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Article

A Case Study of Preliminary Cost-Benefit Analysis of Building Levees to Mitigate the Joint Effects of Sea Level Rise and Storm Surge

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Abstract: Sea-level rise (SLR) will magnify the impacts of storm surge; the resulting severe flooding and inundation can cause huge damage to coastal communities. Community leaders are considering implementing adaptation strategies, typically hard engineering projects, to protect coastal assets and resources. It is important to understand the costs and benefits of the proposed project before any decision is made. To mitigate the flooding impact of joint effects of storm surge and SLR, building levee segments is chosen to be a corresponding adaptation strategy to protect the real estate assets in the study area—the City of Miami, FL, USA. This paper uses the classic Cost-Benefit Analysis (CBA) to assess the cost efficiency and proposes corresponding improvements in the benefit estimation, by estimating the avoided damages of implementing levee projects. Results show that the city will benefit from implementing levee projects along the Miami River in both a one-time 10 year storm event with SLR and cumulative long-term damage scenarios. This study also suggests that conducting CBA is a critical process before making coastal adaptation planning investment. A more meaningful result of cost effectiveness is estimated by accounting for the appreciation and time value. In addition, a sensitivity analysis is conducted to verify how the choice of discount rate influences the result. Uncertain factors including the rate of SLR, storm intensification, land use changes, and real estate appreciation are further analyzed.

Keywords: storm surge; sea level rise; levee; real estate; cost-benefit analysis; Miami

1. Introduction

It has been demonstrated that global sea levels have been rising over the past five decades and will continue to rise in the years to come, even beyond the year 2100, for many centuries [1]. In the last century, the global rate of Sea Level Rise (SLR) was approximately 1.7 mm per year; the Intergovernmental Panel on Climate Change (IPCC) estimated an SLR of 1.8 mm per year between the mid-20th century until 2003 [2], which was followed by a more significant increase to 3.3 mm per year during the last decade [3]. IPCC also proposes global SLR projections between 1990 and 2100 ranging from 0.6 to 2.6 feet [1]. Gallivan, Bailey [4] has proven that most of the Atlantic Coast and Gulf Coast have been experiencing an SLR of 2.03 to 3.05 cm per decade during the last century.

Coastal planners, researchers, and government officials have renewed concerns about the compounding effects of storm surge and SLR [5]. Storm surge is a tsunami-like phenomenon, and it can temporarily raise sea levels beyond the tide range [6]. Surging waves are powerful and destructive and can cause terrible damages to coastal properties. In the last decade, researchers have attempted to relate storm surges to SLR. For example, Frumhoff, McCarthy [7] found that a 100-year storm surge is likely to occur every four years because rising sea-levels provide a higher starting point for all future surges; that is to say, increases in sea levels can amplify the impacts of a storm event and the resulting flooding. Several papers identify the flood heights by adding SLR to surge heights. Kleinosky, Yarnal [8] estimated the vulnerability of roads in Hampton (Virginia) by considering the compounding effect of storm surge with SLR. Frazier, Wood [9] quantified the joint effects on the Coast of Sarasota County in Florida. Several other studies have included SLR into the dynamic modeling of storm surge [10,11].

Storm surges with SLR have brought huge devastation to societies in the 20th century [12,13]. According to Hanson, Nicholls [14], there are millions of exposed people and billions of exposed assets vulnerable to the storm events and SLR at the global scale. SLR has the following effects on coastal regions: loss of wetlands, inundation of property, shoreline erosion, and saltwater intrusion [15]. Significant amounts of research have made attempts to quantify the impacts of storm surge or SLR on the built environment in coastal areas. The annual loss of real estate from inundation due to the projected sea-level rise (45 inches by 2100) will be up to $360 billion [16]. Over the past 20 years, several papers have quantified the impacts of SLR in Florida. For example, Stanton and Ackerman [17] estimated that the value of affected residential real estate will be more than $130 billion with SLR in Florida. Harrington and Walton [18] estimated the lost property value in Monroe County to be up to 5.8 billion with 1.65 m SLR.

To prevent further damage of intensified storm surges and SLR, making large investments and associated maintenance costs became a significant issue in the coastal protection process. Hence, it is important for community leaders to understand the costs and benefits when defining protection and implementing a specific adaptation strategy.

There exists limited and fragmented literature in assessing the cost effectiveness of adaptation strategies—particularly in the domain of real estate, while copious amounts of publications have emerged in agriculture since the 1990s [19–21]. Some literature has focused on the energy sector [22–25] and water resource management [26]. A small number of studies have been done on infrastructure [27,28]. Several studies have been conducted in transportation fields. For example, Lu and Peng [29] developed a model of transportation network vulnerability to quantify the costs and benefits of SLR adaptation strategies. Moreover, two papers from Neumann, Hudgens [30] calculated the benefits of assuming adaptations in both coastal and inland areas when faced with SLR. In terms of real estate, Kirshen, Knee [31] assessed the expected values of annual damages of coastal buildings in metropolitan Boston by 2100 with several adaptation scenarios.

When it comes to quantifying the joint impacts of storm surge and SLR, resources are also limited. Kirshen, Knee [31] modelled the impacts of SLR with storm surges, and the economic damage could be tens of billions of dollars to buildings in metropolitan Boston. A similar result was presented by Colgan and Merrill [32], using coastal Maine as the study area. The Margulis [33] predicted that the costs of adaptation for the developing world will increase from $26 to $89 billion per year by 2040.

The literature review of current economic evaluations of adaptation planning to climate change reveals two research gaps. First, studies assessing the cost effectiveness of adaptation actions at a local level are limited. National or regional-scale studies are abundant in terms of the ecosystem, agriculture, and transportation. Few of them identified the damage to real estate in coastal communities. Second, the joint effects of storm surge and SLR have drawn extensive public concern since 2005 because SLR provides a higher "starting point" for future storm surges, whereas, their compounding effects are often ignored at the local level and much larger than purely summing up their separate effects.

