestions ____

Section 3 Adaptation Plans

3.1 Do you think it is your agency's responsibility to take sea level rise into consideration into planning practice? ☐Yes ☐No

Which agency do you think is responsible for adaptation planning? Please check three (3) primary responsible agencies.

☐city/town government officials ☐county government officials

☐citizen groups ☐corporations

☐state governor ☐state legislators ☐State government officials ☐other state agencies (please specify)

☐U.S. congress

3.2 Does your agency have funding to develop sea level rise adaptation plan?

☐Yes ☐No

What is the approximate budget range? _______

Does your agency have funding to implement sea level rise adaptation plan?

☐Yes ☐No

What is the approximate budget range? _______

3.3 Which of the following adaptation strategy are feasible within your jurisdiction? Please rate according to their feasibility using a number between 1 and 10. Use number 1 as the least feasible strategy and 10 as the most feasible strategy. If two strategies are considered as equally feasible, using the same number for the two. Please specify and rate other strategies if not included in the list.

__ Build dikes, seawalls etc.

__ build up marsh areas and non-structural- Shore nourishment

__ Discourage building new structures in areas at risk from sea level rise

__ Allow beaches and wetlands to naturally migrate inland

__ Purchase land at risk of sea level risk and frequently flooded properties.

__ Elevate buildings in area at risk

__ Elevate infrastructures and facilities at risk

__ Change building codes and regulations to reduce risk in flood prone areas

__ Other - explain

Section 4 Sea Level Rise Perception

4.1 When do you think sea level rise will start to have impacts in Tampa Bay area?

☐now ☐5 years ☐10 years ☐25 years ☐50 years ☐100 years ☐sea levels are not rising (end of the survey) ☐wait for research

4.2 To what degree does your agency consider sea level rise as an issue for future planning? Check the appropriate box.

Not at all 1	2	3	4	Very Serious 5

If “not at all”, please go to question 4.5 and 4.6.

4.3 What is the time range for your sea level rise adaption planning work? (Select all that apply)

☐5 years plan ☐10 years plan ☐25 years plan

☐50 years plan ☐100 years plan ☐No plan (go to question 4.5)

4.4 What planning work does your agency integrate sea level rise into? (Select all that apply)

☐ No plan or action ☐ Comprehensive plan ☐ Land use plan ☐ Zoning plan ☐ Building codes ☐ Design guidelines ☐ hazards plan

☐ coastal zone plan ☐Other (Please specify) ___

4.5 Do you think there is adequate information and tools to support sea level rise planning and adaptation?

☐ not at all

☐ detailed and sufficient for adaptation planning

☐ too much, confusing information

4.6 Which of the following research need to be further explored to support adaptation planning? Please check three(3) most important ones. Specify other needed research.

__Sea level rise in general

__Current or potential impacts of sea level rise

__Actions that can be taken to reduce impacts of sea level rise

__Tools to communicate and engage the public and decision makers on the issue of sea level rise

__Tools to compare the costs and benefits of different adaptation strategies

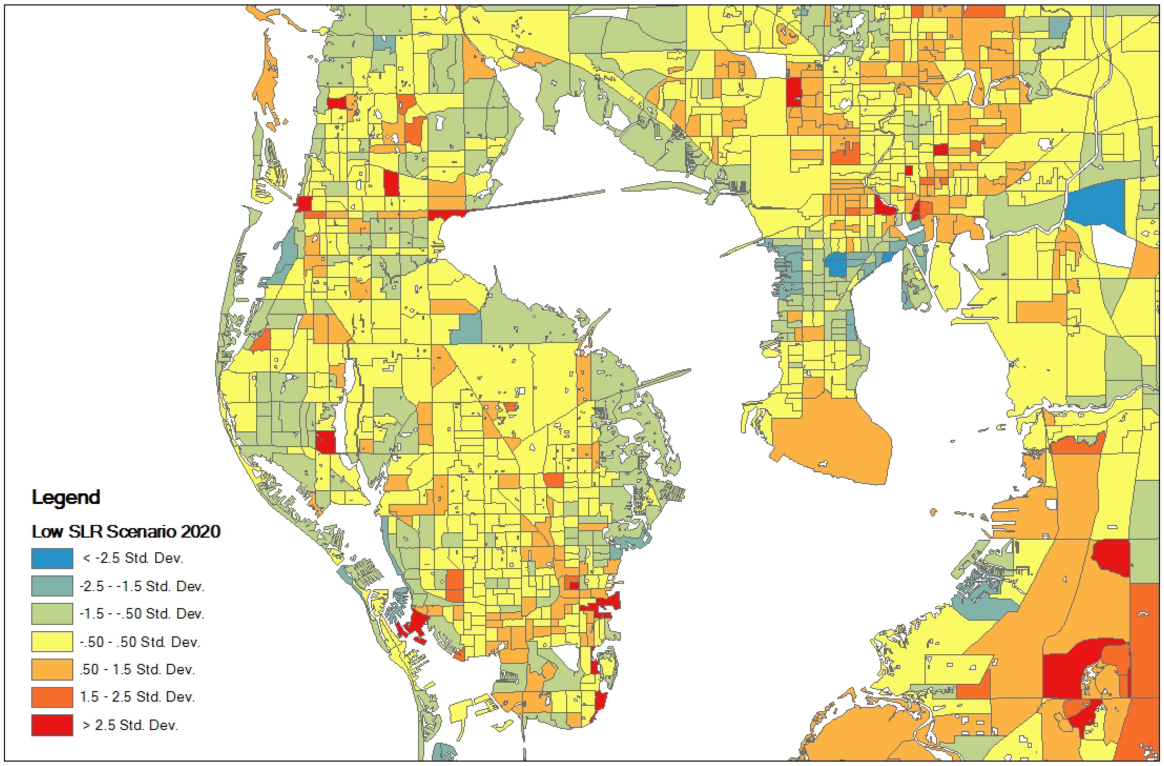
__Funding sources to address sea level rise in Tampa

