



Assessing the Impacts of Population Relocation Induced by Future Sea-Level Rise Scenarios on Transportation Systems in Coastal Communities

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Abstract

Coastal communities will be more vulnerable to floods in low-lying areas and seawater inundation as the sea level rises. Users will have to take a detour to use alternate roads while the vulnerable roads are closed, increasing travel time. A large amount of literature has been focused on addressing climate change and sea-level rise impacts, vulnerability, economic evaluation, and adaptation. However, few research has been conducted to study the impacts of population dynamics due to sea level rise within future transportation network modeling. This study aims to identify the future transportation infrastructure in the 2035 model that is vulnerable to a two-foot sea level rise in the Tampa Bay Region, Florida. The impacts of these changes have been considered within three different relocation scenarios for the affected population in the inundated zones. This analysis uses the two-foot Mean Higher High-Level water surface data and the digital elevation data provided by NOAA for 2035. The findings of this study reveal how different sea level rise scenarios could affect the future estimates of the transportation system and could potentially inform future transportation planning decisions. The analysis found that approximately 358 lane miles of highway links will be inundated. Moreover, the number of trips produced, and the amount of congestion generated with each scenario were dependent on the population and employment relocation. The key recommendation of this research is to incorporate the potential impacts of population relocation due to sea level rise into transportation modeling. Generally, different scenarios for relocating population and employment generate new traffic demands, which could result in traffic congestion. Thus, transportation planners should simulate future sea level rise scenarios and evaluate their impact on the current transportation system. Findings from this study could help transportation planners and decision-makers identify the locations and transportation facilities that are most vulnerable to rising sea levels, allowing them to make more informed decisions about adaptation planning.

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Keywords

Sea-Level Rise; Vulnerability Analysis; Coastal Cities; Transportation Network; Tampa Bay

1. Introduction

The term "climate change" has been used to describe changes in the global atmosphere that may be traced back to human activities in one way or another (Pörtner et al., 2022; Zhongming et al., 2022). Climate change's effects are increasingly being recognized based on solid scientific data (Brozovsky et al., 2021; Lindsey, 2019). As a result of climate change, sea-level rise is considered to be one of the most obvious and certain impacts. As one of the most evident and immediate consequences of climate change, sea level rise has emerged as a critical and urgent issue that threatens the existence of several coastal communities across the world (Milliman & Haq, 1996). Shortly, sea levels are predicted to rise gradually but slowly. Coastal communities will be inundated and flooded as a direct result of rising sea levels, causing significant social, economic, and ecological damage (IPCC, 2013; James et al., 2021).

The effects of increasing sea levels will have enormous implications across a variety of industries, including those relating to housing, employment, and infrastructure (Cooper et al., 2013; Ding et al., 2013; MacDonald et al., 2012). Transportation infrastructure has been increasingly considered one of the most vulnerable sectors to sea level rise (Asariotis, 2020; Meguro & Ogi, 2018; Tewari & Palmer, 2018). Because of the high population density near the coasts, there is a significant risk that the transportation infrastructure will be flooded. For example, along the Gulf of Mexico, an estimated 2,400 miles of major roadways and 246 miles of freight rail lines are at risk of permanent flooding (Burkett, 2002). This risk is posed by the fact that the sea level is expected to rise in the range of 5 feet over the next 50 to 100 years. As sea levels continue to rise, coastal roads and other types of transportation infrastructure will become more vulnerable to inundation by seawater, as well as low-lying areas that are already prone to flooding (Chinowsky et al., 2013). When the roads that are vulnerable to damage are closed, users will be forced to use alternative routes, which will increase the amount of time it takes to travel. Increased use of the surrounding open roads may produce even more severe traffic congestion, which will be felt by those already using the highways.

Numerous studies have been conducted in the last two decades that have addressed climate change and sea level rise impacts, vulnerability, economic evaluation, and adaptation (Azevedo de Almeida & Mostafavi, 2016; Dawson et al., 2016; MacDonald et al., 2012; Pörtner et al., 2022; Titus, 2002; Vantaggiato & Lubell, 2020). Much of the existing literature focuses particular attention on evaluating the social, political, economic, and infrastructure implications of climate change and sea level rise on coastal areas (e.g., impacts on housing, employment, transportation infrastructure, ecosystems, etc.) (Bayard & Elphick, 2011; Cooper et al., 2013; Dawson et al., 2016; Ding et al., 2013; Gomaa & Peng, 2015; Milliman & Haq, 1996; Papakonstantinou et al., 2020; Titus, 2002). Few studies, to the best of our knowledge, have attempted to provide a more comprehensive study of the implications on population relocation dynamics and transportation networks, to the best of our knowledge.

Research about climate change and sea level rise impacts on transportation systems has emerged very recently (Asadabadi & Miller-Hooks, 2017; Asariotis, 2020; Chen & Region, 2019; Fishman, 2018; Jones, 2017; Kwiatkowski, 2017; Lykou et al., 2017; Meguro & Ogi, 2018; Papakonstantinou et al., 2020; Shen & Kim, 2020; Tewari & Palmer, 2018; Tonn et al., 2021; Wang et al., 2020; Zhou et al., 2019). Several attempts have been made to quantify climate risks, adaptation, and transportation planning (Bloetscher et al., 2012; Burkett, 2002; Freckleton et al., 2012; Lambert et al., 2013; Steyn, 2014; Tang et al., 2013; Webster et al., 2013). Nevertheless, it is necessary to address the restrictions of their work. As an illustration, the majority of these studies only concentrated on addressing the direct impacts of sea level rise on transportation systems (Asariotis, 2020; Burkett, 2002; Lykou et al., 2017; Titus, 2002). Some of them attempted to identify the physical transportation infrastructure at risk and to assess the vulnerability of transportation systems due to future scenarios of sea level rise (Bloetscher et al., 2012; Chen & Region, 2019; Fishman, 2018; Shen & Kim, 2020; Tang et al., 2013; Webster et al., 2013). Moreover, previous studies have reported the assessment and evaluation of different adaptation strategies and design measures to increase the resiliency and adaptability of transportation infrastructure (Asariotis, 2020; Kwiatkowski, 2017; Meguro & Ogi, 2018; Wang et al., 2020).