In both short and long terms, it is critical to fully understand the cost effectiveness of adaptation strategies for the built environment. It is a difficult task, however, to estimate the economic impacts of the joint effects of storm surge and SLR, because the bridge between natural hazards and the social economy is complex. The purpose of this paper is to provide an economic reference for local governments when they make decisions and to help communities invest in adaptation strategies in the long run.

2. Materials and Methods

2.1. The Study Area

The City of Miami is located in the northeast of Miami-Dade County along the Atlantic coast (Figure 1), with a population of 417,650. The City of Miami was ranked the second-most vulnerable city of the major coastal cities in the United States in 2005, taking into account all potential floods and existing protection [34]. In addition, the Miami metropolitan region has a huge amount of exposed financial assets, approximately $19 billion dollars in total and is the fourth largest population vulnerable to storm surge and SLR in the world. According to the land use map in Figure 2, about 90% of the real estate is comprised of residential buildings, worth over $13.07 billion, followed by about $5.75 billion commercial real estate and $0.18 billion industrial.

Figure 1. Study area: the City of Miami (the red area in the Miami-Dade County is Miami city).

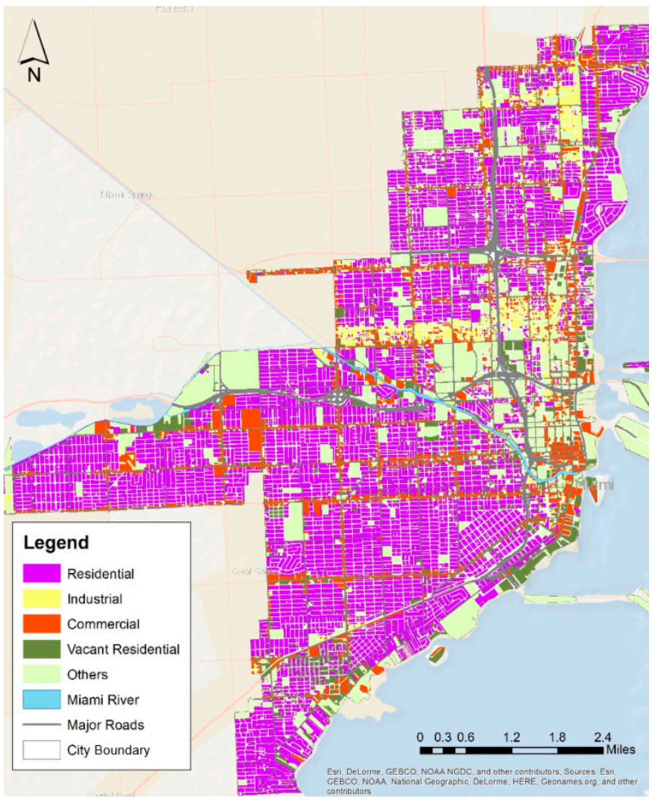

Figure 2. City of Miami land use.

2.2. Methods: Benefits and Costs of Building Levees

This paper uses a cost-benefit analysis to determine the cost effectiveness of proposed adaptation actions for protecting coastal real estate. In general, the cost of an adaptation project includes the costs of planning, preparedness, facilitating, and implementing adaptation measures [1]. For structural adaptation actions in this study, major costs come from construction and maintenance, and the benefits include avoided losses before and after implementing the adaptation project. In other words, the total benefits equal the total losses under a no-action scenario, minus the total losses when the strategy is implemented [35]. For flooding events, loss is estimated by an Exceedance Probability Curve to predict inundation impacts to buildings, including content damage and structural damage. This study utilizes the Depth-Damage Function (DDF) mechanism in estimating the expected damage. DDF is site-specific and also differs depending on the building type. For example, estimated flood damages for a one-story building are greater than those of a multi-story building. DDF reveals a function between flood depth and predicted damage percentage to a building at a given recurrence interval. The flood or storm surge recurrence intervals are derived from the Flood Insurance Study (FIS) conducted by local Federal Emergency Management Agency (FEMA) or hydrologic and hydraulic study. Critically, costs and benefits cannot be calculated exactly due to uncertainties, however, they can be estimated quantitatively and qualitatively based on hypothetical flood events along with the predicted SLR curves and storm surges of various magnitudes.

2.2.1. Benefits from Avoided Flooding Damage

This study applies an Annual Exceedance Probability Curve to calculate the economic damage (Figure 3). An exceedance probability curve maps storm surge to the probability of a storm with a particular severity level happening, which can be derived from the local FEMA Flood Insurance Study (FIS). The flooding depth can be calculated as the sum of base LiDAR elevation and surge height and SLR for that year, thus we can get a flooding depth-probability curve. By applying DDF, the depth-probability curve changes into a damage-probability curve. By multiplying all the damage values and the probabilities, then we can get the expected damage value for that year indicated by the area under the curve. As SLR changes, the curve can be converted by adjusting the Y axes for different years. If this is done for several time intervals, such as the present, 2035, 2055, 2075, 2095, then we can get several values for those years. By interpolating those points, an expected value damage versus time curve can be generated. The area under this curve is the cumulative damages that happen over the entire time period [36]. In order to calculate the cumulative damages during a specific time period, this study derives DDFs for residential, commercial, and industrial properties respectively in the study area.

A DDF estimates direct damage, relating flood depths to predicted damage percentage to a building. Building type, foundations (i.e., open versus closed), and occupancy type are three main factors that determines the DDFs [37,38]. Several studies prove that direct flood damage estimation to buildings is commonly ascertained through the depth-damage function (DDF) method [38,39]. Kelman and Spence [40] mainly analyzed buildings' structural damage, which is determined by flood loads and building resistance. Pistrika, Tsakiris [41] described a detailed relationship between the flooding depth and the expected damage to buildings. In general, different real estate properties have different DDFs. Once we have the DDF for a local real estate, the damage value can be easily calculated by multiplying the DDF by the total building value for the lot (please note that direct costs for cleanup expenses and emergency damage are excluded in these damage functions [36]. To convert both structural and content damage to the economic estimates of building damage, DDF employs a concept called damage percentage. Damage percentage is "a ratio of the total cost of replacement for damaged components of a property in a flooding event to the pre-disaster market value of the property" [37,41,42]. Damage percentage varies between 0 and 1, and here the cost of repairs and the market value of the building should be considered within the same time period.

