EMPLOY COST-BENEFIT ANALYSIS TO EVALUATE THE COST EFFICIENCY OF MAJOR SEA LEVEL RISE ADAPTATION STRATEGIES

By

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To my wife and parents who always support me, and to my advisor who guides me and helps me grow through my graduate school

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LIST OF ABBREVIATIONS

FEMA	Federal Emergency Management Agency
IPCC	Intergovernmental Panel on Climate Change
LISA	Local Indicators of Spatial Association
NOAA	National Oceanic and Atmospheric Administration
SLR	Sea Level Rise
UN	United Nations
U.S. DOA	U.S. Department of Agriculture
U.S. DOT	U.S. Department of Transportation

Abstract of Dissertation Presented to the Advisor Committee
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The rise of sea level, as one of the most obvious and direct impacts of climate change in coastal areas, has become an important and urgent problem. A large amount of efforts have been devoted to sea level rise impact analysis and adaptation planning. However, despite these research efforts and various existing sea level rise adaptive planning tools, decision makers and residents at the coastal area is not making significant progress to prepare for future sea level rise. One of the major reasons for this slow reaction is that people are unaware of the costs of doing nothing or postponed actions, and the benefits of taking adaptation actions. Cost-benefit analysis is a promising tool to address this issue. However, existing literatures applying cost-benefit measure to analyze sea level rise or its adaptation strategies do not take full consideration of indirect economic impacts of various adaptation strategies. Furthermore, existing studies do not evaluate the action time point to implement these strategies.

This dissertation research aims to bridge these gaps by integrating both direct and indirect economic impacts of sea level rise into a cost-benefit analysis framework, which is applied to evaluate most commonly adopted adaptation strategies. This study

selects six commonly discussed and adopted sea level rise adaptation strategies for analysis. It then estimates the economic loss on land value, business revenue, coastal wetland ecosystem services, building damages and value of travel time delay at different time points. These economic losses are considered as benefits of adaptation strategies. Next, the cost of adopting these strategies are quantified at different time points which are consistent with benefit analysis. Finally, all the benefits and costs are put together to analyse the cost efficiency and best time to take actions. It also proposes an adaptation plan that assigns each strategy to its appropriate locations as a guide for local communities. An uncertainty analysis is also conducted to evaluate the cost efficiency of adaptation strategies as well as the proposed adaptation plan under different uncertainty levels.

The analysis results show that different strategies have very different cost efficiency. Generally speaking, the strategies that target to protect built environment have higher cost efficiency than the ones that focus more on preserving ecosystems. Furthermore, cost benefit analysis at different action time points help to decide the best action time for each strategy as well as the adaptation plan. Although current sea level rise projection is associated with high uncertainty, the uncertainty analysis shows that even under the highest uncertainty level, most adaptation strategies and the adaptation plans are more cost efficient than do nothing.

CHAPTER 1
INTRODUCTION

1.1 Background

Sea-level rise is recognized as a major threat to the sustainable development of the coastal areas. Scientists have cited worldwide evidence to show that the fluctuation of sea levels is very broad over the past 200 million years. The range of fluctuation is as high as 300 meters. This sea level rise fluctuation is proven to co-vary with average earth temperature and the content of atmospheric carbon dioxide by extracting isotopic data from ice cores dating back more than 400,000 years (Parkinson, 2009). The Sea-level rise during the 20th Century was faster than during the 18th and 19th Century (Woodworth, 1999; Church et al., 2001). Especially in recent years, the rate of acceleration is even higher. According to Bindoff & Josey (2007), the rate of global sea level rise has increased from a long-term average over the 20th century of 1.7 millimeters per year to 3.1 millimeter per year during the period of 1993 to 2003. While the causes of the sea level rise are hotly debated, there is no disagreement that sea level has been rising and will continue to rise.

Various models have been developed to project sea level rise trend. Although the modeling results generate a wide range of future sea levels by applying different modeling framework and various development scenarios, it is suggested that the sea level by the year 2100 can rise to as much as 11 meters, with the best guess as 0.48 meter (Gornitz, 1995). The Intergovernmental Panel on Climate Change (IPCC) 2007 Fourth Assessment Report provides a comprehensive review and assessment of global climate change trends, expected changes over the next century, and the impacts and challenges that both humans and the natural world are likely to be confronted with during the next century (IPCC, 2007). Based on a range of possible greenhouse gas emissions scenarios for the next century, the IPCC estimates the global increase in temperature will likely be between 1.1 and 6.4ºC. Estimates of sea-level rise for the same scenarios are 0.18 m to 0.59 m, excluding the contribution from accelerated ice discharges from the Greenland and Antarctica ice sheets. By further capturing the dynamics of Greenland and Antarctica ice sheets, IPCC's 5th Assessment Report projects the sea levels 60% higher than its projections in the 4th Assessment Report (IPCC, 2013).

Although the pace of sea level rise is uncertain, the impacts of sea level rise are increasingly visible. A number of studies have documented and projected the impacts of sea level rise. In 2009, the U.S. Climate Change Science Program published a synthesis report, Coastal Sensitivity to Sea Level Rise: a Focus on the Mid-Atlantic Region, which identified a wide range of sea level rise impacts. The report describes sea level rise impacts on coastal elevation, ocean coasts, coastal wetland sustainability, vulnerable species, population, land use, and infrastructure. Some of these impacts have direct effects on human settlements, such as inundation, coastal erosion, and frequent flooding; some of impacts have indirect effects, which will cause potential problems in the long term, such as ecosystem disturbance and loss of species (FitzGerald et al., 2008). The consequence of continued sea level rise impacts will result in the loss of economic activities and assets. The total cost can be enormous.

There are a number of studies trying to quantify the costs and economic losses of sea level rise. In a report to the United States Congress, Ackerman (2008) estimates an annual loss of $360 billion or 0.35% of U.S. production by 2100 if only considering the losses of residential real estate in the 48 mainland states in the business-as-usual case. As sea level rises, the indirect economic impact for shipping, fishing, and manufacturing industries will be huge. For example, such impacts for Maryland amount to roughly $361 million as well as a loss of more than 3,600 jobs (Williamson et al., 2008). Stanton and Ackerman (2007) evaluate the impacts of a 27-inch sea level rise in Florida, and find that 433 square miles i.e. 6.8% of the developed areas in Florida are in the vulnerable region (the business-as-usual scenario). Miami-Dade County in Florida will have almost 70% of its total land area inundated, including 73 square miles of residential neighborhoods, commercial districts, and industrial properties. For the Florida road network, 75.5 miles limited access highways, 390.8 miles other highways and 1972.4 miles major roads are vulnerable to 27 inches sea level rise. If doing nothing, the loss of tourism revenue, increased hurricane damages, at-risk residential real estate, and increased electricity costs will be massive, which is projected to be $92 billion annually by 2050 and $345 billion by 2100, which constitute 2.8% and 5.0% of the state's projected Gross State Product, respectively.

Therefore, there has been an increasing effort to propose adaptation strategies to mitigate the impacts of sea level rise. The state of California has been the forerunner in weaving climate change into its state-wide policy making. On November 14, 2008, Governor Schwarzenegger signed Executive Order S-13-08 to create statewide consistency in planning for sea level rise. The executive order calls for, among other things, the completion of a Sea Level Rise Assessment Report, the consideration of sea level rise scenarios for the years 2050 and 2100, and the development of a Climate Adaptation Strategy (California State Lands Commission, 2009).

Following that, the State of California published a guideline for local governments to help them adapt to sea level rise. The guidance suggests planning procedure for sea level rise, starting from vulnerability assessment, to plan making and implementation, and to evaluation of progress (Russell and Griggs, 2012). It also proposes strategies for developed vs. undeveloped lands, and for the public vs. private properties. California also pays special attention to sea level rise when planning for its state-wide climate change adaptation. There are also other leading states that address the impacts of sea level rise, such as Maryland, Florida and New York (Maryland Commission on Climate Change Adaptation and Response Working Group 2008; Parkinson 2009).

A number of local governments also made great efforts in weaving sea level rise into its decision making. As UN Human Settlements Programme suggests: “much of what is listed in the adaptation options/strategy will fall to local government to implement, even if it needs resources and policy and regulation frameworks from higher levels of government (2006, p148)”. San Diego Bay area is one of the most leading regions to integrate sea level rise adaptation into its regional plan since its economy is heavily dependent on its coastal developments. In its Sea Level Rise Adaptation Strategy for San Diego Bay (ICLEI Local Governments for Sustainability, 2012), the plan specifies 12 sectors that are potentially vulnerable to sea level rise, including ecosystems, contaminated sites, storm water, waste water, potable water, energy facility, transportation facility, building stock, emergency response facility, parks and public facility, airports and vulnerable population. Each sector associates with several primary vulnerabilities which are matched with specific adaptive strategies. For example, ecosystem analysis includes two primary vulnerabilities, inundation and erosion. After detailing ecosystems' vulnerabilities to inundation and erosion, the plan list several optional strategies that local governments can adopt to mitigate their vulnerabilities to sea level rise. The following strategies exemplify how specific the strategies are:

1. Strive to create habitat mitigation projects that are resilient to sea level rise.
2. Evaluate how mitigation projects will be affected and encourage acquisition of upland areas also when analysis indicates that acquired near shore habitat will be lost to sea level rise.
3. Expand or preserve ecological buffers around development to allow for inland migration of ecosystems and habitats.
4. Promote soft and hard low-impact development strategies to reduce storm water runoff and protect water quality.
5. Evaluate threats to habitat connectivity, and protect habitat corridors to facilitate species shift to viable adjacent habitat.

There are also many other similar efforts in proposing sea level rise adaptive strategies, such as Sea Level Rise Response Strategy in Worcester County, Maryland (Worcester County Department of Comprehensive Planning, 2008) which grouped a large number of adaptive strategies under three categories (protection, retreat, and accommodation); and Sea Level Rise in the Tampa Bay Region, which tries to pair sea level rise adaptive strategies with existing coastal management policies (Tampa Bay Regional Planning Council, 2006).

1.2 Research Needs

Since the existing plans just provide options and adaptation alternatives, it is hard to pick the most feasible strategies in practice. Therefore, there is a need to evaluate those proposed strategies to help decision makers actually make decisions on the ground. Sea Level Rise Response Strategy in Worcester County, Maryland (Worcester County Department of Comprehensive Planning, 2008) is among a few planning efforts to assess the proposed strategies. The plan does not only propose a number of adaptive strategies, more importantly, each strategy is heavily evaluated to uncover both of its advantages and disadvantages in a qualitative way. The identified advantages and disadvantages range from cost consideration, legal challenge, engineering challenge, and impacts on local economy. Other qualitative review of sea level rise adaptive strategies are also seen in Nicholls et al. (1995) and Boategn (2008).This information can provide some base for decision making, but this kind of analysis is not as useful as it seems to be, because the qualitative analysis cannot make situations comparable.

First of all, the analysis is not able to suggest if the positive impacts of a strategy can overweight its negative impacts. The impacts of every adaptive strategy are very wide. Usually the loss on one aspect turns out to be gains on others. Therefore, there is a strong need to bring the losses and gains together. For example, beach nourishment is an effective strategy but with very high construction costs. In order to nourish an eroded beach, the choice of the right type of sand is the first step. This is not just for aesthetic consideration, the wrong type of sand can be quickly eroded away or it may be filled with small particles that will leach into the water. Therefore, the dig and movement of right type of sand can be very costly. Accordingly to Trembanis and Pilkey (1998), the average cost per cubic yard of project in Gulf Coast is $5.94 in the year 1998. Considering the consumption of sand for even a small project can go easily up to millions of cubic yard. The cost for a beach nourishment project can bring huge economic costs. But beach nourishment can improve or at least maintain the aesthetic beauty of beaches. As a result, beach nourishment projects have potential to increase coastal property values which in turn can increase local tax bases. Therefore, there is a need for a standardized measure to compare the losses and gains of each strategy.

Secondly, different strategies are not comparable with only qualitative narratives. For those strategies with similar characteristics (advantages and disadvantages), it is hard to say which one is better on which aspect. For instance, structural protection, such as sea walls, and beach nourishment strategies are both associated with high cost. There is a need to quantify which one has higher cost. Comparison is much more complicated for the strategies with different characteristics. Therefore, there is a strong need for a measure to quantify and evaluate sea level rise adaptive strategies.

Among various measures, cost-benefit analysis is the most adopted tools to support decisions when discussing climate related threats with decision makers, since the empirical estimates of costs and benefits can serve as a key criterion for adaptive actions (U.S. EPA Office of Policy, Planning and Evaluation 1995; OECD 2008; Costa, Tekken & Kropp, 2009). Estimates of costs and benefits of climate change, including sea level rise, are usually employed to serve two major purposes. First of all, net benefits of certain adaptive strategies can be used as the criteria to select among competing ones. Such information has the potential to be of direct operational relevance at local level. Secondly, adaptation costs and benefits can inform decision makers on the scale and timing of investment, in other works, on how much and when to make investments. The application of cost-benefit analysis on sea level rise issues emerges very recently. In 2007, Tol (2007) employed cost-benefit analysis to compare the benefits of adaptation, dike building in particular, with the adaptation costs. The results show that the total costs of taking adaptive actions are much smaller than the potential losses and damages of sea level rise with no action (considered as benefits). However, only considering one adaptation strategy decreases the usefulness of this study. Later, Costa et al. (2009) developed a Dynamical Interactive Vulnerability Tool to calculate the benefits of normative protection target versus a business as usual scenario for European Union coastal states. Although it considers several strategies, their scope of analysis still focuses on direct gains and losses. Hinkel and his colleagues (2010) applied the DIVA model to assess cost efficiency of sea level rise adaptation in European Union under the A2 and B1 scenarios of the IPCC. They conclude that although adaptation, which focuses on sea wall in their study, is costly, it still can reduce the sea level rise impacts substantially. One most recent study is conducted by Yang et al. (2012) who apply typical cost-benefit analysis to adaptation actions to sea level rise in major vulnerable regions along the coast of China.

These studies exemplify preliminary efforts to quantify the costs and benefits of sea level rise, but they have some common drawbacks which diminish the values of their implications. First, these studies only focus on one or a few adaptive strategies. Building sea walls or dikes is the most straightforward strategy to cope with sea level rise. But it is not a solution that can work on various conditions since the protection structures come with high construction costs; the engineering work will damage natural ecosystems, especially fragile coastal wetlands; the sea wall construction that does not consider appearance will degrade the aesthetic beauty and will impact property values. Therefore, in practice different local situations should be matched with different strategies.

Second, the existing costs and benefits analysis only evaluate direct impacts. Sea level rise can result in both direct and indirect losses. Direct losses mainly come from inundation of properties and structures. Indirect losses include the losses of ecosystems services from coastal wetlands; impacts on housing market in vulnerable and surrounding areas; potential loss of labors since some susceptible property owners may choose to relocate; and the loss of services of infrastructures such as roads, utilities and medical services. In fact, indirect losses from sea level rise can bring much more economic costs than direct losses. Neglecting these indirect costs may significantly under-estimate the economic benefits of adaptation strategies, leading to the choice of an inferior adaptation strategy. For example, construction of sea walls will damage coastal wetlands' ecosystems. By not considering the indirect impacts on ecosystems, the economic losses of building sea walls will be greatly underestimated.

Third, existing studies do not take into consideration the timing issue of adaptation strategies. Sea level rise is a continuous but also slow process. It will take decades until the sea reach to the certain level that brings serious damages to coastal areas. Therefore, even local governments are aggressive enough to lead sea level rise adaptation, but not well planned ad-hoc responses to sea level rise will put people, property, and scarce financial resources at risk. Existing studies evaluate costs and benefits based only on fixed scenarios which assume an all-or-nothing action manner from one scenario period to the other. This does not make sense in real world. Thus, there is a need to identify the most cost-efficient time point to invest in sea level rise adaptation.

Fourth, existing discussions and studies on sea level rise adaptation planning do not provide location based guidance for local communities. The majority of the existing efforts to promote sea level rise adaptation only focus on providing a wide variety of options for local communities. With so many options, local decision makers feel confused and overwhelmed to choose appropriate strategies for specific locations. Tampa Bay Regional Planning Council is among the few agencies that map the recommended protection level for the coastal areas of Tampa Bay area, ranging from protection unlikely to protection almost certain (Tampa Bay Regional Planning Council, 2006). But focusing on only one strategy overlooks other options. Therefore, there is a need to help local communities develop a measure to assign appropriate strategies to specific locations.

This dissertation research aims to bridge the above gaps of existing studies and practices. Its major goal is to employ a cost-benefit analysis framework to quantify the costs and benefits of adaptation strategies in both built up and natural environment under different scenarios for Hillsborough County, Florida. Unlike prior cost-benefit analysis of the impacts of climate change especially sea-level rise, this study not only considers the direct costs of sea-level rise but also estimates the indirect costs over various action time and over space. The analysis results can uncover cost efficiency of different adaptation strategies and also help to decide the best time to take actions. It also proposes a location-based adaptation plan that assigns various adaptation strategies to appropriate locations.

1.3 Research Questions

In order to achieve the research goal, this dissertation aims to answer the following research questions:

1.3.1 Question 1

Whether adoption of sea level rise adaptive strategies is more cost-efficient than no action? If it is, which adaptive strategies are more cost-efficient than others?

This question plays an essential role in convincing people that taking adaptive action is worthwhile. Although the economic losses from sea level rise can be huge, the implementation of adaptation strategies can also be costly. As sea level rises, the majority of coastal areas will be vulnerable to various impacts. Therefore, the high adaptation cost will be enlarged. Therefore, there is a need to justify adaptive actions and prove that the cost of adaptation is still going to be paid off with even higher benefits that local communities can achieve. When calculating the benefits of adaptation, it is also important to consider the indirect economic impacts. Traditional cost-benefit analysis only takes direct monetary values into consideration. This can be misleading for those events, such as sea level rise, that have a wide range of impacts. This research will answer this question by applying cost-benefit analysis, considering both direct and indirect impacts, to evaluate sea level rise adaptation strategies.

Since there are already various sea level rise adaptation strategies, answers to this question can help prioritize these strategies based on their cost-efficiency. Since most local governments have very limited funding and resources, they cannot implement all strategies at the same time. The answers to this question will help them assign priority to each strategy to optimize their spending. Furthermore, different strategies have different advantages and disadvantages under distinctive scenarios

1.3.2 Question 2

How to better capture the economic impacts of sea level rise adaptation strategies by integrating both direct and indirect impacts into cost-benefit analysis?

Sea level rise are associated with a wide range of economic impacts. Some of the economic impacts are straightforward to be quantified, such as loss of valuable lands, and damages to coastal buildings. Some of the economic impacts cannot be captured by the market, like the value of travel time delay caused by broken road network. The quantification of indirect economic impacts is complicated and always challenging. This is the major reason why very few existing studies consider indirect economic impacts. This research answers this question by linking widely recognized analysis models to the identified economic variables.

Capturing the spatial pattern of some sea level rise impacts is another challenge when consider indirect economic impacts. Sea level rise has strong spatial characteristic in terms of its impacts on coastal areas. Areas close to beaches are more vulnerable than inland areas. The economic impacts tend to have strong spatial lag. Similar to time-series data, which shows time lag, areas are adjacent to each other will have similar impacts. These impacts are also related to their locations to coasts. The traditional cost-benefit analysis cannot account for these spatial characteristics. Spatial econometrics have potential to integrate the spatial effects, however, it needs to be revised to fit the topology of coastal areas. In spatial econometrics, spatial weighted matrix is the major tool to take spatial factors into count. This kind of matrix needs to reflect the neighboring characteristics of coastal areas since they will have fewer neighbors if traditional neighbor definition is used. The answer to this questions calls for theoretical innovations.

1.3.3 Question 3

What is the tipping point to implement adaptation strategies?

The tipping point is the critical point in an evolving situation that leads to a new and irreversible development. The concept of tipping point has numerous applications in different fields. Applying to sea level rise issues, tipping point is the moment when governments start to take actions to implement the proposed strategies and plans. More specifically, tipping point in this research is defined as a point in time when the total benefits of taking actions exceed the costs of adaptation. Sea level rise activists argue that the best time to take action and adapt to sea level rise is right now or, at least, the sooner the better (Johnson 2008; Parkinson 2009). But this is arguably the case since the money spent on sea level rise projects can also be invested anywhere else while still protects coastal areas in a timely manner. Therefore, there needs evidence to show, when considering temporal characteristics of both sea level rise and cash flows, what is tipping point to take adaptation actions.

1.4 Research Contribution

By answering the above research questions, this dissertation contributes to research and practice on sea level rise adaptation planning. Specifically, it makes contributions to the following knowledge on adaptation planning.

Researches in sea level rise adaptation planning have debated the economic impacts of sea level rise adaptation. A few existing literatures try to use cost benefit measure to justify the worthiness of adaptive actions. But focusing on only a few direct economic impacts, such as loss of population and GDP, these studies greatly underestimate sea level rise impacts. This research, instead, takes a comprehensive approach to consider both direct and indirect economic impacts on both built up and natural environment caused by sea level rise. Therefore, the analysis in this study better captures the full picture of sea level rise adaptation.

Furthermore, existing quantitative analysis of adaptation strategies focuses only on the protection strategy which is straightforward to be quantified. However, there are a large amount of options other than protection under discussion. Without a full analysis of these options, local communities are still confused to take further actions. This dissertation research categorizes adaptation strategies into 3 groups, each of which has 2 strategies to represent the group. Therefore, the analysis results provide a relatively comprehensive point of view to understand adaptation strategies.

Existing literatures also lack the study on appropriate action time to implement adaptation strategies. Sea level rise is a continuous but slow process. Existing studies do not address the timing issue of sea level rise adaptation. This research evaluates the benefits and costs of taking adaptive actions at three time points, including the year 2013, 2040 and 2060. The analysis results can provide evidence on deciding the most cost efficient time to adopt adaptation strategies.

In addition to the three academic discussions, this dissertation also provides practical guide for local communities. It proposes an adaptation plan that assigns each adaptation strategy to its appropriate locations based on the cost efficiency and action time point of each strategy. Although this research ties closely to existing literatures, both its academic and practical contributions highlight its importance and set it apart from traditional cost benefit analysis of adaptation strategies as well as adaptation planning for sea level rise.

1.5 Dissertation Structure

This dissertation research employs cost-benefit analysis framework to analyze the costs of 6 sea level rise adaptation strategies, and their economic impacts on 5 variables to evaluate the cost-efficiency and action time points of each strategy, based on which this research proposes an adaptation plan as a guide for local communities. The research is organized under 8 chapters in this dissertation.

The first chapter introduces research topic. It firstly provides background for studying sea level rise adaptation planning and identifying the research gaps from existing literatures and practices. This background introduction helps to justify the importance to analyze adaptation strategies from a cost-benefit point of view. Then it introduces the three major research questions that this dissertation aims to answer through its analysis. Finally, it presents the contribution of the research and the overall dissertation structure.

The second chapter following the introduction focuses on research design which provides a broad picture for the whole research. First, it introduces the logic flows that this research follows, to specify how this dissertation research is going to approach the research topic and to answer the three research questions. In other words, it introduces the measures in this research to quantify the costs and benefits of selected adaptation strategies in a general way. Then it describes the case study area that this research focuses on and justifies the representativeness of the selected case.

The third chapter reviews existing literatures and underlying theories of four major concepts. The literature review helps to summarize major sea level rise adaptation strategies for analysis; it also presents the sea level rise scenario that this research is based upon by reviewing the pros and cons of various sea level rise projections; a major part of literature review is to introduce the economic models that is employed in this research, including the theory and structure of spatial econometric model, and the economic variables that are integrated into the cost-benefit analysis framework.

The fourth and fifth chapters introduce the process and results of quantification of potential losses caused by sea level rise. The potential losses are defined as benefits of adopting adaptation strategies. The potential losses are linked to five economic variables including travel time delay, loss of damaged buildings, change of wetland ecosystem services, changes of land value and business revenues. The first three variables do not have spatial pattern. They are quantified through available modeling tools including FSUTMS-Cube, Hazus, and SLAMM. Their quantification process and results are presented in the fourth chapter. Changes of land value and business revenue have strong spatial pattern. Therefore, spatial econometric models are developed to quantify their value changes, which are presented in Chapter Five.

The sixth chapter introduces the quantification process and results of six sea level rise adaptation strategies. It defines three scenarios based on action time points, including the year 2013, 2040 and 2060. The presentation of each strategy starts from describing the method of quantification: the ways to quantify the unit value and unit changes. Then it presents the total costs of each strategy under three action time points.

The seventh chapter combines the benefits and costs obtained from the last three chapters to analyze the cost efficiency of adaptation from various perspectives. It first evaluates the cost efficiency of each single strategy by assuming the coastal areas are adopting only one strategy at a time. Then it analyzes the action time point for each strategy from a cost efficiency point of view. The cost efficiency and action time point analysis help to decide each strategy’s appropriate land uses. Linking each strategy to its appropriate land use proposes an adaptation plan that can guide the adaptation actions of local communities. Finally, this chapter conducts an uncertainty analysis to evaluate the cost efficiency of each strategy as well as the adaptation plan under different uncertainty levels.

The last chapter summarizes the results and findings to draw lessons that can contribute to existing knowledge on sea level rise adaptation planning. The lessons learned have potential to guide local communities to better adapt to the future. It also presents the limitations that further research is recommended to extend this research and continue to study this research area.

CHAPTER 2
RESEARCH DESIGN

This chapter presents research design of this dissertation. It firstly introduces the research flow, which draws a broad picture for the whole research. Then it describes the selected case study area, Hillsborough County in Florida. The description of case study area introduces the area and also justifies the representativeness of the selected area to study sea level rise adaptation. This chapter provides the foundation for the following chapters.

2.1 Research Framework

This research is a quantitative research which employs various models to quantify the costs and benefits of adaptation planning. The quantification of economic impacts of sea level rise adaptation strategies requires the development of mathematical models to evaluate selected strategies. Furthermore, this research is quantitative in nature since it collects numerical data. Data collection will also borrow measures from other fields such as ecology to quantify the variables. One example is to quantify the monetary value of ecosystem services. The lost functions of ecosystems can cause a chain effects which finally will result in economic losses. Only by weaving the losses into cost-benefit analysis by assigning them monetary values, we can truly capture this huge amount value changes. However, quantifying indirect economic impacts is always a challenging task. There is a need to employ the recent techniques and tools (such as SLAMM model) with innovation.

Figure 2-1 specifies the methodology and procedures employed to conduct this research. It also lists the major tools and techniques that are employed. The details are presented following the flow chart.

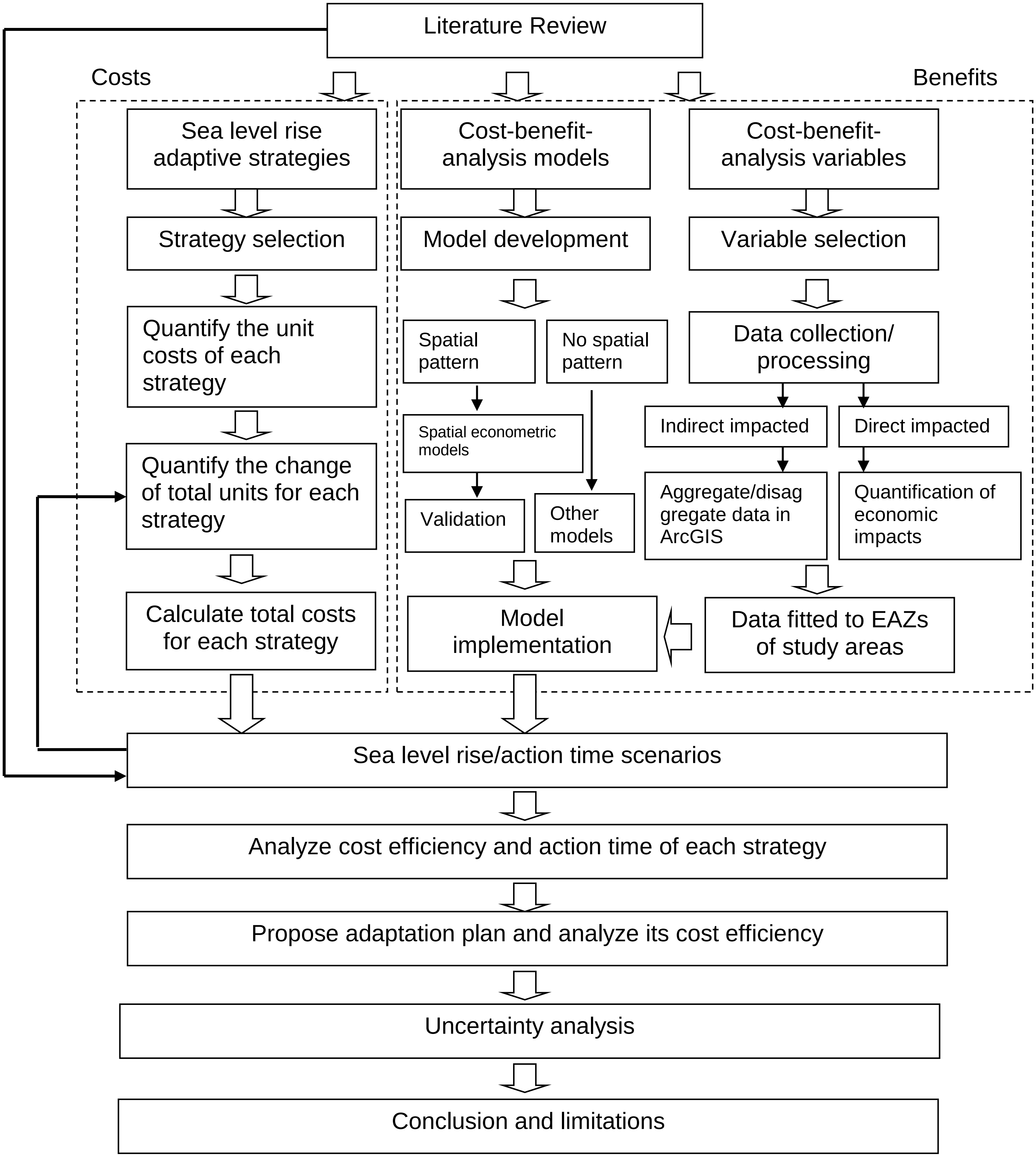


Figure 2-1. Research flow chart (Created by Author)

Figure 2-1 illustrates the flow of this research. This research starts with literature review on sea level rise and cost-benefit analysis framework. Specifically, literature review on sea level rise includes two parts. The first part focuses on identifying and selecting commonly adopted sea level rise adaptation strategies. The selected strategies will be analyzed by cost-benefit analysis models. The other part concerns sea level rise projections. Future sea level rise projections vary from study to study because the projections heavily depend on a wide range of assumptions on future greenhouse gas emissions, changes in people’s behavior that may mitigate climate change impacts. This research will base on existing projections instead of developing models to estimate future sea levels itself.

Literature review on cost-benefit analysis also includes two parts. The first part is the review on model structure. The models to carry cost benefit analysis range from simple linear model to complicated polynomial models. Because of the characteristics of sea level rise issues as addressed in Chapter 1, spatial econometric model can better capture the spatial pattern of economic impacts of sea level rise. Thus, the modeling structure will focus on econometric models with spatial component added. The other part of literature reviews on cost-benefit analysis concerns variables to be analyzed. However, analysis models need to abstract real world and only consider those major impacts that are easier to be quantified but can still represent the real world. Literature reviews will help to identify these major variables that will be plugged into the final spatial econometric models.

Although literature review separates review on sea level rise from review on cost-benefit analysis, the whole research integrates cost-benefit analysis into sea level rise literatures. The major part of this research focuses on employing cost-benefit analysis to evaluate sea level rise adaptation, which includes two modules, the cost module and the benefit module.

Generally speaking, this research considers benefits as potential losses that can be saved with adoption of certain adaptation strategies. In the modeling framework, benefits are those variables that are identified to represent the economic impacts of sea level rise. After economic variable selection, the data collection and processing will be different for directly impacted variables and indirectly impacted variables. Directly-impacted variables measure direct economic loss from sea level rise, such as loss of land and infrastructures. Data collection of these variables is straightforward since it is based on secondary data already made available to the public, such as land value, and census block data. The challenge here is to aggregate or disaggregate the data from different statistical scales to fit the unit of case study areas, namely, the 39 Economic Analysis Zones (EAZs). This process becomes easier with employment of Geographic Information System (GIS) techniques. Indirectly impacted variables refer to the economic losses that cannot be captured by the market, such as the value of travel time delay, and the value of coastal ecosystems. Quantification of indirect economic impacts is much more challenging than quantifying direct impacts, since the quantification required both the unit value and unit change. All the variables that fitted to the units of study area will be plugged into analysis models developed in the paralleling step.

Model development is also divided into two independent processes based on the spatial characteristics of the variables. For the variables, including land value and business revenue, with strong spatial pattern, spatial econometric models are developed to capture the spatial interaction between surrounding areas; for variables without showing spatial pattern, such as travel time delay, ecosystem services and building damages, model development focuses on integrating data into available models that are widely recognized as effective tool to analyze the variables.

The cost module tries to quantify the costs of sea level rise adaptation strategies. Literature reviews helps to identify major sea level rise adaptation strategies which are widely adopted. The intense literature reviews further uncover how existing literatures and studies quantify the unit cost for each strategy, such as the monetary cost for constructing 1-linear-footage sea wall. The pre-defined sea level rise scenarios are integrated to the quantification of unit changes of each adaptation strategy, such as the total area changes of coastal wetlands.

The total benefits and costs of adaptation strategies are linked together under three scenarios based on action times. The analysis firstly assumes that each strategy is applied to the whole coast line to exclude the impacts of different strategies. The cost benefit analysis evaluates the cost efficiency of each strategy. Then it analyzes the best time points to implement the strategies. The cost efficiency and action time fit each strategy to a certain land uses, so linking the strategy to its fitted land use types help propose a location-based adaptation plan. An uncertainty analysis is then conducted to incorporate the impacts of the uncertainty on sea level rise projection into the study. Finally, this research will conclude by summarizing all the results and findings as well as presenting research limitations to further polish this research. This framework guides the whole research process. The structure of this dissertation is also consistent with this logical flow.

2.2 Case Study

The case study area of this research is Hillsborough County, Florida, which surrounds Tampa Bay and is a part of Tampa Bay region. As figure 2-2 shows Hillsborough County is located in southwest of Florida. According to the 2010 census, the county has a total of population as 1,229,226. It has a total area of 1,266.22 square miles, of which 1,050.91 square miles (about 83%) is land and 215.31 square miles (about 17%) is water. There is approximately 918.38 miles of shoreline on Tampa Bay. The County boarders Golf of Mexico on the west. It is vulnerable to sea level rise not only because it has a long shore line, it is also seriously affected by the tidal influence of Tampa Bay. Furthermore, the tidally-influenced rivers increase the vulnerability of the area in terms of sea level rise (Tampa Bay Regional Planning Council, 2006).