The other limitation of existing literature is that these efforts have mostly focused on the direct implications of transportation infrastructure and system performance rather than the economic evaluation of climate change's effects on road traffic (Asariotis, 2020; Burkett, 2002; Dawson et al., 2016; Lykou et al., 2017; Titus, 2002). Recently, investigators have examined the effects of insurance, incentives, and public assistance on achieving transportation infrastructure resilience (Tonn et al., 2021). Surveys that have been conducted by Chinowsky et al. (2013) showed that the assessment of climate change adaptation costs for the US road network has been underestimated.

Numerous studies have been conducted to estimate the effects that rising sea levels will have on the economy (Chinowsky et al., 2013; Gomaa & Peng, 2015; Yevdokimov, 2017). The findings of this research indicated the effects of rising sea levels on coastal elevation, ocean coasts, the sustainability of coastal wetland ecosystems, vulnerable species, population, land use, and infrastructure. Inundation, erosion of the coast, and regular flooding are just examples of the direct impacts that these factors have on human communities. Some have indirect consequences that could potentially cause problems in the long run, such as the disruption of ecosystems or the extinction of certain

species. Loss of economic activity and assets will be the result of the effects of continued sea level rise, which will cause these consequences.

A large and growing body of literature has investigated the impacts of sea-level rise on transportation and population, vulnerability analysis, and adaptation strategies (Bloetscher et al., 2012; Chen & Region, 2019; Dawson et al., 2016; Meguro & Ogi, 2018; Papakonstantinou et al., 2020; Tang et al., 2013; Tewari & Palmer, 2018; Titus, 2002; Vantaggiato & Lubell, 2020). Most of the currently available research focuses only on the direct effects that rising sea levels will have on transportation infrastructure. The flooding of transportation systems, properties, and infrastructure is the primary source of direct damage (Burkett, 2002). However, few research endeavors have been conducted to study the impacts of sea level rise within a future transportation network model based on different scenarios for population relocation (Steyn, 2014). There are a considerable number of indirect effects, such as the loss of employment opportunities and the relocation of affected populations; effects on the housing market in vulnerable and surrounding areas; potential labor loss because some vulnerable property owners may choose to relocate; and the loss of service infrastructures such as roads, utilities, and medical services (MacDonald et al., 2012; Pörtner et al., 2022). These indirect impacts caused by sea level rise can result in significantly higher economic costs than the direct losses. If these indirect influences are ignored, the potential economic benefits of any adaptation strategy may be greatly underestimated, which could result in the selection of a less effective adaptation strategy (Lindsey, 2019; Shen & Kim, 2020; Wang et al., 2020).

This study, therefore, aims to identify and assess the impacts of sea level rise on population relocation dynamics and future transportation systems, utilizing data from the transportation model for the year 2035 in the Tampa Bay region, Florida. This research, in contrast to prior efforts for assessing the vulnerability analysis of the effects of sea level rise, takes into consideration not only the direct implications of sea level rise but also the indirect implications on the transportation system, which were considered within three different relocation scenarios for the affected population in the inundated areas.

The analysis of this research utilizes the NOAA-provided digital elevation data, as well as the two-foot, Mean Higher High-Level sea surface data to represent a worst-case scenario for the year 2035. The study estimated the total population and employment will be affected assuming a homogenous distribution within each transportation analysis zone (TAZ), as well as the transportation networks that will be affected based on segment direction capacity reduction rates. Then, the impact of each scenario has been studied on the transportation system through a series of indicators for vehicular congestion and travel time.

This research aims to determine how different population relocation scenarios induced by sea level rise will cause transportation capacity changes. This research identifies these results by developing different relocation scenarios for the affected populations and studying the impacts of each scenario on the transportation model. The key objectives of this research are; 1) to estimate the affected population and transportation infrastructure under the two-foot SLR scenario in 2035; 2) to develop different scenarios for the relocation of the affected population, and 3) to study the impact of each scenario on the transportation system.

2. Data and Methods

2.1. Case Study Area

The low-lying and densely populated coastal communities that surround Tampa Bay, Florida, are especially vulnerable to the effects of increasing sea levels because of their terrain and population density (Council, 2006; Shen, 2014). Since it has 700 miles of coastline and a 3.2 million population, many of whom live near Tampa Bay or the Gulf of Mexico, the area around Tampa Bay is especially vulnerable to the rising sea level (Council, 2006).

The Gulf of Mexico region is more vulnerable to the rise in sea levels than other locations due to the local subsidence that has occurred there as well as its extensive exposure to the ocean (Burkett, 2002). At the rate of 0.25 inches per year (10 mm/year), the ground surface of the Mississippi River Deltaic Plain is sinking. As the sea level rises by up to 1 meter, even the most stable bay in the eastern Gulf of Mexico will be at risk of being flooded (Burkett, 2002). This is because of the effects of climate change. In light of this, it is particularly essential, when it comes to the process

of long-range planning, to have an understanding of how coastal communities in the Gulf of Mexico region would be impacted by the changing sea levels. This has been done to minimize the negative effects of sea level rise. The following is a synopsis of the study region that encompasses the Tampa Bay region: (Pinellas, Hillsborough, and Pasco counties)(Figures 1 and 2).

- Pinellas County: With a land area totaling only 280 square miles, is the county with the smallest land area. It also has the highest population density in the state of Florida, with more than 1,600 people living in every square mile in the year 2020. Pinellas County is home to twenty-four different municipalities, with the largest being St. Petersburg, which ranks as the fourth largest city in the state. The county's population in 2021 was estimated to be 956,615 people (Council, 2006).
- Hillsborough County: The population density in Hillsborough County is the fourth highest in the state of Florida, despite the county's relatively small geographical size of 1,053 square miles. The City of Tampa serves as the county seat, and it is also the main metropolitan center in the region. In terms of total land area, Tampa ranks third in the state, behind only Jacksonville and Miami. The population of the county was estimated to reach 1,512,070 in 2021, representing a yearly growth rate of 1.34 percent (Council, 2006; Shen, 2014).
- Pasco County: With a land area of 745 square miles, this region contains the greatest proportion of land that has not been developed. Its largest urban centers are located in New Port Richey, Dade City, and Zephyrhills respectively. In 2021, the county was estimated to have a total population of 539,885 residents (Council, 2006).