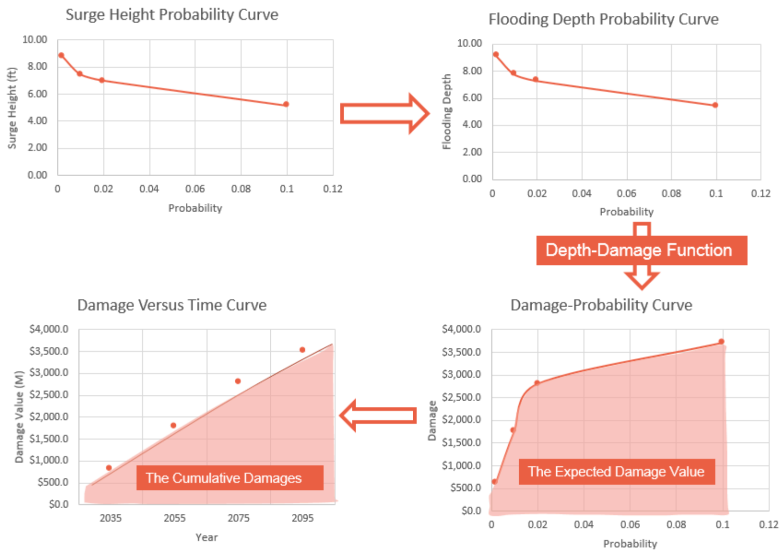

Figure 3. Exceedance probability curve.

The DDFs used in this study come from the North Atlantic Coast Comprehensive Study (NACCS) from the USACE in 2015 because of two reasons: first, DDFs from USACE are currently the most commonly used; second, there is no site-specific function developed locally for south Atlantic coastal areas so far, and the North Atlantic coast possesses conditions similar to the south Atlantic coast. We should note that if there are other damage drivers like erosion, wind, or waves, these DDFs are not applicable. We have separate structure and content DDFs for residential buildings, thus the author does separate estimates and typically adds them together for total damage.

2.2.2. Costs of Building Levees

For the costs estimation, discount rates are applied over the life of the project, i.e., 30 years for a levee, in order to make a comparison between one-time investment in costs of a potential adaptation action and the present value of future benefits. Costs are calculated according to Equation (1).

$$C_T = C_0 + \sum_{T=1}^{T} \frac{C_A}{(1+r)^{T-1}} \quad (1)$$

where

C_T = Construction and maintenance costs over T years.
C_A = Annual maintenance cost
C_0 = Construction cost
T = Useful lifetime of the project

Levees are constructed from compacted materials with impermeable cores inside. To simulate levees, we modified the underlying LiDAR imagery in ArcGIS. Then, in the adaptation scenarios, the water "hits" these "modified landscapes" each year (Figure 4), which helps the authors to define where the optimal location for building levee segments should be. As the figure indicates, most high risk areas are located along the Miami River buffer, and the two "wings" of the river are moderate to low risk areas. The southern coastline of the city is vulnerable to flooding as there are blue shadows over there. Hence, the proposed locations for levee segments are along the Miami River and along the northeast corner of the city (Figure 5); they are 6300, 2400, and 1800 feet long, respectively, with a total of 21,000 feet on both sides of the River. In practice, cost-effective heights of levees are limited to 6 feet and 4 feet, respectively [43], due to the following reasons: first, the higher the levee, the greater the water pressure brings to bear and to withstand the pressures, the cost of the levee must be greatly increased; second, taller and stronger levees need more space; and third, the use, size, and location of levees may be restricted by local zoning and building codes. Although the city of Miami does not restrict related limitations for the levee, it is necessary to account for practical possibilities to make this study more accurate and realistic. Assuming levees are 6 feet high, once they are overtopped, the damages equal the previous damage function, and thus all land areas are flooded up to that elevation. To avoid underestimating the cost of building levees, a constant cost per mile is applied and the maintenance fee is added as well. Based on Heberger's paper in 2009 [44], the construction may cost a maximum of $1500 per linear foot, which is multiplied by the total length, and thus the total construction costs for building levees along the metropolitan Miami coastline is about $32 million.