Other ________

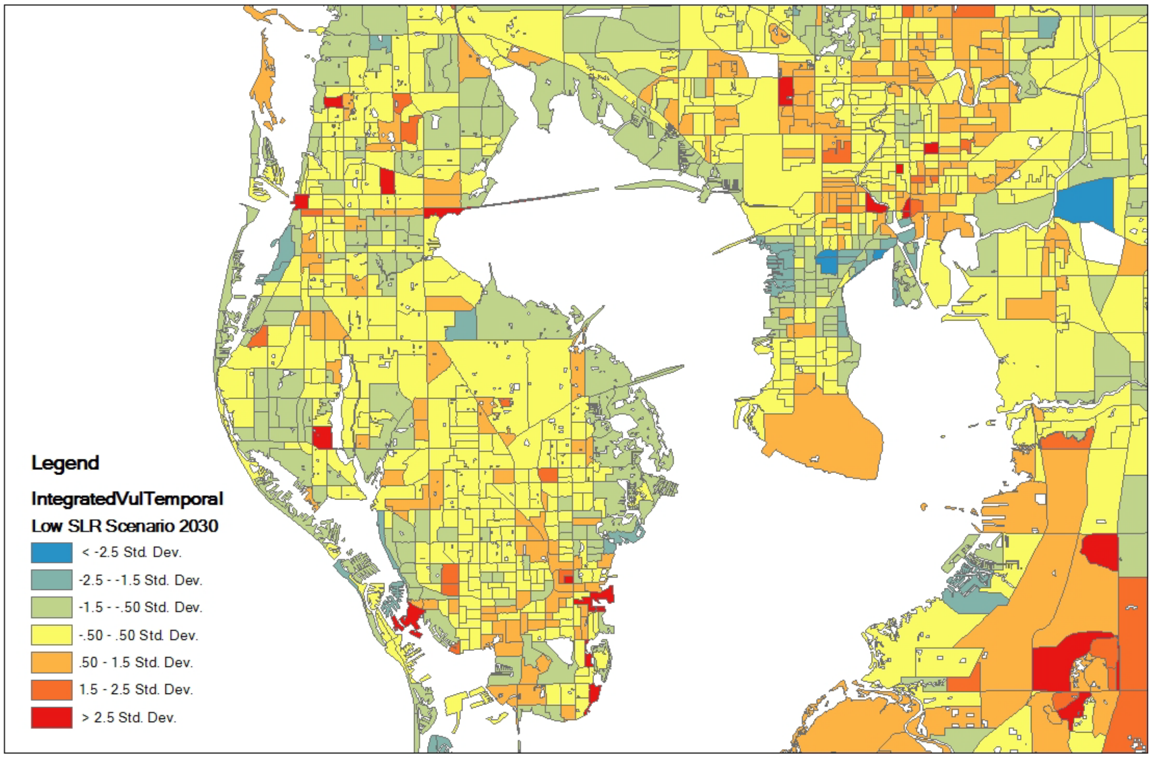
APPENDIX B
RISK ASSESSMENT UNDER SLOW, MEDIUM, FAST SEA LEVEL RISE SCENARIOS

The following maps show the overall vulnerability, which is the sum of $\text{Integrated Vulnerability}_{\text{i ft}} * \text{Annual Flooding Probability}_{\text{i ft}}, i = 1, 2, 5.$, for each decade between 2020 to 2050 by standard deviation under slow, medium, and fast sea level rise scenarios.