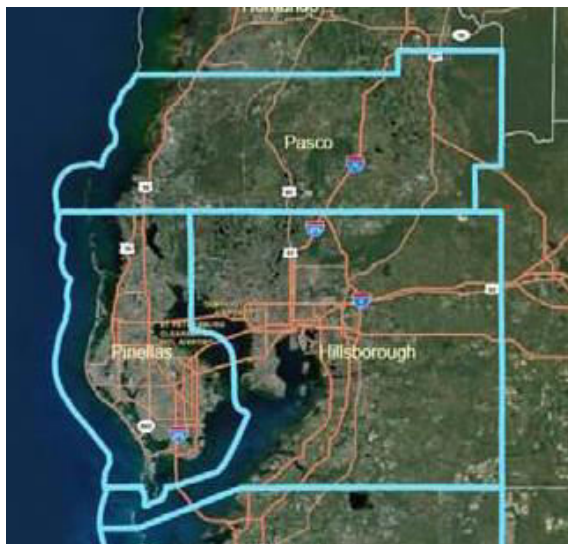


Figure 1 The case study area for the Tampa Bay Region

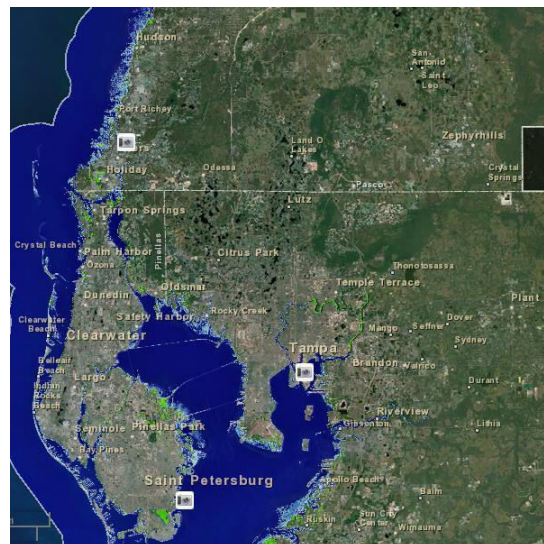


Figure 2 The two feet SLR inundation map, FL under 2035 Sea Level Rise Scenario (NOAA)

2.2. Sea-Level Rise Analysis Scenario

Investigating the various possible outcomes of sea level rise projections for the future is not within the scope of this study. As a result, the sea level rise projection used in this study is fully based on the scientific research regarding climate change that was published by other studies. The projection of the rise in sea level is dependent not only on historical recordings of sea level but also on mathematical models that simulate local estimates for the rise in sea level (James et al., 2021). According to IPCC (IPCC, 2013), throughout the last century, the level of the ocean around the world has risen at a rate that has been on average between 1.7 and 3.1 millimeters per year. Between 1901 and 2018, there was a 15–25 centimeter (about 6–10 inch) rise in the average worldwide sea level. Satellite radar readings have shown a steady increase of 7.5 centimeters in height since 1993 (IPCC, 2013; Lindsey, 2019; Zhongming et al., 2022).

The global average rate of sea level rise is 3.6 mm per year (0.14 inches per year), and the rate of sea level increase in the Tampa Bay region is 2.3 mm to 2.4 mm per year, according to long-term tide gauge measurements and recent satellite data (James et al., 2021). The average annual rate of sea level rise along the coast of the United States is greater than 2.5 mm (Tampa Bay Regional Planning Council, 2006). According to the Tampa Bay Climate Science

Advisory Panel (CSAP), sea level rise might occur in the Tampa Bay region between 11 inches and 2.5 feet in the year 2050, and between 1.9 and 8.5 feet in the year 2100, depending on the historical data.

Because different sea level rise projection models primarily rely on various sets of assumptions, it is necessary to use a case-by-case approach when attempting to forecast the rise in sea level (Lindsey, 2019). However, due to the uneven distribution of the factors that cause sea levels to rise across the globe, even the same model will predict different sea levels (IPCC, 2013; Lindsey, 2019; Pörtner et al., 2022). This is because of the feedback loops that are created when one factor affects another (Milliman & Haq, 1996; Spada et al., 2013). As a result, the identification of suitable sea level rise scenarios was adapted specifically for the area covered by the case study. The Tampa Bay Climate Science Advisory Panel published the most recent projection for the area's sea level. The CSAP has developed a regional collection of SLR projection scenarios up until the year 2100 by making use of the most up-to-date and accurate scientific data that is currently available. St. Petersburg, Florida's relative sea level change (RSLC) scenarios, as determined by calculations made with the regionally corrected NOAA 2017 data (USACE, 2019). The structure of the model incorporates three potential outcomes: a scenario with a low, an intermediate, and a high sea level rise (Figure 3).

In this research, the high scenarios were chosen to represent the sea level rise analysis scenarios. The high scenario was chosen rather than the low scenario because it better accounts for the potential effects of indirect flooding caused by rising sea levels. Studies revealed that the effects of rising sea levels are significantly more substantial than the rise in sea levels itself. To capture the higher projection of global mean sea level rise, the analysis scenario of this study has been selected to be the worst-case scenario, which projects two feet of sea level rise by 2035.