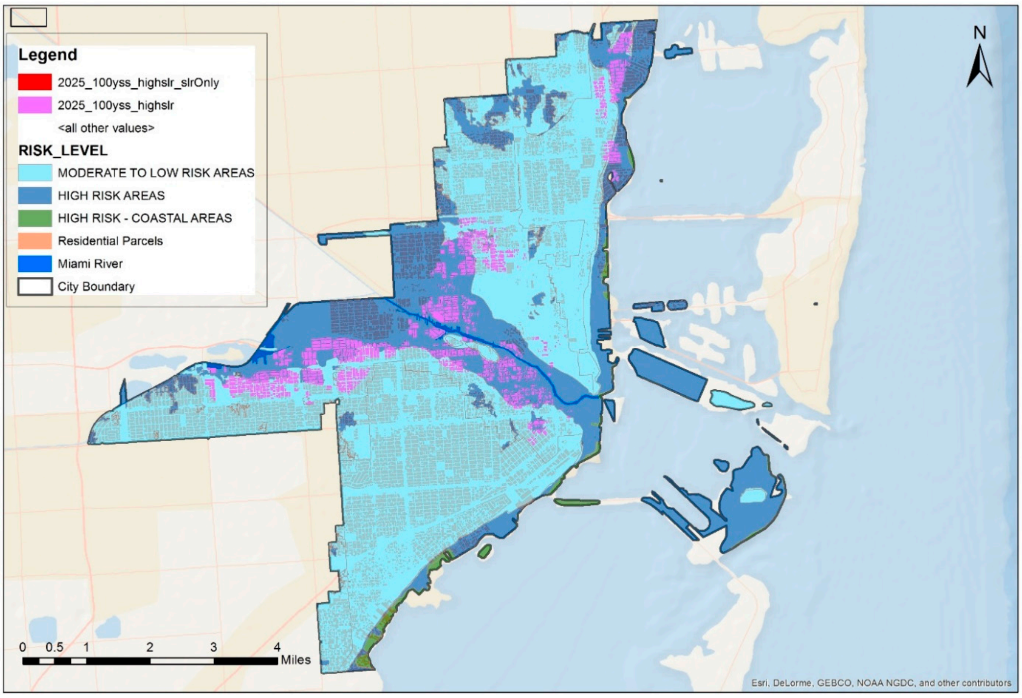

Figure 4. 100-year Storm Flooding Area in the city of Miami, FL, USA.

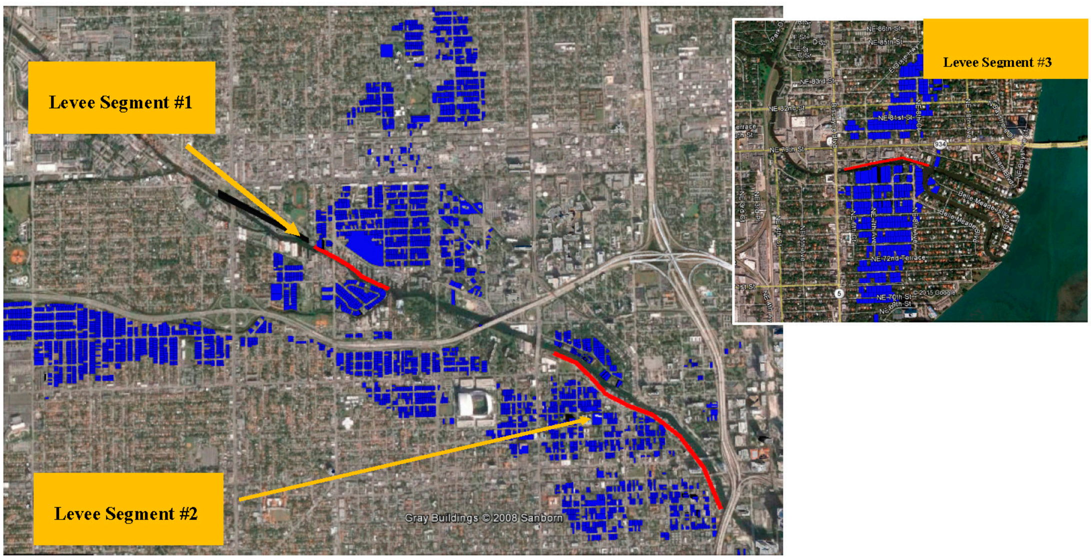

Figure 5. Proposed locations of levee segments along the Miami River.

2.3. The CBA Framework

CBA, also called benefit-cost analysis (BCA), is a systematic approach to estimate and compare future benefits and costs of a project, decision, investment, or policy (FEMA). There are various methods to analyze costs and benefits under different circumstances, but three major approaches are: Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). This paper incorporates NPV and BCR to evaluate the cost effectiveness of adaptation projects. BCR is "the ratio of the present value of benefits to the present value of costs", taking into consideration the time value of money and inflation during the lifetime of a project. It is a numerical expression for describing the cost effectiveness of a project. It is calculated as the present benefits divided by its total present costs, as shown in Equation (2). If BCR is greater than 1, it indicates that the benefits of a proposed adaptation action are sufficient to cover its costs, and that this public investment is reasonable and feasible; if BCR is equal to 1, then it is not necessary to implement this project; if BCR is less than 1, it is not cost efficient.

$$\mathrm{BCR} = B_T / C_T \tag{2}$$

where

BCR = Benefit-Cost Ratio
B_T = Total benefits (U.S. dollars)
C_T = costs in the T year (U.S. dollars)

NPV equals the cumulative damage difference between a no-action scenario and action scenario over T years (Equation (3)). If NPV is greater than 0, a decision to accept this project can be suggested.

$$\mathrm{NPV} = D_{NA} - D_A \tag{3}$$

where

NPV = Net Present Value
D_{NA} = cumulative damage in no-action scenario over T years
D_A = cumulative damage in action scenario over T years

This paper uses CBA to estimate the baseline risk under a doing nothing scenario pertaining to the scenario of protecting the real estate buildings by levees. NPV is assessed as the NPVs between the present future value of benefits under scenarios and without any actions.

3. Results

3.1. Benefits from Avoided Building Damage

3.1.1. One-Time Damage Results

This paper prioritizes a 10-year storm event with high SLR as the simulation foundation. A 10-year storm event is slated to happen every year with a 0.1 probability, which indicates that it may occur once in 10 years. This paper estimated two scenarios: (1) one-time damage; and (2) expected cumulated damages due to the 10-year storm by the years 2025, 2050, 2075, and 2100. Due to the uncertainty of the SLR rate, we will calculate the damage of a 10-year storm surge with high and low SLR projections, and thus the outputs will be presented as a range rather than a series of fixed numbers.