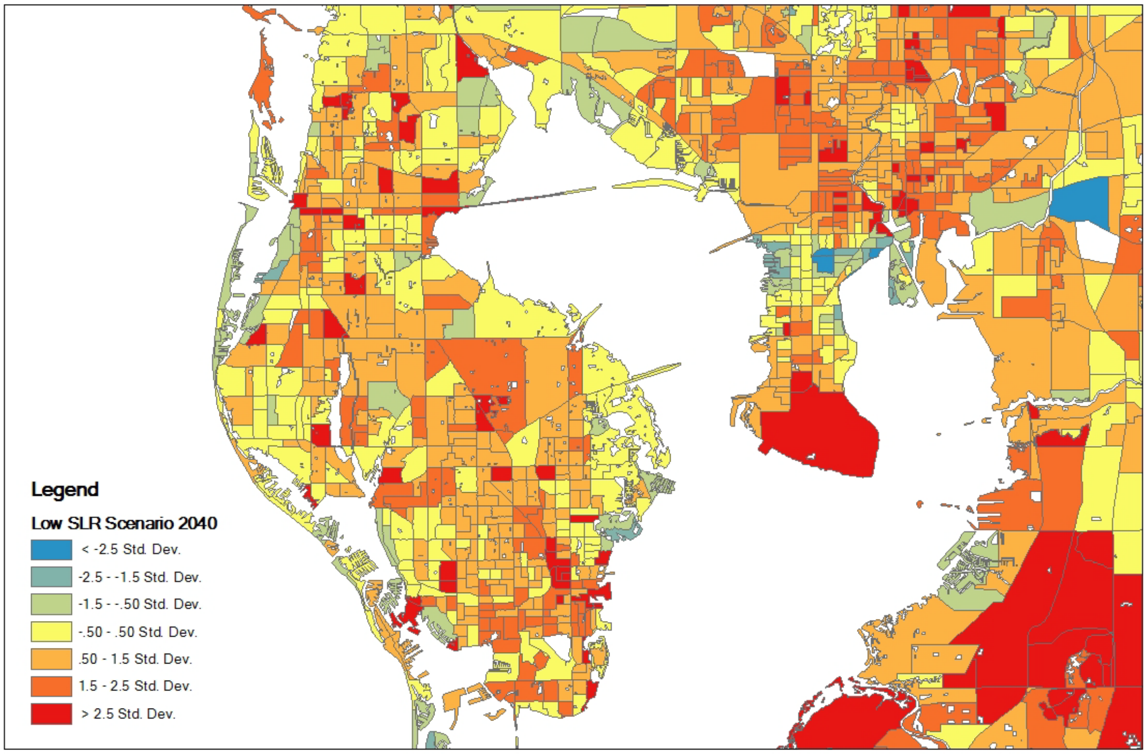
Slow Sea Level Rise Scenario



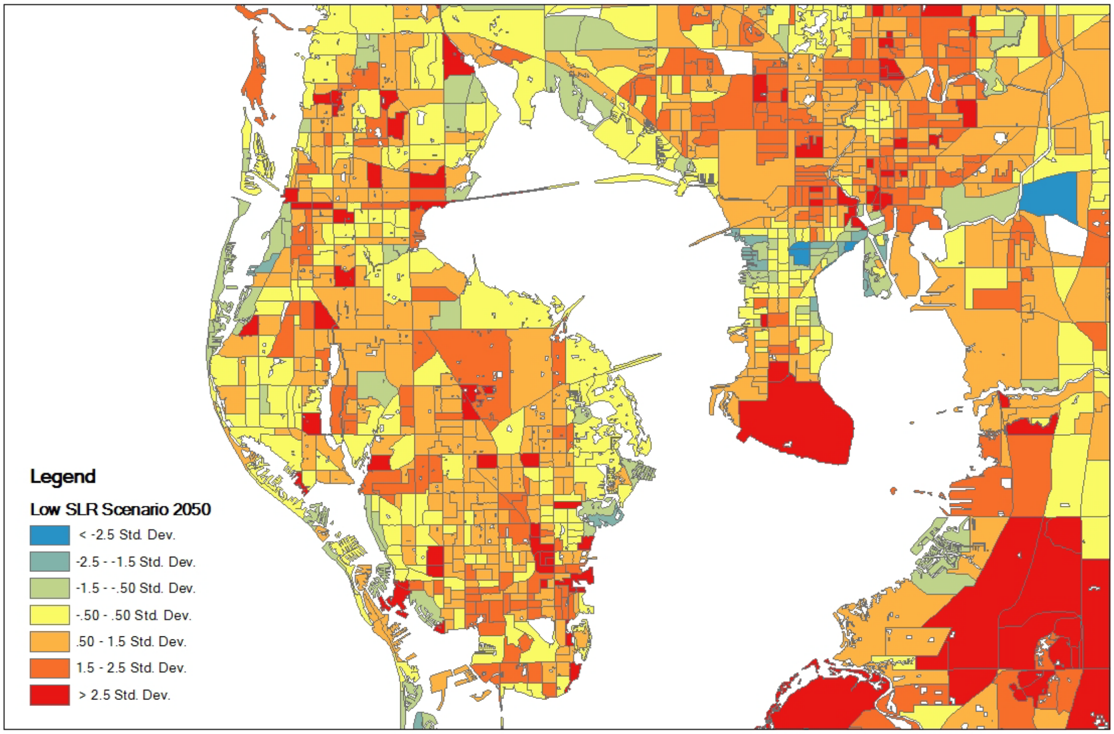
2020 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under low SLR scenario