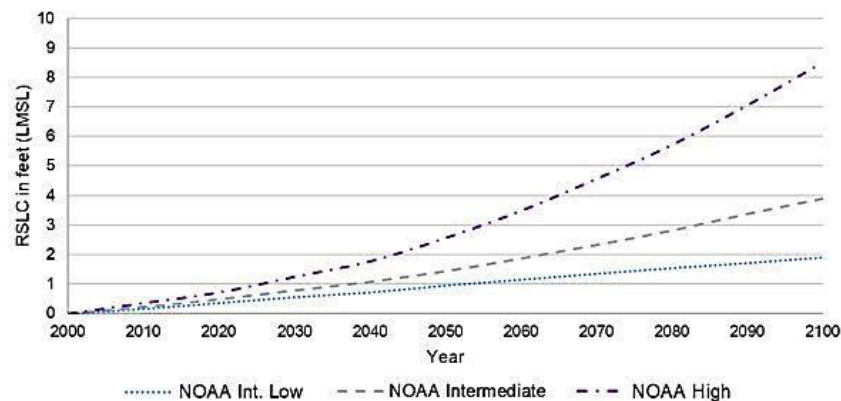


Figure 3 Projected scenarios of relative sea-level change for St. Petersburg, Florida (USACE 2019)

2.3. Research Design and Datasets

The research design of this study involved various procedures, including vulnerability analysis, transportation models of different scenarios, and a relevant comparison between three population relocation scenarios. As shown in Figure 4, this research has been designed through the following steps: 1) estimating the inundated area, population, and transportation infrastructure that will be affected under the 2ft SLR scenario for 2035; 2) developing different relocation scenarios of the affected population and employment; 3) studying the impact of each scenario on the transportation system performance; 4) removing major links between completely flooded areas; 5) proportionally reducing capacity between areas partially flooded.

This study utilized the following data sources: A) The transportation model for Tampa Bay Region; B) NOAA coastal services center coastal change analysis program which allows researchers to use GIS data to determine the inundated areas; C) the number of affected populations in each TAZ, and D) The number of affected employments in each sector for each TAZ. For the roadway data, as shown in Figure 5, the study utilizes the Navteq Streets data, which is one of the most comprehensive roadway datasets in the study region.

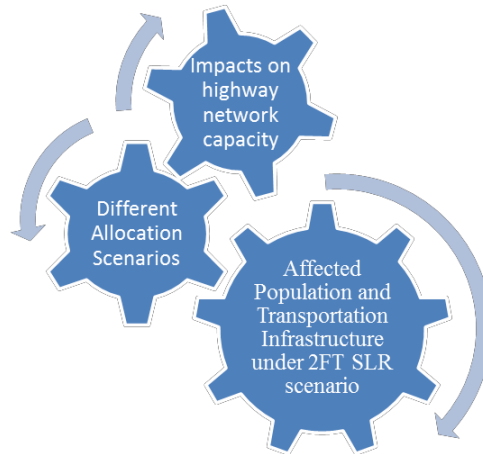


Figure 4 the main elements of the research design of the study

In this study, CUBE Voyager, a transportation and land-use modeling tool, has been used as the analysis tool because it is specified by the Florida Standard Urban Transportation Model Structure (FSUTMS). The framework of CUBE Voyager is script-based and modular, which makes it possible to incorporate any model methodology. This includes all from activity-based methods to discrete choice models to typical four-step models. CUBE Voyager features a highly adaptable network in addition to matrix calculators that may be used to determine trip demand and provide in-depth comparisons of several possible outcomes.

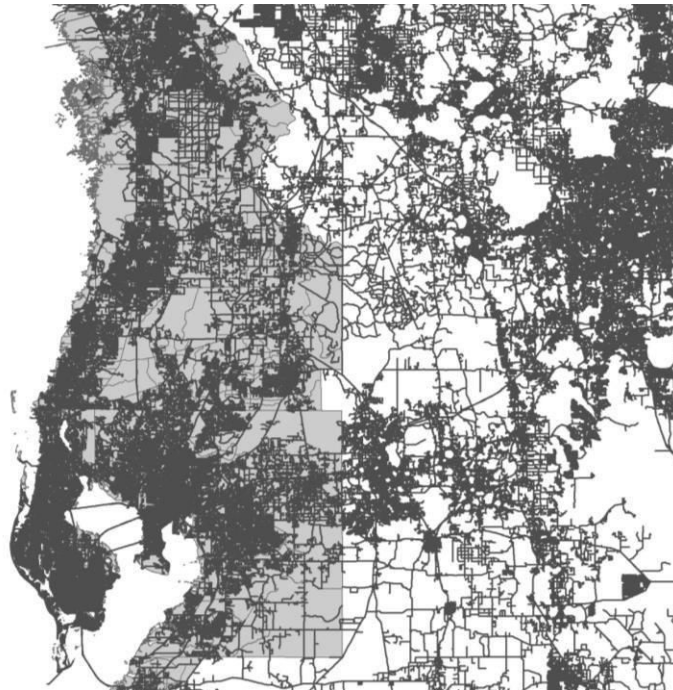


Figure 5 Navteq road data for the study region

2.4. Population Relocation Scenarios

The most extreme local SLR projection for 2035 is 49 centimeters, which is equal to 1 foot and 7 inches. As a result, a sea level rise scenario with a height of 2 feet was utilized as the basis for this model during the analysis of this study. This allowed for the impacts on transportation and land use to be evaluated based on the SLR worst-case scenario. To assess the effects of the various land use options, we developed three relocation scenarios within the context of the two-foot SLR scenario. The following assumptions are used regarding population distribution:

- Scenario I: Populations and jobs are relocated inside the same TAZs despite the flooding: This assumes that there will be no change in the total number of trips created or the number of attractions that were forecast using the 2035 model. On the other hand, it assumes that both the population and the jobs will be shifted within their existing TAZs, acting as though they migrated inland a relatively short distance.
- In the second scenario, population and employment will leave the region because of the flooding: In this hypothetical situation, it is assumed that anyone who could be affected by flooding will immediately evacuate the area. That means that the model will not take into account any of the people living in or holding jobs in the TAZs that have been flooded.
- Scenario III: The flooded population and employment shift in proportion to the growth rate of the TAZ: The population and jobs that are currently located in regions that will be flooded will be spread out across the study region by the zoning that is already in place as well as the most recent estimate for the growth rate in each TAZ (Figure 6). In this hypothetical situation, construction is assumed to go forward as scheduled, but flooded homes and businesses are left abandoned.