For the estimates of one-time damage due to a 10-year storm event with high SLR occurring in the years 2025, 2050, 2075, and 2100, respectively, the total estimated damage value is up to $143.7, $180.0, $119.8, and $115.6 million dollars in building damage without any protection to the real estate (Table 1). Residential real estate forms a significant share of the damage. In the year 2025, a near future, if a 10-year storm occurred, it would result in up to $143.7 million in damage to the real estate, and a maximum of $11 million damage would be caused by SLR, if no action is taken. If levees are built, then the real estate buildings worth up to 400 million can be protected. Only three parcels along the river will be inundated due to their extremely low elevation (Figures 6–8), which does not change until the year 2100. One more commercial parcel is expected to be inundated at the northeast corner of the city (Figure 9). It is interesting to know that the damage slightly decreases after 2050 because these damage values took into consideration the depreciation. For example, the future damage for the year 2075 before discounting is $507.3 million dollars, and it is too far away from right now, thus the discounted value is a bit smaller than that in 2050. The same is true for the year 2100, which highlights the importance of the time value. The computed floodwater increase in the year 2100 is far more than 6 feet high, but assuming levees were built at least 6 feet tall so that levees cannot protect most of the commercial and residential properties in the year 2100. If a 10-year storm surge happens, all BCRs are greater than 1.0, meaning that it is feasible to build levees to protect Miami's real estate property. Actually, there is no need to calculate the BCR for the year 2100 in a one-time damage scenario because: first, no levee has such a long useful lifetime; second, if the storm comes in the year 2100, it means levees result in 80 peaceful and safe years, and the benefits should be calculated cumulatively, not just one time, otherwise it would be unfair to the levee; and third, if it is assumed that a 10-year storm surge might happen every 10 years, calculating its damage within this long period of time is not reasonable. Nevertheless, building levees is still more cost efficient than doing nothing. Due to the uncertainties, this paper re-estimates the monetary loss with the same four future scenarios by presenting number ranges and compare them with the scenario with levees (Table 2). Table 2 also indicates the individual loss from residential, commercial, and industrial buildings. Figure 10 provides a visual comparison of lost real estate value in Miami.

Table 1. Variables for one-time damage.

Year	Total Benefits	Costs	BCR	NPV
2025	$143.7	$32.0	4.49	$111.7
2050	$179.8	$32.0	5.62	$147.8
2075	$119.2	$32.0	3.73	$87.2
2100	$114.6	$32.0	3.58	$82.6

Table 2. Lost real estate value of one-time damage in the future years.

Year	Real Estate Damage (M) Storm Surge		
	Residential	Commercial	Industrial
No Levee			
2025 (0.35 ft.)	106.7–107.3	27.6–28.5	7.5–7.9
2050 (0. 6 ft.)	129.1–130.2	41.9–42.7	7.5–7.9
2075 (3.2 ft.)	85.2–86.1	27.2–28.6	4.0–5.1
2100 (5.9 ft.)	78.9–80.9	28–29.5	4.2–5.2
Levee			
2025 (0.35 ft.)	0.0	0.0	0.0
2050 (0. 6 ft.)	0.0	0.9	0.1
2075 (3.2 ft.)	0.0	0.5	0.1
2100 (5.9 ft.)	0.6	0.4	0.0

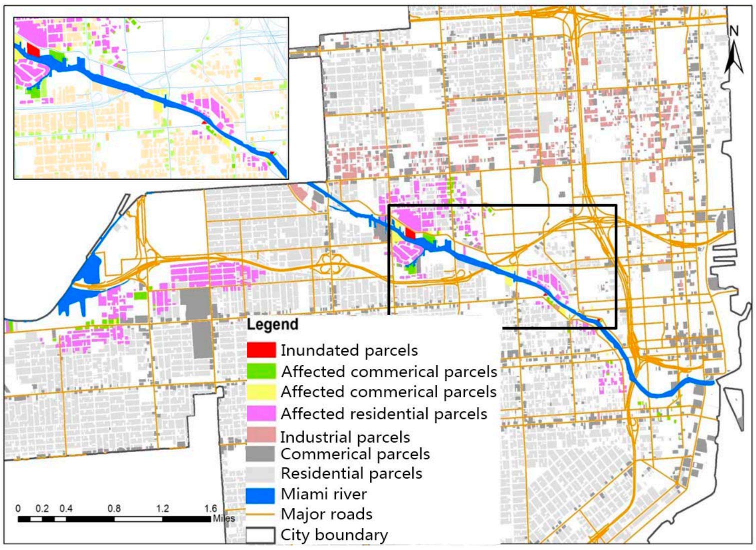

Figure 6. Lost real estate properties in the year 2025, one-time damage.

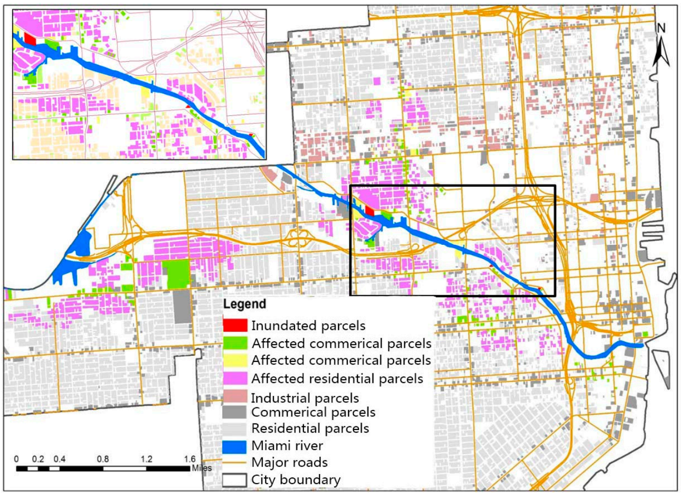

Figure 7. Lost real estate properties in the year 2050, one-time damage.

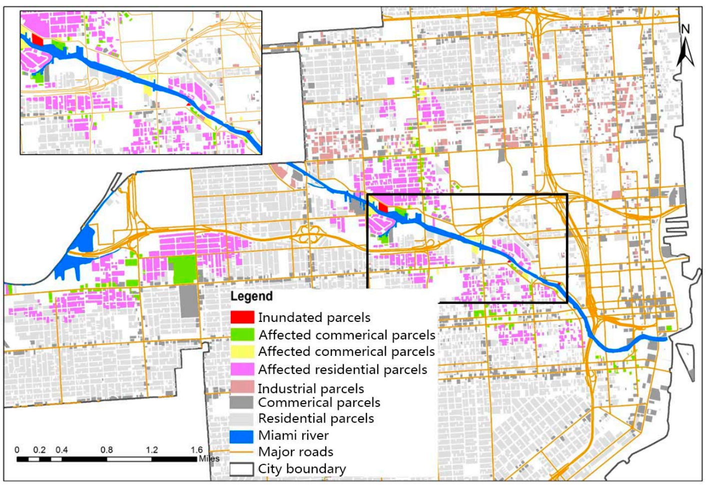

Figure 8. Lost real estate properties in the year 2075, one-time damage.