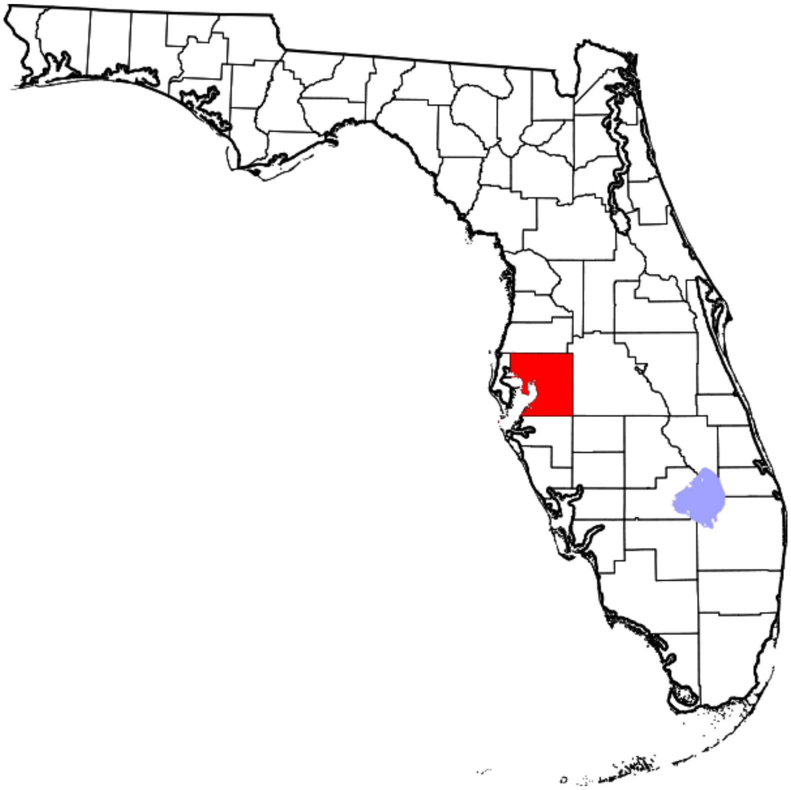


Figure 2-2. Geographic location of Hillsborough County (Source: http://en.wikipedia.org/wiki/Hillsborough_County,_Florida)

Hillsborough County as a case study area is a good representative to study sea level rise adaptation. First of all, the coastal areas of the County has a wide variety of land uses, especially densely populated built environment and natural ecosystems, such as salt marsh and mangrove wetlands. The county seat of Hillsborough is the City of Tampa, which is the third largest city in Florida. Tampa is densely populated with strong economic growth. The concentration of both population and business is within its coastal areas. Therefore, Tampa has a strong motivation to protect its built environment. In addition, the County has valuable natural environments and habitats. It has a large amount of wetlands, which provide various ecosystem services, along its coast. Secondly, the coastal areas of Hillsborough County experience frequent storm surges, and a few major hurricanes. Therefore, Hillsborough County represents a good case to study sea level rise adaptation. The vulnerability to sea level has caught attention of local governments. Several local government agencies have started to study sea level rise impacts and make adaptation plans, such as deciding the degree of projection for coastal areas (Table 2-1).

Table 2-1. Vulnerable and protected lands of Hillsborough County to sea level rise

Type	Acreage
No protection	815
Protection unlikely	4809
Protection reasonably likely	6
Protection almost certain	47736
Wetlands	23611
Water	5638
Totals	82615
Total lands subject to sea level rise	82616

Note: table generated from Table 5 and table 6 in report: Sea Level Rise in Tampa Bay Region (Source: Tampa Bay Regional Planning Council, 2006).

Based on Table 2-1, the majority of vulnerable lands to sea level rise are given a protection scenario of “almost certain”. According to the future land use analysis done by Tampa Bay Regional Planning Council (2006), sea level rise vulnerable areas of Hillsborough County are already developed or have been identified as locations for development as residential or industrial lands in the near future. Some exceptions to this are the areas in the southern portion of the County which are currently held as conservation lands. Therefore, Hillsborough County can serve as a good case to evaluate proposed sea level rise adaptive strategies.

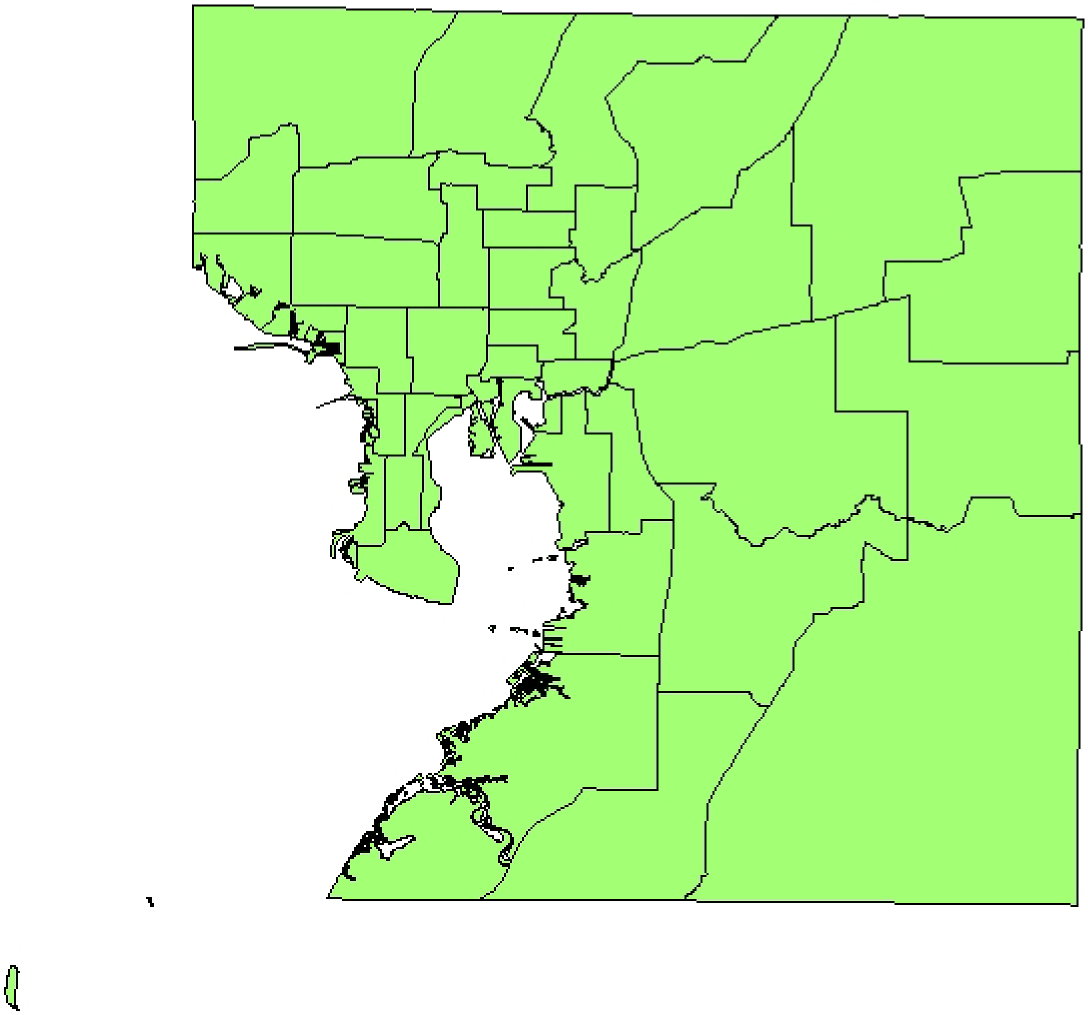


Figure 2-3. Economic analysis zones of Hillsborough County (Created by Author)

Figure 2-3 shows the units of analysis for this research. The delineation of Hillsborough County is based on Evacuation Analysis Zone created by Tampa Bay Regional Planning Council that categorizes Hillsborough County into sub-areas based on their vulnerability to Hurricanes and flooding. This delineation is employed because hurricane and flooding is very much similar to sea level rise impacts among various extreme weather events. This is so because, as Mcinnes et al (2003) points out, as sea level rises, the frequency and intensity of storm tides will significantly increase as well. The most recent version of Evacuation Analysis Zone delineate Hillsborough County into 39 zones that will be used to aggregate data in this research.

In summary, this chapter describes the research framework and case study area which lay foundation for the whole research. The following chapters are consistent with the presentation of this framework by firstly reviewing major theories (Chapter 3), and then introducing the quantification of benefits (Chapter 4, and 5) and costs (Chapter 6) of adaptation strategies, followed by the combination of costs and benefits to evaluate cost efficiency of adaptation (Chapter 7).

CHAPTER 3
LITERATURE REVIEWS

This chapter reviews major concepts and theories associated with this study. Firstly, it presents the conceptual framework which organizes the reviewed concepts and theories. Then it present literature reviews on commonly adopted sea level rise adaptation strategies, sea level rise scenarios, spatial econometric model and the selection of economic variables. Existing literatures are linked to this research by identifying how the same topics are approached in this research.

3.1 Conceptual Framework

This research involves a wide range of concepts. Some of these concepts are the key to conduct research; some of them are not as important as major concepts. For each concept, there are different ways to approach it. Therefore, we need a framework to organize the major concepts and link them together to show how various concepts work together to guide this research.

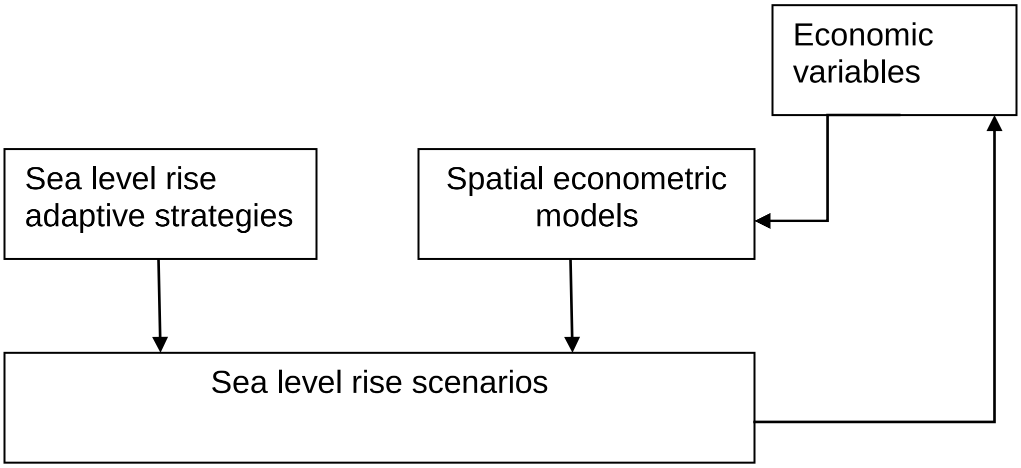


Figure 3-1. Conceptual framework of existing literatures (Created by Author)

According to the above conceptual framework, the literature review of this study involves four major concepts which will be discussed in detail in this chapter. These four concepts coincide with the four literature review topics stated in the research design section of Chapter 2. The first major concept is sea level rise adaptation strategy. Sea level rise adaptation strategies are sets of development strategies that aim to guide sea level rise adaptation. While it is critical to reduce the global greenhouse gas emissions to mitigate the impacts of sea level rise, we must be realistic that the sea level is still going to rise even in an intensified pace. Therefore, we need to adopt adaptation strategies. The literature review on sea level rise adaptation includes both academic work and planning documents since this research needs to identify and evaluate the most commonly adopted strategies. The selected strategies will be evaluated by various models, including econometric models under various sea level rise scenarios.

The second major concept is sea level rise scenario. Sea level rise scenario is the projected sea level at a certain time period based on a set of assumptions. As stated earlier, different studies project different results. The purpose of literature review on this concept is to identify the most appropriate sea level rise scenarios that work for the case study area. The identified sea level rise scenario will serve as the foundation based on which the costs and benefits can be calculated. Furthermore, sea level rise scenarios will also help to quantify economic variables.

The third concept is spatial econometric model that will be employed to evaluate the cost efficiency of each strategy. Spatial econometric model is a “collection of techniques that deal with the peculiarities caused by space in the statistical analysis of regional science models (Anselin 1988, p7)”. Spatial econometric models can capture the effects of spatial dependence and spatial heterogeneity which are ignored in traditional econometric models (Anselin 1988; Anselin 2006; Baltagi & Arbia, 2006;

LeSage & Pace, 2010). Therefore, spatial econometric models have the potential to capture and better represent the spatial effects of sea level rise. The literature review on spatial econometric models will explore the current research status on the modeling framework and empirical application so that appropriate modeling structure will be identified. The selected modeling framework will serve as the base for model development in this study.

Different from other three concepts, identification of economic variable is not actually a concept. But rather, it is a set of literature reviews that aim to identify the vulnerable economic sectors. The impacts of sea level rise can range from each aspect of human society as well as natural systems. Some of the impacts can bring direct economic losses. Some others can cause indirect losses that need to be quantified in monetary terms. The literature reviews on economic variables will distinguish between direct and indirect economic impacts. Furthermore, since the models cannot capture all the impacts, the literature review will help to select the major economic impacts that can represent the whole picture.

3.2 Sea Level Rise Adaptation Strategies

3.2.1 Case Studies

The purpose of the case study on adaptation strategies is to identify sea level rise the strategies which are the most commonly adopted in existing literatures. These strategies are analyzed to select the ones that fit this research. The case study covers two levels, the state and local level, to compare the differences among the strategies adopted at different levels. Case study focuses on Florida, California, and Maryland which are widely recognized as the leaders in adaptive planning for sea level rise. Each case study includes two sections: the first one discusses sea level rise adaptation strategies at the state level; the second section introduces strategies at the local level (city, or county level) within the same state. As Figure 3-1 shows, the selected cases cover three coastal states including the State of Maryland, California and Florida.

Figure 3-2. Case study areas (Created by Author)

3.2.1.1 Case study in Maryland

Worcester County, Maryland: Worcester County Department of Comprehensive Planning asked CSA International, Inc. to prepare its Sea Level Rise Response Strategy in 2008. The report projects several sea level rise scenarios and their impacts on Worcester County coastal areas. It proposes various adaptation strategies as potential response options for the county. The strategies are categorized into three groups: protection, retreat and accommodation.

1. Protection: Protection strategies include both structural protection and non-structural projection. Non-structural protection techniques and construction projects include beach nourishment and the construction of sand dunes and marshes. Beach nourishment is believed to be one of the most effective non-structural protection techniques to respond to sea level rise. Non-structural protection works best in low to moderate erosion shore lines. In other words, these strategies are not designed as long-term solutions. In comparison, structural projection techniques run for long-term sea level rise adaptation.

Structural protection refers to the engineering techniques and construction projects that aim to protect the shoreline by holding back the sea. These techniques include bulkheads, seawalls, riprap, dikes, breakwaters, sills, and revetments. Although the structural projection constructions can withstand sea level rise for a long time, the cost of construction is very high. In addition, environmental degradation may occur by including artificial, non-organic materials. The reports propose the adoption of the protection techniques in a preferred order, beginning with the non-structural techniques that closely resemble living shorelines, and later integrating structural erosion control projects when the sea level continues to rise above a certain level.

2. Accommodation: Accommodation is a response strategy recognizing retreat from sea level rise inundation zones as inevitable, but works to prolong the life of existing development and set rules for eventual retreat (Worcester DCP, 2008). The accommodation is considered most appropriate when protection strategies are not cost effective and inundation is not threatening the areas right away. In other words, accommodation allows for the use of vulnerable lands to continue, but that do not attempt to prevent flooding or inundation with shoreline protection.

3. Retreat: Retreat involves the relocation of people and ecosystem. Generally speaking, retreat enables sea level inundate in a natural way. It aims to mitigate the impacts of the inundation. The report argues that the retreat strategies should not be used solely, since the vulnerable inundation areas are so large that that relocation of the impacted people and ecosystems are improbable considering the costs and the current legal framework. Therefore, the retreat strategies should be utilized in combination with other adaptation strategies.

More specifically, the report lists the following detailed strategies for sea level rise adaptation:

1. Shore armoring: bulkhead, sea wall
2. Shore nourishment: plantation
3. Tidal barriers
4. Rolling easement
5. Elevation and flood proofing retrofits
6. Restrictions on Septic Tank and Hazardous Materials Storage
7. Property Acquisition and Relocation Programs
8. Relocation
9. Restrictions on Shoreline Protection
10. Redevelopment Restrictions

The State of Maryland: Maryland considers adaptation planning as crucial to its ability to achieve sustainability development. Since they envision that without actions, the state will increase the risk and harm from potential impacts. Planners and legislators must realize that the implementation of measures to mitigate climate change and sea-level rise impacts associated with erosion, flooding, and inundation of low-lying lands is imperative to sustainable management, as well as protection of Maryland’s coastal resources and communities. To facilitate adaptation planning, the Adaptation and Response Working Group was established, the stakeholders of which come across the state chaired by the Maryland Department of Natural Resource and the Department of Planning. Its executive order calls for an initial focus on sea-level rise and coastal hazards. In 2008, the Group published a report to specify priority policy recommendations (Maryland Adaptation and Response Working Group, 2008).

The report detailed the adaptation strategy recommendations at the state level.

1. Integrated planning: require the integration of coastal erosion, coastal storm, and sea level rise adaptation and response planning strategies into existing state and local policies and programs
2. Adaptation of vulnerable coastal infrastructure: develop and implement state and local adaptation policies (i.e. protect, retreat, and abandon) for vulnerable public and private sector infrastructure.
3. Building code revisions and infrastructure design standards: strengthen building codes and construction techniques for new infrastructure and buildings in vulnerable coastal areas.
4. Resource-based industry economic initiative: develop and implement long-range plans to minimize the economic impacts of sea level rise to natural resource-based industries.
5. Climate change insurance advisory committee: establish an independent Blue Ribbon Advisory Committee to advise the state of the risks that climate change poses to the availability and affordability of insurance.
6. Disclosure: Develop a Maryland Sea-Level Rise Disclosure and Advisory Statement to inform prospective coastal property purchasers of the potential impacts that climate change and sea-level rise may pose to a particular piece of property.
7. Green economic development initiative: Recruit, foster, and promote market opportunities related to climate change adaptation and response.
8. Inter-agency coordination: Strengthen coordination and management across agencies responsible for human health and safety.
9. Health impact assessments: Conduct health impact assessments to evaluate the public health consequences of climate change and projects and/or policies related to sea-level rise.
10. Vector-borne surveillance and control: Develop a coordinated plan to assure adequacy of vector-borne surveillance and control programs.
11. Natural resource protection areas: Identify high priority protection areas and strategically and cost-effectively direct protection and restoration actions.
12. Forest and wetland protection: Develop and implement a package of appropriate regulations, financial incentives, and educational, outreach, and enforcement

approaches to retain and expand forests and wetlands in areas suitable for long-term survival.

13. Shoreline and buffer area management: Promote and support sustainable shoreline and buffer area management practices.

14. Integrated observation systems: Strengthen federal, state, local, and regional observation systems to improve the detection of biological, physical, and chemical responses to climate change and sea-level rise.

15. GIS mapping, modeling, and monitoring: Update and maintain state-wide sea-level rise mapping, modeling, and monitoring products.

16. Public awareness, outreach, training, and capacity building: Utilize new and existing educational, outreach, training, and capacity building programs to disseminate information and resources related to climate change and sea-level rise.

17. Local government planning guidance: Develop state-wide sea-level rise planning guidance to advice adaptation and response planning at the local level.

18. Adaptation-Stat: Develop and implement a system of performance measures to track Maryland’s success at reducing its vulnerability to climate change and sea-level rise.

19. Future adaptation strategy development: Pursue the development of adaptation strategies to reduce climate change vulnerability among affected sectors, including agriculture, forestry, water resources, aquatic and terrestrial ecosystems, and human health.

3.2.1.2 Case study in California

San Francisco, California: The San Francisco Planning and Urban Research Association (SPUR) has coordinated with multiple agencies to create a sustainable long-range plan for San Francisco’s shoreline. The planning product is called Ocean Beach Master Plan (SPUR et al., 2012). The plan proposed 6 major adaptation strategies specific to adapt its shorelines to rising sea level:

1. Reroute great highway behind the zoo via sloat and skyline. The plan proposes to close the Great Highway South of Sloat Boulevard, replace with a coastal trail; reconfigure Sloat Boulevard and key intersections to create a safer, more efficient street; consolidate street parking, the L-Taraval terminus, and bicycle access along the south side of Sloat; and reconfigure Zoo’s parking lot for access via Skyline and Zoo road

2. Introduce a multi-purpose coastal protection/ restoration/access system. The plan incrementally dismantle the Great Highway and parking lots, allow erosion to proceed inland; protect the Lake Merced Tunnel in place with a gradient of elements; allow storm surges to wash over the Tunnel and dissipate toward higher ground; restore and revegetate the surface to allow recreational and ecological functions
3. Reduce the width of great highway to provide amenities / managed retreat. The plan proposes to narrow the Great Highway from 4 lanes to 2 South of Lincoln; use the current Southbound lanes for parking pockets, restrooms, signage etc.; introduce a multi-use promenade west of the road; allow dunes to migrate inland over the road and transport box between amenities.
4. Middle reach beach dune restoration. Sand nourishment via Army Corps of Engineers along southern end of Middle Reach. Phased native dune restoration in key locations: especially at Lincoln, Vicente. Sand ladders and modular boardwalks provide access while limiting impact.
5. Better connection between golden gate park & beach. The plan proposes to tighten and reconfigure O'Shaughnessy Seawall parking lot to improve pedestrian conditions, bike access and traffic circulation; introduce permeable paving, amenities, and appropriate vegetation to create a more welcoming, attractive space; retain events capacity and historic character.
6. Bicycle + pedestrian improvements north of balboa. It is proposed to narrow Great Highway and Point Lobos Avenue (from 4 to 2 lanes); and to introduce physically separated bikeway with connections to Land's End and beyond.

The State of California: The discussion of adaptation strategies for sea level rise in California can date back to 2001 when the state Coastal Commissions published a report to estimate the impacts of sea level rise on California and propose various strategies as responses to mitigate the impacts. The strategies were categorized into five groups: hard engineering, soft engineering, accommodation, retreat and planning and regulation responses (California Coastal Commission, 2001). The Commission considers these strategies in order to fight against rising sea levels.

1. Hard engineering: Hard engineering refers to the hard structures separating the ocean and the property that is being threatened. The adoption of hard engineering includes the fortification of existing structures and construction of new sea walls, bulkheads, revetments, breakwaters, and levees. This strategy is similar to the structural protection strategy in Worcester County, Maryland.

2. Soft engineering: Soft engineering strategy is similar to the non-structural protection strategy in Worcester County. It refers to beach or dune nourishment or the creation of perched beaches. The Commission also considers soft engineering as a short-term effective strategy. However, the single beach nourishment is not a permanent solution for rising sea level.

3. Accommodation: Accommodation is the adaption to gradual changes. The vulnerable structures can be elevated so they will not be inundated. Islands and spits can also be raised to keep pace with the rising sea levels. Concerning agricultural production, accommodation can include the change of vegetation type so that new plants can withstand the rising salt level. Accommodation is neither a one-time solution. It requires continued efforts to effectively deal with rising sea levels to meeting the ongoing conditions.

4. Retreat: Retreat is considered as the final response. Retreat strategy is more effective in wetlands preservation, and the protection of developments or movable property. The state already had some experience in relocating some vulnerable or damaged properties and facilities after extreme weather events, such as EI Nino storms. As the coastal erosions become more severe in the future, this strategy will become more pervasive.

5. Planning and regulation responses: This strategy is more policy oriented than the others. New regulations and policies would be developed to adapt to sea level rise. Some of the regulations can include: requirement of new developments to setback to assure site stability for foreseeable future conditions, the establishment of buffer areas surrounding wetlands, notification of vulnerable property owners. The new regulations can also encourage the research that identify hazards, evaluate impacts and propose new solutions.

After that, more state agencies joined the efforts to work on sea level rise adaptation planning, especially after Governor Schwarzenegger signed Executive Order S-13-08 to create statewide consistency in planning for sea level rise on November 14, 2008. In order to achieve the statewide consistency mentioned in the Order, more attention being paid to the policy and regulation oriented strategies. California Sea-Level Rise Task Force published its guidelines to facilitate the planning process for sea level rise. The major strategies are listed below (California Sea-Level Rise Task Force, 2010):

1. Use the ranges of SLR presented in the December 2009 Proceedings of National Academy of Sciences publication by Vermeer and Rahmstorf 3 ("Vermeer and Rahmstorf publication") as a starting place and select SLR values based on agency and context ‐ specific considerations of risk tolerance and adaptive capacity.
2. Consider timeframes, adaptive capacity, and risk tolerance when selecting estimates of SLR.
3. Coordinate with other state agencies when selecting values of SLR and, where appropriate and feasible, use the same projections of sea ‐ level rise.
4. Future SLR projections should not be based on linear extrapolation of historic sea level observations.
5. Consider trends in relative local mean sea level.
6. Consider storms and other extreme events.
7. Consider changing shorelines

3.2.1.3 Case study in Florida

Tampa Bay Region, Florida: Tampa Bay Regional Planning Council (TBRPC) is an active regional planning agency involved in sea level rise adaptive planning. It distributed a document in 2006 titled Sea Level Rise in the Tampa Bay Region, which provides the evaluation of potential sea level rise impacts and the existing efforts to adapt to foreseeable sea level rises. The region includes four counties, including Hillsborough County, Manatee County, Pasco County and Pinellas County. The report summarized the adaptive strategies these four counties have adopted. These strategies include:

1. Protect wetlands and continue to seek to achieve a measurable annual increase in restored tidal wetland acreage through the restoration of degraded natural wetlands.
2. Stabilize man-made beaches prone to erosional problems and only permit the development of artificial beaches in environmentally-acceptable areas.
3. Development on residential centers vulnerable to sea level rise should be limited to those areas planned to adapt to sea level rises with adequate evacuation capability and the ability to stand severe storms.
4. Protect historical resources.
5. Limit expending on vulnerable facilities and infrastructures to sea level rise.
6. Direct population and development outside the Coastal Storm Vulnerability Area.
7. Protect, enhance and restore beach and dune areas by Beach Enhancement Program and construction standards and regulations.
8. Implement land use criteria for the coastal planning area which prioritizes the siting and development of water-dependent and other shoreline uses.
9. Increase public access to the beaches and shorelines through acquisition, development, and expansion of facilities.

State of Florida: Florida is one of the most vulnerable coastal states to rising sea levels. In Florida, the impacts of sea level rise are already visible, such as the beach erosion in Miami Beach. As a result, unlike most other coastal states, where sea level adaptive planning is still under discussion, Florida has already initiated several state programs which put adaptation strategies into practice. These legislative efforts include Coastal Construction Line Program, the Beach Erosion Control Program, Coastal Building Zone and Strategic Beach Management Plans (The Florida Department of Environmental Protection, 2006).

Coastal Construction Line Program aims to protect Florida's beach and dune system from irresponsible construction that put damage on dune system. The Program enables local governments to apply strict design and construction criteria within coastal lines. The lines delineated in the Program gives the State authority to regulate construction projects. Coastal Building Zone program also aims to protect beach and dune system by regulating construction programs along coastal lines. Local governments enforce this program by incorporating it into their building codes. These programs closely relate to sea level rise adaptation since they provide legislation foundation for sea level rise planning and regulation.

Beach Erosion Control Program implements the recommendations from Florida Department of Environmental Protection. The main purpose of this program is to coordinate the efforts from different levels of governments. The most effective tool this program adopts is its ability to offer financial assistance to local efforts aiming to protect and preserve their shorelines. The assistance can be up to half of the project costs. Beach Erosion and Control Program is also authorized to develop and update the Strategic Beach Management Plan, which involves comprehensive and long-term state efforts for erosion control, beach restoration, and nourishment.

If we relate back to the categorization of adaptive strategies used by IPCC, California and Maryland, the state legislature efforts of Florida focus on protection techniques. Actually, there are also discussions on the planned retreat and accommodation strategies (Deyle, 2007; Parkinson, 2009). But these discussions are not in detail.

3.2.2 Strategies Selection

3.2.2.1 Strategy framework

Strategy framework (Figure 3-3) of this study is based on case study in the previous section. Sea level rise adaptation strategies are categorized into two groups: the hard strategies and soft strategies. Hard strategies refer to the engineering techniques, and construction projects that physically change the built up environment. Soft strategies, on the other hand, refer to the policy-oriented tools that regulate and manage coastal areas.

To be consistent to the commonly adopted categorization as identified through case study, hard strategies are further categorized into three groups: protection, retreat and accommodation (Deyle et al, 2007). Soft strategies include planning tools, regulation policies and financial incentives that support the implementation of hard strategies.

Our study will evaluate adaptation strategies from economic perspective. Therefore, the strategies for analysis need to be quantifiable. So in terms of cost-benefit analysis, this study focuses on hard strategies. Then, the soft strategies will be matched to hard ones as a guideline toolkit helping local planners and planning agencies implement those hard strategies.

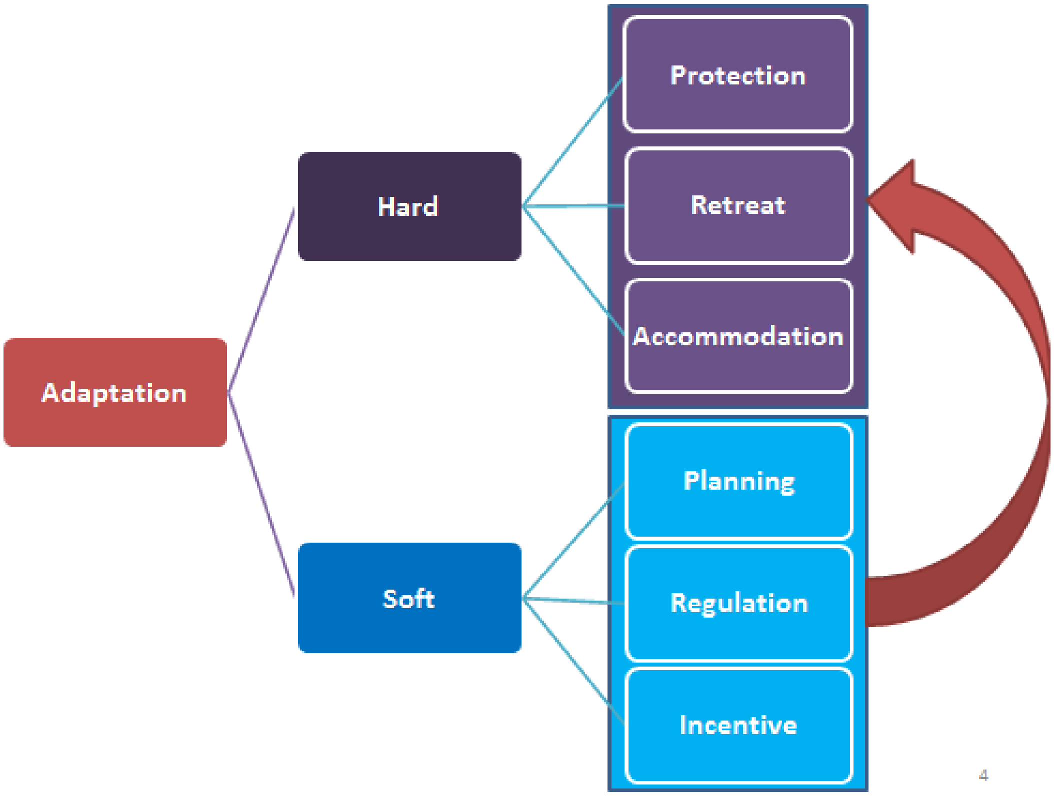


Figure 3-3. Strategy framework (Created by Author)

3.2.2.2 Strategies for cost-benefit analysis

Based on case studies, six SLR adaptation strategies are identified as commonly adopted strategies which will be evaluated by cost-benefit analysis. The strategies are categorized into three groups as presented in the above framework:

1. Protection:
    - Build seawalls and other structural constructions
    - Build up marsh areas and non-structural shore protection techniques
2. Retreat
    - Avoid building new structures and repairing damaged structures
    - Purchase land at risk of sea level risk and frequently flooded properties
3. Accommodation
    - Elevate buildings and structures at risk
    - Employ rolling easement

Strategy 1: Build seawalls, bulkheads, or other structural constructions to protect shoreline. Structural protection, or shoreline armoring, includes any attempt to stabilize the shore through “hard” erosion control techniques, such as building seawalls, bulkheads or other structural protection projects.

Strategy 2: Apply non-structural shore protection techniques, which include beach nourishment and the building up of sand dunes and marshes. These erosion control techniques aim to protect shoreline with natural materials to decrease environmental impacts. Typically, these techniques employ beach restoration and re-vegetation with natural hard structures, such as sand and stones.

Strategy 3: Avoid building new structures or redeveloping damaged structures in areas at risk: This strategy is the retreat response for sea level rise. That is, employing policies and zoning ordinances to avoid further development in these vulnerable areas to minimize risks and prepare for an eventual retreat.

Strategy4. Purchase land/properties at risk of sea level rise and frequent floods. This strategy is a straightforward retreat response. The purchase is a typical property acquisition strategy, which asks local government to determine the most vulnerable properties and raise funds to purchase the property and assist the owners at risk to relocate. The acquired property can then be used for conservation or recreation purposes.

Strategy 5. Elevate buildings/structures at risk. As sea level rises, the safety concern will leave vulnerable houses in storm surge zones less appropriate for occupation. The storm surge flooding will also disable the safe use of some infrastructures before they are finally inundated. These vulnerable buildings and structures can be elevated or lifted to continue their occupation. Piers, posts, columns, or pilings can be used on frame, veneer, basement and foundations based on the types of structures and building techniques.

Strategy 6. Employ rolling easement policy to accommodate rising sea level. This strategy refers to regulations or policies prohibiting shore protection so that wetlands, beaches, barrier islands can naturally move inland. It allows the current use of buildings/structures to continue. But after a set period of time or the footprint of the buildings/structures is below mean high tide, the property will be removed to give way for nature otherwise the State may charge rent for continued occupation.

3.3 Sea Level Rise Projections

Sea level rise projection is not the main focus of this research. Therefore, sea level rise projection in this study relies entirely on climate change science published by external research. The projection of sea level rise depends on the historical sea level record as well as mathematical models that simulate sea level rise process.

The tidal gauge stations are widely distributed around the world for a long time. Therefore, sea levels have been well recorded. According to IPCC (2007), in the past 20th century, the global sea level increased in a long term in an average rate of about 1.7mm/year to 3.1mm/year for the period 1993 to 2003. In terms of local sea level record, the closest tidal gauge station with long time service near Hillsborough County is located in St Petersburg, Florida. According to Penland (1990), from 1940 to 1970s, data collected from the St. Petersburg tide gauge station near Tampa Bay yield an average sea level growth rate of 2.4mm/year (Figure 3-4). This historical average sea level growth rate is still being used today.