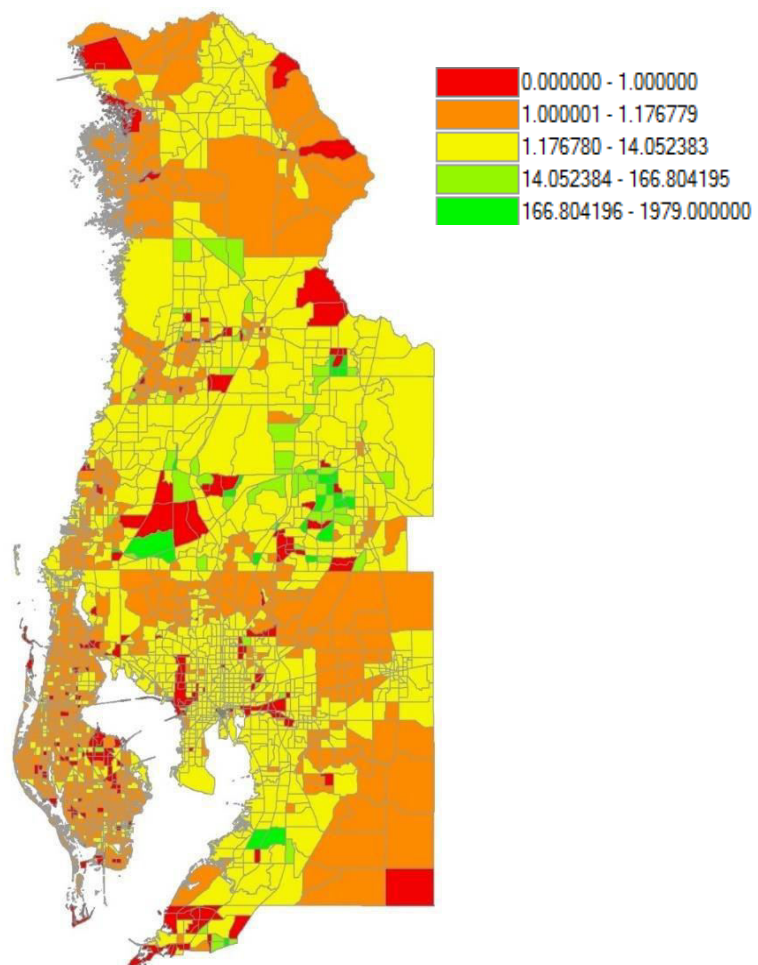


Figure 6 The base growth rate for transportation analysis zones from 2006 to 2035

2.5. Estimates of the capacity of the highway network

To evaluate the extent to which SLR will impact the capacity of the highway network. Using Navteq Streets data, this analysis identified the actual highway network that would be inundated. To ensure that the model appropriately represents the inundated roadway capacity, it was calculated based on lane miles. The model's network consists of the majority of minor arterials and all major highways. However, the network's capacity in a certain direction through a TAZ also includes minor and parallel facilities.

Roads have been classified into three categories: 1) two-lane facilities with one lane in each direction, 2) four or six-lane facilities with two or three lanes in each direction; and 3) eight or more-lane facilities with four or more lanes in each direction. Category two roads were given five lane miles for every highway mile because the study region has many important four- and six-lane facilities. Five lanes were seen as a fair compromise because better data does not exist for all roads, and within the built-up area of the study region, both cross-sections are common. Category three roads were given eight lane miles for each highway mile because there are very few facilities in the region with more than four lanes in each direction.

Many of the inundated roads travel parallel to shorelines, and in some places, roads running perpendicular to the shoreline do not become inundated. This could result in TAZs where highway capacity is constrained in one direction but not necessarily in the other. As a result, we calculated the percentage of lane miles inundated in each TAZ for roads traveling generally north-south (45 degrees from the north) and east-west (45 degrees from the east). The total number of lane miles within each TAZ was compared to those touching the two-foot inundation to create a separate capacity reduction index for north-south and east-west roads within each TAZ. The 2035 highway network was then given the capacity reduction factors to represent the overall changes in highway capacity within each TAZ for each direction.

3. Results

3.1. Impacts on population and employment

The results reveal significant impacts on population and employment by the direct inundation due to the two-foot sea-level rise scenario (Figure 7). According to the model estimate for the year 2035, the total population of the study region will be a total of 4.13 million residents. As summarized in Table 1, assuming an even distribution of housing and employment within each TAZ, a total of 96,688 people will be directly inundated, while 78,493 jobs will be lost or relocated due to the inundation of the business zones. This research attempted to determine a range of possible population and employment relocation outcomes by developing three possible scenarios. The first scenario will not consider population or employment relocation as the key assumption of this scenario is that the relocation process will be within the same TAZ. The second scenario assumes that the affected population and employment will move out of the study region. This means that the number of people and jobs lost due to flooding will be subtracted from the total population and employment in each TAZ. Lastly, the third scenario assumes that the inundated population and employment will remain in the study region but will be proportionately relocated to other TAZs based on the TAZ growth rate.

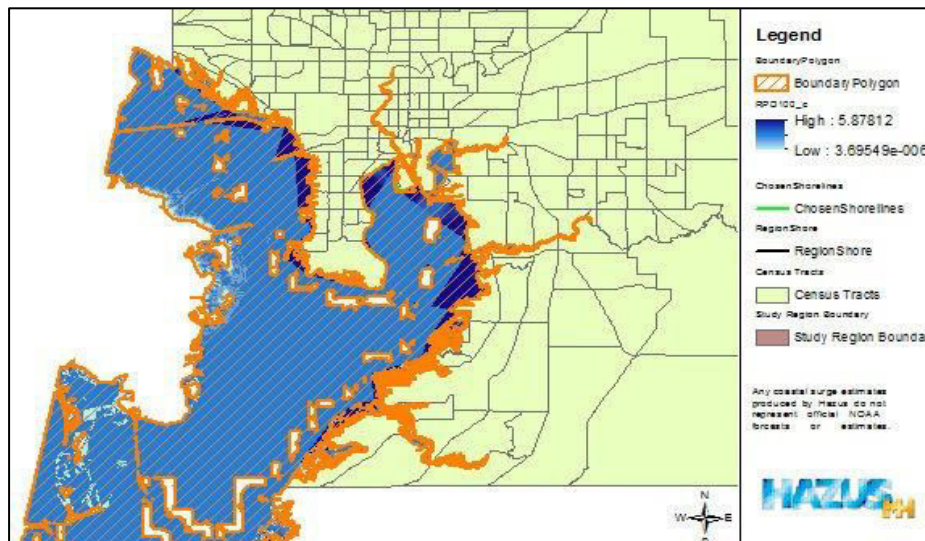


Figure 7 Inundation Map under 2ft Sea Level Rise Scenario generated using HAZUS-MH developed by FEMA