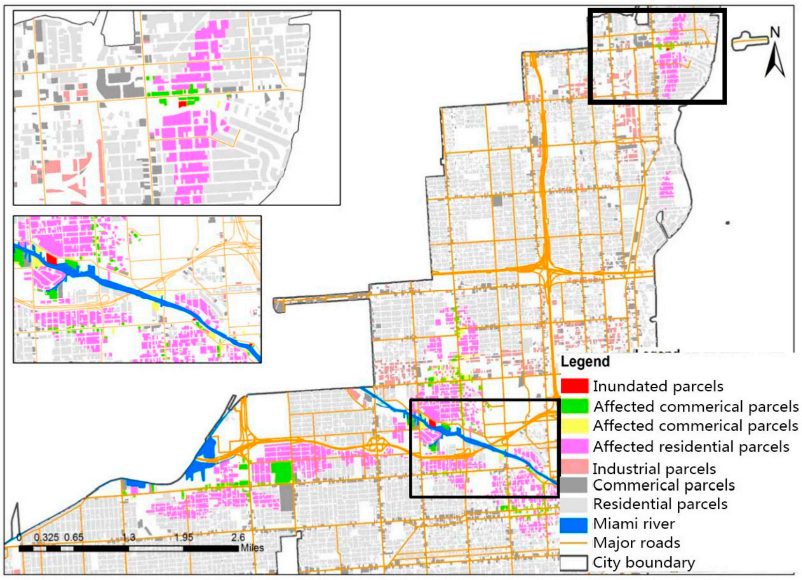

Figure 9. Lost real estate properties in the year 2100, one-time damage.

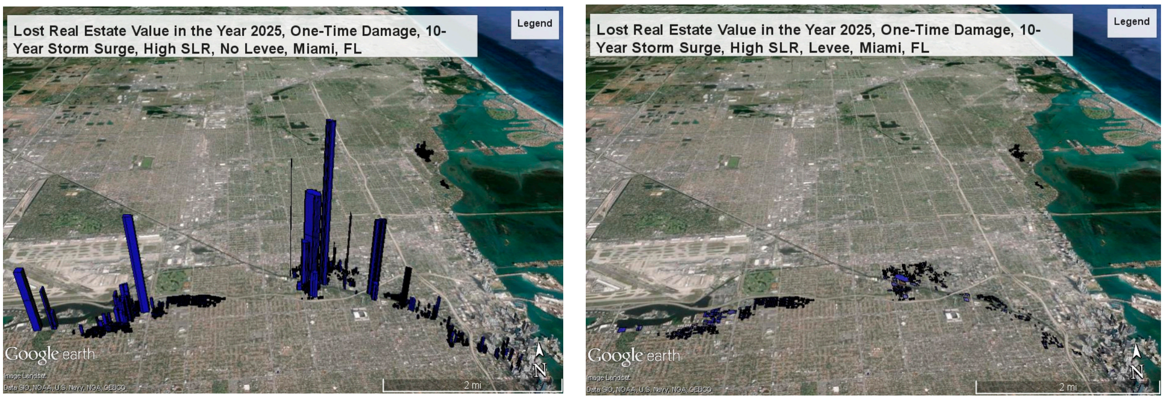

Figure 10. Comparison of lost real estate values, one-time damage in 2025.

3.1.2. Cumulative Expected Damage Results

Before making any comparisons, it is very necessary to summarize the effects of storm surge only and sea level rise only on the coastal real estate (Table 3). For the estimates of cumulative expected damages to real estate by the year 2025, 2050, 2075, and 2100, Tables 4–6 summarize the cumulative damages from the joint effects with or without levees, and most importantly, the total benefits. Compared to a single storm event, cumulative damages are much more serious. The model estimates $628 million dollars in cumulative real estate damage in the 10 years from now to the year 2025. Over the next 35 years, approximately $1771 million dollars in cumulative damages is estimated. BCRs in Table 7 for accumulative damages will present a more reasonable and convincing result. Table 8 summarizes the BCRs for all cumulative expected damages to real estate by the year 2025, 2050, 2075, and 2100. The discount rate is 3% for both benefits and costs. Costs here include the construction cost of $32 million dollars in the first year (2015) and the maintenance fee of $10 million per year. In general, the useful lifetime for a high quality levee is about 30 to 50 years, thus the BCR trend here shows an ideal condition. However, if the budget allows it, regular maintenance checks can be made during the lifetime, and coastal communities will then benefit from levees for up to 70 years.

Table 3. Total monetary damage values of one-time damage in 2025, 2050, 2075, and 2100.

Year	Adaptation	Cost	Real Estate Damage (M)		Percent of Damage from	
			Storm Surge	SLR ONLY	Storm Surge	SLR ONLY
2025	No Action	$0	$144.3–$143.7	$11.10	91–92.8%	7.2%
	Levee	$32.00	$0.0	$11.10	0.0%	100.0%
2050	No Action	$0	$177.6–$180.8	$11.10	93.6–94.2%	5.8%
	Levee	$32.00	$1.0	$11.10	8.3%	91.7%
2075	No Action	$0	110.4–$119.8	$11.10	90–91.5%	8.5%
	Levee	$32.00	$0.6	$11.10	5.1%	94.9%
2100	No Action	$0	$113.8–$115.6	$11.80	88.7–90.7%	9.3%
	Levee	$32.00	$1.0	$11.80	7.8%	92.2%

Table 4. Cumulative results for 10-year storm surge by the years 2025, 2050, 2075, and 2100, discount rate 3%.