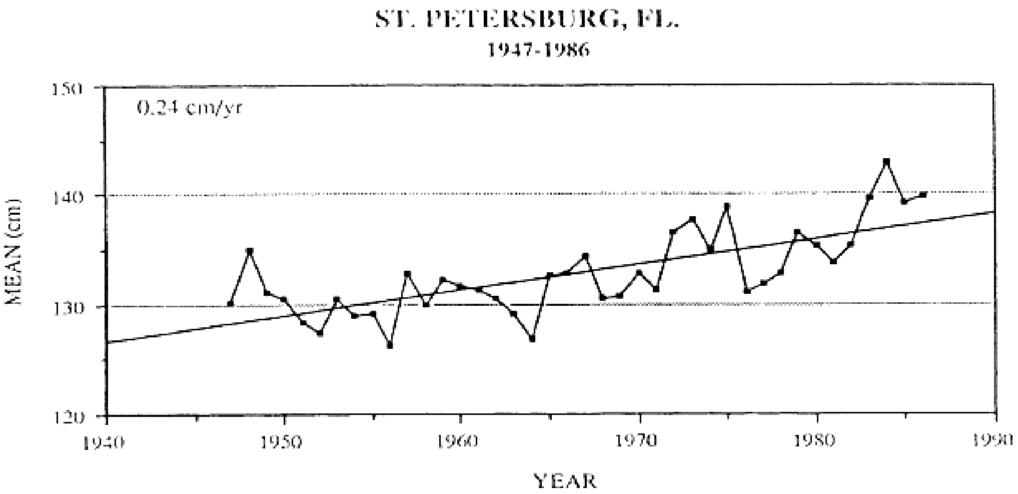


Figure 3-4. Historical sea Level rise growth rate in St Petersburg, FL (Source: Penland, 1990, p 331)

The projection of sea level rise incorporates historical sea level record into a range of mathematical models. However, development of projection models is a scientific challenge since, firstly, existing knowledge on the geological process of sea level rise is limited. Due to uncertainty in "paleo water depth of sea level indicators, radiocarbon chronology, postglacial isostatic adjustment, and other processes affecting vertical position of former shorelines produces scatter in RSL curves" (Cronin et al., 2007, p 323), our knowledge of sea level rise during periods of rapid glacial decay is limited. Therefore, despite decades of study, the results of sea level rise studies in the Gulf of Mexico/Florida region is still conflicting. Some studies suggest progressive submergence with a decelerating rate during the past 5000 years (Scholl et al, 1969), while the others show high sea level during the middle of the Holocene (Blum et al, 2001; Balsillie & Donoghue, 2004) (Figure 3-5). This discrepancy is the representation of the uncertainty surrounding Holocene sea level and ice volume history in general (Cronin et al., 2007), and due to this uncertainty there is no consensus reached towards the future long term trend of sea level rise.

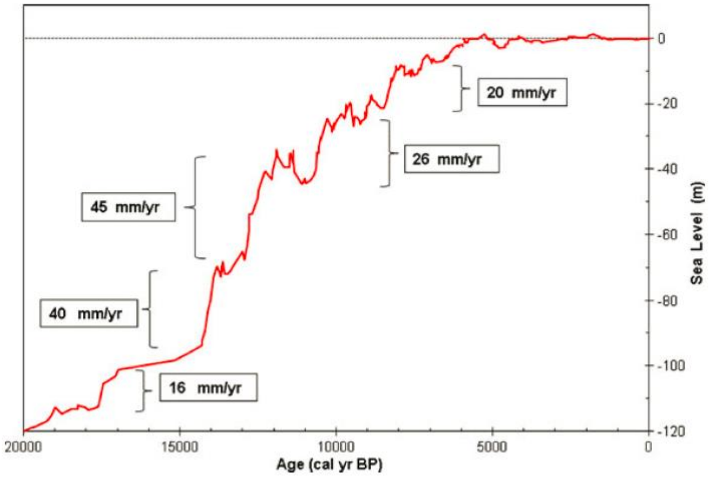


Figure 3-5. Sea Level history for the northern Gulf of Mexico since the last glacial maximum (Source: Donoghue, 2011, p 21)

Furthermore, different model frameworks heavily depend on different, while sometimes conflicting, sets of assumptions, especially the level of greenhouse gas emissions. This adds uncertainty to sea level projection. EPA (1995) provide a suggested procedure for estimating sea level rise at a specific location using the formula: “local(t)=normalized(t) + (t-1990)*trend”, t representing the calendar year. 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). Using these historical data, combined with EPA’s suggested procedure, Tampa Bay Regional Planning Council (2006) projected that there is a 50% probability that average global sea levels will rise 24cm by 2050, and 50mm by 2100.

As already presented in the first chapter, sea level rise projection is a case by case study since the projection models heavily depend on different sets of assumptions, But even the same model will project different sea levels worldwide since the factors, that drive sea level to rise, distribute unequally around the world (Raper et al 1996;

Spada, 2012). Therefore, the identification of appropriate sea level rise scenario should be tailored to the case study area. The latest sea level projection for Hillsborough Bay area was published in November 2013 by Climate Central (2013). The study employed model framework developed by the National Research Council (1987) and also adapted by the U.S. Army Corps of Engineers (2011). The projection model is represented by:

$$E_{(t)} = 0.0017t + bt^2 \tag{3-1}$$

Where, E is the sea level change in meters, t represents years starting in 1992, b is a constant which captures assumption for future greenhouse gas emissions. The model framework includes three scenarios: low, intermediate and high sea level rise scenarios (Figure 3-6).

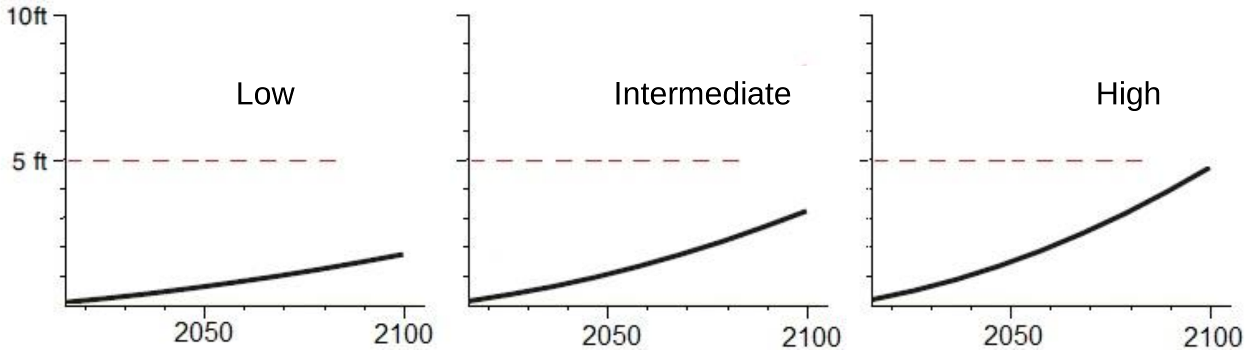


Figure 3-6. Sea level rise projection for St Petersburg, FL. (Source: Climate Central, 2013)

This set of projections is based on IPCC's 4th Assessment Report published in 2007. However, IPCC released its 5th climate science report around June 2013. The overall projection from the 5th Report is considerably higher than in the last version. The 4th Report underestimates ice loss from the glaciers and Greenland observed by satellites and field experiments conducted after the release of the 4th Report (IPCC, 2013). Therefore, the High scenario that the Climate Central generated for St Petersburg is more likely to happen for Hillsborough Bay area in the future. The High scenario represents an unmitigated future that human society as a whole will not make great efforts to reduce greenhouse gas emissions. Although global optimists believe that developing and developed countries will reach consensus to monitor and cut off their emission back to 2009 when UN Climate Change Conference was held in Copenhagen, the world has witnessed little progress toward a mitigated future. Thus, it is hard to say that the worst case scenario presented in Figure 3-6 is less likely than other two scenarios.

This study selects the High scenarios in Figure 3-5 as the analysis scenario. There are studies showing that sea level rise's impact is far more significant than direct inundation itself, so the selection of High scenario is also in consideration of the other impacts of sea level rise rather than direct inundation. Summarized in Donoghue (2011)'s paper, even under recent rates of sea level rise (1.7mm/year), U.S. shorelines are retreating on an average rate of 1m/year. The average shoreline recession rate in Florida is monitored as 1.5 meters per year (Deyle et al., 2007). Under the worst scenario with the fast projected sea level rise rate by IPCC, Deyle et al. (2007) estimated that the annual shoreline recession rate due to global average sea level rise alone could reach 9.7 meters per year, and a mid-level of 6 meters per year using the above gradient relation. As a summary, consensus is reached regarding the conclusion that coastal morphologic systems (e.g. barrier islands, wetlands) will move towards new equilibrium much quickly than sea level rise, and the difference only exist in the estimation of rates (Deyle et al, 2007).

Therefore, worst-case scenario, which projects 5 feet sea level rise by the 2100, is selected for the analysis scenario of this study to capture the higher projection of global mean sea level rise, the slow motion moving toward emission reduction, and coastal erosion that enlarging sea level rise impacts. In order to uncover the tipping point for adaptation, three time points are selected including the year 2013, 2040, and 2060 which correspond to 1 foot, 2 feet and 5 feet sea level changes (Figure 3-7).

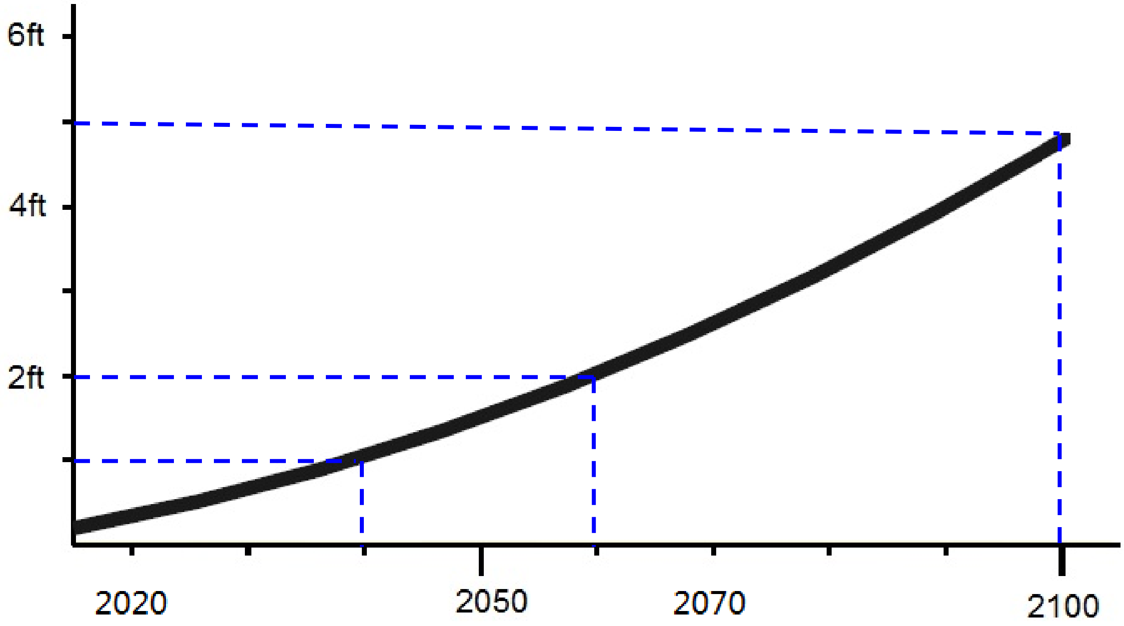


Figure 3-7. Analysis scenarios (Created by Author)

3.4 Spatial Econometric Model

Spatial econometric model has potential to incorporate and integrate the spatial correlations that are present in sea level rise impacts on human societies. The panel data techniques and models that focus on temporal correlation are in widespread use in many research fields. However, the methods that account for spatial autocorrelation are less well known. Existing studies incorporating spatial autocorrelation do not focus on sea level rise-based applications. This research aims to employ spatial econometric models to better capture and estimate the economic impacts of sea level rise adaptation strategies at different time points.

3.4.1 Spatial Econometric Models

The focus on location component and spatial effects in econometric models has a long history. But the early works that try to capture spatial effects are limited to simple problems in the linear regression models (Anselin, 1988). In order to better understand spatial interaction from economic point of view, spatial econometric model was developed with a set of specialized techniques that aim to capture spatial autocorrelation and spatial structure within the econometric modeling framework. Therefore, rather than an individual field, spatial econometric is a subfield of econometrics (Paelinck & Klaassen, 1979; Anselin, 1988; and Anselin, 2006).

The origin of the term of spatial econometrics was traced back to early 1970s when Paelinck designated “a growing body of the regional science literature that dealt primarily with estimation and testing problem encountered in the implementation of multiregional econometric models (Auselin, 1988, p 7).” Since then, spatial econometrics found a wide acceptance, especially from regional science and urban economics which pay substantial attention to spatial interaction among various entities. But more recent research works have greatly broadened the application of spatial econometrics. Some of this kind of studies includes assessing the errors in variables and spatial effects in hedonic house price models of ambient air quality (Anselin and Lozano-Gracia, 2009), applying spatial shift-share analysis to evaluate employment data (Lopez & Mayor, 2009), as well as the application in agricultural economics (Benirschka & Binkley, 1994; Bell & Bockstael, 1999; and Baylis et al 2011), and labor economics (Topa, 1996). Some applications of spatial econometrics are evenly applied to the demand/supply analysis which is considered as the domain of traditional econometrics (Case, 1991; Cohen & Paul, 2009). There is very little research that ties spatial econometrics to study sea level rise, although sea level rise issues have strong spatial pattern. Spatial econometrics has been applied in many different fields and ways. The essential consideration for its application is to capture the spatial effects, including spatial dependence and spatial heterogeneity.

3.4.1.1 Spatial dependence

Spatial dependence, or sometimes referred to as spatial autocorrelation, is the existence of statistical dependence in a set of random variables. Different from variable and error dependence in traditional econometrics, spatial dependence considered dependence among variable caused solely by geographic location of the observations. The mathematical expression of spatial dependence is the moment condition of covariance:

$$Cov[yi, yj] = E[yiyj] - E[yi] \times E[yj] \quad (3\text{-}2)$$

Where i and j refers to individual observations with i≠j; yi and yj are the value of observations at location i and j. Spatial dependence exists when Cov[yi, yj] ≠0 and the configuration of i and j pairs has spatial interpretation, such as spatial data measurement errors and spatial interaction. In fact, measurement errors and spatial interaction are believed to be the two major reasons that cause spatial dependence (Anselin, 1988).

Measurement errors are bounded in the data collection methods. Due to the high cost of data collection, socioeconomic data are always aggregated to a certain level, such as census block, metropolitan statistical areas, county, and state level. However, the delineation of the statistical boundaries is rather subjective in most of times. It cannot exactly represent the true spatial scales of the data.

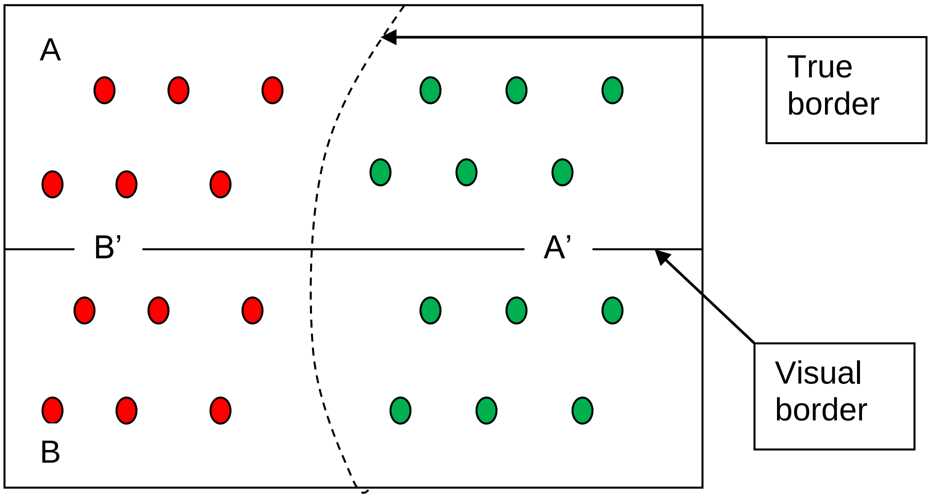


Figure 3-8. Existence of spatial errors (Created by Author)

Figure 3-8 hypothetically illustrates how spatial dependence exists in data collection. A and B are two census blocks delineated by a visual border, a road that runs across A and B. However, households living on the east of Block A are much more similar with their counterparts in Block B, rather than with households living on the west side of the Block A. There is an invisible boundary that delineates the true blocks A' and B'. This is so because the two blocks locate on the urban edges. Thus, the distance to urban core areas plays more important roles than roads. As a results, the value of variables Y_A and Y_B aggregate partially both $Y_{A'}$ and $Y_{B'}$. Therefore, the measurement errors of Y_A and Y_B may generate a pattern which shows spatial dependence, which is represented by spatial relationship of errors.

The second reason for spatial dependence is spatial interaction which is more fundamental and theoretical in terms of regional science as well as human behavior. Spatial interaction is a broad term "encompassing any movement over space that results from a human process. It includes journey-to-work, migration, information and community flows, student enrollment and conference attendance, the utilization of public and private facilities, and even the transmission of knowledge (Hayness & Fotheringhan, 1984, p9)”. The simple version of this dependence is described by Anselin (1988) as “what is observed at one point is determined by what happens elsewhere in the system (p12).” In traditional economics, the spatial interaction is sometimes referred to as spillover effects or spatial externality, which considers the relationship between economic activities across spaces. Capturing these spatial effects is one of the major applications for spatial econometric models (Fingleton, 2003; Bode 2004; Arbia et al, 2009).

The empirical application of spatial dependence in modeling climate change impacts so far is still very limited and in its infancy. The majority of empirical research on climate change issue is to account spatial effects when evaluating climate change impacts on agriculture and agricultural production (Dormann et al, 2007; Seo, 2008; Kumar, 2011). The application for sea level rise is even sparser. The only existing field of research that integrating spatial econometric models is to evaluate the impacts of sea level rise on real estate market, which integrates the spatial dependence of properties over space into hedonic pricing model (Bin et al, 2011; Baylis et al, 2011; Lu & Peng, 2011).

3.4.1.2 Spatial heterogeneity

Spatial heterogeneity refers to the uniformity of the spatial effects on different observations at different locations. From an economic view, spatial heterogeneity implies that the parameters in a model are different across various observations. Take the following model as an example:

$$Y_i = f(x_i, \alpha_i, \varepsilon_i) \tag{3-3}$$

Where, Y_i is the value of observations at location i; x_i is the independent variable that impacts Y_i; α_i is parameter assigned to x_i; ε_i is the error term. Spatial heterogeneity means that at different locations, α_i varies rather than remains as constant. This structural instability can be solved by traditional econometric models rather than requiring a different set of techniques. But in practice, the solvation of a spatial heterogeneity model calls for sufficient data since the model imposes a large number of parameters, sometimes more than the number of observations. Therefore, spatial heterogeneity is more theoretical and less empirical than spatial dependence in existing literatures (Anselin, 2009). Since climate change research involves dealing with uncertainty, data requirement is much more challenging for the application of spatial heterogeneity in modeling climate change impacts. So this research will consider the impacts of spatial heterogeneity, but the main focus of model development will concentrate on spatial dependence.

3.4.2 Formal Model Expression

The previous sections introduce how spatial dependence can improve the understanding of spatial effects. However, only by formally expressing the spatial effects, especially spatial dependence effects, spatial econometrics starts to have operational meaning. However, the spatial econometric formation is much more complicated than time-series analysis. This is because, first of all, the spatially lagged variables are far more ambiguous than time lagged variables; second, the definition of spatial lag is rather arbitrary (Anselin, 1988). Different literatures treat this issue differently. Therefore, there are a wide variety of methods and approaches developed to solve the issue. Generally speaking, spatial regression specification fall into two major categories, including spatial lag models and spatial error models (Anselin, 2006). Next, these two model specifications are reviewed. But before that, there is a need to introduce a fundamental concept which is bounded into spatial econometrics and separates it from traditional econometrics. That is spatial weight matrix.

3.4.2.1 Spatial weight matrix

Spatial weight matrix summarizes spatial relations among all the units in a certain surface. The interpretation of this kind of matrix can be seen as capturing the spatial influence between units on location i and unit on location j. The notation for spatial weight matrix is w_{ij}.

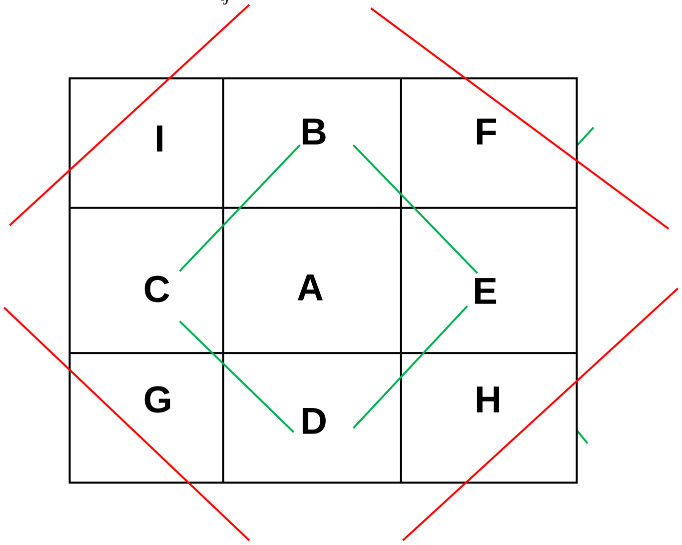


Figure 3-9. Spatial congruity of unit A (Created by Author)

Spatial contiguity matrix is the earliest version of spatial weight matrix. Moran (1948) developed a binary contiguity notion for contiguous units. After that, the contiguity matrix is widely used in spatial analysis. Even until today when there is a wide variety of measures to specify spatial weight matrix, the contiguity matrix still plays an important role. As illustrated in Figure 3-10, the structure of the geographic neighborhood is expressed by a binary notation with value 1 or 0. When the two units share the same boundary, their relation is assigned a value 1; or 0 otherwise. The definition of contiguity can also vary. Take Figure 3-9 as an example. If contiguity is defined as units with a none-zero length of border, only B, C, D and E are considered as A’s neighbors. If the definition of contiguity is based on common vertex, then F, G, I and H become A’s neighbors. For the common edge definition, a spatial weight matrix of A, B, C, D and E can be written in the following format. Note that we assume there is no self-contiguity effect, therefore, the diagonal of the matrix is assigned value 0:

$$\begin{pmatrix} 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Figure 3-10. Example of spatial weight matrix (Created by Author)

However, the contiguity matrix works best for regular surfaces for polygon features, especially rectangular features. It needs to be extended to irregular surfaces, point features. Etc. The following specifications of spatial weight matrix are commonly adopted in recent research.

K-Nearest Neighbor Weights: Let d_{ij} denote the distance between the centroid of unit i and the centroids of all other units j (i≠j). Then rank all the distances. Suppose there are N total units. For each k=1, …, N-1, the set $N_K = \left\{ j_{1,} ..., j_k \right\}$ contains k closest units to i. The specification for the K-nearest neighbor is:

$$\begin{cases} w_{ij} = \quad 1, \text{j} \in N_k \\ 0, \text{ otherwise} \end{cases} \qquad \text{(3-4)}$$

Radial Distance Weights: Sometimes distance is the major consideration of the spatial effects which only exist within a certain distance (from 0 to $d_{\max}$). Then the Radial Distance Weights will be employed to specify spatial weight matrix. Let d_{ij} denote the distance between the centroid of unit i and the centroids of all other units j (i≠j). Wij then becomes:

$$w_{ij} = \begin{cases} 1, & 0 \le d_{ij} \le d_{\max} \\ 0, & d_{ij} \ge d_{\max} \end{cases} \qquad (3\text{-}5)$$

Power Distance Weights: In Radial Distance Weight we assume the spatial effect remains constantly within a certain distance. But that is not always the case since, as the first rule of geography states, the spatial influence diminishes with the increase of distance. Power Distance Weight aims to capture this effect by introducing the diminishing effect as the negative power function of the distance. The specification suggests:

$$w_{ij} = 1 / d_{ij}^{a} \qquad (3\text{-}6)$$

There are also many other specifications of spatial weight matrix based on different conditions. Anselin (1988) argues that “the structure of spatial dependence incorporated in the spatial weight matrix should be chosen judiciously, and related to general concepts from spatial interaction theory. In line with a model-driven approach to spatial econometrics, the weight matrix should bear a direct relation to a theoretical conceptualization of the structure of dependence, rather than reflecting an ad hoc description of spatial pattern (Anselin, 1988, p 21)”. Therefore, the choice of specification is a case-by-case problem. The unit of analysis in this study is Economic Analysis Zone, which is a polygon surface with irregular shapes. So this research employs the “Queen” specification for neighbor features. The Queen specification is one type of contiguity spatial weight that considers the first-order neighbors that share either a vertex or edge.

3.4.2.2 Spatial lag model

The concept of lag is heavily used in time series model, which try to shift the variable under analysis to other time periods. In other words, it links the variable at one time period to others. While in spatial econometrics, the concept of lag is to relate the observation at one location to its surrounding observations. Unlike lag in time series models, the direction of which is straightforward, the direction of lag is more complex for spatial lag. This problem can well be solved with the spatially weighted sums of all surrounding observations. Spatial weight matrix is then employed to capture the spatially weighted sums.

The formal expression of spatial lag model is given by:

$$y = \rho Wy + X\beta + \varepsilon \tag{3-7}$$

Where y is an N×1 variable under analysis, X is the N×1 factors that impact the values of y, β is the parameter associated with exogenous variables X. ρ is an autoregressive parameter, W is weight matrix specifying the relations between spatial units. ε is a vector of independently distributed errors.

The spatial lag model is typically considered as the formal specification for the equilibrium outcome of a spatial interaction process. For the spatial interaction, the value of the dependent variable at one specific location is jointly determined by the same dependent variable at the neighboring locations (Elhorse, 2010). For instance, in the existing literature on interaction among various local governments, the tested model specification of spatial lag model represents the fact that the taxation and expenditures on public services are impacted by taxation and expenditures on public services in surrounding jurisdictions (Brueckner, 2003).

3.4.2.3 Spatial error model

While spatial lag model aims to capture the spatial interaction, the spatial error model, on the other hand assumes that the dependent variables depends on a set of local characteristics and, therefore, the error terms are correlated across space. The formal expression of spatial error model is:

$$\begin{aligned} y &= X\beta + \varepsilon \\ \varepsilon &= \lambda W\varepsilon + \mu \end{aligned} \tag{3-8}$$

Where y is a vector of the dependent variable; X is a vector of independent variable that capture local characteristics; β is a vector of parameters associated with variable X; ε is spatial disturbance/error term; λ is spatial coefficient in the spatial autoregressive structure for spatial errors; W the specified spatial matrix; μ is an error term with normal distribution.

Different from spatial lag model which calls for regional science theory to back up the model specification, the spatial error model does not require a theoretical basis for spatial interaction. Instead, spatial error model is a special case of non-spherical error covariance matrix. In other words, spatial error model integrate the spatial perspective into the model disturbance. It assumes that some important independent variables, which are spatially auto-correlated, are missing from the selected variables in the current model. In some special cases, a spatially auto-correlated error term may also have empirical interpretation. For example in studying the property tax rate in the Netherlands, Allers & Elhorst (2005) employed spatial econometric models to find evidence of tax mimicking, which is represented by the similar tax policy in neighboring municipalities. This dissertation research aims to capture the value changes, such as property value and business revenue, of indirectly impacted areas due to spatial dependence. Several existing studies report the existence of spatial autocorrelation in real estate market (Dubin et al, 1999; Lu, 2012).

3.4.3 Spatial Diagnostic Test

The above sections present spatial error and spatial lag models. Although the two models are developed for different purposes, they are not mutually exclusive from each other. Actually, a spatial problem may engage both models at the same time. Anselin (1988) presents a general specification of spatial dependence model which captures both spatial lag and spatial error model at the same time and form a framework to organize different modeling situations of interest. The general model can be written as:

$$\begin{aligned} y &= \rho W_1 y + X\beta + \varepsilon \\ \varepsilon &= \lambda W_2 \varepsilon + \mu \end{aligned} \tag{3-9}$$

If we set some of the parameters to be zero, the general form turns out to be either a spatial lag model or a spatial error model. From the above two sections, it is easy to generalize that spatial lag model is a special case of this general formation with λ set to be zero; spatial error model with ρ set to be zero. The spatial model becomes a classic linear regression model with both spatial coefficients λ and ρ equals to zero. Therefore, the essential model specification problem is to diagnose the types of spatial effects and spatial pattern.

The choice between the spatial error model and the spatial lag model is a difficult question and is largely context specific. Although the two models are largely distinctive, they are difficult to distinguish empirically (Anselin, 1999; 2002). Lagrange Multiplier test was employed in early days to diagnose spatial dependence. However, as Anselin et al (1996) observed the use of Lagrange Multiplier cannot effectively decompose further the spatial dependence into spatial error and spatial lag effects. To solve this, they apply a modified Lagrange Multiplier test to spatial models and propose simple diagnostic tests for spatial dependence that are based on the results of ordinary learst-squares estimation. Later, Anselin (2001) proposed and evaluated the effectiveness of Rao’s test in distinguishing spatial lag and spatial error effects. He compared Rao’s test to other approaches and concluded that the Rao’s test offer significant advantages over others. There are also a wide variety of tests developed, such as Likelihood Ratio test (LR), Marginal Lagrange Multiplier test (Baltagi et al, 2003), BDS (Brock, Dechert, Scheinkman) test (Graaff et al, 1998), and robust test (Guo et al, 2011). With the advance of econometric software, especially GeoDa and R Project, the diagnostic process is much easier. Chapter 5 introduces the spatial diagnostics that is employed this research.

3.5 Variable Selection

The selection of important economic variables is crucial for cost-benefit analysis. The selected variables should capture both direct and indirect impacts. However, it should also consider data availability. So the first step of variable selection is to identify major impacts of sea level rise. This is followed by data availability analysis.

The impacts of sea level rise are heavily investigated at different scales. Local scale, including city and county levels, is most relevant to this research. At local levels, indicators are more specific to daily lives of local residents. Nicholls (2003) categorizes sea level rise impacts at local level into two groups: biogeophysical effects and socioeconomic effects.

1. Biogeophysical effects. This variable group includes variable such as, inundation, flood and storm damages, including surge and backwater effect; wetland loss; erosion; saltwater intrusion for both ground water and surface water; and rising water tables and impeded drainage.
2. Socioeconomic effects. Those impacts include increased loss of property and coastal habitats; increase flood risk and potential loss of life; damage to coastal protection works and other infrastructures; loss of renewable and subsistence resources; loss of tourism, recreation, and transportation functions; loss of non-monetary cultural resources and values; and impacts on agriculture and aquaculture through decline in soil and water quality.

This list also coincides with other studies seen in Nicholls (2002), McLean et al (2001) and Nicholls & Cazenave (2010). The U.S. Climate Change Science Program (2009) provides a similar but more concise list of sea level rise impacts:

- Land loss through submergence and erosion of lands in coastal areas;
- Migration of coastal landforms and habitats;
- Increased frequency and extent of storm-related flooding; wetland losses; and
- Increased salinity in estuaries and coastal freshwater aquifers

Furthermore, the Program differentiates different sectors that will be impacted by sea level rise, including coastal elevation, coastal wetlands, vulnerable species, population, land use, and infrastructure.

Laushe (2009) investigated specific impacts on local communities of Florida. The local impacts on Florida includes: damage to wetland, water quality for ecosystem, as well as damages to coastal properties, job losses, tourism, fishery, and heath problem as a result of salt water intrusion. At local level, the impacts of sea level rise are more specific than higher levels, since the

According to the identified sea level rise impacts, the major impacted sectors include:

- wetlands
- water quality
- coastal properties
- public infrastructures
- tourism
- industries, including fishery and agriculture

Among them, impacts on surface and ground water quality are hard to be quantified in monetary terms because the exchange of water and the change of chemistry in fresh water are so complicated that is beyond this research. Therefore, water quality is excluded from economic analysis. Furthermore, tourism is not considered in this research since the site analysis suggests that there is little tourist spot under threat of sea level rise in Hillsborough County. Clear Water Beach and the surrounding areas comprise a major tourist attraction within Tampa Bay Region. However, the area is out of the study area. The following list shows the variable that will be included in cost-benefit analysis:

- Wetland: monetary value of eco service
- Coastal land: land value
- Coastal buildings: the value of building damage
- Transportation: the value of delayed travel time
- Business: loss of business revenue

In summary, this chapter presents literature reviews on commonly adopted sea level rise adaptation strategies, sea level rise projections, spatial econometric model and the selection of economic variables. The following chapters are built upon the findings from existing literatures in this chapter by tying the cost-benefit analysis to the identified adaptation strategies and scenarios, as well as modeling framework and variable selection. The quantification of costs and benefits in the next few chapters starts from presenting the process and results of quantifying economic variables without spatial pattern in Chapter 4, followed by presenting the process and results of quantifying economic variables with a spatial pattern.

CHAPTER 4
QUANTIFICATION OF ECONOMIC LOSS WITHOUT SPATIAL ATTRIBUTES

The major purpose of this chapter is to quantify the economic losses of those variables that do not present spatial dependence, specifically the economic losses from delayed travel time, damaged buildings, and change of wetland habitats. The quantification of each variable employs commonly recognized models.

4.1 Quantification of Travel Time Delay

4.1.1 Travel Time Delay

The purpose of transportation network is to move people and goods around cities. However, as the cities continue to grow, urban transportation networks tend to be over utilized. As a result, congestion is inevitable. Transportation network congestion delays the users' travel time which is considered to have monetary values. This is so because, first of all, the delayed travel time has opportunities cost that can be utilized to do other things rather than spending times in traffic queues. Secondly, the delayed travel time can actually have economic cost if the travelers are late for work. Therefore, travel time delay is an important consideration when evaluating any transportation networks. A report published by Greater London Authority (2005) found out that the quantifiable economic cost of transport delays in Central London area was estimated to be £ 1,190 million a year.

As sea level rises, coastal roads will be vulnerable to sea water inundation and frequent flooding in low-lying areas. When the vulnerable roads are closed, users will have to detour to use alternative roads with increased travel time. More usage of surrounding open roads will cause more serious traffic congestion that impact existing users. Therefore, sea level rise will cause travel time delays which are involved with indirect economic loss. Lu and Peng (2012) studied increased travel time when sea level rises in Hillsborough County. The results show that when sea level rises 0.6 meter by 2060, the increased travel time is equivalent to 510 million dollars a year.

In this study, delayed travel time is defined as the difference between times traveled on a damaged road network caused by sea level rise and completely uncongested network. In other words, the delayed travel time is the system travel time difference before and after sea level rise. The system travel time will be calculated by Florida Standard Urban Transportation Model Structure (FSUTMS) run on Cube software platform.

4.1.2 FSUTMS/Cube Suite Platform

Florida Standard Urban Transportation Modeling Structure (FSUTMS) is developed to serve as the standard transportation model for the State of Florida. The FSUTMS models are developed and implemented in Cube software, a transportation modeling software. Florida Department of Transportation has led all the efforts to collect transportation data for more than 10 years. The model parameters are calibrated for each of the 7 Transportation Districts and major metropolitan areas. The Hillsborough County model consists of 758 traffic analysis zones (TAZs). The transportation network in the model includes highways, interstates, and arterials. FSUTMS is a typical TAZ-based transportation model. It generates travel demand for each TAZ as well as travel time between each TAZ pairs.

Cube software bundle, developed by Citilabs, is the major modeling platform to run FSUTMS models. Since Cube is developed upon an embedded version of ArcGIS, the input and output maps can be shared with ArcGIS. This enables the creation of transportation network under different sea level rise scenarios. In this study, the system travel time with no-damage network is generated first; then, the transportation network from Cube is overlaid with inundation maps to produce the inundated transportation network; finally, the system travel time is generated for inundated network to calculate the travel time delay.