Table 1 Summary of the model results for the affected population and employment under the relocation scenarios

2035 Scenario	No change	Reduced Capacity Network		
		Relocation Scenario I	Relocation Scenario II	Relocation Scenario III
Total Population	4,130,166	4,130,166	4,033,478	4,130,166
Population Reallocated	-	-	-	96,688
Total Industry Employment	419,656	419,656	341,163	419,656
Industry Employment Reallocated	-	-	-	78,493

3.2. Impacts on Total Loss of Lane Miles

According to the findings, the direct two-foot inundation scenario will have an impact on a variety of transportation system components. According to Navteq data, a total of 357.84 miles will be directly inundated as a total loss of real lane miles. However, the model's findings indicate that a total of 84.09 lane miles will be inundated. Figure 8 shows that the total lane miles of East-West roads that will be inundated will be 200.83 miles, while the North-South road networks will lose a total of 157.01 lane miles (Table 2).

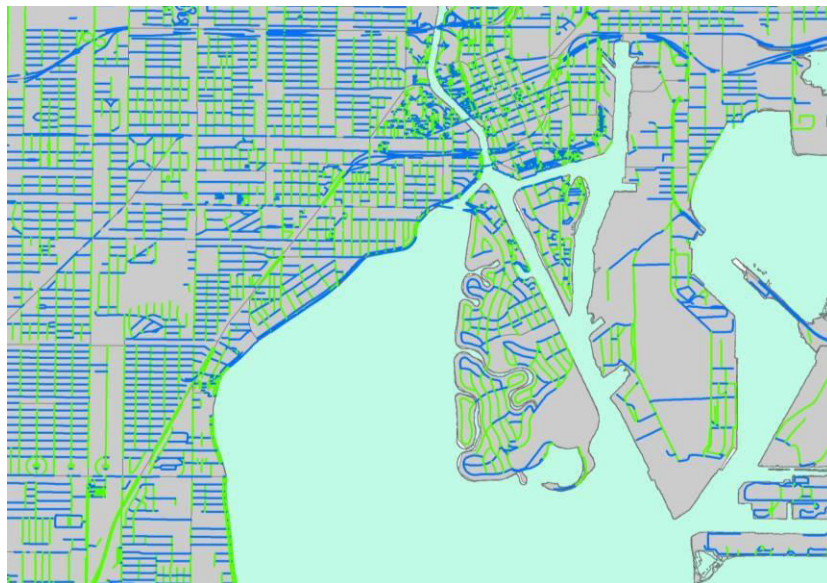


Figure 8 Calculate Share of Lane Miles Inundated at TAZs (N-S and E-W)

Table 2 Summary of the model results for the total loss of lane miles under relocation scenarios

2035 Scenario	No change	Reduced Capacity Network		
		Relocation Scenario I	Relocation Scenario II	Relocation Scenario III
Total Real Lane Miles	43,500	43,142.16	43,142.16	43,142.16
Total Loss Real Lane Miles	-	357.84	357.84	357.84

Total In Model Lane Miles	10,150.08	10,065.99	10,065.99	10,065.99
Total Loss In Model Lane Miles	-	84.09	84.09	84.09
EW	-	200.83	200.83	200.83
NS	-	157.01	157.01	157.01

3.3. Impacts on Total Trips Produced

The findings indicate that the direct two-foot flooding scenario will have an impact on a variety of types of produced trips. In particular, as shown in Table 3, the total number of trips produced by the model before the inundation, including single occupancy vehicles, 2 and +3 persons carpooling, and highway trips, were 10,604,763; 3,252,306; 726,733 and 14,640,202 respectively. When evaluating the total trips for the proposed relocation scenarios, the results reveal the extent to which the inundated zones may affect the estimations. In the first scenario, there will be no major change in the total number of different types of trips. The decrease in total trips was negligible relative to the size of the model.

Table 3 Summary of the model results for the total trips produced

2035 Scenario	No change	Reduced Capacity Network		
		Relocation Scenario I	Relocation Scenario II	Relocation Scenario III
Total SOV Trips	10,604,763	10,604,740	10,567,130	10,611,030
Decrease/Increase		- 23	- 37,633	+ 6,267
Total 2-Person Carpool Trips	3,252,306	3,252,294	3,241,866	3,254,397
Decrease/Increase		- 12	- 10,440	+ 2,091
Total +3 Person Carpool Trips	726,733	726,729	724,436	727,196
Decrease/Increase		- 4	- 2,297	+ 463
Total Highway Trips	14,640,202	14,640,163	14,589,832	14,649,023
Decrease/Increase		- 39	- 50,370	+ 8,821

The potential effects of the other two scenarios on the model outputs have been greater. In the second scenario, where the population leaves the region, the total number of trips produced decreased significantly. There will be a drop of 37,633 total SOV trips, 12,737 carpooling trips, and 50,370 highway trips (Table 3). In the third scenario, where population and employment relocate proportionally based on the TAZ's growth rate, there will be an increase in the total trips produced. The total increase in trips produced by SOV, carpooling, and highways will be 6267, 2554, and 8821, respectively.

3.4. Impacts on Total Volume-to-Capacity (V/C) Ratio

The volume to capacity (V/C) ratio compares the number of trips assigned to a link with the total capacity of that link. Links with V/C ratios greater than one are operating over their capacity and are consequently congested. To compare the performance of various scenarios, it is important to identify the length of the highway network operating above

capacity. The scenario with the highest percentage of the network operating with a V/C ratio greater than one was scenario II, where inundated population and employment leave the region with 16.5% of the network operating over capacity (Table 4). The percentages for the baseline scenario, the reallocate within the TAZ scenario, and the proportional relocation scenario were 16.4%, 16.3%, and 16.4%, respectively (Figure 9). This was unexpected, as it was believed that the last scenario would be the least congested. Upon further consideration, however, because large employment centers are not as low-lying as residential neighborhoods, this scenario may have required all employers from a wider distance to fill all the positions.