Year	SLR Scenario	Model of SLR above MHHW in 2015 Selected (ft.)	Total Flood Elevation for Each Scenario, NAVD 88 (ft.)	Damage from Joint Effects (M)	Damage from Joint Effects with Levee (M)	Total Benefit (Avoided Damages) (M)
2025	V&R 2009 High	0.35	5.6	$628.2	$12.1	$616.1
2050	V&R 2009 High	1.3	6.1	$1771.2	$37.2	$1734.0
2075	V&R 2009 High	3.2	6.9	$2803.1	$77.1	$2726.0
2100	V&R 2009 High	5.9	7.9	$3708.5	$148.1	$3560.4

Table 5. Cumulative lost real estate value by the years 2025, 2050, 2075, and 2100, 10-year storm surge with high SLR, without levee, Miami, FL, USA.

Year	Residential	Commercial	Industrial	Subtotal
2025	$413.2	$193.3	$21.7	$628.2
2050	$1156	$556	$59	$1771.2
2075	$1819.5	$895.7	$87.9	$2803.1
2100	$2386.6	$1211.5	$110.4	$3708.5

Table 6. Cumulative lost real estate value by the year 2025, 2050, 2075, and 2100, 10Y storm surge with high SLR, with levee, Miami, FL, USA.

Year	Residential	Commercial	Industrial	Subtotal
2025	$6.1	$5.6	$0.4	$12.1
2050	$20	$16	$1	$37.2
2075	$47.4	$26.3	$3.4	$77.1
2100	$100.3	$42.1	$5.7	$148.1

Table 7. Variables for cumulative damage.

Year	Total Benefits	Costs	NPV	BCR
2025	$628.2	$120.7	$507.5	5.20
2050	$1771.2	$208.9	$1562.3	8.48
2075	$2803.1	$235.0	$2568.1	11.93
2100	$3708.5	$242.7	$3465.8	15.28

Table 8. Sensitivity analysis—variables for discount rates from 1% to 10%.

Discount Rate	Avoided Damage (M)	Total Costs (M)	BCR	NPV
0.01	$678.63	$108.70	6.48	$569.93
0.02	$646.12	$103.80	6.47	$542.32
0.03	$615.90	$103.00	6.22	$512.90
0.04	$588.21	$102.10	6.00	$486.11
0.05	$562.39	$101.30	5.78	$461.09
0.06	$538.41	$100.40	5.59	$438.01
0.07	$516.12	$99.60	5.40	$416.52
0.08	$495.36	$98.80	5.23	$396.56
0.09	$476.02	$98.10	5.06	$377.92
0.1	$457.97	$97.30	4.91	$360.67

3.2. Sensitivity Analysis

Sensitivity analysis is the process of studying how the uncertainties in climate change influence the output of a mathematical model. One important task during the CBA process is to define the discount rate. The discount rate reflects the time value of money, expressing the relationship between future expected costs, and benefits and present ones. This paper applies classic conversion of future expected streams of costs and benefits into present values (Equation 4). In order to determine the impacts of different discount rates on the output, this part recalculates the avoided damages, NPVs, and BCRs under a series of discounting assumptions by the year 2025. The total benefits and NPVs are decreasing as the discount rate increases (Table 8). The larger the discount rate, the more valuable present money can be. The slope of the Benefit-Discount Rate line was calculated to be -2331.96, and no matter what the discount rate is, this project is earning profits. NPVs are not sensitive to the discount rates, therefore, the project is economically feasible.

Theoretically, if decision makers make an investment in an adaptation project through one-time investment in the first year, they might want the discount rate to be as large as possible, so it seems like they saved on costs. However, a larger discount rate will actually generate a smaller NPV value. In conclusion, the choice of discount rate is an important tradeoff during the decision making process, because it has to meet the requirements of different stakeholders, such as the government, residents, and companies, as well as achieve the maximum social, economic, and environmental welfare.

$$F_T = P \times (1 + r)^T \tag{4}$$

where

F_T = future value in the year T
P = value in the first year
r = discount rate
T = years

4. Discussions

4.1. Uncertainties of Models and Parameters

This study is essentially a simulation of reality. Many have argued that models are different levels of the approximations of observed phenomena [45,46] rather than perfect replicas of the objects. Computer simulation integrated with risk probability climate change uncertainty is still a much debated area and has to be validated through field study and qualitative judgment [47,48]. Thus, this paper aims at developing a generable framework of cost-benefit analysis—instead of offering a highly accurate figure for the municipality of Miami to gauge the possible loss due to a potential storm surge.

Second, there are several uncertainties in terms of the parameters in this study, which may influence the accuracy of the results. The most uncertain parameters are the rates of SLR and the intensity of storm surge. The global rate of SLR has been accelerating in recent decades, so to predict it with a high accuracy is extremely difficult. Furthermore, it is not a consensus that SLR appears at a constant rate. Moreover, the situations become more unpredictable when the predictions are extrapolated into 2100, since SLR from 0.7 to 1.7 m by the end of this century has been justified to be reasonable by different scientists or organizations [49–51]. For example, Vermeer and Rahmstorf [52] predicted in 2009 that the sea level has been rising at a high-and-low rate, thus the economic damages of the joint effects of storm surge and SLR are shown as a range rather than fixed numbers. This study assumes that storm surge damage is changed only through SLR, but it is also significantly affected by pressure, wind, and other factors [53]. Therefore, this assumption deserves validation by future simulations and field observations. The final uncertainty is that 1 percent of appreciation for real estate is conservative. In the last 50 years, the annual real estate appreciation in Miami was 1%, but increased to 1.5% in the last 20 years. Historic data shows the appreciation rate is also increasing, thus 1% real estate appreciation may be accurate for 10 to 20 years, but definitely conservative beyond the year 2050.