4.1.3 Cost Quantification of Travel Time Delay

The transportation network is loaded into ArcGIS to identify the inundated roads.

Figure 4-1. Inundated roads under A) 1 foot, B) 2 feet, and C) 5 feet sea level rise (Created by Author)

As Figure 4-1 illustrates that there is a minor difference between maps A) and map B). However, as Table 4-1shows that these minor differences can generate a large amount of travel delay cost in a one-year time period. In terms of the value of travel time, the U.S. Department of Transportation synthesizes existing research on quantifying the monetary value of travel time. Generally speaking, there are two measures to quantify the value of travel time: capturing travelers' willingness to pay to reduce a certain amount of travel time, and use opportunities cost to represent the value of travel time. The synthesis also suggests a 50% of local hourly income for value local personal travel (USDOT, 2011). Therefore, this study employs 50% of local hourly income as the value of travel time delay. According to the Bureau of Economic Analysis, the average wage of Hillsborough County is $26.6/hour& person. Figure 4-1 shows the

Table 4-1. Annual travel delay costs

Sea level rise	1 foot	2 feet	5 feet
Total travel time delay per day (in million $)	1.12	1.61	1.92
Total value of travel time delay per year (in million $)	409	577	701

4.2 Quantification of Wetland Conversion

4.2.1 Value of Wetlands

It has been widely recognized that coastal wetlandsplays an important role in both built and natural environment, since they provide various services, including aesthetics, recreation, climate regulation, water filtration, disturbance regulation, food, habitat for different species, nutrient cycling, raw materials, water supply (Acharya, 2000; Keddy, 2010). The value of wetland products can be captured by market with monetary values. However, the values of their services are greatly underestimated since the market cannot directly assign monetary values to those services. There are a number of studies trying to quantify the value of wetland services with the adoption of travel cost quantification method, contingent valuation method, replacement cost method, and hedonic pricing methods (Woodward & Wui, 2001; Brauman et al, 2007).

The quantification of wetland services alone could be a separate research, which is not the focus of this study. Therefore, this study generates the unit monetary value by researching existing literatures. The calculation is based on the average value for different ecosystem services provided by Gulf of Mexico Ecosystem Service Valuation Database (http://www.gecoserv.org/). The outlier values are removed so that the unit value for different types of wetland is an average of the numbers generated from over 200 literatures (refer to Appendix A for the average values of various ecosystem services). The synchronized wetland values are shown in Table 4-2.

Table 4-2. Value of wetlands (unit is dollar per ha)

Type	Beach value	Freshwater value	Mangrove value	Marine open water	Salt water value
Value	195,838	61,959	125,991	2,913	28,629

4.2.2. SLAMM Model

SLAMM model stands for Sea Level Affecting Marshes Model which aims to simulate the dominant processes of wetland conversion and shoreline modification during sea level rise. SLAMM simulates these processes by dividing each site into cells with equal size. The cell records the elevation, slope and aspect. Then a complex decision tree integrates geometric, geological and qualitative relationships into cell analysis to represent transfers among different types of coastal wetlands.

SLAMM simulates five major processes under different sea level rise scenarios:

1. Inundation
2. Erosion
3. Overwash

4. Saturation
5. Accretion

4.2.3 Wetland Value Change

This study employs SLAMM model to simulate the quantity change of coastal wetlands. Figure 4-2 illustrates the conversion of coastal wetlands under different sea levels. Under 1-foot sea level rise, the conversion is not visually obvious. As sea level continues to rise, wetland conversion tends to be obvious at the lower end of the case study area. Under 5-foot sea level rise, the landward migration of wetlands is seen along the entire coast.

Figure 4-3 illustrates the coverage and value change of different types of coastal wetlands. It suggests that as sea level continues to rise, four types of coastal wetlands will increase their coverage, including freshwater wetlands, marine/open water wetlands, beach and salt water wetlands. In comparison, mangrove decreases its total value with decreased coverage.

This simulation results coincide with existing literatures, since mangrove ecosystem tend to collapse during predicted sea level rise (Ellison & Stoddart, 1991). Craft and his colleagues used field and laboratory measurements, and simulation models to investigate the potential effects of sea level rise on coastal marshes along the Georgia coast.

The results suggest that both saltwater and freshwater marshes will keep the pace with rising sea levels. Under IPCC sea level rise projections, their coverage can increase as much as 2% (Draft et al, 2009). Morris et al (2002) also argue that the wetland habitats will stay stable with modest coastal elevation or even increase their coverage if topology of surrounding inland areas enables wetland migration and the sea level rise leaves enough time to the natural migration of wetlands. These arguments apply to the simulation results since, except the mangrove wetlands, other types of coastal wetlands do show the increase areas.

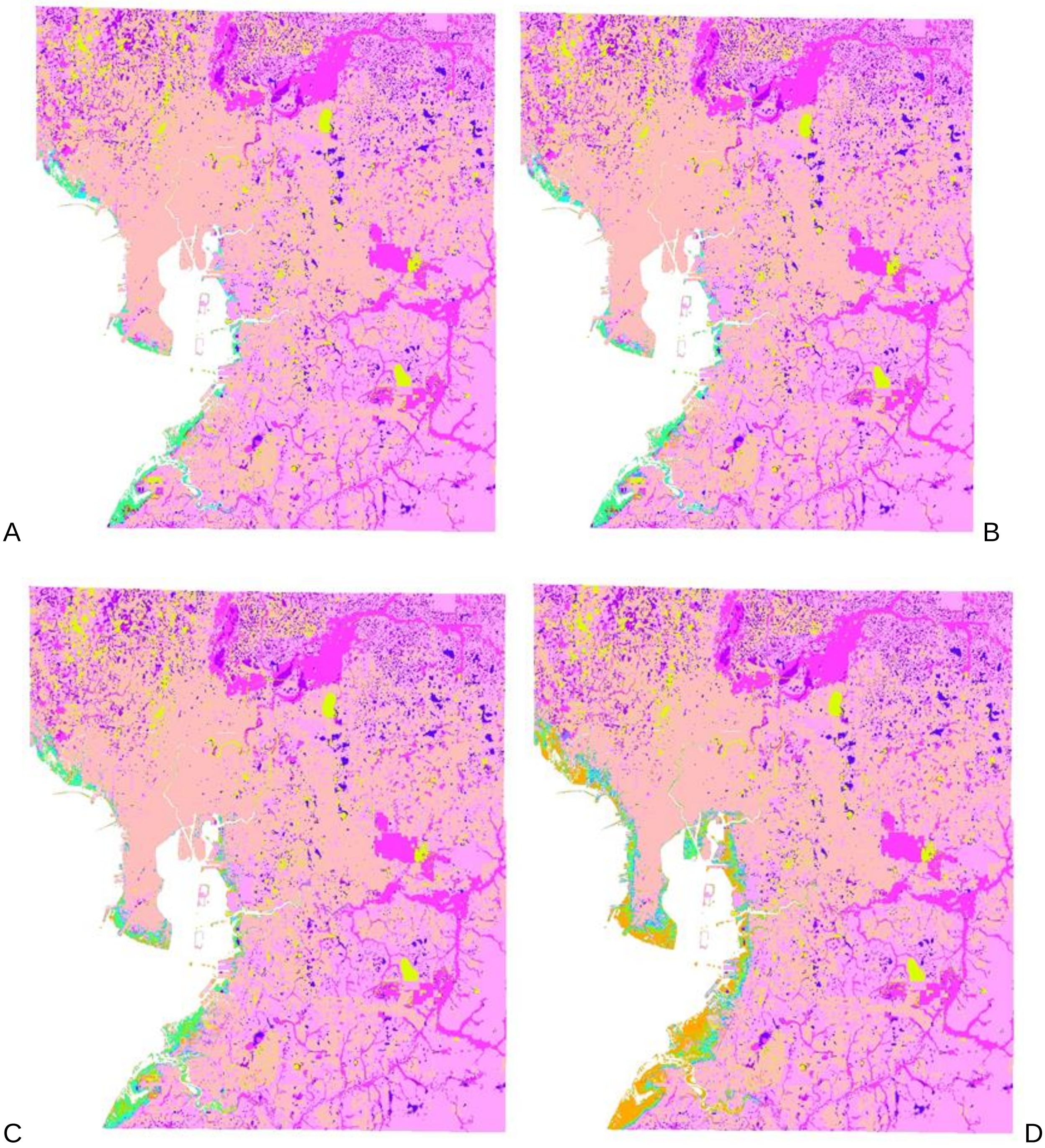
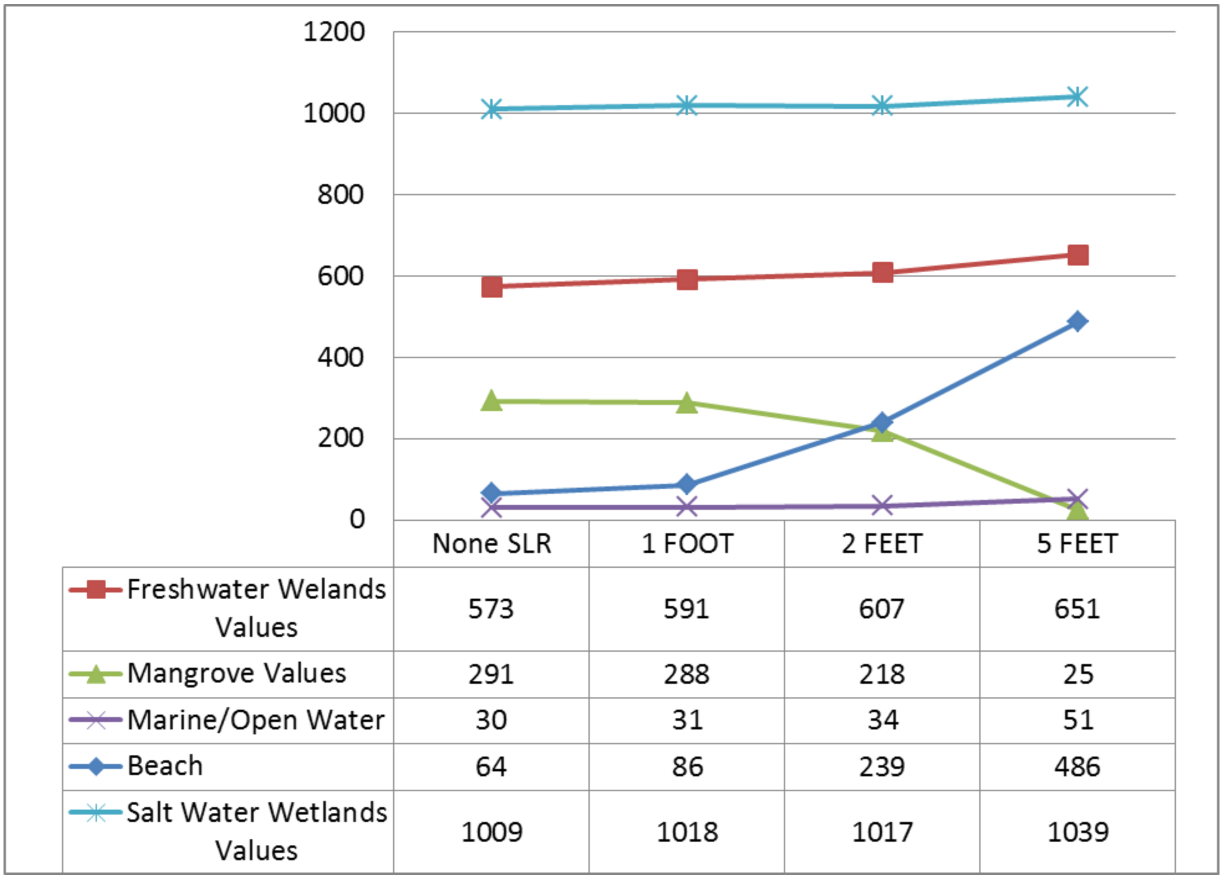


Figure 4-2. Conversion of coastal wetlands under A) no sea level rise, B)1 foot sea level rise, C) 2 feet sea level rise, and D) 5 feet sea level rise (Created by Author)



	None SLR	1 FOOT	2 FEET	5 FEET
Freshwater Welands Values	573	591	607	651
Mangrove Values	291	288	218	25
Marine/Open Water	30	31	34	51
Beach	64	86	239	486
Salt Water Wetlands Values	1009	1018	1017	1039

Figure 4-3. The total values of five major types of wetlands-value in millions (Created by Author)

Table 4-3. Value changes for five major types of wetlands (value in million)

Sea level rises	1 foot	2 feet	5 feet
Total value	$2,014	$2,115	$2,252
Value loss	-$47	-$148	-$285

Table 4-3 lists the total value changes for coastal wetlands as a whole. The lost values are negative numbers, which indicate that as wetlands migrate natural without disturbance of human activities, the wetlands will increase its total values.

4.3 Quantification of Building Damages

4.3.1 Quantification of Building Damages with Hazus Model

As sea level rises, costal buildings are vulnerable to both inundation and frequent flooding caused by sea level rise. However, quantification of coastal building damages is complicated because of the limited data and knowledge on the cost of building materials for each individual building. Therefore, there is a need to employ a widely recognized methodology that can estimate building damages with available data. Hazus model developed by Federal Management Agency can fit this need.

Hazus is a risk assessment tool aims to use various models to estimate potential losses from different natural hazards, including earthquakes, floods, and hurricanes. The simulation and estimation models embedded in Hazus are based on Geographic Information System. It allows the users to estimate the potential losses from hazards-related damages. Its impact analysis includes physical, social and economic losses. Federal Emergency Management Agency (FEMA) released its first version, which is later named Hazus97, in 1997. After continuous efforts to update the embedded models, the hazards that can be modeled by Hazus has been greatly expanded. The current version is Hazus-MH v2.1, which stands for ‘Hazus multi-hazards version 2.1’. This version of software package is employed to quantify the value of damaged buildings in this study.

4.3.2 Economic Losses from Building Damages

Hazus model keeps the state-wide data for the state of Florida. Its database includes the land use and building information for each parcel. The model has an inventory of replacement cost for each type of buildings, including residential, commercial, governmental, industrial, and religious buildings; as well as each type of structures, such as wood, steel, concrete, masonry, and mobile homes. The costs include both replacement costs for building loss and content loss. Building loss refers to the damage of structures; while content loss refers to the personal properties within the buildings. The cost information is collected nationally from a large amount of flood insurance claims. Hazus outputs the total loss on a regional level in summary reports.

Table 4-4 shows total economic loss from building damages under different sea levels. It is obvious to sea that the lost values from building damage are a huge numbers. As sea level rises, the lost values increase rapidly.

Table 4-4. Total economic loss from building damages

Sea level rise	1 foot	2 feet	5 feet
Values of building damages (in millions)	$3,381	$4,128	$5,319

In summary, this chapter estimates the potential economic loss caused by travel time delay, change of wetland ecosystem services, and building damages. The estimation is based on direct sea level rise inundation. However, sea level rise impacts also extend beyond direct inundation and impact the surrounding areas because of spatial relationships among adjacent areas, such as the similar land prices for closer areas. Next chapter will estimate the economic impacts of sea level rise on land value and business revenue which present spatial patterns.

CHAPTER 5

QUANTIFICATION OF ECONOMIC LOSS WITH SPATIAL ATTRIBUTES

This chapter estimates the economic costs of sea level rise on land value and business revenue. Unlike the existing literatures which only consider the value loss from direct sea level rise inundation (Yohe et al, 1996; Darwin and Tol, 2001), this chapter analyzes the economic impacts on inland areas which are not directly vulnerable to inundation. This is achieved through employment of spatial econometric models which enable the projection of indirectly impacted areas by linking the value change to directly impacted areas as a result of spatial dependence. There are economic variables under analysis in this chapter, the land value as presented in Section 5.1, and business revenue as presented in Section 5.2.

5.1 Model Development Platforms

The spatial econometrics and its formal expression are introduced in Chapter 3. This dissertation research employs a typical spatial lag model which captures the spatial interaction between the potentially inundated areas by sea level rise and the inland areas. There are various platforms available for spatial econometric model development. This research selects R project, introduced in 5.1.1, and GeoDa, discussed in 5.1.2, since their ease of use and modeling capability.

5.1.1 Spatial Econometric Model in R-project

R is a free software environment for statistical computing and graphics. It is based on the object-oriented mathematical programming language S. R is open source software which allows numerous statisticians and mathematicians around the world to weave their own contributions to the existing coding. R is highly extensible through the use of user-submitted packages. Usually, the submissions are specific for a certain functions or case study areas. But other users can also make modification to fit their own needs.

The user-developed package is the key for R's popularity and capability. These packages are developed in R, and sometimes in Java, C and Fortran. A core set of packages are included with the installation of R. The 'spdep (which stands for spatial dependence analysis)' package is one of these pre-packed packages that is included with R installation and is developed specifically for spatial econometric modeling.

The current version of the spdep package is a collection of functions to create spatial weight matrix objects from polygon contiguities, from point patterns by distance and tessellations, for summarizing these objects, and for permitting their use in spatial data analysis; a collection of tests for spatial autocorrelation, including global Moran's I, Geary's c, Hubert-Mantel general cross product statistic, and local Moran's I and Getis-Ord G, saddle point approximations for global and local Moran's I; and functions for estimating spatial regression models (Bivand, 2010); as well as estimating spatial simultaneous autoregressive lag and error model, impact measures for lag models, weighted and un-weighted Simultaneous Autoregressive (SAR) and Conditional Autoregressive (CAR) spatial regression models; Moran eighenvector filtering, and generalized spatial two stage lease square models (Bivand et al, 2013). It contains contributions including code and/or assistance in creating code and access to legacy data sets from quite a number of spatial data analysts.

5.2.2 Spatial Econometrics in GeoDa

GeoDa is a free software package that focuses on conducting spatial data analysis. The software was firstly developed in the Spatial Analysis Laboratory of the University of Illinois at Urbana-Champaign under the direct of Luc Anselin. Then, its development continues at Arizona State University when Anselin relocates and establishes the GeoDa Center for Geospatial Analysis and Computation.

In terms of the range of spatial statistical techniques included, GeoDa is most alike to the collection of functions developed in the open-source R environment. For example, descriptive spatial autocorrelation measures, rate smoothing, and spatial regression are included in the spdep package, as described by Bivand (2010, 2013). In contrast to R, GeoDa is completely driven by a point and click interface and does not require any programming. It also has more extensive mapping capability (still somewhat experimental in R) and full linking and brushing in dynamic graphics, which is currently not possible in R due to limitations in its architecture. On the other hand, GeoDa is not customizable or extensible by the user, which is one of the strengths of the R environment. In that sense, the two are seen as highly complementary, ideally with more sophisticated users ‘‘graduating’’ to R after being introduced to the techniques in GeoDa (Anselin et al, 2006).

GeoDa is good at analyzing spatial data. Its strongest power is to do spatial diagnostic analysis and spatial regression. Spatial diagnostic analysis or spatial autocorrelation analysis includes tests and visualization of both global (test for clustering) and local (test for clusters) Moran’s I statistic. The global test is visualized by means of a Moran scatter plot, in which the slope of the regression line corresponds to Moran’sI. Significance is based on a permutation test. Local analysis is based on the Local Moran statistic, visualized in the form of significance and cluster maps. It also includes several options for sensitivity analysis, such as changing the number of permutations (to as many as 9999), rerunning the permutations several times, and changing the significance cutoff value.

Spatial regression is the other major advantage of GeoDa. Estimation of the spatial lag and spatial error models is supported by means of the Maximum Likelihood (ML) method. In addition to the estimation itself, predicted values and residuals are calculated and made available for mapping. The ML estimation in GeoDa distinguishes itself by the use of extremely efficient algorithms that allow the estimation of models for very large data sets. The standard eigenvalue simplification is used for data sets up to 1,000 observations.

Therefore, the use of GeoDa and R project can take advantages of the two tools while. R is fully customizable but the visualization and quantification of spatial data are not comparable to GeoDa. Thus, this research employs both software packages to develop the spatial econometric models.

5.2 Model Development Flow

Figure 5-1 illustrates the model development process. Raw data, including tables and map shape files that contain socio-economic data, are imported into ArcGIS to aggregate the data into Economic Analysis Zones as map shape files. The challenge for this step is rather technical since the primary data have different scales. There is a need to aggregate or disaggregate the data so that the available data and fit the analysis unit of his tudy.

Then the shape files are loaded into GeoDa to process the data that R software can read. The outputs of GeoDa module include spatial weight matrix that defines the neighboring relationship of study areas which is in .GAL format and .CSV table.

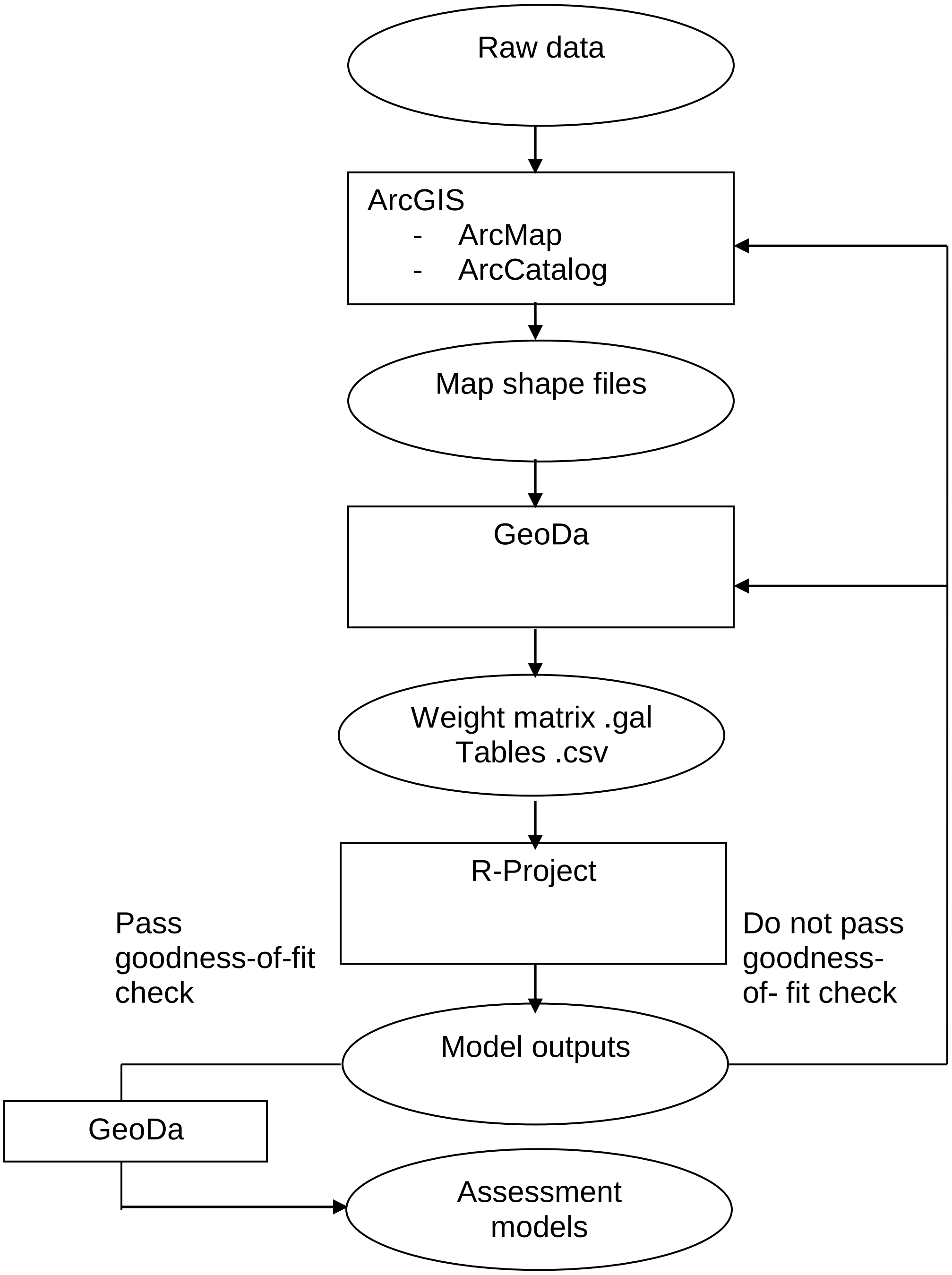


Figure 5-1. Model development flow chart (Created by Author)

Then the weight matrix and data table are read into R project which is the main platform to test the significance of spatial autocorrelation. R will run dependence test first to uncover whether the target variable has spatial dependence. If the results show that there is spatial dependence by Moran’s I test and Lagrange multiplier diagnostics, the process goes back to GeoDa to build the model; if not, there is a need to go back to check whether there is a need to modify the representation of raw data through ArcGIS, such as replacing employment per square miles with employments per square meters, or there is a need to refine spatial weight matrix through GeoDa.

The model building process actually involves both the modification of raw data and spatial weight matrix. The first tentative model focuses on the total property value of Economic Analysis Zones (EAZs), as shown in Figure 5-2. The outputs of R suggest very weak, almost no, spatial autocorrelation for EAZ’s total property value. However, it is a basic wisdom in land economics that the value of property will heavily depend on its location where lands locate closer have similar prices. Therefore, the intuition of weak autocorrelation might be caused by inaccurate spatial weight matrix, or wrong representation of target variables. The actual process checked both the representation of the variable as well as the spatial weight matrix. It started by checking the spatial weight matrix since the corrected spatial weight matrix can also prepare for the model building of other variables as well.

Figure 5-3 shows the histogram of default weights. The histogram shows the number of polygons (within the brackets) that have a certain number of neighbors (on the left of brackets). It suggests that, by default, there are two EAZs that have no neighbors; and two EAZs that have only one neighbor. The problems is obvious since, according to visual check of the relationship among 39 EAZs (Figure 5-2), none of 39 EAZs is isolated or has less than two neighbors. This suggests that the automatically generated spatial weight matrix by GeoDa has some problem that needs to be further checked and corrected.

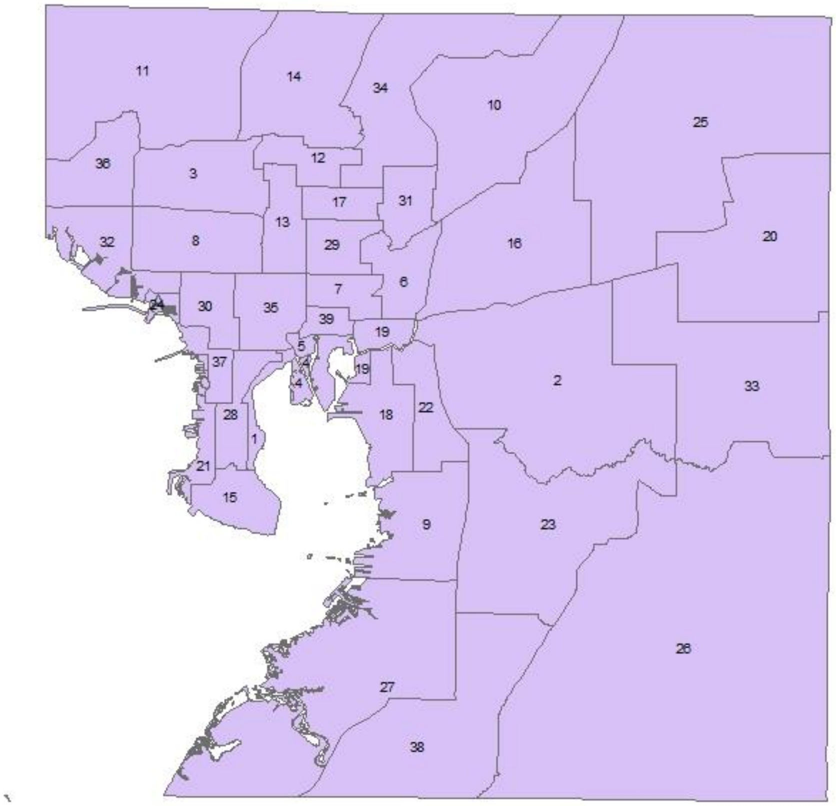


Figure 5-2. Map of 39 Economic Analysis Zones-EAZs (Created by Author)

The search for this problem indicates that in almost all cases, the wrong number of neighbors is caused by the digitizing problem of polygon shapefiles. The correction of this kind of problem requires polygon cleaning in ArcGIS to remove gaps between neighboring polygons. This study applies topology redefinition to clean shapefiles that represent 39 EAZs. Figure 5-4 illustrates the histogram of corrected spatial weight matrix. The corrected spatial weight matrix coincides with manual counting. This indicates the effectiveness of spatial weight matrix fixing.

The model check process also tested various representation of property value. The tested representations of property value include total property value, average property value by count, average property value by area, total land value, average land value by count, and average land value by area. The outputs of R suggest that only the average land value by area has strong spatial autocorrelation.

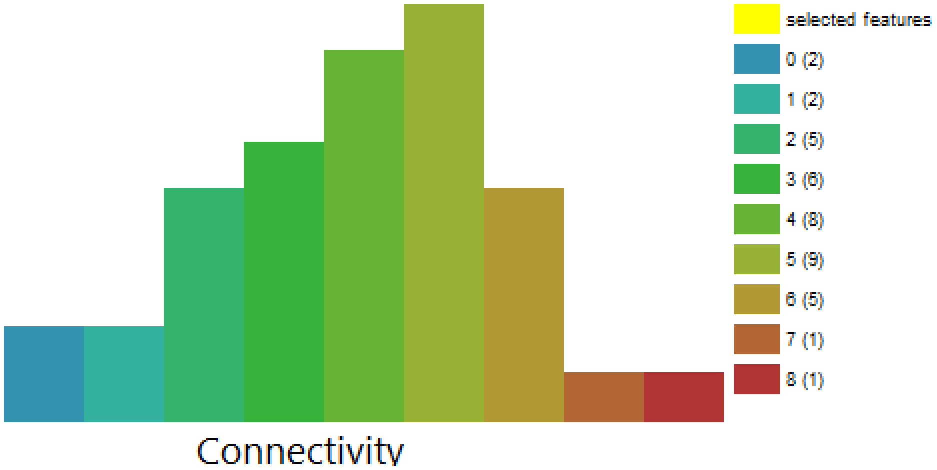


Figure 5-3. Histogram of default spatial weight matrix from GeoDa (Created by Author)

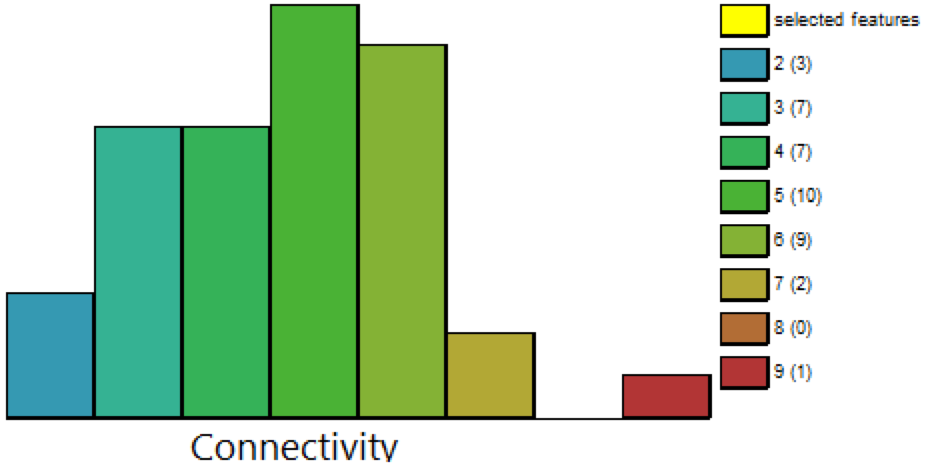


Figure 5-4. The histogram of corrected spatial weight matrix (Created by Author)

After passing the spatial autocorrelation test, the target variable is reloaded into GeoDa to build spatial econometric models by linking the target variable to various independent variables such as population, employment, and household size. The final model selection considers both the goodness of fit and calculation efficiency. This process is detailed in next two sections.

5.3 Quantification for the Loss of Land Value

5.3.1 Spatial Econometric Model Development for Land Value

As presented in the previous section, average land value per square kilometer for each Economic Analysis Zone (EAZ) is selected to represent property value since it is shown with significant spatial autocorrelation. Theoretically, Moran's I ranges from -1 (means perfect dispersion) to 1 (means perfect correlation). Table 5-1 shows the R outputs for Moran's I test. Moran's I statistic is very high, which is 0.53. This indicates a strong spatial cluster for EAZs with similar average land values. This spatial correlation is further proved by significance test of Moran's I statistic. The test result is represented by p value in Table 5-1. Since the P value of the test is extreme low, it indicates a statistically strong spatial correlation.

Table 5-1. Moran's I test for average land value

Moran'I statistic	Expectation	Variance	Standard deviate	P-value
0.53	-0.03	0.01	6.39	8.33e-11

The spatial exploration in GeoDa also indicates a strong spatial dependence, by exporting both cluster map and significant map. Figure 5-5 shows Local Indicators of Spatial Association (LISA) cluster map for average land value. The high-high and low-low locations suggest clustering of similar values, whereas the high-low and low-high locations indicate spatial outliers. Figure 5-5 suggests that there are 4 areas with high average land value locate together; and 8 areas with low average land value locate together. There is only 1 outlier identified. Although 26 areas do not turn out to be significant, the areas with significant spatial association cover the majority of Hillsborough County.

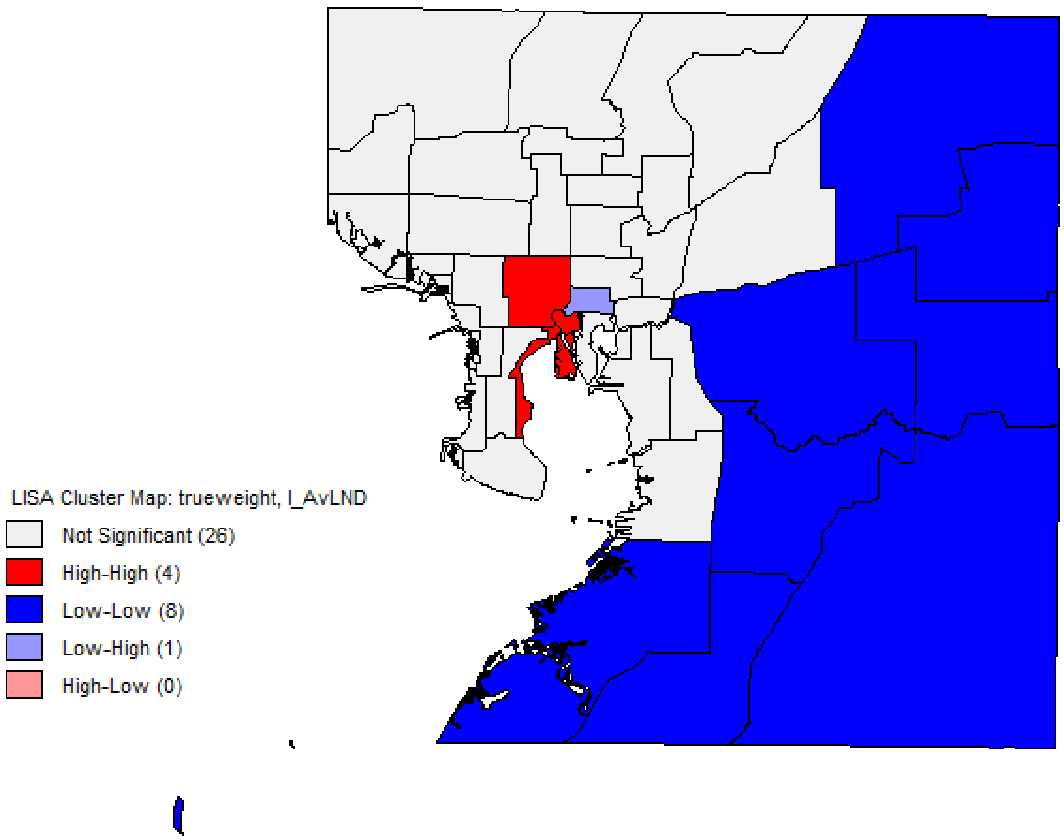


Figure 5-5. LISA cluster map for average land value (Created by Author)

A spatial association is also shown by LISA significance map (Figure 5-6). The significance map shows the locations with significant local Moran'I statistics in different shades of green: the darker the green color is, the more significant the area represents. This figure indicates that there is spatial pattern embedded into the average land use. The significance map and cluster map both visually represent the spatial pattern of variables. However, spatial significance map directly map the significance of spatial statistics. The green areas cover more land than grey areas. This means the variable representing average land value per square kilometers has strong spatial correlation, which further suggests that the variable is ready to be loaded into GeoDa for model building process.