2030 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under low SLR scenario

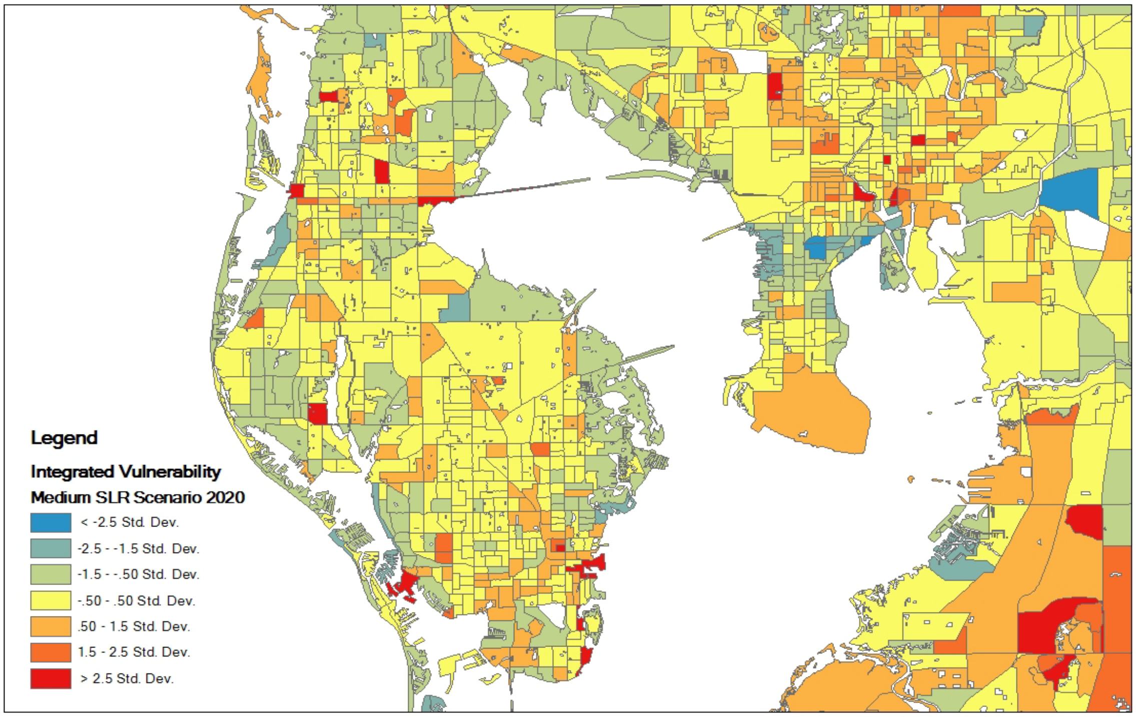


2040 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under low SLR scenario

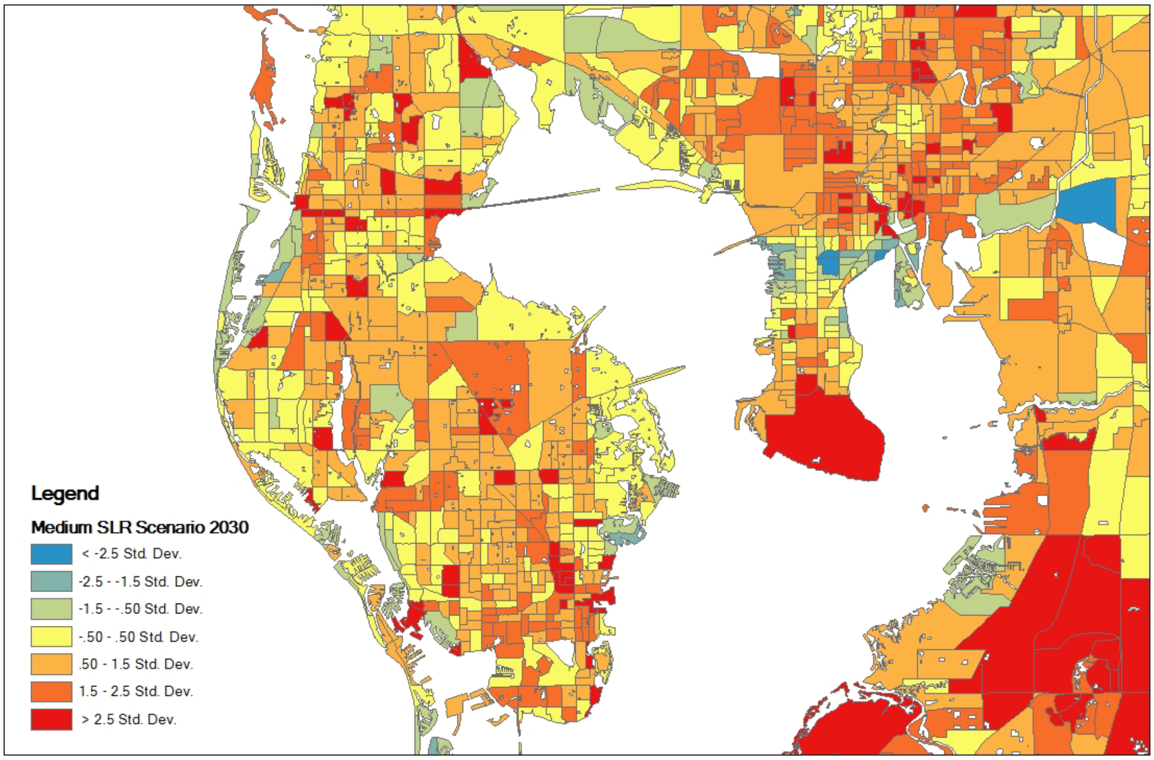


2050 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under low SLR scenario

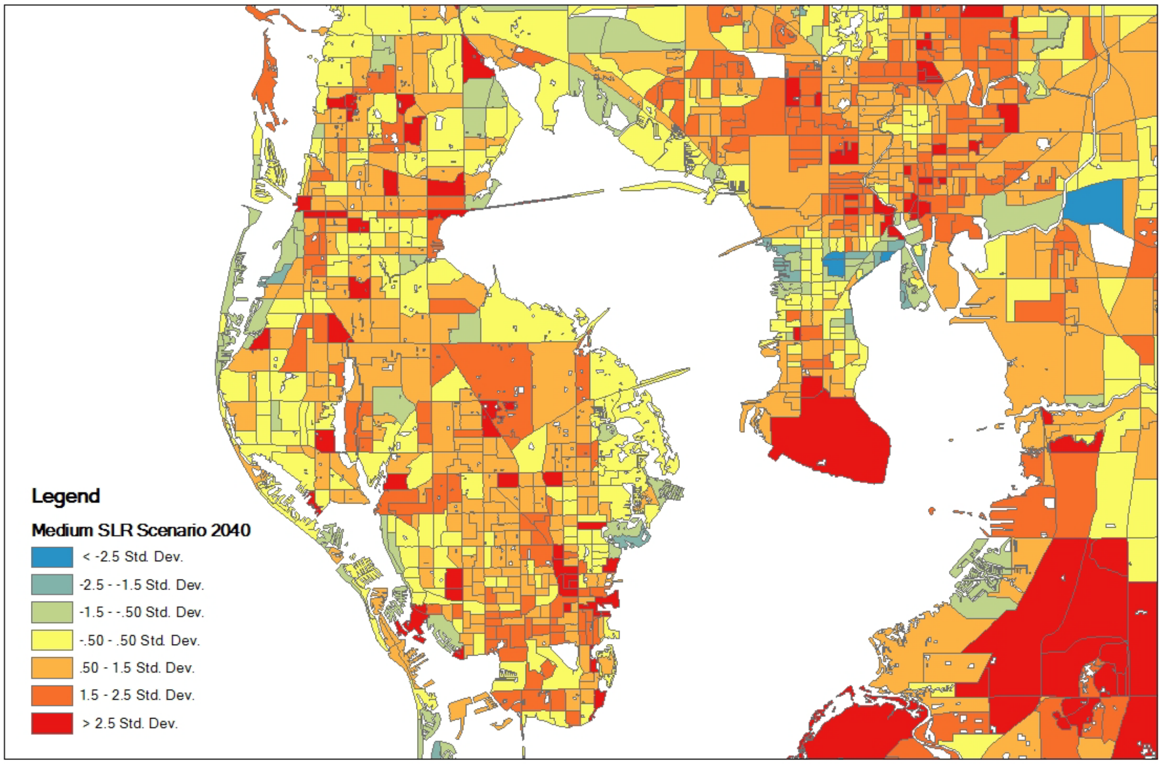
Medium Sea Level Rise Scenario



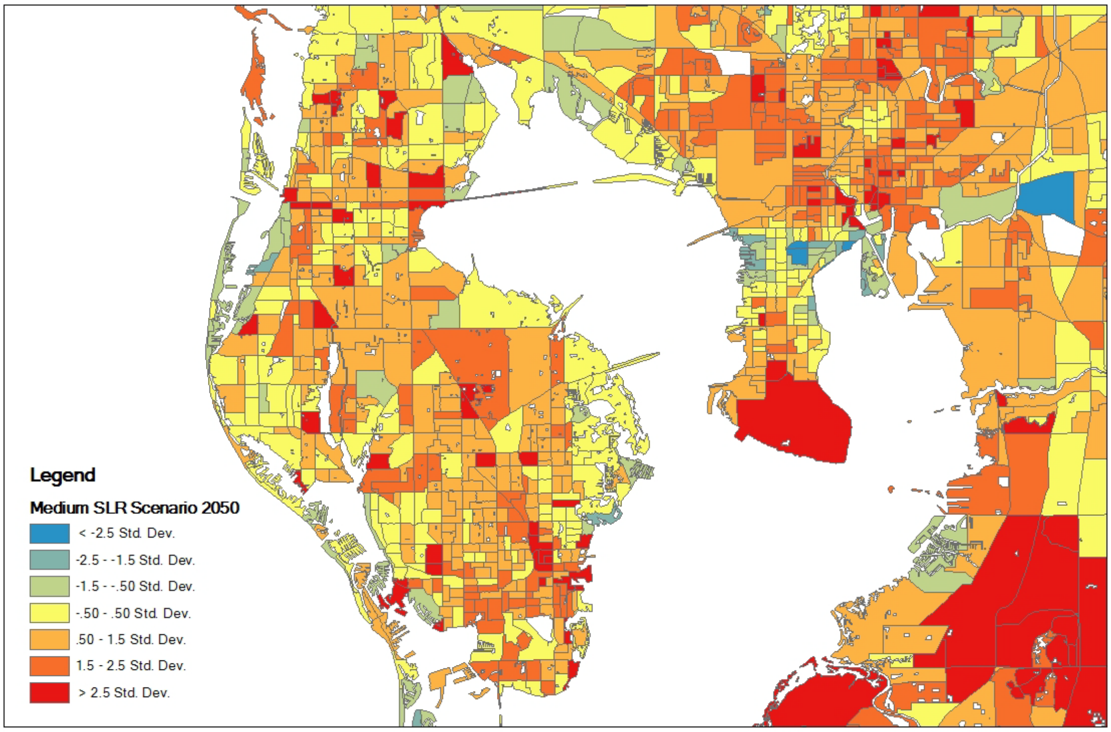
2020 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under medium SLR scenario