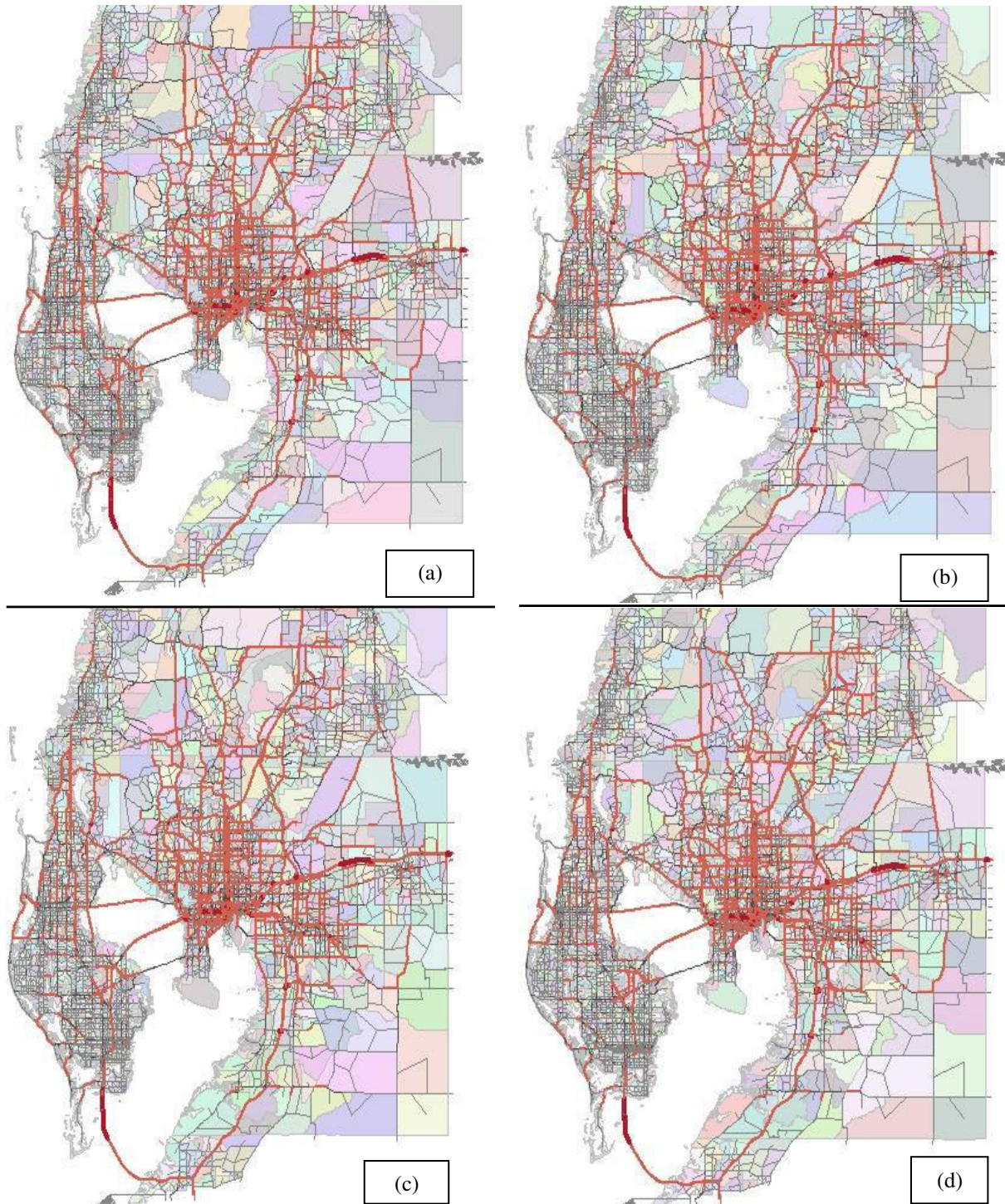


Figure 9 Model results for the total volume-to-capacity ratio for all relocation scenarios; (a) 2035 base scenario; (b) Scenario I: relocate within TAZ scenario; (c) Scenario II: leave region scenario; (d) Scenario III: proportional relocation scenario.

The intuition about the V/C ratio is potentially validated by the average V/C ratio for links operating above capacity. The average V/C ratio within the second scenario is lower than the V/C ratio within the reallocated TAZ scenario. Therefore, although more miles are congested in the former scenario, there is a higher level of congestion in each link in the latter scenario. It is also interesting to note that the proportional relocation scenario has fewer miles of congestion and lower average V/C ratios than the 2035 base scenario. This is probably because coastal transportation links are already at capacity and may have longer commutes, so reallocating them to places with excess capacity might relieve some of the congested corridors not affected by SLR.

Table 4 Summary of the model results for the total volume-to-capacity ratio

2035 Scenario	No change	Reduced Capacity Network		
		Relocation Scenario I	Relocation Scenario II	Relocation Scenario III
Total Miles V/C Ratio Greater Than 1	2,155.48	2,147.53	2,170.96	2,148.60
Percentage of V/C Ratio Greater Than 1	16.4%	16.3%	16.5%	16.4%
Average V/C Ratio for V/C Ratio Greater Than 1 Weighted by Distance	2.43	2.50	2.43	2.42

3.5. Impacts on Total Congestion

The results demonstrate that the direct 2 ft inundation scenario will have an impact on total congestion. Specifically, there will be a total of 6,318.93 minutes of total congestion before the inundation (Table 5), while the model predicts that there will be a difference in overall congestion due to direct inundation. Table 5 indicates that the overall congestion time will increase by 15.24, 19.30, and 78.13 minutes in the three proposed scenarios. However, these times are rather modest in comparison to the model's total congestion time.