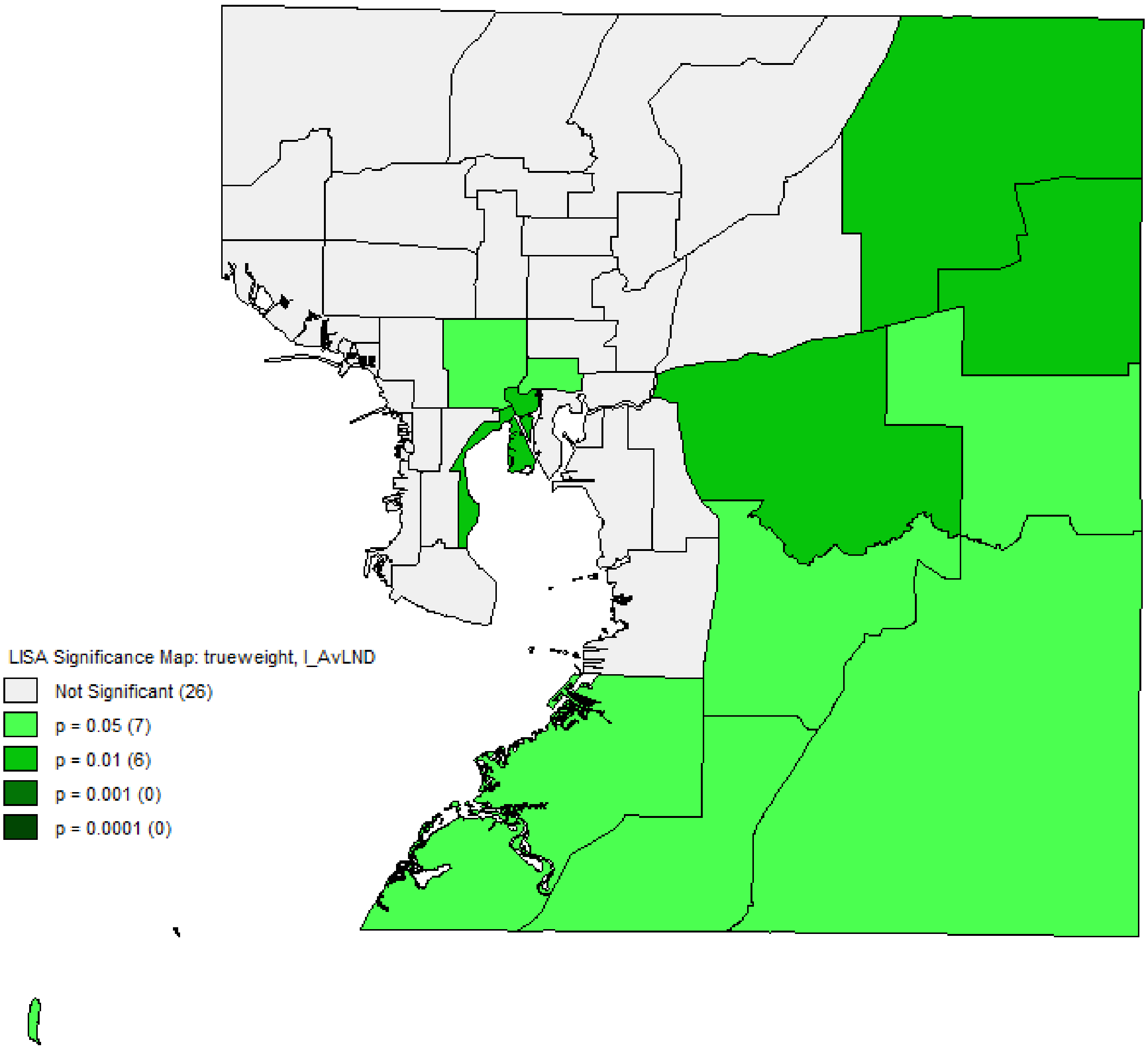


Figure 5-6. LISA significance map for average land value (Created by Author)

As presented in Chapter 3, the formal expression of spatial dependence model for average land value is:

$$Y = \rho\omega Y + \alpha X + \beta + \varepsilon \tag{5-1}$$

Where, Y is the dependent variable representing the average land value; X represents a set of independent variables relate to EAZ's demographic characteristics;

β is a constant; ρ is an autoregressive parameter, ω is spatial weight matrix specifying the relations between EAZs. ε is an independently and identically distributed error term.

GeoDa employs maximum likelihood estimation to estimate model parameters. Various independent variables were tested, including population density, employment density, building density, density of households with more than two cars, and density of households with different racial and income backgrounds. However, only population density turns out to generate best goodness of fit. Other tentative independent variables do not significantly increase the goodness of fit when adding more computation work. Therefore, the final model is:

$$AvLND = \rho\omega \bullet AvLND + \alpha \bullet PopDens + \beta + \varepsilon \tag{5-2}$$

The estimated parameters are shown in Table 5-2. The table also suggests that all the model parameters are statistically significant, since the probability of rejecting null hypothesis, which states none significance of dependent variable, is extremely small.

Table 5-2. Estimated model parameters

Variable	Coefficient	Std.Error	z-value	Probability
W_AVLND	0.60	0.08	7.47	0.00
POPDENS0	17194.12	1978.79	8.69	0.00
CONSTANT	-1.39e+007	4900879	-2.84	0.00

The model has a high goodness of fit with R-squared value equals to 0.84. R square ranges from 0 to 1. 0.84 suggests that the model can well explain the distribution of average land value. In addition, the absolute value of log likelihood is very high. These all suggest that the established model has a good fit with the data to estimate average land value.

Table 5-3. Model goodness of fit

R-squared	Log likelihood	Akaike info criterion	S.E of regression
0.84	-719.14	1444.29	2.35e+007

5.3.2 Comparison with Classic Statistical Model

In order to test the improvement of model by integrating spatial factors, the model building process also built a classic regression model without spatial dependence considered. The formal expression of the comparison model is:

$$AvLND = \alpha \bullet PopDens + \beta + \varepsilon \tag{5-3}$$

Based on Table 5-5 and 5-6, we can conclude that the model parameter is statistically significant (Table 5-4). However, by removing the spatial dependence, the model goodness of fit is greatly reduced (Table 5-5) by almost 24%.

Table 5-4. Model parameters of comparison model

Variable	Coefficient	Std.Error	z-value	Probability
POPDENS0	22058.87	2672.45	8.25	0.00
CONSTANT	-1643889	7066242	-0.23	0.82

Table 5-5. Goodness of fit of comparison model

R-squared	Adjusted R-squared	F-statistic	Log likelihood
0.65	0.64	68.13	732.58

In order to further compare the spatial econometric model to classic regression model with no consideration of spatial lag impacts, this study used R to run a Lagrange Multiplier test to diagnose spatial dependence. Lagrange Multiplier test compares a spatial econometric model to a regression model by hypothesizing that the spatial parameter equals to zero which shows no spatial correlation. The result of the test shows an extreme small number for P value. Accordingly, the probability of accepting the null hypothesis is extremely small. Therefore, the test concludes that average land value shows strong spatial lag effects and there is a need to involve spatial factors into estimation model.

5.3.3 Estimate of Land Value Loss

The estimation process categorizes EAZs into two groups: the directly impacted areas and indirectly impacted areas. The directly impacted EAZs are the areas that have parts of theirs areas inundated by rising sea levels; the indirectly impacted EAZs are those areas that do not have directly inundated areas but the values will be impacted by directly impacted EAZs because of spatial dependence. The designation of directly and indirectly impacted EAZs is illustrated in Figure 5-7.

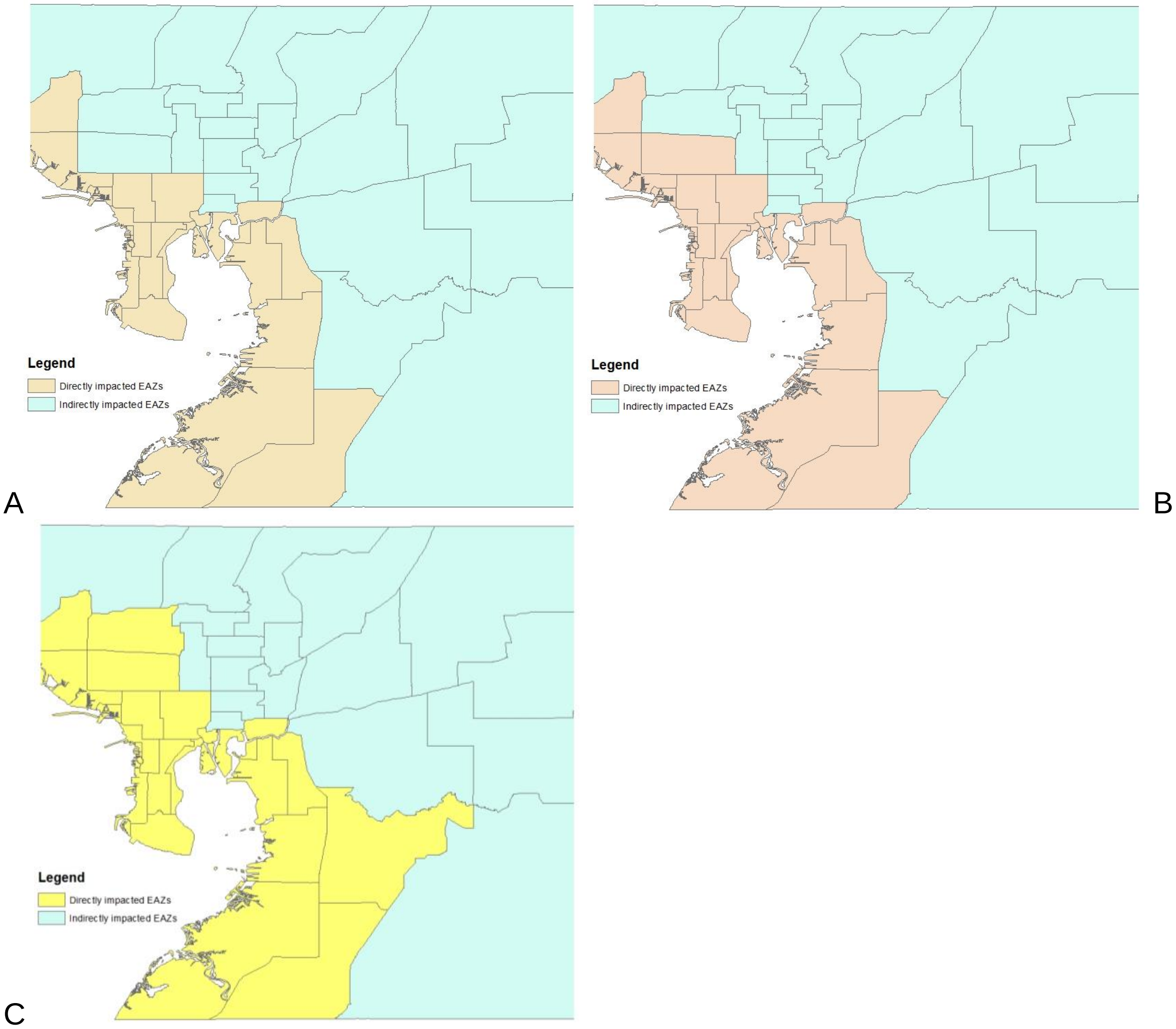


Figure 5-7. The directly and indirectly impacted EAZs under A) 1 foot sea level rise, B) 2 feet sea level rise, and C) 5 feet sea level rise (Created by Author)

The estimation of land value losses plug the values of dependent variables into the spatial econometric model built in section 5.3.1. Table 5-6 shows the land value loss from model calculation. It suggests that as sea level rises, the land value losses from direct inundation will increase. Because of spatial dependence, the decreased land value also impacts surrounding inland EAZs.

Table 5-6. Land value loss under different rising sea levels

Sea level rise	1 foot	2 feet	5 feet
Direct loss	2,217,016,149	2,481,451,721	4,345,311,093
Indirect loss	4,189,120,844	10,292,166,796	11,391,067,456
Total loss	6,406,136,993	12,773,618,517	15,736,378,549

5.4 Quantification of Losses of Business

5.4.1 Business Revenue Quantification

Due to the data unavailability of business revenue, this study cannot estimate the impacts on business directly. This study estimates business loss by linking the employment to business revenue. Since existing literatures suggest a close relationship between the percentages of payroll to gross revenue, this study uses the expenditure on payrolls to proximate the business revenue.

Since the average payroll of Hillsborough County is already available, the next challenge becomes the selection of payroll to gross revenue ratio. The safe zone for payroll expenditure falls between 15%-30% of total business revenue. When the ratio grows above 30%, the businesses have the risk of losing money (Harris, 1999). There is no data showing the business health in Hillsborough County. Therefore, this study assumes that all businesses in Hillsborough County are healthy but run on a 30% payroll percentage. As a result, the business revenue is estimated by:

Total business revenue = (Total number of employment * average personal income)/30%. With the average personal income given in Hillsborough County, the key of estimation is to calculate the change of employments.

5.4.2 Spatial Econometric Models for Employment Density

As presented in the previous section, employment for each EAZ is selected to link to business impact. Both total employments of each EAZ and employment density (per square kilometers) are loaded into R to test the spatial dependence of the variable. Table 5-7 shows the R outputs for Moran's I test. It suggests that Moran's I statistic is very high. Given that Moran's I ranges from -1 (means perfect dispersion) to 1 (means perfect correlation), this high Moran's I statistic indicates a strong spatial cluster for EAZs with similar average employments. This spatial correlation is further proved by significance test. Since the P value of the test is extremely low, it indicates a statistically strong spatial correlation.

Table 5-7. Moran's I test for average land value

Moran' I statistic	Expectation	Variance	Standard deviate	P-value
0.54	-0.02	0.01	6.79	5.5e-12

The spatial exploration in GeoDa also indicates a strong spatial dependence. Figure 5-7 illustrates LISA cluster map for average land value. The high-high and low-low locations suggest clustering of similar values, whereas the high-low and low-high locations indicate spatial outliers. Figure 5-8 suggests that there are 5 areas, with high average land value, that locate together; and 8 areas, with low average land value, that locate together. There is only 1 outlier identified. Although 24 areas do not turn out to be significant for clustering together, the areas with significant spatial association cover the majority of Hillsborough County.

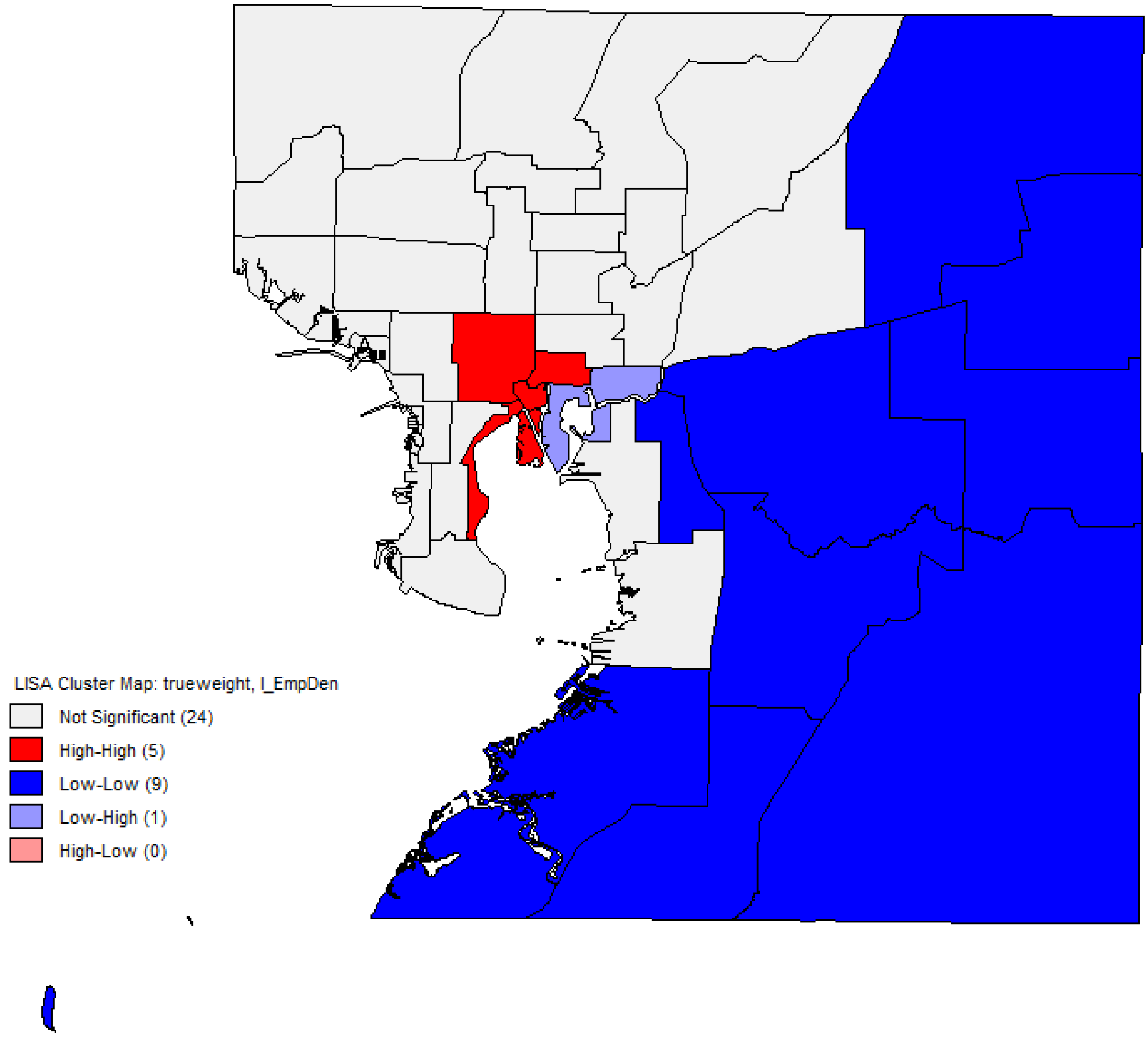


Figure 5-8. LISA cluster map for employment density (Created by Author)

A spatial association is also shown by LISA significance map (Figure 5-9). The significance map shows the locations with significant local Moran statistics in different shades of green. The green areas cover more land than grey areas. This means the variable representing average employment per square kilometers has strong spatial correlation.

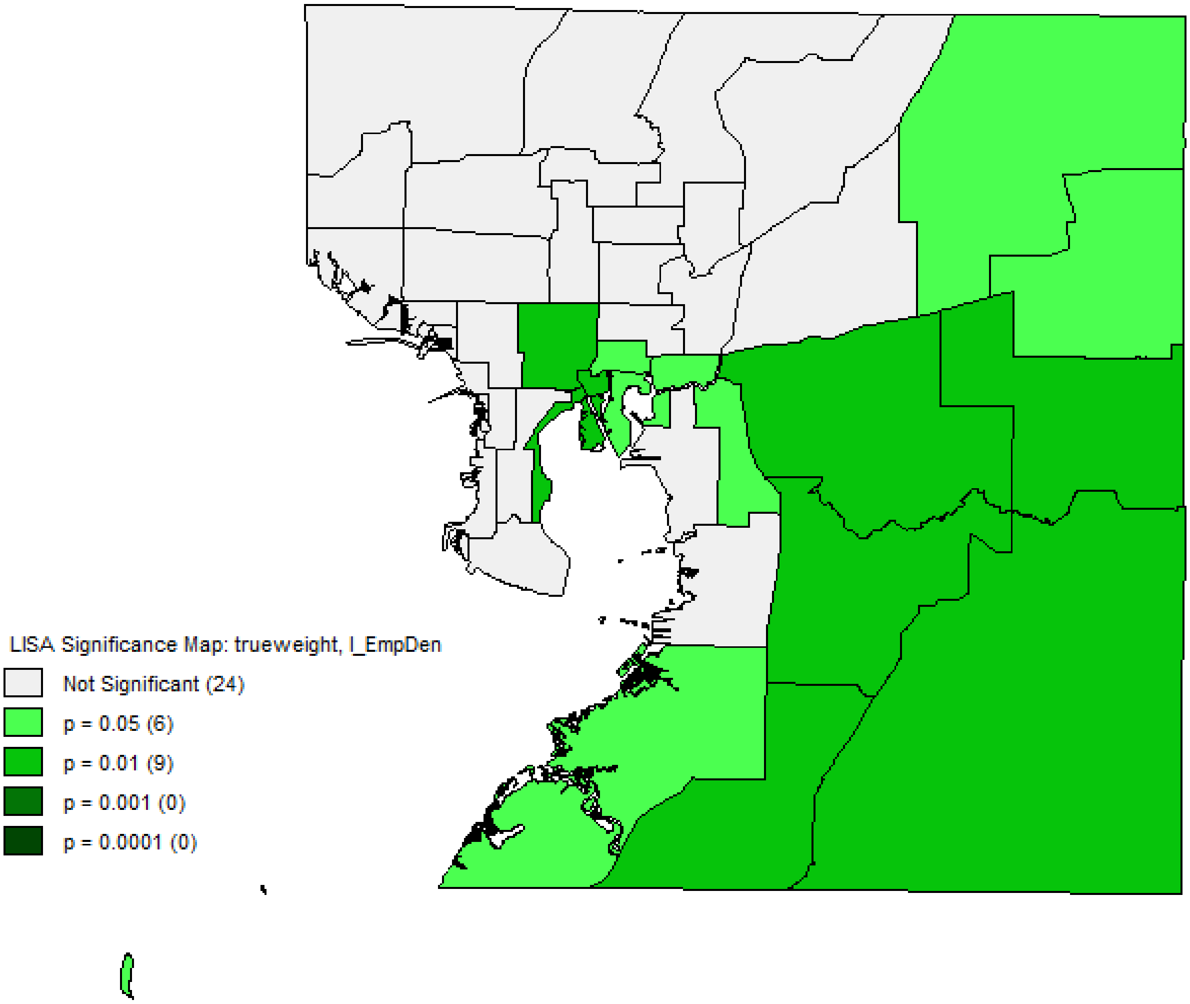


Figure 5-9. LISA significance map for average land value (Created by Author)

As presented in Chapter 3, the formal expression of spatial dependence model for average land value is:

$$Y = \rho\omega Y + \alpha X + \beta + \varepsilon \tag{5-4}$$

Where, Y is the dependent variable representing employment density of each EAZ; X represents a set of independent variables relating to EAZ's demographic characteristics; β is a constant; ρ is an autoregressive parameter, ω is spatial weight matrix specifying the relations between EAZs. ε is an independently and identically distributed error term.

GeoDa employs maximum likelihood estimation to estimate model parameters. Various independent variables were tested, including population density, building density, density of households with more than two cars, and density of households with different racial and income backgrounds. However, only population density turns out to generate best goodness of fit. Other tentative independent variables do not significantly increase the goodness of fit when adding more computation work. Therefore, the final model is:

$$EmpDens = \rho\omega \bullet EmpDens + \alpha \bullet PopDens + \beta + \varepsilon \tag{5-5}$$

The estimated parameters are shown in Table 5-8. The table also suggests that all the model parameters are statistically significant. This is because the probability of rejecting null hypothesis, which states none significance of dependent variable, is extremely small.

Table 5-8. Estimated model parameters

Variable	Coefficient	Std.Error	z-value	Probability
W_EMPDEN	0.59	0.07	7.96	0.00
POPDENS0	1.56	0.16	9.71	0.00
CONSTANT	-1318.59	393.04	-3.35	0.00

The model has a high goodness of fit with R-squared value equals to .87. R square ranges from 0 to 1. 0.84 suggests that the model can well explain the distribution of average land value. Furthermore, the absolute value of log likelihood is very high (Table 5-9). These all suggest that the established model is accurate to estimate average land value.

Table 5-9. Model goodness of fit

R-squared	Log likelihood	Akaike info criterion	S.E of regression
0.87	-351.50	709.00	1892.34

5.4.3 Comparison to Classic Statistical Models

In order to test the improvement of model by integrating spatial factors, the model building process also built a classic regression model without spatial dependence considered. The formal expression of the comparison model is:

$$EmpDens = \alpha \bullet PopDens + \beta + \varepsilon \tag{5-6}$$

Based on Table 5-12 and 5-13, we can conclude that the model parameter is still statistically significant (Table 5-10). However, by removing the spatial dependence, the model goodness of fit is greatly reduced (Table 5-11) by almost 19%.

Table 5-10. Model parameters of comparison model

Variable	Coefficient	Std.Error	z-value	Probability
POPDENS0	2.06	0.22	9.38	0.00
CONSTANT	-522.77	579.40	-0.90	0.37

Table 5-11. Goodness of fit of comparison model

R-squared	Adjusted R-squared	F-statistic	Log likelihood
0.70	0.70	88.00	-365.64

In order to further compare the spatial econometric model to classic regression model with no consideration for spatial lag impacts, this study used R to run a Lagrange Multiplier test to diagnose spatial dependence. Lagrange Multiplier test compares a spatial econometric model to a regression model by hypothesizing that the spatial parameter equals to zero which shows no spatial correlation. Table 5-12 shows the test results. Accordingly, the probability of accepting the null hypothesis is extremely small.

Therefore, the test concludes that average employment shows strong spatial lag effects and there is a need to involve spatial factors into estimation model.

Table 5-12. Lagrange multiplier diagnostics for spatial lag

Lagrange multiplier	Degree of freedom	P-value
19.9	1	1.3e-05

5.4.4 Estimation of the Loss of Business Revenue

The estimation process categorizes EAZs into two groups: the directly impacted areas and indirectly impacted areas as presented in Section 5.3.4. Table 5-13 indicates, as the sea level continues to rise, the case study area tends to lose employments. At the 1-foot sea level rise, the total number of employments will increase. Under the 2 feet and 5 feet sea level rises, the Hillsborough County will lose employments which indicate the loss of business revenues. This is so maybe because that under small sea level rise, coastal business tend to relocate to surrounding inland areas. But as sea level continues to rise, and the impacts become more and more serious, the coastal businesses tend to move further inland and cause the decrease of total employments in Hillsborough County.

Table 5-13. Estimated business losses

Rising sea levels	1 foot	2 feet	5feet
Direct employment loss	25,341	25,633	50,523
Indirect employment loss	-65,316	219,849	365,746
Total employment loss	-39,975	245,482	416,269
Total business loss	-$6,103,375,182	$37,480,216,764	$63,555,948,223

In summary, this chapter estimates the economic impacts of sea level rise on land use and business changes. As the analysis results show that land value and business revenue have strong spatial dependence. This suggests that the value change of directly impacted areas can impact inland areas as well. Without considering the value change of inland areas, the impacts of sea level rise will be underestimated. The study results show that the indirect losses are huge. So by applying spatial econometric models, this study better capture the direct and indirect losses of land value and business revenue caused by sea level rise.

CHAPTER 6
QUANTIFICATION OF ADAPTATION COSTS

This chapter focuses on quantifying the costs of sea level rise adaptation strategies. Firstly, it introduces the process used to select specific adaptation strategies, which are defined as sub-strategies, under analysis. This is followed by presenting the quantification process and results to assign monetary values to each strategy and the total cost for implementation.

6.1 Adaptation Strategy Specification

As presented in Chapter 2, the case study identified 6 sea level rise adaptation strategies which are categorized into 3 groups. However, these strategies are not specific enough for quantification. This is because first of all, some strategies include different measures of implementation. Structural protection of shoreline, for example, includes construction of sea walls, bulkheading, barrier islands, and riprap revetments. The construction cost can range from a hundred dollars to several thousand dollars per linear foot. Therefore, specific measure needs to be identified to represent the strategy. Secondly, some strategy needs to be well defined to clarify its meaning. For instance, public purchase can mean public ownership of the vulnerable lands by purchasing the property with public finance. Instead of owning the property, public agencies can purchase only the easement by paying the property owner a one-time payment or property tax deduction. Therefore, the quantification process needs further specify the identified adaptation strategies..

In order to specify adaptation strategies for quantification, this study established the following rules:

1. Represent the selected strategies. Literature reviews are employed to uncover the most commonly used sub-strategies which can represent the strategy to which the sub-strategies belonged.

2. Minimize uncertainties. The analysis will look into almost 100 years, therefore there are uncertainties associated with each strategy no matter how accurately it can simulate the future. However, different strategies have different degrees of uncertainties, such as future land use, policy change, etc. The strategies under quantitative analysis should have less unforeseeable factors so that its quantification can capture its condition in the future.

3. Easy for quantification. Some sub-strategies are technically difficult to be quantified. This may be caused by uncertainties which are linked to the second rule, or by the intense data requirement and engineering details. Take barrier islands for example. Barrier islands are made of sand or sediment that are parallel to inward coastline. They can function as a barrier to hold sea water back when sea level rises. However, the quantification of artificial barrier island construction or restoration needs to understand coastal profile, scale of construction, storm surge impacts which are beyond the scope of this study. Therefore, the selected sub-strategies need to be relatively straightforward for quantification with data availability and limited engineering background requirement.

4. Meet cost-efficiency requirement. Cost efficiency is defined as achieving the same goal with least cost (Borger & Kerstens, 1996). This rule may also relate to other rules. The expensive and less cost-efficient sub-strategies are not commonly employed by existing practices. These kinds of projects are often linked to overwhelming uncertainties that are difficult to be quantified. However, even some sub strategies can meet the previous rules, they may not pass the cost-efficiency check.

The selected sub-strategies are shown in Figure 6-1. As presented in Chapter 3, the adaptation strategies under analysis of this research focus on hard strategies which are associated with direct change of physical and built-up environments. The selected strategies now are grouped into three levels, including the strategy group, strategy and sub strategy. Each strategy group has two commonly adopted strategies to represent the group. Furthermore, each strategy has a sub strategy to match and represent that strategy. Therefore, there are 6 strategies and 6 associated sub-strategies under analysis. The sub-strategies will be detailed from section 6.3 through section 6.5 in this chapter.

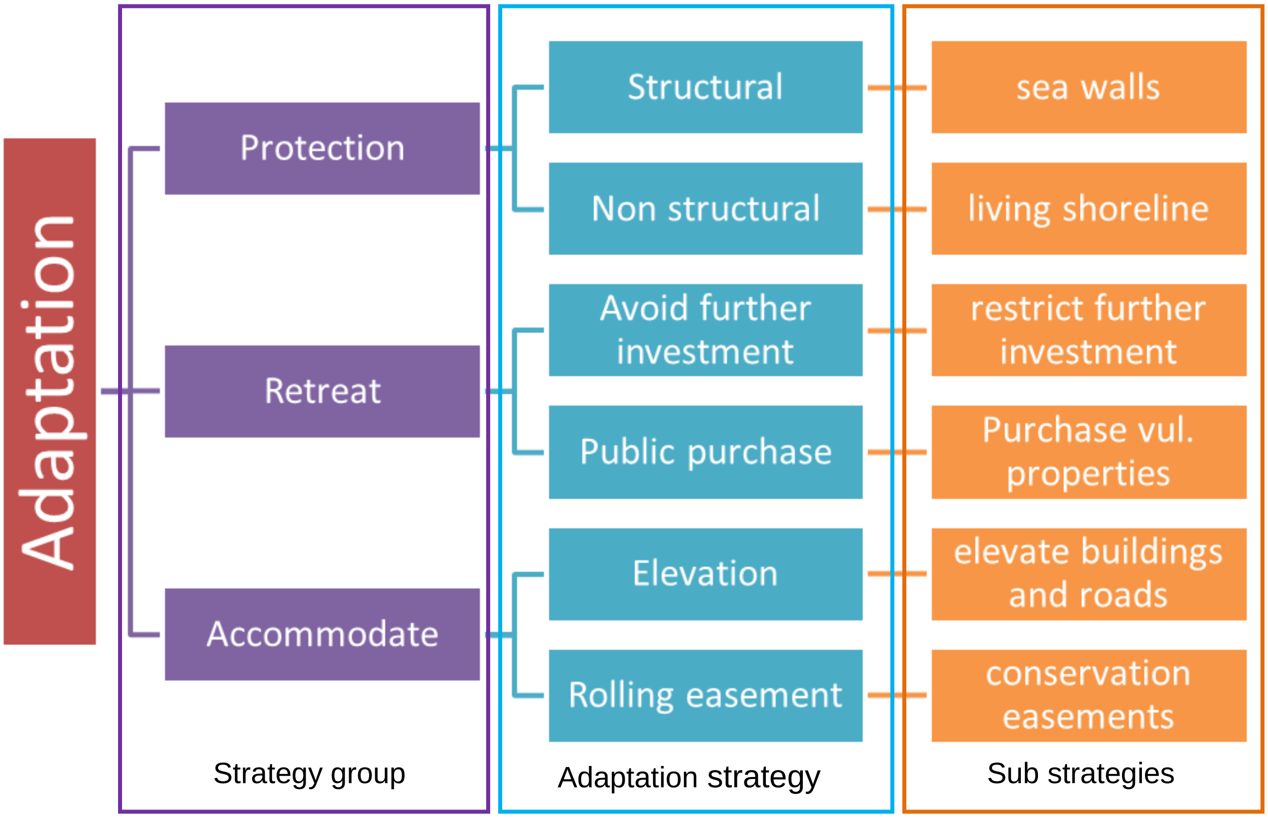


Figure 6-1. Selected adaptation strategies and its sub-strategies (Created by Author)

6.2 Sea Level Rise Scenarios for Quantifying the Costs of Adaptation

6.2.1 Hillsborough County Coastline

The quantification of adaptation follows the worst-case scenario generated by Climate Central (2013). Hillsborough County coastline data was downloaded from Florida Geographic Data Library (http://www.fgdl.org/metadataexplorer/explorer.jsp) as shown in Figure 6-2. The total length of Hillsborough County coastline is 918.38 miles. The length of coastal line in the Library includes both sea side costal lines and estuary coastal lines. The length of coastline changes as sea level rises since rising sea levels alternate coastal profile. However, this study assumes that as coastline retreats toward inland, the new coastlines are parallel to each other so that the length of coastline stays as constant.