2030 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under medium SLR scenario

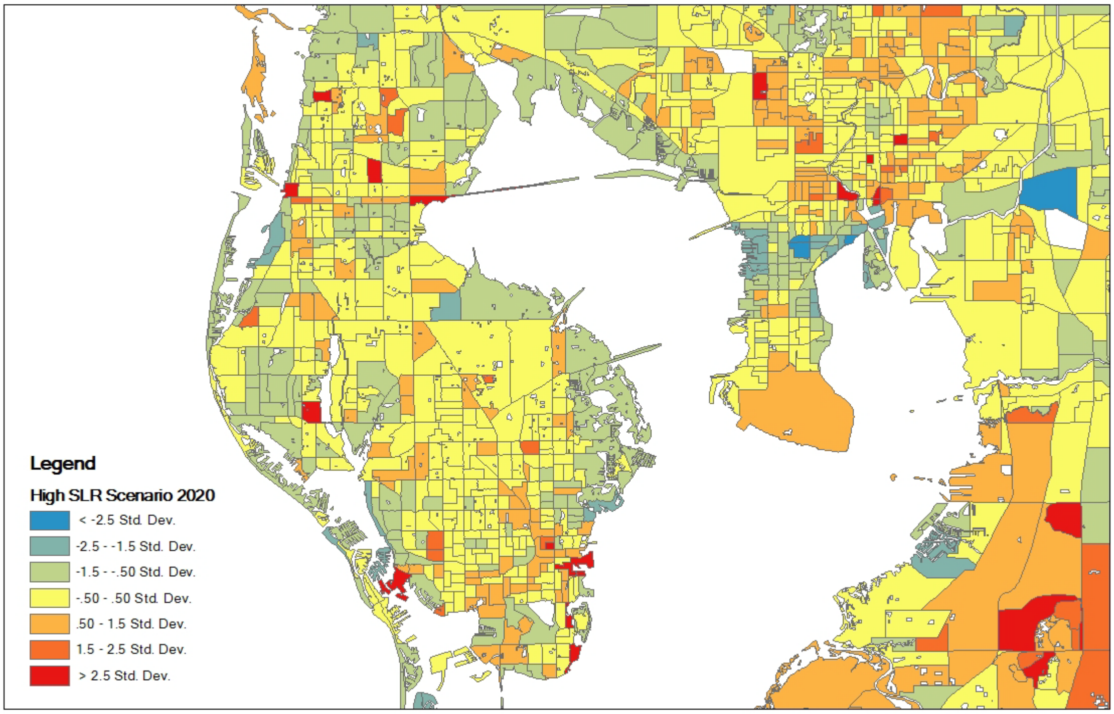


2040 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under medium SLR scenario

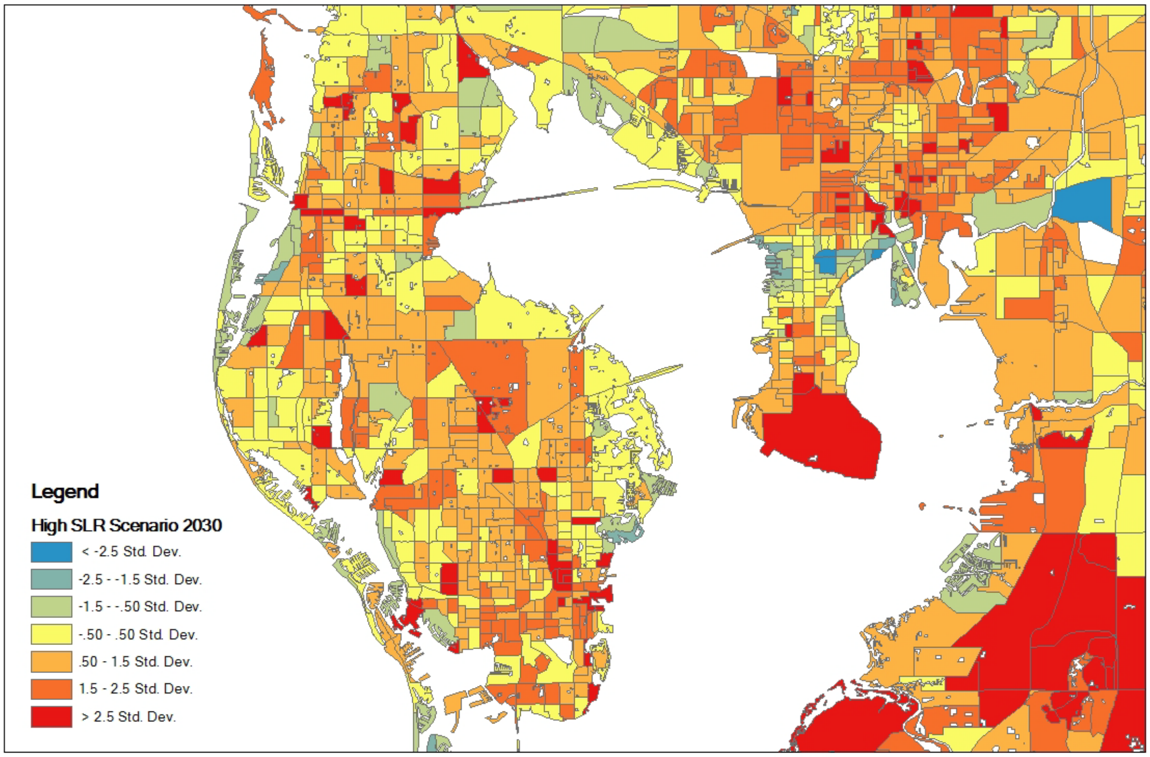


2050 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under medium SLR scenario