Table 5. Summary of the model results for the total congestion

2035 Scenario	No change	Reduced Capacity Network		
		Relocation Scenario I	Relocation Scenario II	Relocation Scenario III
Total congestion (minutes)	6,318.93	6,334.17	6,338.230	6,397.06
Scenario congestion minus the base	-	15.24	19.299	78.13

4. Discussions

The rise in sea level will have both direct and indirect effects on population and employment, in addition to influencing transportation networks. As a result of increasing sea levels, low-lying areas are inundated in water, beach, and wetland ecosystems are destroyed, and the severity of storm surges and flooding caused by rainfall is exacerbated. All of these consequences could potentially have an impact on the modes of transportation. According to the findings of this study, the total population and employment that will be impacted (under the assumption of a homogenous distribution within each TAZ), as well as the transportation networks that will be impacted (based on segment direction capacity reduction rates), have been estimated. After that, we investigated the effects of each scenario on the transportation system by analyzing several indicators for the amount of time spent in traffic and the distance traveled.

The findings of this study provide insights into the potential methods in which future estimations of transportation network analyses could be affected by future scenarios of sea level rise. This study proposed three possible relocation scenarios for the affected population and employment and then evaluated how those varied scenarios impacted the transportation model. The scenarios involved the relocation of the affected population and employment.

One of the most important findings from this research is that the immediate inundation that would be caused by a rise of two feet in sea level would have a significant impact on both employment and population. This was one of the most significant findings that emerged from this investigation. According to the model estimate for the year 2035 for the Tampa Bay area, assuming an even distribution of housing and employment within each TAZ, a total of 96,688 people will be directly impacted by the inundation, and approximately 78,493 jobs will either be eliminated or relocated because of the inundation of the business zones. In addition, the scenario in which there is direct flooding of two feet will influence a variety of components of the transportation system. According to the findings of this study, a total of more than 357.84 kilometers will be lost due to direct inundation in the study region.

The second major finding shows that diverse types of trips in the transportation analysis will be affected by the direct two-foot sea-level rise inundation scenario. The evaluation of the total trips for the proposed relocation scenarios reveals the extent to which the inundated zones may impact the model estimations. When comparing different relocation scenarios, the change in total trips was significant. The potential effects on the model outputs have been greater. In one of the scenarios where the population will move out of the region, the total number of trips produced decreased significantly. There was a drop of 37,633 total SOV trips, 12,737 carpooling trips, and 50,370 highway trips. While in the other scenario where the inundated population relocate proportionately based on the growth rate, the increase in total trips produced was greater. The total increase in trips produced by SOV, carpooling, and highways were 6267, 2554, and 8821, respectively.

Furthermore, the results indicate that direct flooding will affect both the volume-to-capacity ratio and total congestion estimations. The findings of the volume-to-capacity ratio estimations reveal that the majority of the relocation scenarios exceed network capacity by between 16.3 and 16.5 percent. While in terms of total congestion, there will be a total of 6,318.93 minutes of total congestion before the inundation. Additionally, the overall congestion time will increase by 15.24, 19.30, and 78.13 minutes in the three proposed scenarios.

The interpretation of the results of this study is not without certain limitations. Firstly, the only roadways that have been determined to be impacted by increasing sea levels are those that are located within the flood zones. If storm surges and coastline erosion were also taken into consideration, the impact that rising sea levels have on the transportation network will be substantially more severe. Second, because the transportation model has limits on the networks that it uses, this analysis does not take into account all of the transportation networks. Inside the TAZ, local routes that could potentially be exploited as detours have been replaced with centroid links so that traffic can move more efficiently.

Furthermore, other limitations of this study are related to the proposed distribution scenarios of the projected population and employment. Other distribution scenarios should be considered to build more reliable and reasonable relocation models. In addition to the assumptions made in the population relocation methodology, this methodology could not recognize whether an entire portion of the network is cut off by SLR or if just parts of the capacity are reduced. A comprehensive survey of the inundated links along coastal routes would need to be performed to identify places where the directional network proportional capacity reduction methodology is inappropriately indicating that capacity is still present within a corridor.

Numerous concerns could be the focus of future research. First, increasing the number of different relocation scenarios that could occur could lead to a more varied set of results. Additionally, in scenario III, population and employment were distributed in a manner that corresponded to the growth rate of each TAZ. Utilizing several other distribution methods for this investigation would affect the results. In addition, within each scenario, critical links may be identified for preservation, and the model may be approximated to examine the effects of retaining individual links. For instance, it may be more vital to retain a road that connects two large areas that are not at risk of flooding than it would be to preserve a route that serves only low-lying communities because the former road travels through a low-lying area. This model and the GIS analysis that preceded it would be a valuable starting point for the development

of a methodology that would allow for the consistent ranking and prioritization of corridors that should be preserved as part of a regional SLR adaptation strategy.

5. Conclusions

Sea-level rise will have considerable direct and indirect impacts on population and employment, as well as on transportation systems and infrastructure. The primary goal of this research is to incorporate the potential effects of population relocation due to sea level rise into transportation modeling. In general, different scenarios for relocating population and employment generate new traffic demands, which could result in traffic congestion. Thus, transportation planners should simulate future sea level rise scenarios and evaluate their impact on the current transportation system. Then the new transportation planning should take into consideration these possible adverse impacts produced by the relocation development.

The results of this investigation show that more than 357.84 miles will be directly inundated in the study region under a two-foot sea-level rise. More than 78,493 jobs will be lost or relocated due to the inundation of the business zones. On the other hand, the evaluation of the total trips for the proposed relocation scenarios reveals the extent to which the inundated zones may impact the model estimations. In one of the scenarios where the population would move out of the region, the total number of trips produced decreased significantly. While in the other scenario, where the inundated population relocates proportionately based on the growth rate, the increase in total trips produced was greater. Finally, between 16.3 and 16.5 percent of the relocation scenarios exceed network capacity. In terms of total congestion, there will be a total of 6,318.93 minutes before the inundation. Additionally, the overall congestion time will increase by 15.24, 19.30, and 78.13 minutes in the three proposed scenarios.

The results of this study have several significant implications for future practice. These findings can assist local transportation planners, engineers, and decision-makers in identifying the most vulnerable areas and transportation facilities to rising sea levels. As a result, these individuals will be able to make more informed decisions regarding adaptation planning and resiliency.

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