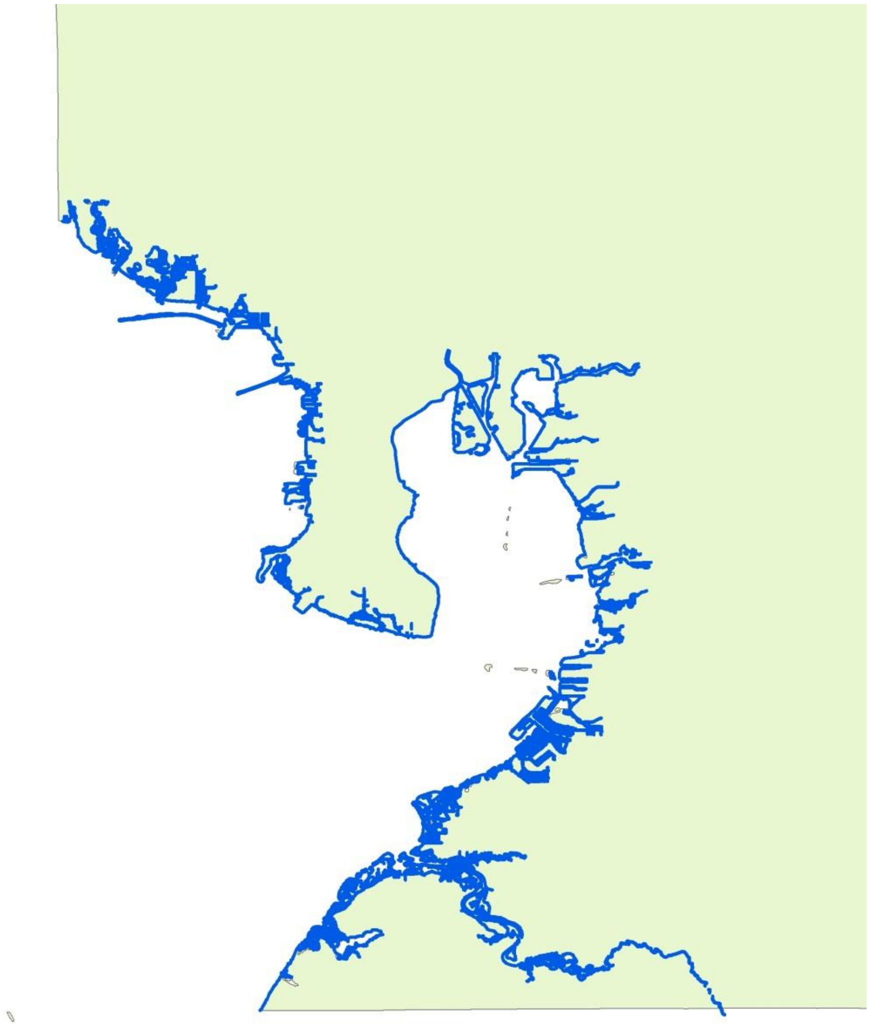


Figure 6-2. Hillsborough County coastline (Created by Author)

6.2.2. Critical Time Points

As presented in Chapter 4, this study considers the year 2013, 2040 and 2060 as critical time points when sea level rises 1 foot, 2 feet and 5 feet. In order to identify tipping points for implementation of adaptive strategies, this study defines two different kinds of time points: analysis time points and action time points.

6.2.2.1 Analysis time points

Analysis time points are defined as the year when adaptation strategies are updated to prepare for the next time period. There are four analysis time points being accounted into consideration: 2013, 2040, 2060 and 2100. Figure 6-3 illustrates how analysis time points work to help quantification. For example, when one adaptation strategy is implemented in 2013 when the sea level remains at the current level, it does not make sense if the strategy targets the current sea level. So actually, this strategy is implemented for future sea levels. Since the next analysis time point is 2040, this study assumes that its adaption is preparing for the year 2040 when sea level rises 1 foot. In the same manner, the adaption action in the year 2040 is preparing coastal areas to adapt to the sea level in 2060, which is 2 feet high. Between the two adjacent analysis time points, this study assumes that same strategy will keep constant.

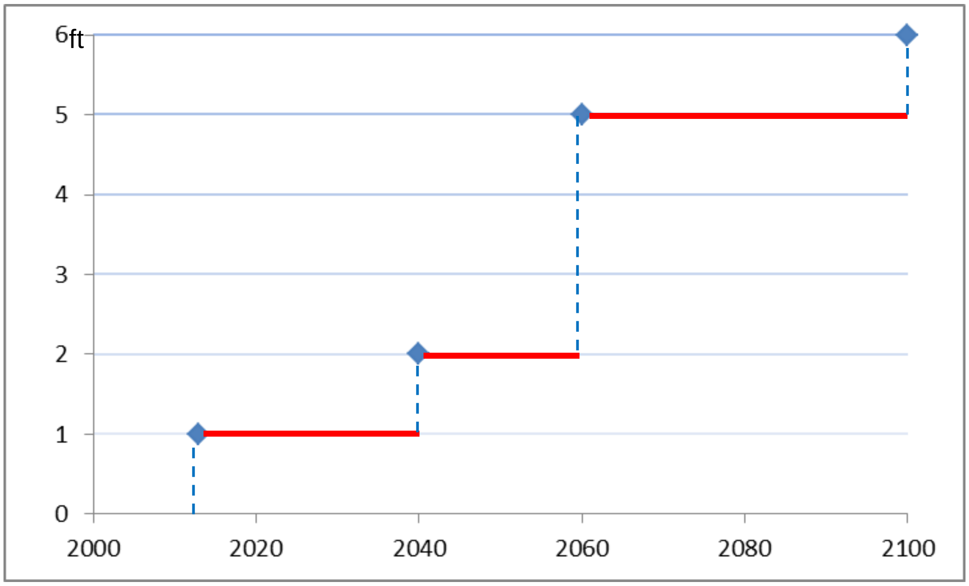


Figure 6-3. Analysis time points (Created by Author)

The reason to define analysis time point is twofold. First, this will make practical sense. Sea level rise is a slow process. Even under the worst case scenario, it takes almost 100 years to reach 5 feet high. Therefore, it makes more sense to implement a strategy in consideration of its lifespan. For example, the construction of sea walls is extremely expensive. A reasonable person will not construct a sea wall right now that target 5 feet sea level rise since this is not cost efficient, especially considering that the life span of sea walls range between 30 to 40 years. The existing cost quantification of adaptation strategies all assumes a one-time investment that targets 100 years period or longer (Eastern Research Group, 2013). Secondly, this measure will simplify the quantification analysis. The ideal way for adaptation analysis is to update the strategy annually. However, this requires estimation of sea level rise for each year and its associated inundation maps. Furthermore, the inundation maps need to be overlaid with other layers, such as parcel data. The work load will be overwhelmingly high. Therefore, by assuming each strategy will remain constant between two adjacent analysis time points can simplify the analysis process while still keeps relative accuracy of analysis.

6.2.2.2 Action time points

Action time points are defined as the year when a sea level rise adaptation strategy is implemented. As illustrated in Figure 6-4, there are three action time points, including the year 2013, 2040, and 2060. The year periods are the same with four analysis time points. However, these four action time points differentiate analysis into four scenarios. The major difference between two types of time points is that analysis time points apply to the same strategy for one scenario; action time points apply to the same strategy for three different scenarios. Action time point 2013 means adaptation is implemented right away; action time point 2040 means that adaptation will be implemented in the year 2040; action time points 2060 indicates adaptation action taken in the year 2060.

The three action time points present three scenarios under analysis. The first scenario assumes that immediate adaptation actions are taken place in 2013, which is the starting year of analysis. Under this scenario, all coastal areas will be covered by implementing various strategies.

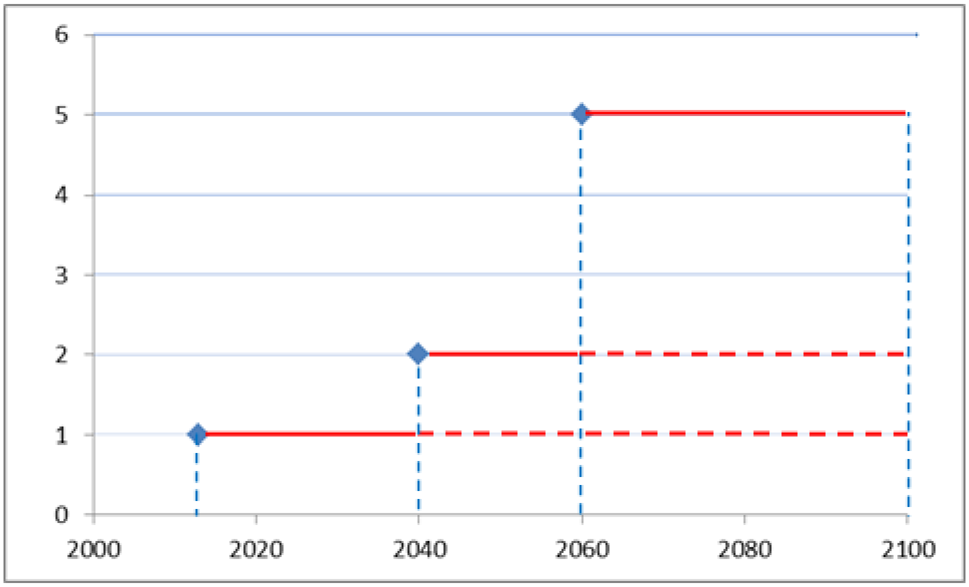


Figure 6-4 Illustration of action time points (Created by Author)

Scenario 2 assumes that all adaptation efforts will be taken in the year 2040. Under this scenario, there are already losses by 1 foot sea level rise. So the total benefits of adaptation will decrease. However, the adaptation costs will decrease too since rather than dealing with 5 feet sea level rise within 90 years, Scenarios 2 aims to adapt to 4 feet sea level rise. This number is obtained by the total 5 feet sea level rise minus the 1 foot sea level rise that is already present in the case study area.

The third scenario, Scenario 3, assumes the implementation of adaptation actions starting in the year 2060. Under this scenario, the sea water will have already inundated all the areas under 2 feet sea level rise. Therefore, the adoption of sea level rise adaptation strategies aim to prevent further losses that will be caused by 3 more feet sea level rise. The strategy implementation therefore targets 3 feet sea level rise. As a result, both the total benefits and costs will be reduced.

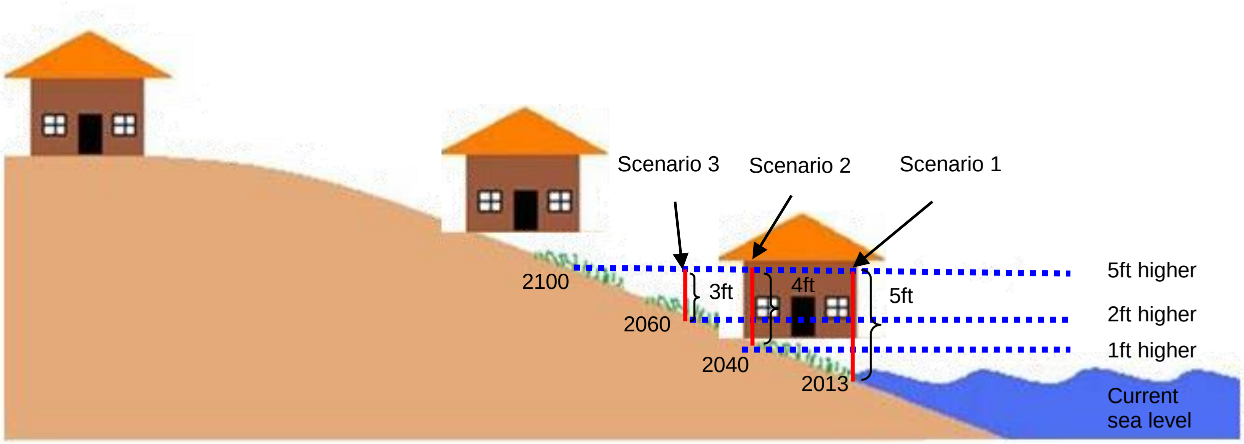


Figure 6-5 Illustration of 3 analysis scenarios (Created by Author)

6.3 Protection Strategies

As presented in previous sections, sub protection strategies under analysis include the construction of sea walls and establishment of living shoreline. The major purpose of these two sub strategies is to protect built environment from increasing sea level rise impacts.

6.3.1 The Cost of Constructing Sea Walls

The construction cost range is huge from $100 to $1,200 per linear foot depending on the height and designed life span of the projects (City of Marco Island, 2007; North Carolina Division of Coastal Management, 2011). This study assumes the sea wall projects focus on the lower end of the cost range as shown in Table 6-1. The costs are initial construction cost without considering maintenance cost.

Table 6-1. The construction cost of sea walls

Sea level rise	3 foot	4 feet	5 feet
Construct cost ($/linear foot)	300	400	500

According to the IPCC Fourth Assessment Report, the life span of seawalls is between 20-40 years. Since this study considers 2013, 2040, and 2060 as the action time point, it assumes the life span of seawalls construction in 2013, 2040 and 2060 have a life span of 30 years, 20 years and 40 years. This indicates the seawalls will reach their life span by the end of next action time point.

Table 6-2. Grading chart for common seawall repairs

Types of repairs	Average cost compared to cost for new seawall
Seal leaks	3%
Install drains	3%
Secondary anchors	30%
Cap and anchors	50%
Beam and anchors	45%
Beach and anchors with new cap	75%
Beach and anchors with new cap and anchors	85%
New low seawall in front of existing	90%
New seawall in front of existing seawall	100%

*Reproduced from DANN SAPP and SON, INC

DANN SAPP and SON, INC-a major seawall building and repair contractor, located in St. Petersburg, FL, quotes the maintenance cost for repairing sea walls (Table 6-2). Since this study already assumes the life spans for constructing seawalls, the annual maintenance cost falls under the lower range of the repair cost which is 3% to the cost of constructing a new sea wall. Table 6-3 shows the total adaptation cost for constructing sea walls for the three scenarios under three different discount rates.

Table 6-3. Total adaptation cost for seawalls (in millions)

Adaptation scenarios	Scenario 1	Scenario 2	Scenario 3
Discount rate 2.5%	4,597	2,734	1,801
Discount rate 5%	3,737	2,207	1,533
Discount rate 10%	3,133	1,982	1,460

6.3.2 Establishing Living Shorelines

The selection of living shore line strategy to represent non-structural protection strategy is in consideration of the coastal landscapes and functions in the case study area, the process of which is supported by Google Maps.

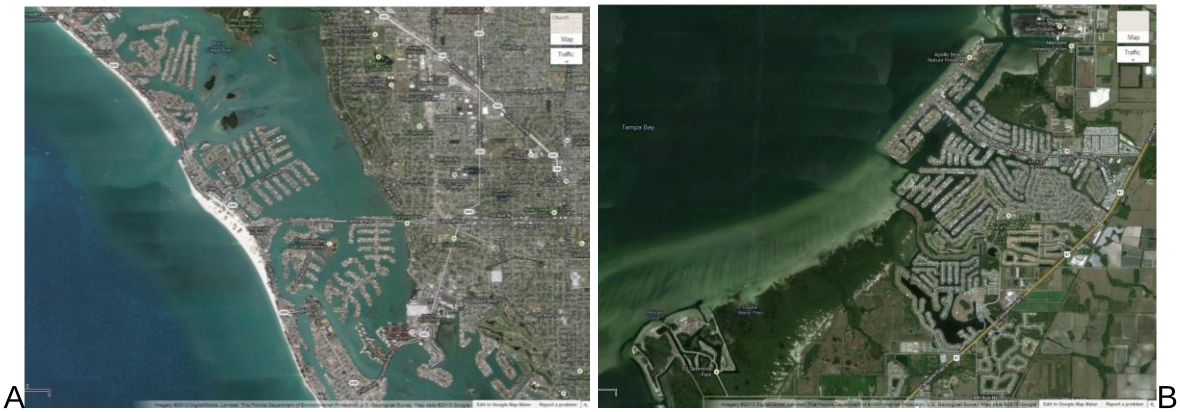


Figure 6-4. Air image of A) a recreational beach in Clear Water, and B) costal wetland near Tampa. (Source: Google Maps)

As Figure 6-4 shows, map B) is a typical air view of Hillsborough County's coastal areas which are different from recreational beaches illustrated in map A). For recreational beaches, beach nourishment is the best non-structural adaptation strategy. Beach nourishment strategy is able to maintain the sand on the beach so that the recreational function will remain.

However, for the vegetated coastal areas, establishing living shorelines provides a more natural approach for erosion control, which allowing access for coastal and estuarine organisms.

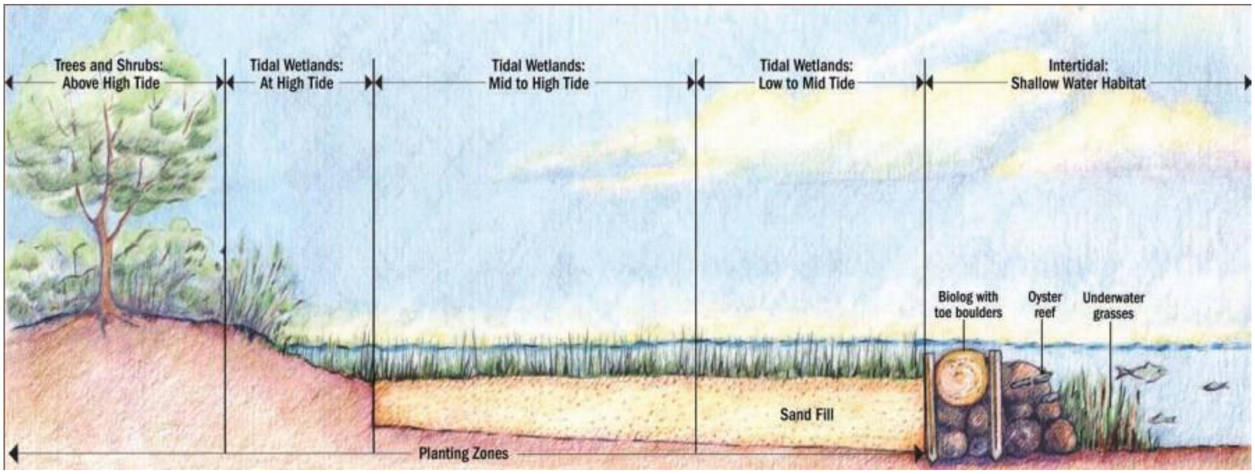


Figure 6-5. Illustration of living shorelines (Source: Debbie L. DeVore. 2010. Cost and maintenance of living shorelines. Vero Beach, FL: South Florida Ecological Service Office)

Figure 6-5 illustrates how living shorelines work in practice. The vulnerable areas are firstly filled with sand as the base to plant living vegetation on it. To better control coastal erosion, wooden or shell boulders are sometimes applied. The living shoreline cannot only better control coastal erosion, more importantly, it can protect inland ecosystems.

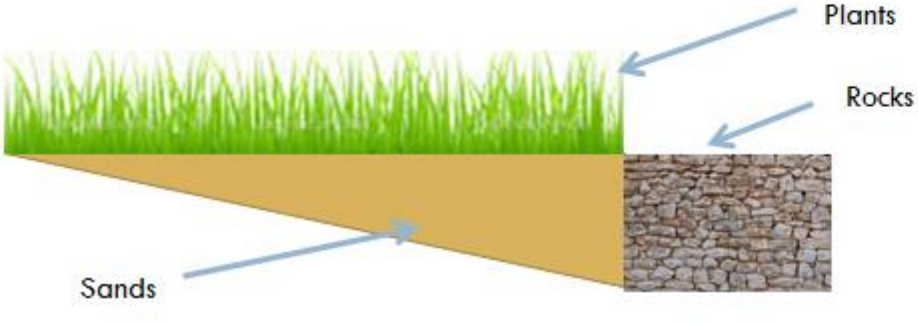


Figure 6-6. Living shoreline strategy in this study (Created by Author)

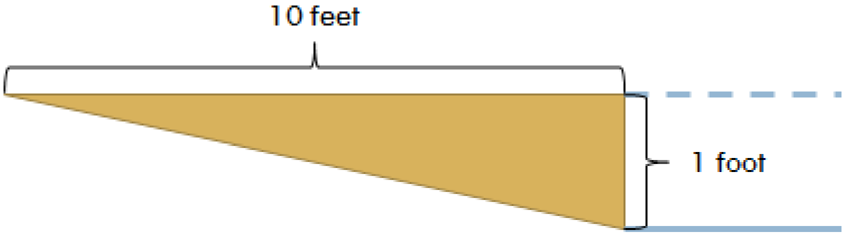


Figure 6-7. Coastal erosion based on Bruun Rule (Created by Author)

As Figure 6-6 shows, this study assumes a simple application of living shorelines by planting vegetation on filled sands with rocks controlling seaside erosion. The sand volumes needed is based on Bruun Rule. Bruun Rule provides a relationship between rising sea levels and the dynamic shoreline profile (Bruun, 1962). Although in the past decades, a large number of studies trying to modify Bruun Rule to better capture the relationship, it is still widely recognized as an effective tool to capture beach profile movement as sea level rises (Rosati, Dean & Walton, 2013). As Figure 6-7 illustrates, the simple version of Bruun Rule argues that one unit of sea level rise will erode 10 times more coast line horizontally. The eroded coastal profile is assumed to have triangle shape.

The unit cost for filling sands heavily depends on the moving distance. According to a report published by the U.S. EPA in 1989 (Leatherman, 1989), the sand filling coast is \$4/cubic yard for sand reserve within on mile of the shore. There is another \$1/cubic yard for each additional mile offshore. The sand requirements and near shore sand reserve determines the unit cost for sand movement. Leatherman (1989) estimated the sand volume required to apply beach nourishment to adapt to different rising sea levels for the State of Florida. As Table 6-4 shows, in order to adapt to 1 foot sea level rise, beach nourishment projects consume sands within 3 miles offshore. Therefore, the unit cost in 1989 value is 4+(4+1)+(4+1+1)=15 \$/ $yard^3$. Table 6-4 shows the unit costs for different sea levels in present value.

Table 6-4. Sand volume needed and unit cost

Sea level rise	3 feet	4 feet	5 feet
Sand requirements (million $yard^3$)	230	307	384
Distance offshore (mile)	3	4	5
Sand reserve (million $yard^3$)	269	317	417
Cost in 1989 (\$/ $yard^3$)	15	22	29
Cost in present value (\$/ $yard^3$)	28.18	41.33	54.48

The surface planting combines the use of Smooth Cordgrass and Saltmeadow Cordgrass. These two species fit the needs of both tidal areas and dry land areas. According to the U.S. Department of Agriculture (USDA), Smooth Cordgrass grow along tidal salt marshes that is extensively used for erosion control in sea water soil interface. Saltmeadow Cordgrass, instead, grows on dry land such as coastal beaches or barrier islands to protect shoreline and stabilize dunes. Furthermore, as Figure 5-8 illustrates, both species grow in Florida.

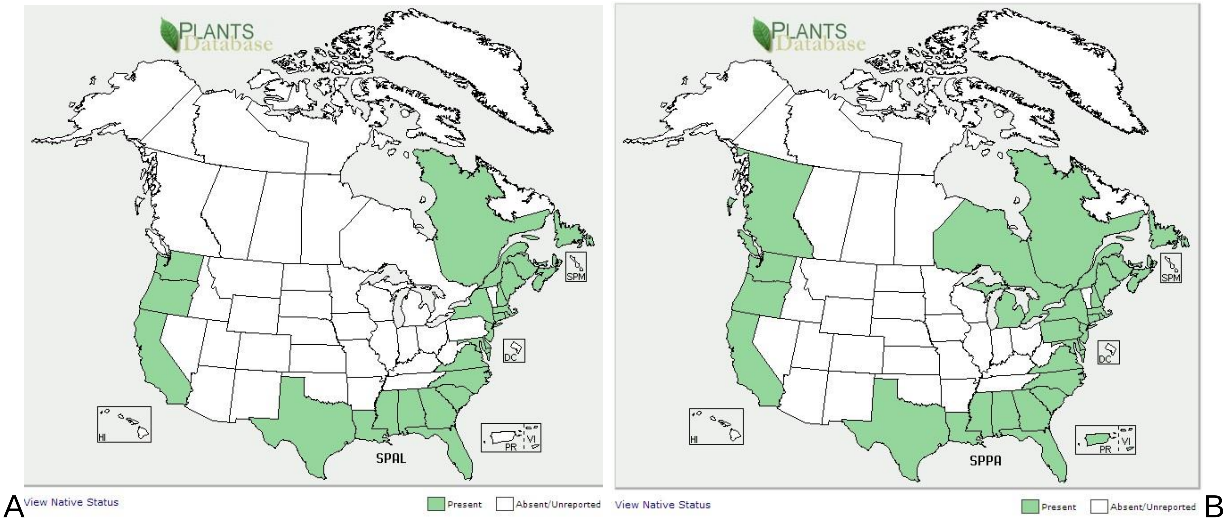


Figure 6-8. The species growing areas of A) Smooth Cordgrass and B) Saltmeadow Cordgrass (Source: USDA, Natural Resources Conservation Service, at: http://plants.usda.gov/core/profile?symbol=sppa)

Table 6-5. The adaptation costs of living shoreline under different discount rates (in millions)

	2.50%	5%	10%
Scenario 1	3,244	3,086	3,009
Scenario 2	1,946	1,846	1,811
Scenario 3	918	867	853

The planting cost for the two species is the same. The cost of one plug is $1.25 (DeVore, 2012). In the planting process, the spacing distance is between 2’ and 4’ (DeVore, 2012). That means each plug covers about10ft^2, therefore the unit cost is 0.125ft^2. In order to maximize the life span of living shoreline projects, limestone rock is selected to control the sand erosion, which costs $125 per linear foot. Since the living shorelines crate a living environment which sustains itself, only minimal maintenance is required.

6.4 Accommodation Strategies

6.4.1 Conservation Easement

Conservation easement is one type of rolling easement which enables coastal society to gradually adapt to rising sea levels while enabling ecosystems to migrate inland. U.S. EPA Climate Ready Estuaries published a report in 2011 to introduce the concepts and approaches of rolling easement (Titus, 2011). The report divides rolling easement into three categories which represent three ways of thinking about a rolling easement, including easement, conservation easement, and covenants; defeasible estates and future interests in land; and ambulatory boundaries. Among the three, conservation easement is selected to represent rolling easement strategy since it better fits the selection criteria set for sub-strategy selection.

By signing a conservation easement, the land owners are required to avoid any activities harmful to natural environment. Usually, the ownership of conservation easement is limited to government or public agencies, such as land trust. Conservation easement is not a new approach. Instead, it has been the most significant tool used to prevent developing environment sensitive areas (Sundberg & Dye, 2006). Some land trusts and government agencies can pay full value for the rights extinguished in a conservation easement. More often, they are only able to acquire these rights through either a “bargain sale” (below fair market value) or a donation. Therefore, the cost of conservation easement is different case by case.

However, by studying actual conservation expenditures by various conservation organizations totaling more than $2.5 billion over 15 years, World Resources Institute suggests that each acre protected with a conservation easement costs on average $2,000 (World Resources Institute 2002) in the year 2002. By considering the inflation between 2002 and 2013, the average cost of conservation easement per acre is $2,589.85. Table 6-6 shows the adaptation cost for conservation easement.

Table 6-6. Adaptation cost of conservation easement (in millions)

	Scenario 1	Scenario 2	Scenario 3
Total cost	$113	$83	$78

6.4.2 Structure Elevation

This specific strategy involves the elevation of vulnerable buildings as well as the elevation of vulnerable roads.

The elevation of buildings is a complicated engineering process involving various factors such as building material, types of use and foundations. According to Federal Emergency Management Agency (FEMA), the techniques for building elevation can be grouped into two categories (FEMA, 2009), including the lifting of foundation and elevation of upper floors.

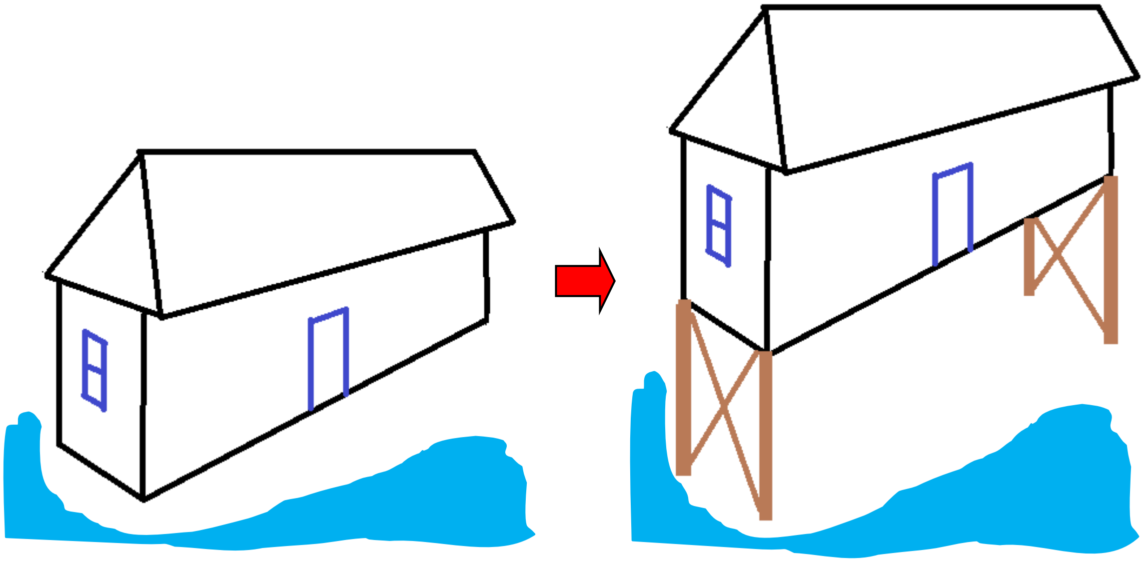


Figure 6-9. Building elevation by lifting foundatoin (Created by Author)

Figure 6-9 illustrates the first category which aims to elevate the building by adding a new or extending an existing foundation below it. In practices, piles and columns are used to support the lifted foundation.

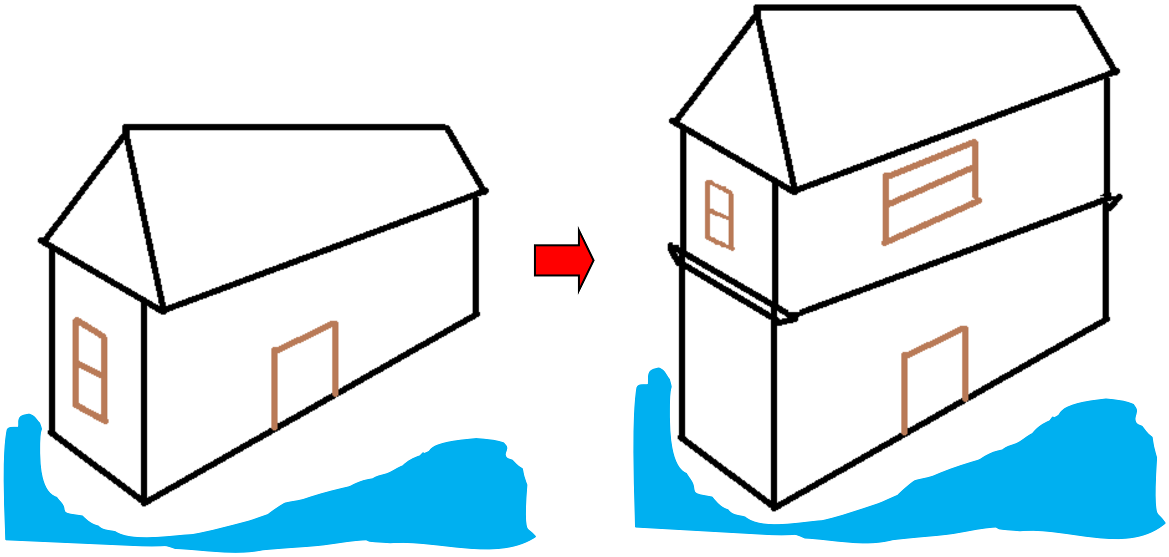


Figure 6-10. Building elevation by adding upper stories (Created by Author)

Figure 6-10 shows the other building elevation technique which keeps the original foundation but either building an elevated floor within the house or adding a new upper story. By adding upper stories, first floor will be used for garage or basement. The best fit technique heavily depends on the type of foundations. According to FEMA (2007), elevation of different types of foundations is associated with different costs (Table 6-7). Since there is no data showing the foundation types for each building in Hillsborough, this study uses average unit cost which is $39 per square feet.

Table 6-7. The elevation cost for different types of foundations

Foundation Type	Wood-frame building on piles, posts, or columns	Wood frame on concrete or block foundation walls	Brick walls	Slab-on-grade
Unit Cost ($/SF)	36	32	43	45

However, the quantification of elevation costs needs the floor area of each building which is unavailable and extremely time consuming to count manually. The best available data is to use the living area as a proxy. Since dominant building pattern in Hillsborough County is one-story, this proxy is reasonable. The total number of livings areas and associated total adaptation costs are shown in Table 6-8.

Table 6-8. Total adaptation costs for building elevation (in millions)

Scenarios	Scenario 1	Scenario 2	Scenario 3
Total living areas (SF)	147	81	65
Total adaptation costs	$5,734	$3,187	$2,552

For road elevation, the average cost per centerline mile is estimated to be $8 million for elevating 5 feet, $4 million for elevating 2 feet, and $2 million for elevating 1 foot. The total adaptation cost is shown in Table 6-9. The total adaptation costs considering both roads and buildings are shown in Table 6-10.

Table 6-9. Total adaptation cost of road elevation

Scenarios	Scenario 1	Scenario 2	Scenario 3
Total living areas (mile)	422.74	257.24	248.64
Total adaptation costs (millions)	$3,381	$1,028	$497

Table 6-10. Total adaptation cost for structure elevation strategy (in millions)

Scenarios	Scenario 1	Scenario 2	Scenario 3
Total adaptation costs	$9,116	$4,216	$3,049

6.5 Retreat Strategies

Retreat strategy group includes two sub strategies: avoid further investment in vulnerable areas and use public money to purchase vulnerable properties. The avoidance of further investment is the retreat response for sea level rise. That is, employing policies and zoning ordinances to avoid further development in these vulnerable areas to minimize risks and prepare for an eventual retreat. This is similar to a business-as-usual scenario.

Public purchase strategy is a straightforward retreat response. The purchase is a typical property acquisition strategy, which asks local government to determine the most vulnerable properties and raise funds to purchase the property and assist the owners at risk to relocate. The acquired property can then be used for conservation or recreation purposes. The two strategies target for a planned retreat. The major difference between investment avoidance strategy and public purchase strategy is that under investment avoidance strategy, it is hard to estimate when people are going to leave the vulnerable areas. However, under public purchase strategy, government can well control the timing and pace of relocation to maximize the benefits. The adaptation cost for public purchase strategy is monetary value of vulnerable properties. The total costs for the two sub strategies under retreat strategy group are listed in Table 6-11.