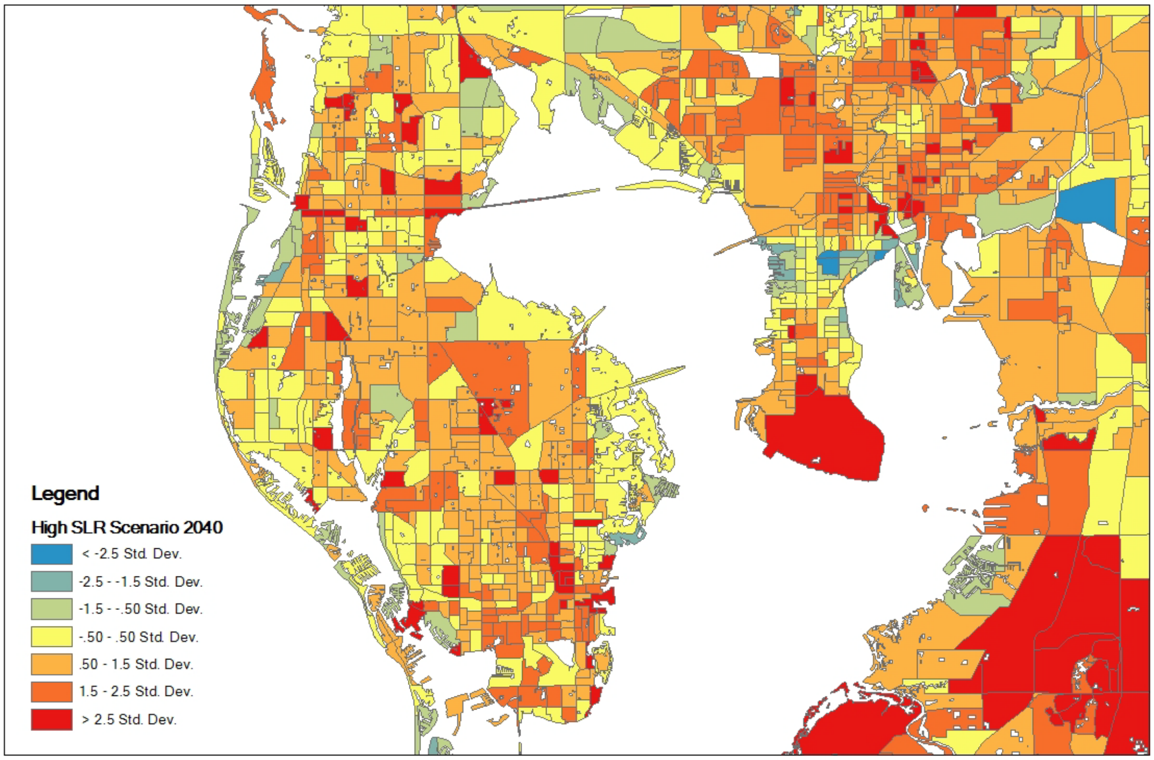
Fast Sea Level Rise Scenario



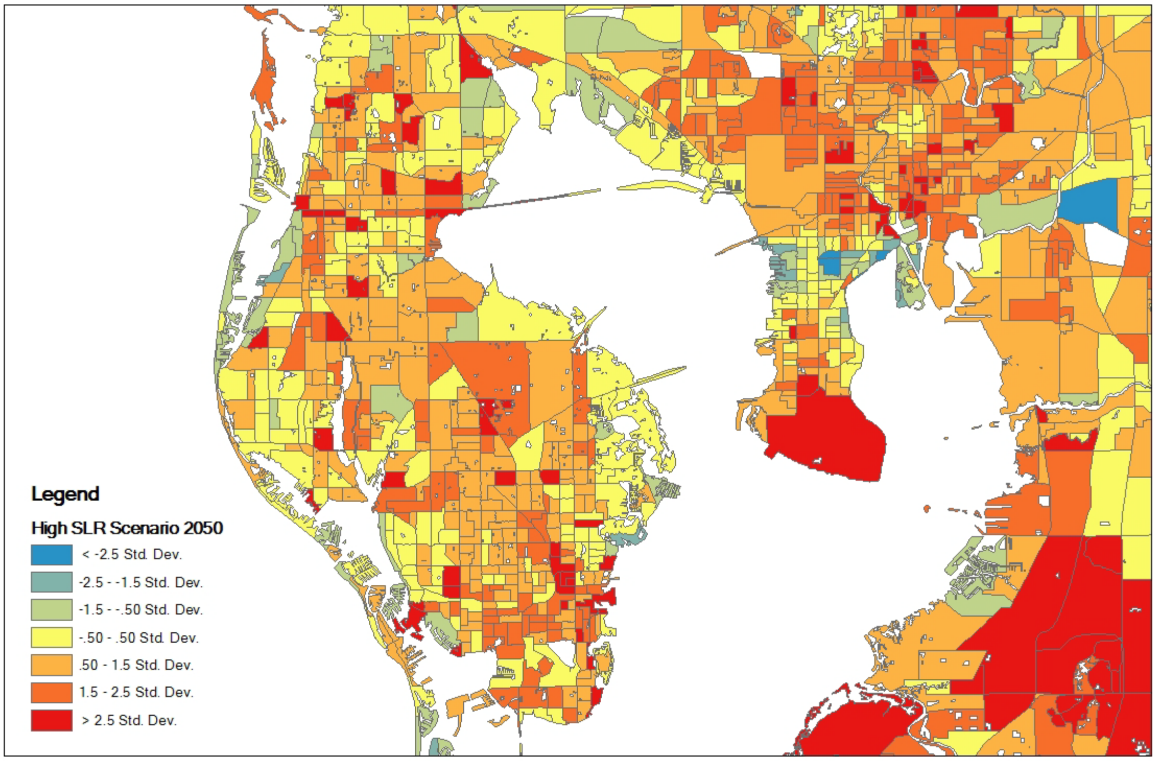
2020 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under fast SLR scenario



2030 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under fast SLR scenario



2040 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under fast SLR scenario



2050 annual coastal flooding vulnerability (1ft, 2ft, 5ft) under fast SLR scenario

LIST OF REFERENCES

ABP Marine Environmental Research. (2004). Climate Change 2003 Port Template: Findings from the First Assessment. Report Number R.1061, Associated British Ports – Head Office, March.