4.2. Other Crucial Aspects of Cost-Benefit Analysis

Land use changes were not considered in the case study. The assumption that urban form remains unchanged over the next several decades is problematic. Researchers have to make a trade-off when addressing climate change-related issues. In other words, SLR is a slow going process, but urban expansion is appreciable in coastal cities. While SLR becomes apparent only after several decades, urban development can be obvious within a few years. How to balance such inconsistency in growth rates remain a major challenge for climate change scientists. Land use change, particularly in urbanized areas, is also controlled by such variables as governmental regulation, zoning and comprehensive planning, economic growth, and population immigration. As the global economy recovers and the coast consistently attracts population, future studies should factor these variables into similar analyses or hazard resilience research.

Another limitation of the current study is that it only considers levees built along the Miami River where storm surge is expected to cause huge damages. The study excluded the seawalls that are constructed near beaches and can combat the direct consequences of SLR. It also did not consider other adaptation strategies such as beach nourishment, realignment of the coast, and the elevation of vulnerable structures. These countermeasures to SLR are focal points for cost-benefit analysis as well.

Finally, the current study only accounts for direct benefits and costs, but indirect dimensions of the analysis are also important. Indirect costs, apart from construction and maintenance expenditure, may result from the affected recreational value of the coast and impaired ecosystem services. Indirect benefits of levees may include the protected efficiency of transportation systems during and after storms, avoided travel time delays, preserved coastal scenery, and sustained property values. These considerations can be integrated into future research.

4.3. Integrating the Analysis into Coastal Disaster Management

The cost-benefit analysis should not be confined only to levees and needs to embrace other adaptation strategies. Accelerated climate change due to human activities requires the rethinking of hazard risk management to incorporate the BCA approach. Traditional disaster management practice has four successive phases: mitigation, preparedness, response, and recovery [54]. The preparedness phase requires the consideration of a combination of adaptation strategies that are "no-regret" and cost-efficient. Early implementation ensures a significant reduction of adaptation costs in the long term [55]. Therefore, cost-benefit appraisal can be a useful guidance for the design and deployment of countermeasures to SLR in the preparedness phase. It should be a critical component of a broader risk-based policy assessment under an integrated disaster management framework. Specifically, during preparation, the (in)direct costs and benefits of different adaptation strategies should be calculated and contrasted. This process is accompanied by uncertainty considerations based on sensitivity analysis regarding climate change scenarios, discount rates of monetary values, and the layout of defense systems. The results could then inform decision makers as to which strategies are to be implemented and where to deploy these.

The implementation of adaptation strategies is also determined by a variety of additional factors. These variables include the economic atmosphere of the whole region, impacts on leading industry, socio-political sensitivity of the region's constituents that are threatened by SLR, and coastal disasters [56]. Policymakers should formulate adaptation measures by a holistic multicriteria analysis based on these variables.

Policymakers should consider the feasibility of action plans in the near, medium, and long term. Protection and accommodation strategies—such as seawalls, levees, and beach nourishment—may generate short-term benefits and are less controversial in terms of implementation, but they are less cost-efficient in the long term. However, the resettlement of vulnerable populations could produce long-term benefits but generate huge costs in the short term. Thus, policymakers should be aware that planned retreat may be strongly objected by stakeholders, unless they provide convincing cost-benefit analysis and assess other important factors that were mentioned previously.

The responsible parties and beneficiaries of adaptation strategies should be determined. Such questions may be raised to governments as to who will benefit from and will pay for adaptation strategies. This information may be used to identify primary taxpayers who will be protected by proposed seawalls. A social study can be conducted to investigate how much households are willing to pay for the construction and maintenance of seawalls, and governments could use this information to leverage the development of vulnerable regions, where unaffordable residents will choose to relocate because of high protection costs.

Finally, a centerpiece for successful adaptation is to build an adaptive and capacity building institution system. The failure of adaptation largely results from a lack of institutional capacity [45]. Therefore, a strong institutional capacity for enforcement is the key to policy implementation [56]. It requires central governments to devolve powers and responsibilities to local governmental agencies and properly allocate resources and authority. A well-coordinated network should be established to connect different agencies to enforce disaster management practices. Coastal disaster management is to be integrated into land use policies and laws. Policymakers should tolerate the uncertainties underlying risk-based analysis and develop land use plans that are responsive to these uncertainties.

5. Conclusions

As Harrington and Walton proposed in 2008, the estimated lost property value at a county level is up to 5.8 billion with 1.65 m SLR. However, the cumulative damage by the year 2100 at a city level is approaching almost $1 billion, which indicates that the joint effects of storm surge and SLR exceed the expected effects. Hence, this paper conducted a cost-benefit analysis of building levees in the City of Miami, a region that is highly vulnerable to SLR.

The results suggest the following policy implications for adaptation planning:

1. It is imperative to conduct a BCA early in the project development process to ensure the possibility of meeting cost effective parameters. Understanding the costs and benefits of adaptation strategies before putting them into practice is critical for making fiscally-responsible decisions.
2. Faced with more severe storm surges and rising sea levels, implementing adaptation strategies are more cost-efficient than doing nothing. The results can be far more significant when we calculate the cumulative economic impacts due to increased storm surges and SLR; nevertheless, adaptation mechanisms can help communities benefit in the future and increase their resiliency.
3. The joint effects of storm surges and SLR cannot be disregarded anymore. Their effects cannot be seen as simply addition or subtraction. The compounding effects of storm surge and SLR depend heavily upon the adaptation protections.

To achieve minimum risk and protect the habitability of the built environment, the local government must have a high awareness of their community's vulnerability and be clear about when, where, and how to invest in an adaptation project.

However, the economy is only one facet in the decision-making process. For every undertaking of such a project, decision-makers need to consider as many substantial challenges as possible, such as technical, economic, social, and environmental aspects. In the case of building levees, which belongs to somewhat no-regret actions, it is imperative to consider the comprehensive economic, social, ecological, and environmental effects, and even cultural factors, before making any decisions.

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