Table 6-11. Adaptation costs for investment avoidance and public purchase

Scenarios	Scenario 1	Scenario 2	Scenario 3
Investment avoidance	0	0	0
Public purchase (in millions)	$3,729	$2,481	$2,217

In summary, this chapter estimates the costs of sea level rise adaptation based on three scenarios which assume the identified strategies are implemented in the year 2013, 2040 and 2060. The results show that the implementation costs for adapting these strategies are in a large number. In the next chapter, these costs of implementation will be compared with its benefits to calculate the cost efficiency for each strategy and find the tipping point for taking adaptation actions.

CHAPTER 7
COST EFFICIENCY AND TIPPING POINT ANALYSIS

This chapter first analyzes the cost efficiency of each strategy. Then it evaluates the action time points for each strategy. The cost efficiency and action time point provide foundation for an adaptation plan proposed in this research. The cost efficiency of the adaptation plan is also analyzed. Finally, uncertainty analysis is conducted to evaluate the impacts of uncertain sea level rise projections.

7.1 Cost Efficiency Analysis

Different strategies have very different impacts on economic variables. The loss for some strategies could be benefit for others. For example, sea wall construction interferes with natural wetland conversion. Therefore, sea wall will reduce the eco service values of wetlands. In comparison, conservation easement enables natural migration of wetlands. Thus, adoption of conservation easement increases the service values of wetlands. Table 7-1 summarizes the different impacts for each strategy on selected economic variables.

Table 7-1. Impacts of adaptation strategies on different variables

Variables	Land value	Business revenue	Wetland conversion	Building damage	Transport-ation
Sea wall	P ↑	P ↑	N ↓	P ↑	P ↑
Living shoreline	P ↑	P ↑	P ↑	P ↑	P ↑
Elevation	H↕	P ↑	P ↑	P ↑	P ↑
Easement	N ↓	N ↓	P ↑	N ↓	P ↑
Public purchase	N ↓	N ↓	P ↑	N ↓	P ↑
Avoidance	N ↓	N ↓	H↕	N ↓	N ↓

Note: the notation of P ↑ means positive impacts; N ↓ means negative impacts; H↕ means partially positive impacts

In Table 7-1, P indicates the strategy has positive impacts on a certain variable. This means that strategy can stabilize the variable to maintain its values. N indicates a negative impact that reduces the value of a certain economic variable. H indicates partially positive impact that can stabilize some parts of the values. The impact fall under this notation is the impact of elevation strategies on land values, and the impact of further investment avoidance on wetlands. Elevation of structures can prevent the buildings and structure from losing their functions. But since the land is still going to be inundated, the vulnerable lands will lose parts of its values. By avoiding further investments, the migration path of wetlands can be cleared, but there is no guarantee that the owners are willing to tier the vulnerable buildings down, wetland migration will still be impacted. For the partial impact, this study assumes half of the total values will be lost.

Table 7-2. Cost efficiency under Scenario 1

Strategies	Sea wall	Living shoreline	Elevat-ion	Easem-ent	Public purchase	Avoidance
Total benefits	$86,533	$87,103	$79,234	-$82,119	-$82,119	-$86,675
Total costs	$3,737	$3,086	$9,116	$113	$3,729	$0
B/C ratio	23	28	9	-728	-22	NA
Net benefits	$82,795	$84,017	$70,119	-$82,232	-$85,849	-$86,675

Note: money is in million dollars

Table 7-3. Cost efficiency under Scenario 2

Strategies	Sea wall	Living shoreline	Elevat-ion	Easem-ent	Public purchase	Avoidance
Total benefits	$80,702	$81,178	$67,183	-$80,677	-$80,677	-$80,821
Total costs	$2,207	$1,846	$4,216	$83	$2,481	$0
B/C ratio	37	44	16	-976	-33	NA
Net benefits	$78,495	$79,332	$62,967	-$80,759	-$83,158	-$80,821

Note: money is in million dollars

Table 7-4. Cost efficiency under Scenario 3

Strategies	Sea wall	Living shoreline	Elevat-ion	Easem-ent	Public purchase	Avoidance
Total benefits	$30,099	$30,373	$28,892	-$28,604	-$28,604	-$28,686
Total costs	$1,533	$867	$3,049	$78	$2,217	$0
B/C ratio	20	35	9	-366	-13	NA
Net benefits	$28,566	$29,506	$25,843	-$28,682	-$30,821	-$28,686

Note: money is in million dollars

This study employs both benefit-cost ratio and net benefits to represent the cost efficiency of each strategy. As Table 7-2 through 7-4 show, for all the three scenarios, construction of sea wall, establishment of living shorelines, and elevation of structures have positive net benefits in very large numbers. In comparison, adoption of conservation easement, public purchase and avoidance of further investment are not worth to be implemented since their implementation will lost money. The reason why this is the case is because the built environment values are more than natural environments because built environment has greater economic impacts. If a strategy is designed to protect only natural environment in sacrifice of the built environment, it needs to be carefully designed to minimize the impacts on built environment.

Among the cost efficient strategies, living shoreline is proven to be more cost efficient since under each of the three scenarios, living shoreline strategy has the highest benefit-cost ratio. That indicates that the same investment on building living shoreline can generate the highest returns. This is so because this strategy focuses on protecting both built and natural environment that generate the greatest total benefits.

Among the less cost efficient strategies, public purchase has the lowest cost efficiency even lower than a do-nothing strategy, since the implementation cost is huge. For the cost efficient strategies, later actions reduce both benefits and costs However, since benefits decrease much faster than costs, the total present values of net benefits will decrease sharply. This implies that the longer we wait to take adaptation actions, the fewer benefits we will get.

7.2 Tipping Point Analysis

A tipping point in this study indicates the time point to take adaptive actions. As presented in the section 7.1, this study divides all the selected strategies into two groups, the ones that generate benefits if being implemented; and the ones that lose money if being adopted. As Figure 7-1 and 7-2 illustrates, the tipping point for cost efficient strategies is the year 2013 which provides the highest net benefits. The tipping point for unprofitable strategy is infinite since no matter how, they are still going to lose money if being adopted.

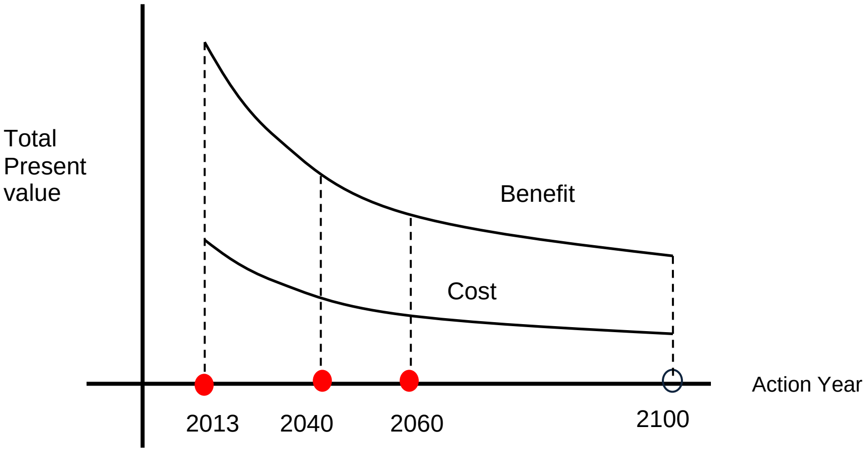


Figure 7-1. Benefit/cost curve for profitable strategies (Created by Author)

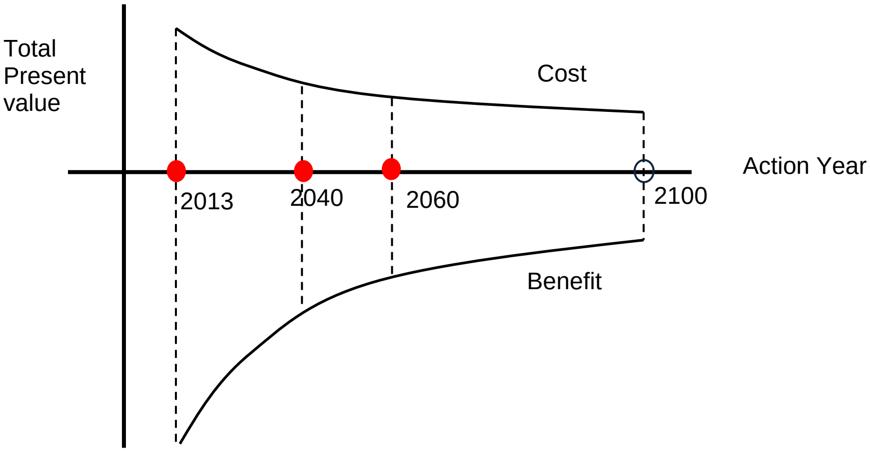


Figure 7-2. Benefit/cost curve for unprofitable strategies (Created by Author)

However, there is a need to realize that each strategy is assumed to be applied to the whole vulnerable coastal areas. Therefore, an infinite tipping point for unprofitable strategies does not mean that strategy should never being adopted. The implication is that those strategies should not have large scale application, especially for the areas with built environment as the dominant land use pattern.

It also needs to be cautious to extend the analysis out of the analysis time range. The starting point of analysis is 2013, when profitable strategies have highest net benefits. However, it is incorrect to imply that if those strategies were adopted much earlier than 2013, it will have greater net benefits. The results of analysis only apply to the time range between 2013 and 2100, as well as the areas that potential sea water will inundate.

7.3 Proposed Adaptation Plan

Section 7.1 and 7.2 in this chapter analyze the cost efficiency of each strategy and its tipping point for action. The reason to assume that the whole coast line is adopting a single strategy is that, by applying only one strategy, it is earlier to exclude the economic impacts of strategies from each other. However, this assumption only works to capture the characteristics of each strategy, such as how efficiently each strategy performs to protect built environment or preserve ecosystems. The assumption does not have practical value in guiding sea level rise adaptation plan. Therefore, in order to bridge this gap, this section proposes an adaptation plan and analyzes its cost efficiency.

There are very few existing literatures that conduct location specific adaptation plans, which propose adaptation strategies for specific locations. Most sea level rise adaptation plans discuss adaptation strategies at policy level, rather than relating those strategies to appropriate locations. The adaptation plan, Sea Level Rise in the Tampa Bay Region (Tampa Bay Regional Planning Council, 2006), developed by Tampa Bay Regional Planning Council is among the few plans that make effort to link adaptation strategies to coastal areas. The plan divides coastal areas of Tampa Bay region into four groups, including no protection, protection unlikely, protection reasonably likely and protection almost certain. The division is based on existing land use and potential vulnerability to sea level rise. The majority of the study areas are classified as protection almost certain. However, this division focuses protection strategy only and leaves out other available adaptation strategies which have been analyzed in this study. This study tries to bridge this gap by assigning the selected strategies to coastal areas and better guide sea level rise adaptation actions.

This study assigns the 6 selected strategies to the study area based on future land use and the characteristics of each strategy, including cost efficiency for different land uses and action time points. Figure 7-3 shows the future land use map of Hillsborough County. Inland areas include seven land uses: agriculture, barren land, rangeland, urban and built-up land, wetlands, upland forest and land for transportation. This study integrates the future land use change by use the future projected land use map. However, it does not consider the land use dynamics. This is because the simulation of land use dynamics alone is very complicated and it alone can be a separate dissertation research.

As the analysis results in section 7.1 and 7.2 indicate, different strategies fit different land uses from an economic point of view. Some strategies can protect built environment in a cost-efficient way, such as sea wall; some strategies can encourage natural wetland migration, such as a conservation easement; while some others can balance the protection of built environment and ecosystem, such as living shoreline and structure elevation.

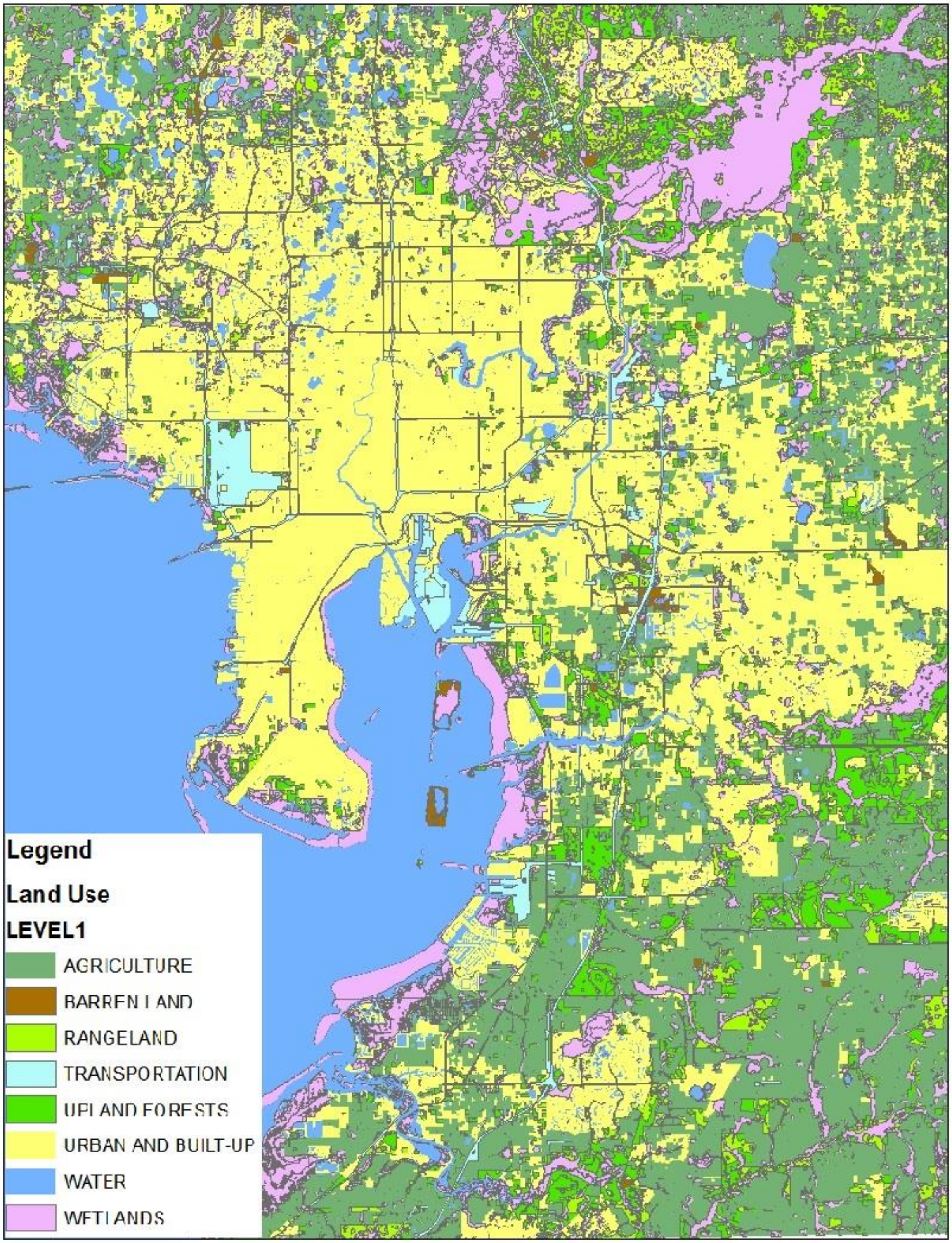


Figure 7-3. Hillsborough County future land use map (Created by Author)

Table 7-5. Sea level rise adaptation strategies and their fitted land use types

Strategy	Fitted area type	Corresponding formal land use type
Sea wall	Built up land close to the sea	Urban and built-up Transportation
Living shoreline	Built up land with wetlands as buffers separating it from the sea	Wetland Urban and built-up Transportation
Elevation	Single family residential land, and roads with wetlands as buffers separating it from the sea	Wetland Urban and built-up Transportation
Easement	Lands that continue the current use with little interruption on built-up lands	Agriculture Barren lands Rangeland
Avoidance	Wetland-dominant areas with little built-up lands	Wetland Barren lands Rangeland
Purchase	Wetland-dominant areas with small amount of built-up land	Wetland Urban and built-up Rangeland

Table 7-5 shows the fitted land use types for each strategy. The linkage between each strategy and its land use type consider the land use code specified on Figure 7-3. Rather than listing the general land use code, the fitted land use explains the characteristics that a certain type of land uses fitted to each strategy. This can differentiate the similar land uses. For example, sea wall construction and establishment of living shorelines both target on urban and built up areas. But since living shoreline also aims to preserve coastal wetlands, this study assigns the strategy to the areas that have a mix of both built and natural environment.

It also links the fitted land use to the formal land use types (shown in Figure 7-3) which are defined by Florida Land Cover and Land Use Classification System (FLUSS). This way, the adaptation strategy assignment can match the future land use map, so that each strategy can be assigned to appropriate areas.

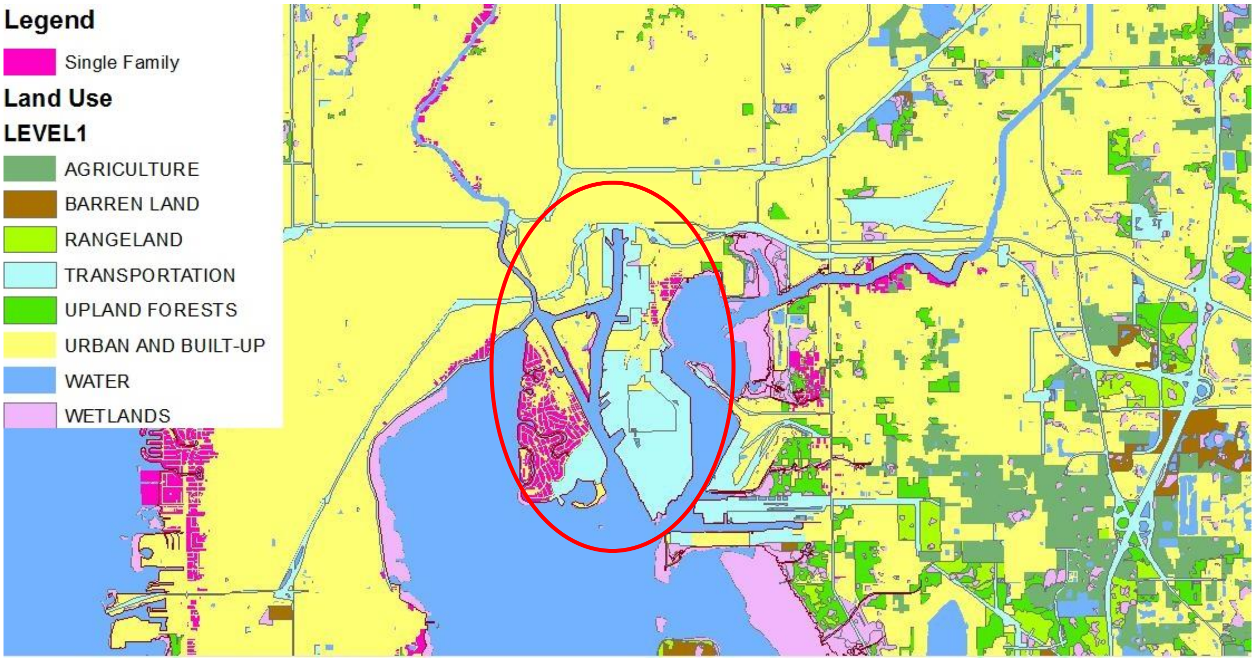


Figure 7-4. Example of areas fitted for sea wall within red circle (Created by Author)

As Figure 7-4 shows, the construction of sea wall fits the built-up areas (including areas for transportation) that are directly next to the sea. This is because sea wall can protect built environment but damaging natural systems at the same time.

Figure 7-5. Example of areas fitted for living shoreline (Created by Author)

Figure 7-5 illustrates the example of areas fitted for living shoreline. Living shoreline balances the protection of built up areas and the preservation of wetlands. Sea wall construction and establishment of living shorelines both target on urban and built up areas. But since living shoreline also aims to preserve coastal wetlands, this study assigns the strategy to the areas that have a mix of both built and natural environment. Therefore, the fitted areas for this strategy have a mix of both built up lands and wetlands with wetlands separating the built-up lands from the sea.

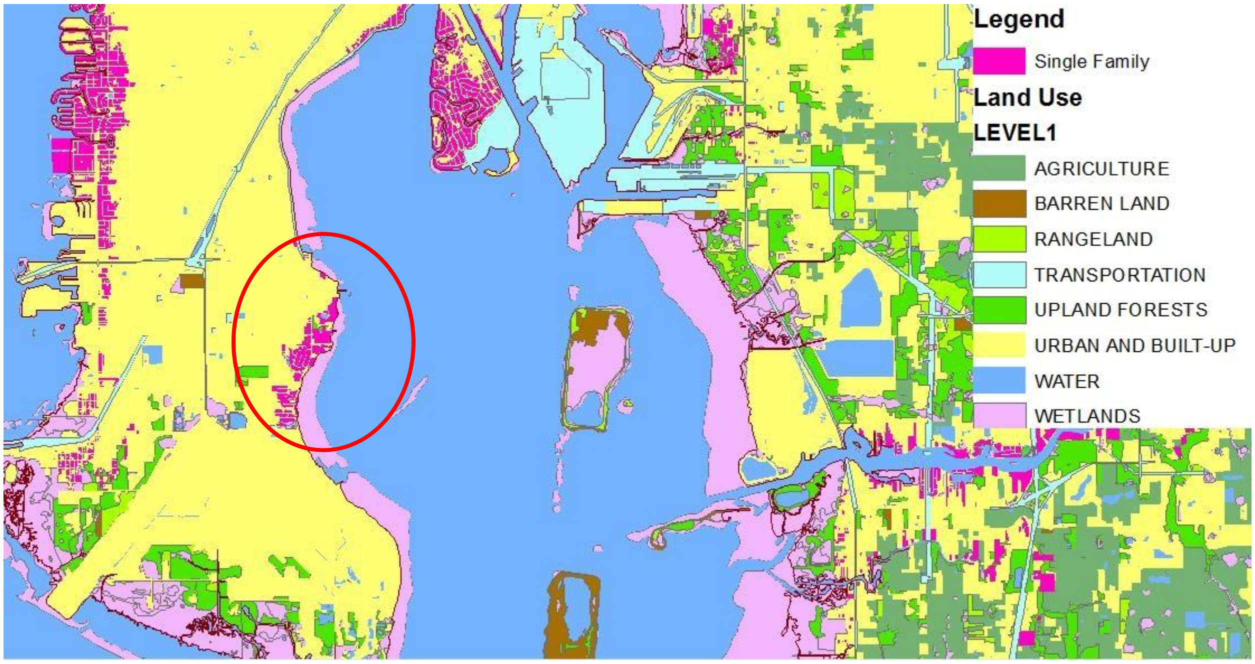


Figure 7-6. Example of areas fitted for structural elevation (Created by Author)

Structural elevation can continue the existing use of the structure while allowing wetlands to migrate. However, the elevation of large buildings in terms of both bulk and height is technically challenging and economically inefficient. Therefore, the application of building elevation focuses on single family houses as illustrated in purple on the map. As Figure 7-6 shows, the areas that fit for structural elevation focus on single family residential lands that are separated by wetland buffer from the sea.

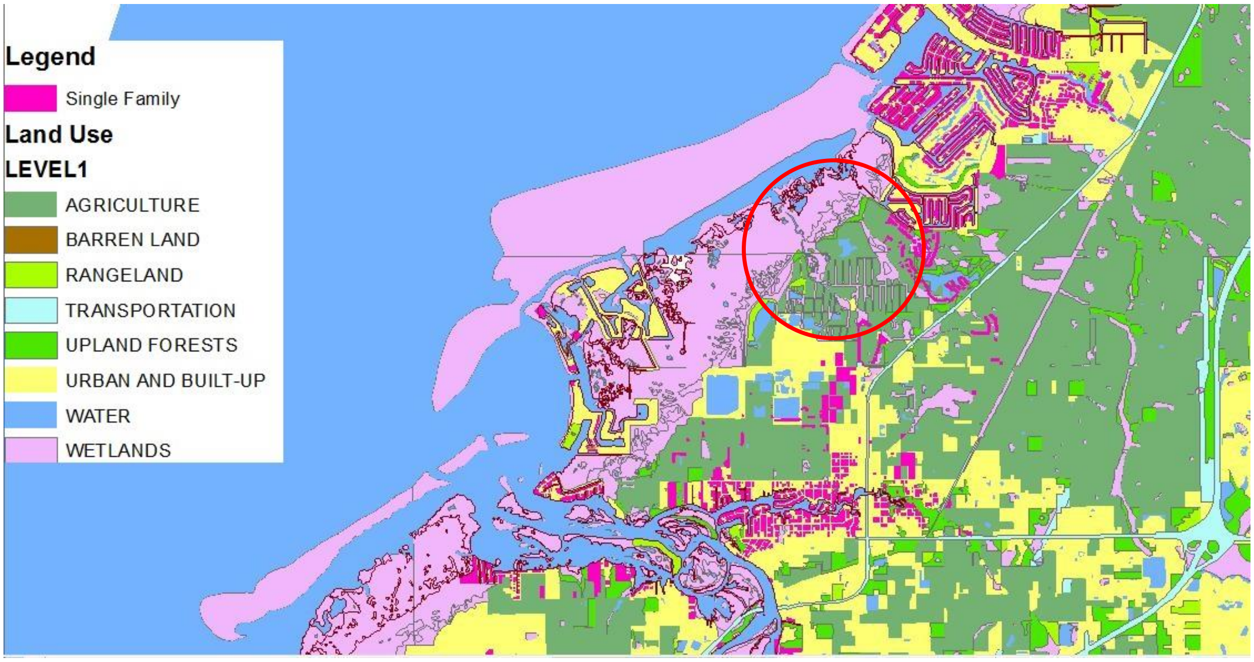


Figure 7-7. Example of areas fitted for conservation easement (Created by Author)

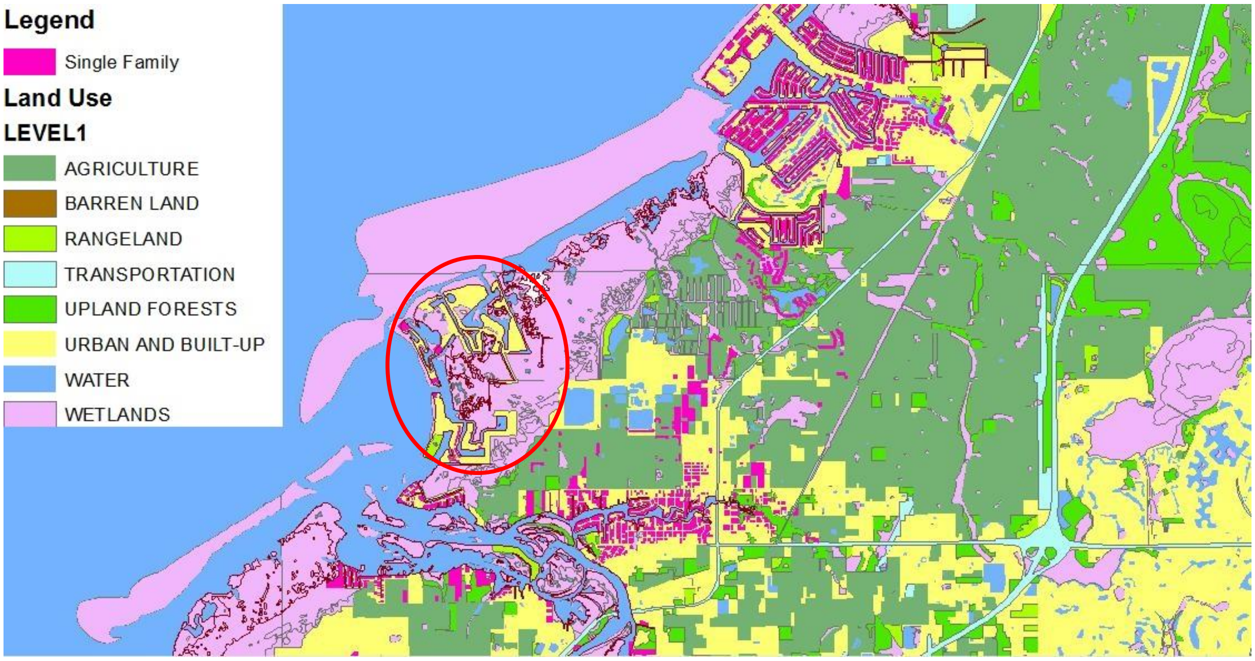


Figure 7-8. Example of areas fitted for public purchase (Created by Author)

Conservation easement fits agriculture land the best. When sea level rises, conservation easement will restrict the use of the lands that block the natural migration of wetlands. This strategy does not fit the built-up land since paying the property owner to give up the built up areas are not cost efficient overall. However, farmland is a good candidate for conservation easement since giving up farmland will not damage built up areas while restricting farmers to further build hard structures to block the path of wetland migration. Furthermore, after selling the easement of farmlands, farmers can continue to use the land before sea level rise inundates it.

Figure 7-8 illustrates the example of areas fitted for public purchase. The major purpose of public purchase is to clear the way for wetland migration while compensating vulnerable property owners. Since in practice, local government or land trust have limited funding, this strategy can only be implemented at small scale with less property owners involved. Therefore, the fitted areas for this strategy are small areas surrounded by wetlands.

Figure 7-9. Example of areas fitted for avoiding further investments (Created by Author)

Figure 7-9 shows the example of areas that fit for avoiding further investment strategy. As the analysis results of this strategy indicate, avoiding further investment will greatly put potential danger to built environment although it can clear the migration path of wetlands and avoid greater economic loss by investing on the vulnerable properties. Therefore, this strategy fit the areas that are currently less developed.

The planning period for this adaptation plan is still 2100 when Hillsborough County face 5 feet sea level rise. Therefore, the plan targets on the areas that are vulnerable to 5 feet sea level rise. This research assigns each strategy to its appropriate areas based on the above discussion. The final adaptation plan is illustrated in Figure 7-10. It shows that the coastal areas have a good mix of different adaptation strategies. There is no dominant strategy. Various strategies are distributed relatively evenly along the coast.

The adaptation areas that adopt the proposed strategy are the areas that vulnerable to 5-foot sea level rise. Specifically, the adaptation area for each strategy is bounded by shoreline and landward intrusion boundary of 5-foot sea level (Figure 7-11).

After proposing the adaptation plan, this research calculates the costs and benefits of the plan at three action time points which are consistent with previous analysis. As table 7-6 shows, the adaptation plan has positive net benefits with large numbers if being implemented in the year 2013, 2040 and 2060. Furthermore, the benefit –cost ratio (BCR) at the three time points are all much greater than 1. These results mean that the proposed adaptation plan is very cost efficient. This cost efficiency is also seen throughout the three scenarios.

Table 7-6. Costs and benefits of adaptation plan

Scenarios	Benefits (in millions)	Costs (in millions)	Benefit –cost ratio	Net benefits (in millions)
Scenario 1	87,103	2,404	36	84,698
Scenario 2	81,178	1,360	60	79,818
Scenario 3	30,373	1,167	26	29,206

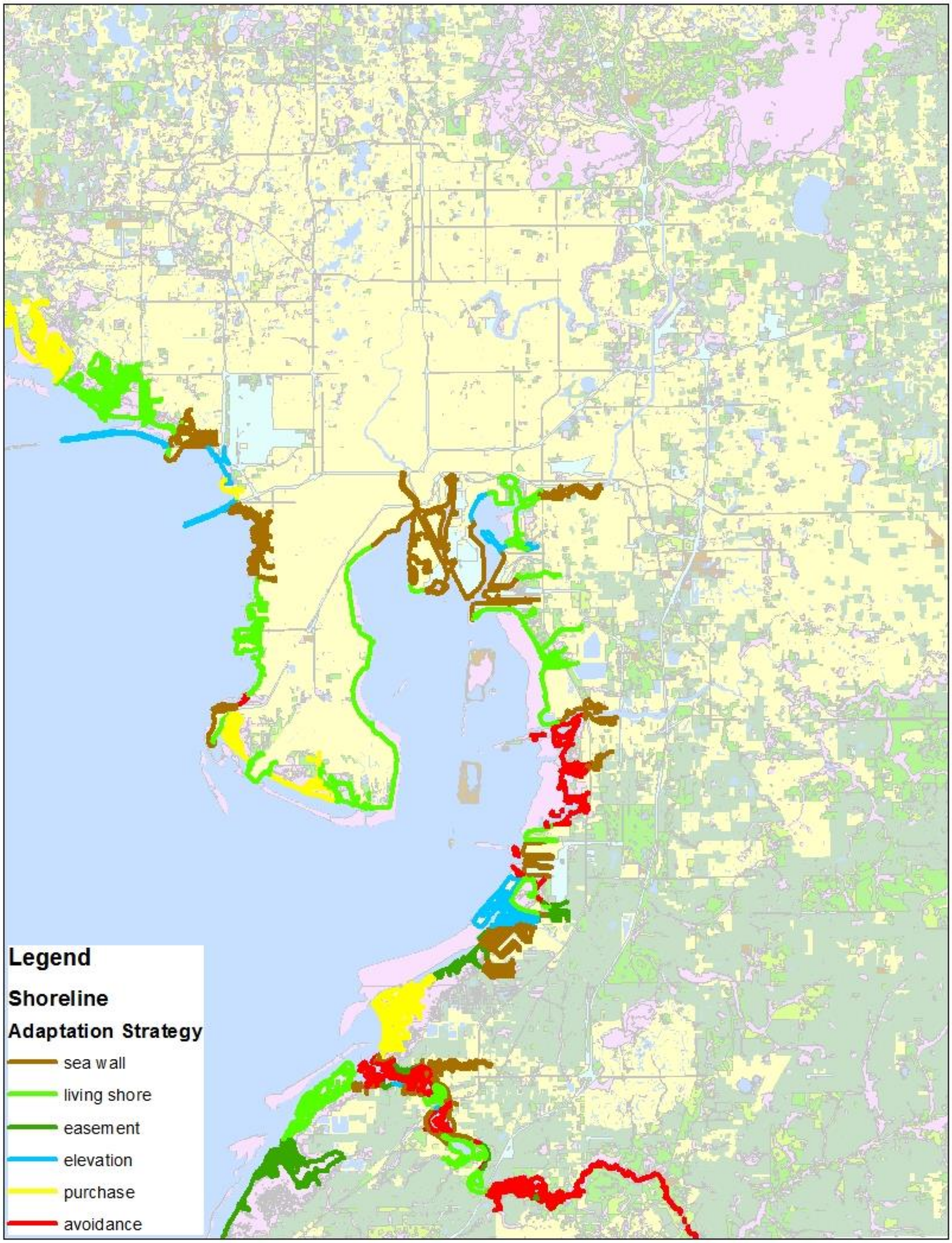


Figure 7-10. Adaptation plan for Hillsborough County, FL (Created by Author)

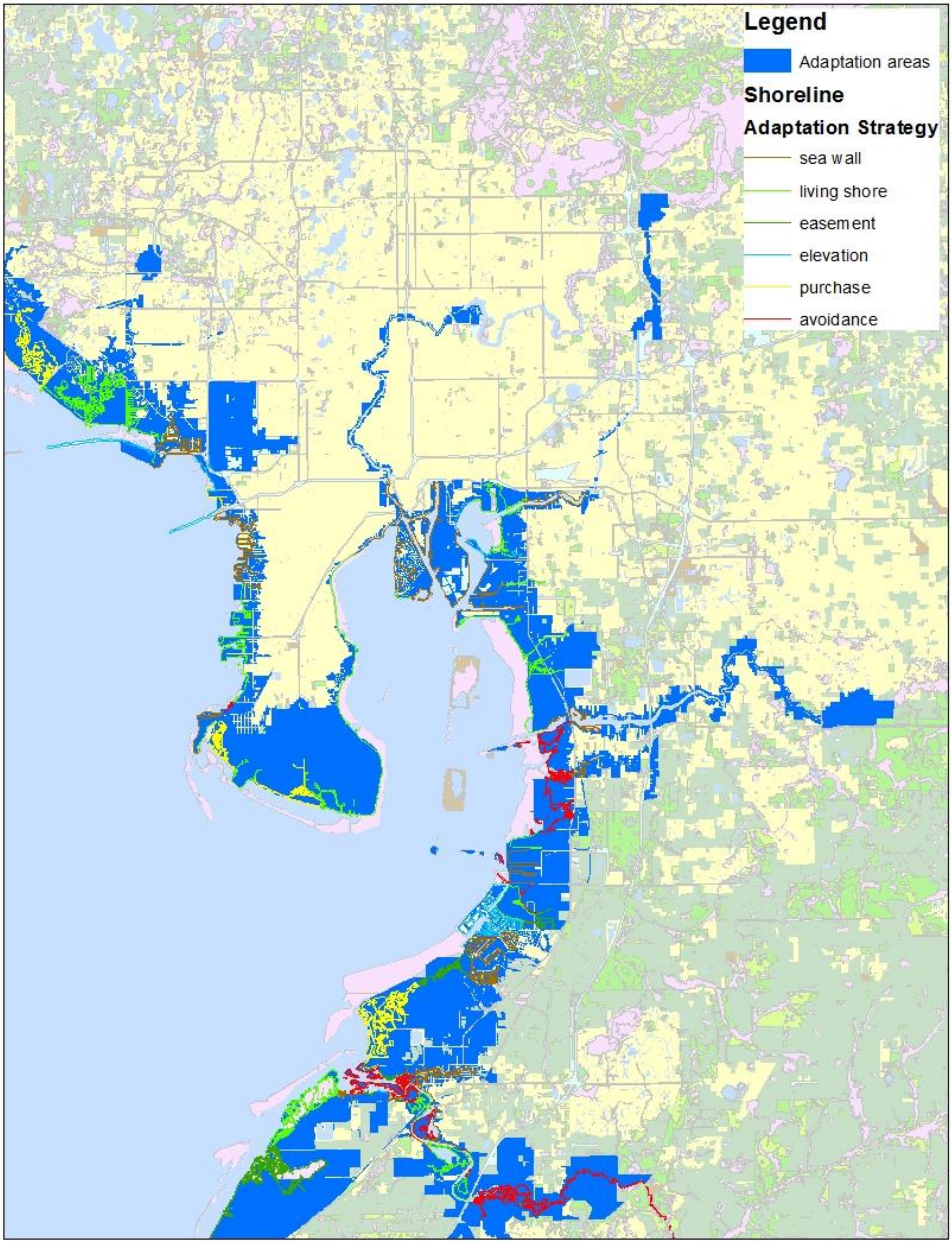


Figure 7-11. Adaptation areas for the proposed adaptation plan (Created by Author)

Based on this cost-benefit analysis, local decision makers can feel confident to invest into sea level rise adaptation plan. The timing of implementation or adoption of the plan is still subject to different perspectives. If the decision maker prefers the greatest investment return, he/she should take action in an early manner, since the earlier the implementation is, the greater the net benefits will be. Some decision makers favor higher benefit cost ration, which indicates the same amount of investment can generate more benefits. The choice between higher BCR and higher net benefits is greatly impacted by funding constraints in practice (Sassone & Schaffer, 1978). With the absence of funding as major constraint, a reasonable decision is to favor the implementation time point that has higher net benefits. But with limited funding, decision makers can choose to select a time point that has highest BCR.