Adger, W. N., & Vincent, K. (2005). Uncertainty in adaptive capacity. *Comptes Rendus Geoscience*, 337(4), 399-410.

Aguirre, B. E. (2007). Dialectics of vulnerability and resilience. *Georgetown Journal on Poverty Law & Policy*, 14, 39-60.

Bedsworth, L. W., & Hanak, E. (2010). Adaptation to climate change, A Review of Challenges and Tradeoffs in Six Areas Journal of the American Planning *Association*, 76(4), 477-495

Blaikie, P. C., & Cannon, T. T., Davis, I. & Wisner, B. (1994): At risk: natural hazards, people's vulnerability, and disasters. *Disaster and society–from hazard assessment to risk reduction*, Berlin, 75-82.

Bloetscher, F., Romah, T., Berry, L., Hernandez Hammer, N., & Abadal Cahill, M. (2012). Identification of Physical Transportation Infrastructure Vulnerable to Sea Level Rise. *Journal of Sustainable Development*, Vol 5, No 12.

Burkett. (2002). Potential impacts of climate change and variability on transportation in the Gulf Coast/Mississippi Delta Region. The Potential Impacts of Climate Change on Transportation. Federal Research Partnership Workshop Summary and Discussion Papers. DOT Center for Climate Change and Environmental Forecasting.

Chang and Nojima.(2001). Measuring post-disaster transportation system performance: The 1995 Kobe earthquake in comparative perspective. *Transportation Research Part A*, 35, 475-494

Chen et al. (2002). Capacity reliability of a road network: an assessment methodology and numerical results. *Transportation Research Part B*, 36, 225-252.

Climate Central. (2013). Florida and the Surging Sea, A Vulnerability Assessment with Projections for Sea Level Rise and Coastal Flood Risk. Princeton, NJ. Available at http://sealevel.climatecentral.org/uploads/ssrf/FL-Report.pdf.

Cronin et al. (2007). Sea Level Rise in Tampa Bay. *EOS, Transactions American Geophysical Union*, Vol. 88, No. 10, pp. 117.

Csanyi N. (2006). Precision LiDAR Mapping of Transportation Corridors Using LiDAR-Specific Ground Targets, Geospatial Information Systems for Transportation Symposium, March 27-29, 2006, http://www.gist.org/yr2006/Proceedings/csanyi-Submission.pdf , accessed August 2013.

Curtis, Katherine J., and Annemarie Schneider. (2011). Understanding the Demographic Implications of Climate Change: Estimates of Localized Population Predictions under Future Scenarios of Sea-level Rise. *Population Environment*, 33, 28-54.

Donoghue, Joseph F. (2011). Sea level history of the northern Gulf of Mexico coast and Sea level Rise scenarios for the near future. *Climate Change*, 107, 17-33.

Entek U.K. Limited. (2000). The Potential Impacts of Climate Change on the East Midlands – Summary Report. East Midlands Sustainable Development Round Table, Warwickshire, England, July.

Environmental Protection Agency (EPA). (1995). The Probability of Sea Level Rise. http://repositories.tdl.org/tamug-ir/bitstream/handle/1969.3/25952/8881-Probability%20of%20Sea%20Level%20Rise.pdf?sequence=1, accessed August 2013.

Environmental Protection Agency (EPA). (2005). Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel, http://www.epa.gov/otaq/climate/420f05001.htm, accessed August 2013.

Fleming, Gannett. (2010). Technical Report 1 – Tampa Bay Regional Planning Model (TBRPM) Version 7.0 Validation Report. Tampa Bay Regional Transportation Analysis, 125-128.

Florida Division of Emergency Management. (2012). Critical Facilities. http://www.floridadisaster.org/gis/criticalfacilities/index.htm, accessed March 2013

Freckleton et al. (2012). Evaluation of resiliency of transportation networks after disasters. *Transportation Research Record: Journal of the Transportation Research Board*, *Network Modeling* 2 (2012), 109-116

Hazards and Vulnerability Research Institute (2011). Social Vulnerability Index for the United States 2006-2010. http://webra.cas.sc.edu/hvri/products/sovi.aspx accessed March, 2013

Hickman, H. (2006). Flood hazard and vulnerability in new found land communities. Memorial University of Newfoundland (Canada)). Dissertations and Theses, http://search.proquest.com/docview/304959181?accountid=10920. (304959181) accessed August 2013.

ICF International. (2007). The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure. Phase 1 - Final Report: the District of Columbia, Maryland, North Carolina and Virginia

IPCC, (2001). Climate Change Impacts, Adaptation, and Vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. New York. Cambridge University Press.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jacob, et al. (2007). Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: Inferences for urban coastal risk management and adaptation policies. *Managing Coastal Vulnerability*. Elsevier,139-156.

Jenelius. (2009). Network structure and travel patterns: explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography*, 17, 234-244.

Jenelius, Erik, and Lars-Göran Mattsson (2012). Road network vulnerability analysis of area-covering disruptions: A grid-based approach with case study. *Transportation Research Part A* 46, 746-760.

Jerry et al. (2000). US Global Change Research Program: National assessments of the potential consequences of climate variability and change. National Assessment Synthesis Team, U.S. Global Change Research Program, 2000. http://www.gcrio.org/NationalAssessment/overpdf/overview.htmlH Accessed June 30th, 2010.

Kinsella, Y. and F. McGuire. (2005). Climate Change Uncertainty and the State Highway Network: A moving target. *Transit New Zealand* , Auckland, New Zealand.

Kirshen, P.H., M. Ruth, W. Anderson, and T.R. Lakshmanan. (2004). Infrastructure Systems, Services, and Climate Change: Integrated Impacts and Response Strategies for the Boston Metropolitan Area (CLIMB Final Report). U.S. Environmental Protection Agency, Washington, D.C.

Leng, J. Q., Zhang, Y. P., Zhang, Q., & Zhao, Y. P. (2010). Integrated reliability of travel time and capacity of urban road network under ice and snowfall conditions. *Journal of Central South University of Technology*, 17(2), 419-424

Lu, Q.C, and Peng.Z.R. (2011). Vulnerability Analysis of Transportation Network Under Scenarios of Sea Level Rise. Transportation Research Record, Journal of the Transportation Research Board, 2263, 174-181.

Murray-Tuite, P.M. (2006). A Comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. *Simulation Conference, 2006. WSC 06. Proceedings of the Winter*, 1398-1405

Nagurney, Anna, and Qiang Qiang. (2009). A relative total cost index for the evaluation of transportation network robustness in the presence of degradable links and alternative travel behavior. *International Transactions in Operational Research* 16(1), 49-67.

National Assessment Synthesis Team. (2000). Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. U.S. Global Change Research Program, Cambridge University Press, New York.

National Research Council. (2008). Potential Impacts of Climate Change on U.S. Transportation. Transportation Research Board Special Report 290. Transportation Research Board, Washington, D.C. Hhttp://onlinepubs.trb.org/onlinepubs/sr/sr290.pdfH Accessed May 5th, 2010.

Nicholls et al. (2007). Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future. Executive Summary. Organization for Economic Cooperation and Development Environment Working Paper No. 1.

Olsen, J.R., L.J. Zepp, and C. Dager. (2005). Climate Impacts on Inland Navigation. Conference Proceeding: Environmental and Water Resources Institute of ASCE: Impacts of Global Climate Change.

Penland and Ramsey. (1990). Relative Sea Level Rise in Louisiana and the Gulf of Mexico 1908-1988. *Journal of Coastal Research*, 6(2), 323-342.

Peterson T.C., McGuirk, M., Houston, T. G., Horvitz, A. H., & Wehner, M. F. (2008). Climate variability and change with implications for transportation. Transportation Research Board.

Sato, N. and S.M. Robeson. (2006). Climate Change and Its Potential Impact on Winter-Road Maintenance: Temporal Trends in Hazardous Temperature Days in the United States And Canada. In TRB 85th Annual Meeting, January 22, 2006, Washington, D.C.

Scott, Darren M., David C. Novak, Lisa Aultman-Hall, and Feng Guo. (2006). Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *Journal of Transport Geography,* 14(3), 215-227.

Serulle, N. U., Heaslip, K., Brady, B., Louisell, W. C., & Collura, J. (2011). Resiliency of Transportation Network of Santo Domingo, Dominican Republic. *Transportation Research Record: Journal of the Transportation Research Board*, 2234(1), 22-30.

Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global environmental change*, 16(3), 282-292.

Sohn,J. (2006). Evaluating the significance of highway network links under the flood damage: An accessibility approach. Transportation Research Part A, 40, 491-506

Stanton, E. A., and F. Ackerman. Florida and Climate Change (2007): The cost of inaction. Tufts University, Medford, Mass..

Suarez, P., Anderson, W., Mahal, V., & Lakshmanan, T. R. (2005). Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D: transport and environment*, 10(3), 231-244.

Sullivan, J. L., Novak, D. C., Aultman-Hall, L., & Scott, D. M. (2010). Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice*, 44(5), 323-336.

Tampa Bay Regional Planning Council. (2005). Future of the Region: A Strategic Regional Policy Plan for the Tampa Bay Region. Available at http://www.tbrpc.org/about_us/pdfs/srpp/SRPP_2005.pdf accessed March, 2013.

Tampa Bay Regional Planning Council. (2006). Pinellas County, FL Comprehensive Plan; http://www.pinellascounty.org/Plan/comp_plan/05coastal/ch-6.pdf accessed March, 2013

Taylor, M. A., & D'Este, G. M. (2007). Transport network vulnerability: a method for diagnosis of critical locations in transport infrastructure systems. In *Critical Infrastructure: Advances in Spatial Science*, Springer Berlin Heidelberg, 9-30.

Titus, J. G., & Anderson, K. E. (2009). Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region. Government Printing Office.

Titus. (2002). Does Sea Level Rise Matter to Transportation Along the Atlantic Coast? In The Potential Impacts of Climate Change on Transportation, Summary and Discussion Papers, Federal Research Partnership Workshop, Brookings Institution, Washington, D.C., Oct. 1–2, 135–150.

U.S. Climate Change Program. (2008). Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I

Winkelman, S., Bishins, A., & Kooshian, C. (2010). Planning for economic and environmental resilience. *Transportation Research Part A: Policy and Practice*,44(8), 575-586.

Wu, Y. J., Hayat, T., Clarens, A., & Smith, B. L. (2013). Scenario-based climate change risk analysis for transportation infrastructure using GIS. InTransportation Research Board 92nd Annual Meeting, Transportation Research Board, Washington, DC.

Yoon, D. K. (2012). Assessment of social vulnerability to natural disasters: a comparative study. *Natural hazards*, 63(2), 823-843.

BIOGRAPHICAL SKETCH

Suwan Shen is a Ph.D. student at the University of Florida, with a major in urban and regional planning and a special interest in climate adaptation and transportation planning. She got her undergraduate degree in Geographical Information System (GIS) from Southeast University, China and master degrees in Urban and Regional Planning department and Civil Engineering department respectively at University of Florida. Over the years, she is particularly interested in using GIS to explore the relationship between land use, infrastructure and the environment. She has conducted research analyzing how the environmental changes in terms of climate changes influence urban planning, especially transportation planning. Her master thesis focused on analyzing the impacts of changing riverine flood frequencies caused by climate change on land use and transportation system using coastal city Pensacola in Florida as a case study. She expanded the research to sea level rise vulnerability analysis and adaptation in her Ph.D. study. Her research is supported by “Development of Sea Level Rise Adaptation Planning Procedures and Tools Using NOAA Sea Level Rise Impacts Viewer” project funded by NOAA and Gulf of Mexico Sea Grant. During her study at University of Florida, she has presented her works at Transportation Research Board annual meetings, the Association of Collegiate Schools of Planning meetings, and International Association for China Planning meetings, and has won the Karen R. Polenske Best Student Award. She also worked as a planning intern for the North Central Florida Regional Planning Council (NCFRPC) for several years since spring 2010. Suwan is preparing herself for a career in urban planning with a focus on environment and transportation planning. Her future research plans include further improvements of vulnerability studies by considering potential social behavior change.