7.4 Uncertainty Analysis

As presented in Chapter 2, sea level rise estimation is associated with various uncertainties. Therefore, the projection of sea level rise has not achieved consensus. This research employs the worst case scenario developed by Climate Central (2013) based on the most recent tidal gauge data. However, the worst case scenario is not ensured to happen. Instead, the likelihood of worst case scenario is based on the assumption that human beings will continue to emit greenhouse gas in the same speed. Furthermore, there is also no consensus on the semi-empirical models that are widely used for sea level rise projection. By adding more factors into the projection models, the projection can be very different. For instance, after adding the change of ice-sheet dynamics in the 5th Assessment Report, Intergovernmental Panel of Climate Change (IPCC) estimates the global sea level rise 60% higher than its 4th version. Therefore, there is a strong need to capture the projection uncertainties embedded in model assumption and framework, so that the analysis results can better represent the future reality and avoid bias toward higher sea level.

Development of probability-based projections is a commonly recognized tool to capture uncertainties associated with sea level rise (Titus & Narayanan, 1995). By assigning possibility to projected sea levels, the estimation of probability-based model can present uncertainties associated with the projection process. Schaeffer et al (2012) employed semi-empirical model to link possibility of greenhouse gas emission scenarios to the change of temperatures, which in turn impact future sea levels. The analysis results show the global sea levels in the year 2100 rise between 59 and 102 cm with associated probability of 95%(almost certain) to 5% (most unlikely). Obeysekera et al (2013) also integrate uncertainty for acceleration at the local level (Key West, FL) into probabilistic models, which specify probabilistic density for acceleration distribution. The modeling results report the 5th and 95th percentile of mean sea level rise which range between 27 and 177cm. Rather than developing a single model to estimate sea level rise under various possibility levels, Houston (2013) develop models for each of the 4 major contributor of sea level rise based on IPCC 4th Assessment Report, including Greenland ice melting, Antarctica dynamics, thermal expansion, and Glaciers & ice caps. The models generate sea level changes come from each contributor under 5%, 50% and 95% uncertainty levels.

However, the existing uncertainty analysis does not catch up with the newly released data from IPCC's 5th Assessment Report. Therefore, existing studies do not provide possibility of the worst case scenario in this study. Therefore, the uncertainty analysis in this study does not assign fixed probability to the selected sea level rise scenario, instead, it analyzes sea level rise adaptation strategies and the proposed adaptation plan under a series of probabilities, ranging from almost certain (95%) to very unlikely (5%). These probabilities are incorporated into cost benefit analysis to capture the impacts of uncertainty. The net benefit (NB) and benefit cost ratio (BCR), which represent cost efficiency, are calculated by the following equations:

$$NB_{ij} = B_{ij} \times P_{uj} - C_{ij} \tag{7-1}$$

$$NB_{ij} = \frac{B_{ij} \times P_{uj}}{C_{ij}} \tag{7-2}$$

Where, B_{ij} and C_{ij} are the benefits and costs of adaptation strategy i under scenario j; P_{uj} is uncertainty level u for scenario j, including 5%(very unlikely), 25%(unlikely), 50%(medium), 75%(likely), 95%(almost certain).

Table 7-7. Benefit cost ratio (BCR) under 3 scenarios at different uncertainty level for each adaptation strategy

Scenarios	strategy	5%	25%	50%	75%	95%
Scenario1	Sea wall	1.2	5.8	11.6	17.4	22.0
	Living shoreline	1.4	7.1	14.1	21.2	26.8
	Elevation	0.4	2.2	4.3	6.5	8.3
	Easement	-36.4	-182.1	-364.2	-546.4	-692.1
	Public purchase	-1.1	-5.5	-11.0	-16.5	-20.9
	Avoidance	NA	NA	NA	NA	NA
Scenario 2	Sea wall	1.8	9.1	18.3	27.4	34.7
	Living shoreline	2.2	11.0	22.0	33.0	41.8
	Elevation	0.8	4.0	8.0	12.0	15.1
	Easement	-48.8	-244.1	-488.2	-732.3	-927.6
	Public purchase	-1.6	-8.1	-16.3	-24.4	-30.9
	Avoidance	NA	NA	NA	NA	NA
Scenario 3	Sea wall	1.0	4.9	9.8	14.7	18.6
	Living shoreline	1.8	8.8	17.5	26.3	33.3
	Elevation	0.5	2.4	4.7	7.1	9.0
	Easement	-18.3	-91.6	-183.2	-274.9	-348.2
	Public purchase	-0.6	-3.2	-6.5	-9.7	-12.3
	Avoidance	NA	NA	NA	NA	NA

As Table 7-7 shows, when the probability of worst case scenario decreases, the BCR decreases sharply. Generally speaking, similar to the results presented in Section 7.1, building sea walls, establishing living shorelines, and elevating structures are cost efficiency for most uncertainty levels. The major difference is the elevation strategy under the highest uncertainty level, under which the elevation strategy is not cost efficient. Furthermore, for the highest uncertainty level, only living shoreline strategy proves to be cost efficient throughout the three scenarios. Building sea walls is cost efficient when being implemented in an early manner since the investment has the similar amount of return when being implemented in 2060. Net benefits (NB) shown in Table 7-8 also coincide with the conclusions drawn from the BCR analysis. The cost efficiency of building sea walls is more obvious in Table 7-8, although BCR ratio equals to 1 for scenario 3 under highest uncertainty level, the NB indicates a negative investment return which means that it is not worthwhile to implement it.

The uncertainty analysis of each strategy also highlights the cost efficiency of living shoreline. Even for the third scenario under highest uncertainty level, establishing living shorelines is still cost efficient. This suggests that a strategy that can balance the protection of built environment and preservation of ecosystems are cost efficient.

Table 7-9 shows the cost efficiency of the proposed adaptation plan under different uncertainties. The implantation of the plan in different action time point is cost efficient even under the highest uncertainty level, which represents 5% probability of worst case scenario. This means that, although the projection of sea level rise is associated with high uncertainty, adaptation actions are strongly recommended in an early manner to ensure high investment returns.

Table 7-8. Net benefits (NB) under 3 scenarios at different uncertainty level for each adaptation strategy (unit is in million $)

Scenario	strategy	5%	25%	50%	75%	95%
Scenario1	Sea wall	589.4	17896.0	39529.1	61162.3	78468.8
	Living shoreline	1269.6	18690.1	40465.7	62241.4	79661.9
	Elevation	-5153.8	10693.1	30501.7	50310.3	66157.2
	Easement	-4218.7	-20642.6	-41172.4	-61702.2	-78126.1
	Public purchase	-7835.4	-24259.3	-44789.2	-65319.0	-81742.9
	Avoidance	-4333.8	-21668.8	-43337.6	-65006.3	-82341.4
Scenario2	Sea wall	1828.4	17968.8	38144.3	58319.8	74460.2
	Living shoreline	2212.5	18448.1	38742.6	59037.1	75272.7
	Elevation	-856.5	12580.1	29375.7	46171.4	59607.9
	Easement	-4116.4	-20251.8	-40420.9	-60590.0	-76725.3
	Public purchase	-6515.3	-22650.6	-42819.7	-62988.8	-79124.1
	Avoidance	-4041.1	-20205.3	-40410.5	-60615.8	-76780.0
Scenario3	Sea wall	-28.5	5991.4	13516.2	21040.9	27060.8
	Living shoreline	652.0	6726.6	14319.9	21913.2	27987.8
	Elevation	-1604.2	4174.1	11397.1	18620.0	24398.4
	Easement	-1508.2	-7229.0	-14380.0	-21531.0	-27251.8
	Public purchase	-3647.2	-9368.0	-16519.0	-23670.0	-29390.7
	Avoidance	-1434.3	-7171.6	-14343.1	-21514.7	-27252.0

Table 7-9. Cost efficiency of proposed adaptation plan under different uncertainty level

Scenarios	Indicators	5%	25%	50%	75%	95%
Scenario 1	BCR	1.8	9.1	18.1	27.2	34.4
	NB (in million $)	1950.8	19371.3	41147.0	62922.7	80343.2
Scenario 2	BCR	3.0	14.9	29.8	44.8	56.7
	NB (in million $)	2698.5	18934.1	39228.6	59523.1	75758.7
Scenario 3	BCR	1.3	6.5	13.0	19.5	24.7
	NB (in million $)	351.7	6426.4	14019.6	21612.9	27687.6

In summary, this chapter combines the benefits and costs of sea level rise adaptation strategies. It first evaluates the cost efficiency of each single strategy by assuming the coastal areas are adopting only one strategy. Then it analyzes the action time point for each strategy from a cost efficiency point of view. The cost efficiency and tipping point analysis help to decide each strategy’s appropriate land uses. Linking each strategy to its appropriate land use proposes an adaptation plan that can guide the adaptation actions of local communities. Finally, this chapter conducts an uncertainty analysis to evaluate the cost efficiency as well as the adaptation plan under different uncertainty levels. The conclusions drawn from this chapter provide new knowledge that is further summarized in the last chapter which presents conclusions and limitations.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

This research employs cost-benefit analysis framework to quantify the costs and benefits of adaptation strategies in response to sea-level rise in Hillsborough County, Florida. It contributes to the existing efforts to promote sea level rise adaptation planning. Although there are several literatures trying to evaluate adaptation strategies from an economic point of view, these studies leave a few major gaps that impede adaptation actions. This research tie into these gaps to better plan for sea level rise adaptation planning.

First of all, the existing quantitative analysis of adaptation strategies only evaluates very few strategies. Since protection strategies are much easier to be quantified, most economic analysis focuses on protection strategies. This research scanned the majority of existing strategies and grouped them into 3 categories, including protection, accommodation and retreat. Each category is linked to two commonly adopted strategies. For the analysis of each strategy, this research applies one single strategy to the whole coast of Hillsborough County to understand its characteristics, such as cost efficiency for different land uses, and action time points. This way, this study does not only take a comprehensive picture of existing strategies, it also provides foundation for the adaptation plan in this study.

Secondly, most existing studies do not capture the major picture of the economic impacts of sea level rise adaptation by considering only a few aspects of the impacts and focusing on direct impacts only. This research takes into consideration five economic impacts of sea level rise, including land value, business revenue, travel time delay, building damages, and ecosystem services. More importantly, it does not only consider the impacts of direct inundation, it also captures the value change of inland area as a result of spatial dependence. This is achieved through developing spatial econometric models to estimate the value change, including land value and business revenue, of indirectly inundated areas. The analysis results show that, the indirect economic loss from inland areas turns out to be a huge number, without considering these indirectly impacted areas, sea level rise impacts are greatly under estimated. The five economic impacts do not include every component of sea level rise impacts, but they can capture the major direct and indirect economic impacts on both built and natural environment.

Thirdly, this research analyzes, for the first time, the action time points for various adaptation strategies from economic point of view. Existing literatures address timing issue of adaptation only by projecting the height of sea level rise. However, the implementation in practice needs evidence better than inundation to justify investment in adaptation. This research analyzes the cost efficiency of each strategy based on three scenarios, which assume that adaptation actions are taken in the year 2013, 2040 and 2060. The results indicate that adaptation strategies targeting on built environment should be taken earlier since losing built-up areas will pose greater economic loss.

Fourthly, this research proposes an adaptation plan and also analyzes its implementation time points. There is very few existing literature that proposes a location- specific adaptation plan for vulnerable coastal areas. Based on the analysis results of each strategy, this study links each strategy to specific land use types and assign it to appropriate locations. In addition, the cost-benefit analysis under three scenarios justifies the cost efficiency of the plan and provides decision makers with options to optimize investment with or without funding constraint. This way, local decision makers are confident with their investments.

Fifthly, this research successfully experiments the cross-platform data sharing to fit into a cost-benefit analysis framework. Since this research involves five different variables, the calculation for each variable requires very different tool kit. It used Hazus to estimate building damages; SLAMM model to quantify wet land conversion; Cube software to calculate travel time delay; and R & GeoDa to develop spatial econometric models. This study successfully develops the process to integrate the outputs from different platforms and also to facilitate input sharing for different models.

At the county level, the analysis in this study is rather an approximation with the best available data. However, its analysis results do uncover the cost efficiency of different selected strategies. Construction of sea wall, establishment of living shorelines, and elevation of structures have positive net benefits with very large numbers. In comparison, adoption of conservation easement, public purchase and avoidance of further investment are not worth to be implemented since their implementation will lose money. Among all the strategies, living shoreline gives the highest return on investment; while public purchase tends to lose the largest amount of money.

The cost efficiency does not necessity imply the uselessness of those strategies aimed to protect natural environment. Instead, it means that if a strategy is designed to protect only natural environment in sacrifice of the built environment, it needs to be carefully designed to minimize the impacts on built environment.

However, because of the limitation of this research, these findings cannot be over generalized. First all of, the analysis results are specific to Hillsborough County, FL.

The analysis results may significantly change some of the conclusions if applying the same analysis framework to other case study areas. Tampa Bay area has strong economic development, especially around coastal areas. The economic activities can increase land values and business revenue sharply. In order to support economic development, roads are densely built along the coast. Therefore, if the same analysis framework is applied to a case which has weak economy and is less populated, the loss of built up areas may turn out to be less than the cost of adopting adaptation strategies.

Furthermore, this study does not consider the dynamics of coastal areas, including the movement of population and land use change. This study assumes that vulnerable people and business relocate out of the study area after inundation. But this may not be the case in real world because some people may just choose to move inland a few blocks away. Land use change is only captured by using future land use map when proposing adaptation plan. But the economic analysis does not consider land use dynamics between 2013 and 2100 when analyzing the cost efficiency of each adaptation strategy.

Further study is also recommended to consider local residents' preferences toward different adaptation strategies. This study assumes neutral preference for each strategy. But our stated preference survey indicates that people do show preference toward a certain strategies over others. This can potentially change the benefits of the strategies. Since the survey sample size is not big enough, the analysis does not include this part. Our research grouping is currently working on to continue the survey collection to capture local residents' preferences toward various adaptation strategies.

Another promising research direction that is out of the scope of this research but can fully extend is to capture the decision making process of different stakeholders, including local government officials, residents, and business owners. This research focuses on costs and benefits of adaptation strategies. However, economic consideration is always one part of decision making process. The stakeholders have other considerations that impact their adaptation actions, such as public support. Therefore, by mimicking the behavior of the people involved in planning and implementation of adaptation plan can better simulate the real world and promote sea level rise adaptation.

APPENDIX A
AVERAGE VALUE OF VARIOUS ECOSYSTEM SERVICES

Table A-1. Average ecosystem service values for beach, freshwater wetlands and mangrove wetlands

Types of ecosystems	Types of ecosystem services	Average values ($ per ha)
Beach	Aesthetics, Recreation	$42,305.00
	Cultural, Spiritual, and Historic	$58.03
	Disturbance Regulation	$70,475.00
	Erosion Control/Soil Retention	$83,000.00
	Subtotal	$195,838.03
Freshwater wetlands	Aesthetics, Recreation	$4,909.14
	Climate Regulation, Gas Regulation	$696.05
	Disturbance Regulation	$5,556.40
	Food	$6,229.65
	Gas Regulatiom, Climate Regulation	$653.75
	Habitat	$4,271.26
	Medicinal Resources	$536.00
	Nutrient Cycling, Nutrient Regulation	$674.70
	Raw Materials	$3,529.50
	Waste Regulation	$8,527.82
	Water Regulation	$13,676.63
	Water Supply	$12,698.17
	Subtotal	$61,959.07
Mangrove	Bequest, Existence, Option	$17,373.00
	Disturbance Regulation	$3,116.00
	Food	$23,613.00
	Gas Regulation	$967.00
	Habitat	$88.70
	Nutrient Regulation	$44.00
	Raw Materials	$38,115.00
	Recreation	$37,927.00
	Waste Regulation	$4,748.00
	Subtotal	$125,991.70

Table A-2. Average ecosystem service values for beach, freshwater wetlands and mangrove wetlands

Types of ecosystems	Types of ecosystem services	Average values ($ per ha)
Marine open water	Aesthetics	$1,080.00
	Climate Regulation, Gas Regulation	$60.00
	Food	$23.50
	Habitat	$4.61
	Nutrient Cycling	$185.00
	Water Supply	$1,560.00
	Subtotal	$2,913.11
Salt water wetlands	Aesthetics, Recreation	$187.00
	Biological Control	$301.00
	Cultural, Spiritual, and Historic	$311.33
	Disturbance Regulation	$3,365.00
	Food	$246.50
	Gas Regulation	$1,285
	Nutrient Cycling, Nutrient Regulation	$27.60
	Waste Regulation	$10,969.50
	Water Regulation	$11,774.50
	Water Supply	$161.50
	Subtotal	$28,628.93

APPENDIX B
CODING AND OUTPUTS IN R FOR LAND VALUE

```
version 2.15.3 (2013-03-01) -- "Security Blanket"
Copyright (C) 2013 The R Foundation for Statistical Computing
ISBN 3-900051-07-0
Platform: x86_64-w64-mingw32/x64 (64-bit)

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R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.

Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

> #priliminary modeling development Fei Yang
> #set working directary
> #install.packages("spdep")
> setwd("D:/Econometrics/Data")
>
> #load spatial analysis package
> library(spdep)
Loading required package: sp
Loading required package: boot
Loading required package: Matrix
Loading required package: lattice

Attaching package: ‘lattice’

The following object(s) are masked from ‘package:boot’:

    melanoma

Loading required package: MASS
Loading required package: nlme
Loading required package: maptools
Loading required package: foreign
Loading required package: grid
Checking rgeos availability: FALSE
        Note: when rgeos is not available, polygon geometry   computations in 
maptools depend on gpclib,
        which has a restricted licence. It is disabled by default;
        to enable gpclib, type gpclibPermit()
Loading required package: deldir
deldir 0.0-21
Loading required package: coda
Loading required package: splines
> # read in spatial weight matrix
> weightmx <- read.gal("trueweight.gal")
> summary.nb(weightmx)
Neighbour list object:
Number of regions: 39
Number of nonzero links: 182
Percentage nonzero weights: 11.96581
Average number of links: 4.666667
```
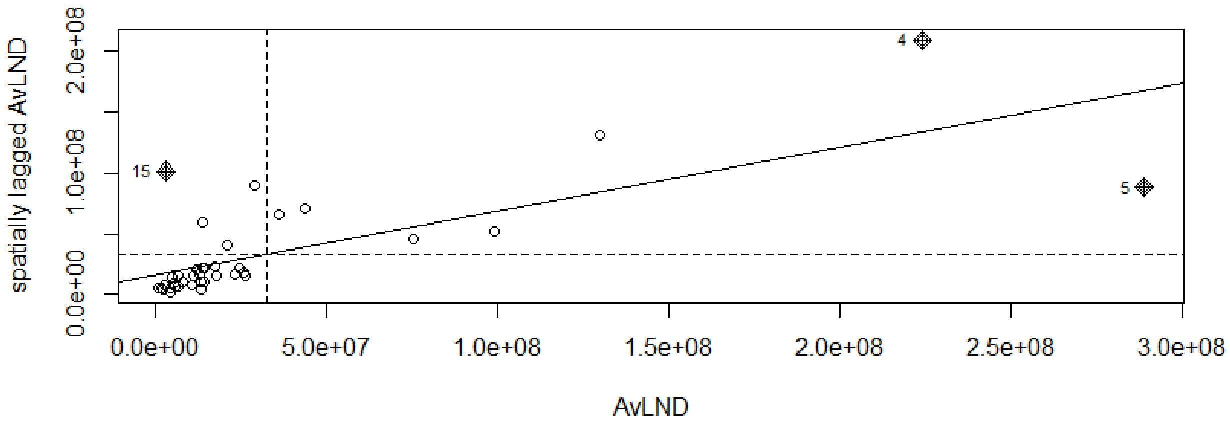

```
Link number distribution:

 2  3  4  5  6  7  9
 3  7  7 10  9  2  1
3 least connected regions:
4 20 24 with 2 links
1 most connected region:
35 with 9 links
>
> #read in raw data
> hills <- read.csv ("LANEMP1.csv")
> attach(hills)
The following object(s) are masked from 'hills (position 3)':

    AvLND, AvLNDVSKM, EmpDenSKM, POLY_ID, PopDenPar, PopDens0, PopDenSKM
>
> #test raw data
> head(hills)
  POLY_ID    AvLND PopDens0 AvLNDVSKM PopDenSKM EmpDenSKM PopDenPar
1       1 1.30e+08     3950  1.31e+08      4000     10900      5450
2       2 1.33e+07     1140  1.43e+07      1130       375      1270
3       3 2.33e+07     1920  2.34e+07      2010       852      2350
4       4 2.24e+08     2380  2.32e+08      2610     16200      3340
5       5 2.89e+08    12800  3.00e+08      5500     27400      8480
6       6 1.33e+07     1240  1.35e+07      1420      1540      1740
> table(AvLND)
AvLND
  858000  1530000  1780000  2290000  2680000  3120000  4220000  4280000
4860000  5500000
       1        1        1        1        1        1        1        1
1        1
 5910000  6460000  6470000  8150000 10800000 11300000 12200000  1.3e+07
13300000 13700000
       1        1        1        1        1        1        1        1
2        1
 1.4e+07 14100000 14200000 17300000 17900000 21100000 23300000 24700000
25900000 26300000
       1        1        1        1        1        1        1        1
1        1
29100000 35900000 43500000 75600000 99100000  1.3e+08 2.24e+08 2.89e+08
       1        1        1        1        1        1        1        1
>
> Y <- cbind(AvLND)
> X <- cbind(PopDens0)
>
> # OLS regression
> olsreg <- lm(Y ~ X)
> summary(olsreg)

Call:
lm(formula = Y ~ X)

Residuals:
      Min        1Q    Median        3Q       Max
-49184148 -16032251    -90324   4227061 173187271

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -1614036    7066234  -0.228    0.821
X              22028       2669   8.254 6.51e-10 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 35750000 on 37 degrees of freedom
```

```
Multiple R-squared: 0.648,     Adjusted R-squared: 0.6385
F-statistic: 68.13 on 1 and 37 DF,  p-value: 6.505e-10

>
> ## SPATIAL ANALYSIS BASED ON CONTIGUITY
>
> # Spatial weight matrix based on contiguity
> #create spatial weight matrix
> listw <- nb2listw(weightmx)
> summary(listw)
Characteristics of weights list object:
Neighbour list object:
Number of regions: 39
Number of nonzero links: 182
Percentage nonzero weights: 11.96581
Average number of links: 4.666667
Link number distribution:

 2  3  4  5  6  7  9
 3  7  7 10  9  2  1
3 least connected regions:
4 20 24 with 2 links
1 most connected region:
35 with 9 links

Weights style: W
Weights constants summary:
   n   nn S0       S1       S2
W 39 1521 39 17.95838 159.9058
>
> # Moran's I test
> moran.test(AvLND, listw)

        Moran's I test under randomisation

data:  AvLND
weights: listw

Moran I statistic standard deviate = 6.3894, p-value = 8.326e-11
alternative hypothesis: greater
sample estimates:
Moran I statistic       Expectation          Variance
      0.526230637      -0.026315789       0.007478512

> moran.plot(AvLND, listw)
>
```



```
> # Lagrange multiplier test for spatial lag and spatial error dependencies
> lm.LMtests(olsreg, listw, test=c("LMlag", "LMerr"))

        Lagrange multiplier diagnostics for spatial dependence

data:
model: lm(formula = Y ~ X)
weights: listw

LMlag = 20.4324, df = 1, p-value = 6.178e-06


        Lagrange multiplier diagnostics for spatial dependence

data:
model: lm(formula = Y ~ X)
weights: listw

LMerr = 7.8605, df = 1, p-value = 0.005053
```

APPENDIX C
CODING AND OUTPUTS IN R FOR EMPLOYMENT

```
R version 2.15.3 (2013-03-01) -- "Security Blanket"
Copyright (C) 2013 The R Foundation for Statistical Computing
ISBN 3-900051-07-0
Platform: x86_64-w64-mingw32/x64 (64-bit)

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Type 'license()' or 'licence()' for distribution details.

  Natural language support but running in an English locale

R is a collaborative project with many contributors.
Type 'contributors()' for more information and
'citation()' on how to cite R or R packages in publications.

Type 'demo()' for some demos, 'help()' for on-line help, or
'help.start()' for an HTML browser interface to help.
Type 'q()' to quit R.

> #priliminary modeling development Fei Yang
> #set working directary
> #install.packages("spdep")
> setwd("D:/Econometrics/Data")
>
> #load spatial analysis package
> library(spdep)
Loading required package: sp
Loading required package: boot
Loading required package: Matrix
Loading required package: lattice

Attaching package: ‘lattice’

The following object(s) are masked from ‘package:boot’:

    melanoma

Loading required package: MASS
Loading required package: nlme
Loading required package: maptools
Loading required package: foreign
Loading required package: grid
Checking rgeos availability: FALSE
        Note: when rgeos is not available, polygon geometry  computations in
maptools depend on gpclib,
        which has a restricted licence. It is disabled by default;
        to enable gpclib, type gpclibPermit()
Loading required package: deldir
deldir 0.0-21
Loading required package: coda
Loading required package: splines
>
> # read in spatial weight matrix
> weightmx <- read.gal("trueweight.gal")
> summary.nb(weightmx)
Neighbour list object:
Number of regions: 39
Number of nonzero links: 182
Percentage nonzero weights: 11.96581
```
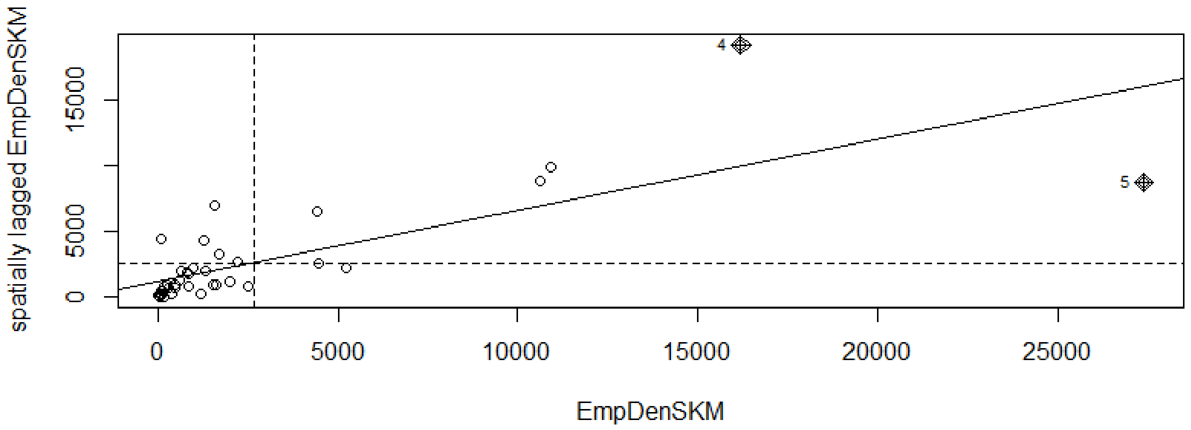

```
Average number of links: 4.666667 
Link number distribution:

 2  3  4  5  6  7  9 
 3  7  7 10  9  2  1 
3 least connected regions:
4 20 24 with 2 links
1 most connected region:
35 with 9 links
> 
> #read in raw data
> hills <- read.csv ("LANEMP1.csv")
> attach(hills)
> 
> #test raw data
> head(hills)
  POLY_ID    AvLND PopDens0 AvLNDVSKM PopDenSKM EmpDenSKM PopDenPar
1       1 1.30e+08     3950  1.31e+08      4000     10900      5450
2       2 1.33e+07     1140  1.43e+07      1130       375      1270
3       3 2.33e+07     1920  2.34e+07      2010       852      2350
4       4 2.24e+08     2380  2.32e+08      2610     16200      3340
5       5 2.89e+08    12800  3.00e+08      5500     27400      8480
6       6 1.33e+07     1240  1.35e+07      1420      1540      1740
> table(EmpDenSKM)
EmpDenSKM
 8.86  31.9  65.2  66.7    73  91.4  97.2  97.8   147   158   163   260   312 
375   456   494 
    1     1     1     1     1     1     1     1     1     1     1     1     1 
1     1     1 
  614   647   831   851   852   980  1190  1290  1310  1540  1560  1630  1720 
2000  2210  2500 
    1     1     1     1     1     1     1     1     1     1     1     1     1 
1     1     1 
 4440  4480  5240 10600 10900 16200 27400 
    1     1     1     1     1     1     1 
> 
> Y <- cbind(EmpDenSKM)
> X <- cbind(PopDens0)
> 
> # OLS regression
> olsreg <- lm(Y ~ X)
> summary(olsreg)

Call:
lm(formula = Y ~ X)

Residuals:
    Min      1Q  Median      3Q     Max 
-4607.7 -1451.2  -269.0   507.4 11839.8 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept) -518.7485   577.7045  -0.898    0.375    
X              2.0500     0.2182   9.395 2.44e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

Residual standard error: 2923 on 37 degrees of freedom
Multiple R-squared: 0.7046,	Adjusted R-squared: 0.6967 
F-statistic: 88.27 on 1 and 37 DF,  p-value: 2.442e-11 

> 
> ## SPATIAL ANALYSIS BASED ON CONTIGUITY
> 
```

```
> # Spatial weight matrix based on contiguity
> #create spatial weight matrix
> listw <- nb2listw(weightmx)
> summary(listw)
Characteristics of weights list object:
Neighbour list object:
Number of regions: 39
Number of nonzero links: 182
Percentage nonzero weights: 11.96581
Average number of links: 4.666667
Link number distribution:

 2  3  4  5  6  7  9
 3  7  7 10  9  2  1
3 least connected regions:
4 20 24 with 2 links
1 most connected region:
35 with 9 links

Weights style: W
Weights constants summary:
   n   nn S0       S1       S2
W 39 1521 39 17.95838 159.9058
>
> # Moran's I test
> moran.test(EmpDenSKM, listw)

        Moran's I test under randomisation

data:  EmpDenSKM
weights: listw

Moran I statistic standard deviate = 6.7906, p-value = 5.584e-12
alternative hypothesis: greater
sample estimates:
Moran I statistic       Expectation          Variance
      0.540344467      -0.026315789       0.006963554

> moran.plot(EmpDenSKM, listw)
>
```



```
> # Lagrange multiplier test for spatial lag and spatial error dependencies
> lm.LMtests(olsreg, listw, test=c("LMlag", "LMerr"))

        Lagrange multiplier diagnostics for spatial dependence
```

```
data:
model: lm(formula = Y ~ X)
weights: listw

LMlag = 18.9675, df = 1, p-value = 1.33e-05


        Lagrange multiplier diagnostics for spatial dependence

data:
model: lm(formula = Y ~ X)
weights: listw

LMerr = 3.4916, df = 1, p-value = 0.06168
```

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BIOGRAPHICAL SKETCH

Fei Yang earned his Bachelor of Science degree in geography from Beijing Normal University, China, in 2007. He received his Master of Community and Regional Planning degree in 2009 from Iowa State University. In 2010 fall semester, he joined the doctoral program in Urban and Regional Planning at the University of Florida.

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