Article

Protecting Infrastructure and Public Buildings against Sea Level Rise and Storm Surge

Paul Chinowsky ^{1,*} and Jacob Helman ²

¹ Program in Environmental Design, University of Colorado Boulder, Boulder, CO 80309, USA

² Resilient Analytics, Inc., Louisville, CO 80027, USA; jhelman@resilient-analytics.com

* Correspondence: paul.chinowsky@colorado.edu

Abstract: The national study analyzes sea level rise (SLR) impacts based on 36 different SLR and storm surge scenarios across 5.7 million geographic locations and 3 time periods. Taking an approach based on engineering design guidelines and current cost estimates, the study details projected cost impacts for states and cities. These impacts are presented from multiple perspectives, including total cost for constructing seawalls, costs per capita, and costs per square kilometer. The purpose of the study is to identify specific locations where infrastructure is vulnerable to rising sea levels. The study finds that Sea Level Rise (SLR) and minimal storm surge is a USD 400 billion threat to the coastline of the lower 48 United States by 2040 that includes a need for at least 80,000 km of protective barriers. The research is limited in its scope to protecting coastal infrastructure with seawalls to enable consistency throughout the study. The study is original in that it is an effort across the lower 48 states to identify infrastructure that is vulnerable, as well as the cost associated with protecting this infrastructure.

Keywords: sea level rise; climate change; infrastructure; coastal engineering

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1. Introduction

Climate change presents a wide range of challenges for infrastructure owners, planners, and users. Of these potential impacts, the one that is predicted to have one of the largest ramifications in the United States, is Sea Level Rise (SLR). If a rising temperature continues to manifest on a global scale, then sea level rise will occur mainly due to a combination of thermal expansion of sea water and the melting of land-based ice into the ocean [1]. The consequences of this sea level rise on coastal road networks, buildings, and infrastructure due to economic, social, and environmental costs are predicted to be substantial [2–4].

According to the National Oceanic and Atmospheric Administration (NOAA), the United States' tidal shoreline is 153,645 km long [5], of which 97,111 km is along the lower 48 states. Estimates for the number of people that could be impacted by SLR vary, based on the expected depth associated with the SLR, but range from a potential 4.2 million people at immediate risk of inundation to 13.1 million people at extreme risk in the year 2100 [6].

For the median estimates of SLR at 2100, Ref. [7] propose a likely range of 49–174 cm for the 17–83% likelihood interval and a likely range of 36–238 cm for the 5–95% likelihood interval, depending on the progress in mitigating greenhouse gas emissions. The alternatives considered are a +2 °C stabilization scenario and the no-mitigation option. In 2050, the corresponding intervals are 22 to 47 cm and 16 to 61 cm. On the other hand, [8] indicate a likely range of 20–139 cm at 2100 and of 13–35 cm at 2050 for the 10–90% likelihood interval (qualitatively extrapolated from their Figure 2b) for a set of scenarios that range from the fixed present-rate of SLR (which is slower than that implied by any mitigation option) to the no-mitigation reference. In either study, the estimated rates of SLR start to diverge by the 2050s.

Because coastal areas have historically been attractive areas to establish communities, the predicted SLR leaves many systems along the coast vulnerable to damage. A total of 96,560 km of US roads and bridges in the existing coastal floodplain are already at risk to extreme storms and hurricanes [2]. When put in perspective of the overall US economy, coastal zone counties account for 48% of the Gross Domestic Product (GDP) or USD 8 trillion dollars [9].

The size and extent of this threat is focusing discussions on the question of what should be done to protect coastal communities from the threat of sea level rise and the associated greater floodwater depths. This discussion crosses the political, economic, and engineering domains as the question emerges as to the appropriate approach that should be taken in response to the threats [10–13]. While the scientific determination of what areas are at the greatest risk continues to dominate the discussion, the challenge of how to respond to this vulnerability requires greater attention. Specifically, the question of whether SLR vulnerability requires new policies to relocate communities, new investments to construct protection barriers, or whether communities should take a wait-and-see approach is one that needs further attention.

Currently, the approaches to the SLR response can be divided into three broad categories: protection, accommodation, and retreat. The protection category includes creating dikes, surge barriers, closure dams, constructing dunes, nourishment and sediment management of wetlands, creating coast defenses, sea walls and land claims, creating saltwater intrusion barriers, and implementing drainage systems/polders. The accommodation category includes implementing building codes to minimize the flooding of critical building spaces, ensuring land use planning that accommodates for wetland loss, changing water extraction practices, using freshwater injections to stop saltwater intrusions, and increasing the delineation of natural hazard areas. Finally, practices that pertain to retreating focus heavily on policies that minimize new building in areas where SLR threatens infrastructure, as well as considering the movement of existing structures in threatened areas [1].

While protection, accommodation, and retreat present a large array of approaches to protecting against SLR, historically, the implementation of sea walls, also known as rock revetments, or armoring, has been the most common approach to reducing the impact of ocean activity on coastal communities [14,15]. Similarly, the building of inland sea walls, also known as bulkheads, along the banks of inland waterways have been a common approach to protecting property against rising waterway levels. While these are the predominant approaches to protecting coastal properties, seawalls do not work in every circumstance. Specifically, in cases where porous materials such as limestone form the bed of the waterway, water can infiltrate through the rock and under the seawall. In these cases, alternatives, including the addition of pumping, may be necessary.

Based on the historic focus on seawalls as a protection strategy, the current study provides an estimate of the construction costs associated with armoring areas of the coast that are projected to be flooded and which contain built assets within the lower 48 states. These assets include both public and private assets such as roads, rails, and public buildings. Private residences are not specifically modelled in this effort but are included indirectly by protecting the locations that include roads and other public infrastructure elements that support these properties.

The intent of the current study is to provide the best estimate of expenses that have the highest likelihood of being incurred by 2040. These estimates are necessary as researchers have not published a study with a similar scope focusing on the costs of protecting coastal infrastructure along the lower 48 states from SLR.

2. Literature Review

The analysis of sea level rise impact is a growing field of study. A variety of approaches have been used to model the potential economic, social, and environmental costs created by sea level rise. These procedures vary in their methodologies used, geographies assessed, and scales implemented.

The first class of models consists of systems that are used to predict and model the amount of land along the coastline that will be inundated, which may include inundation models and Sea Level Affecting Marshes Model (SLAMM) [16]. Inundation models utilize climate models to predict what areas will be flooded, using Geographic Information Systems (GIS) and Digital Elevation Models (DEM). SLAMM specializes in incorporating habitat changes and processes that are likely to be impacted by climate change. Kirshen et al. take a more simplified approach to modeling the impacts of sea level rise by “developing damage-flooding depth probability exceedance curves for various scenarios over a given planning period and determining the areas under the curve” [17].

Neumann et al. incorporate “a tropical cyclone simulation model, a storm surge model and a model for economic impact and adaptation” to estimate the impacts of sea level rise for the US coastline through 2100. The model integrates site-specific elevation, land subsidence, and property values to estimate the costs incurred due to shoreline armoring, beach nourishment, and property abandonment. Neumann et al. identify that those coastal areas are densely populated, further intensifying the impact of sea level rise on human populations [18–20].

In addition to measuring the financial impact of land inundation, ecological landscape spatial simulation models account for the detrimental environmental consequences of SLR. The Ecological landscape spatial simulation models are a category of model that broadly analyze environmental factors such as subsidence, sea-level rise, changes in river discharge, and climate variability and their impacts on coastal habitats. These models are able to incorporate a larger range of variables, including “coastal and estuarine hydrodynamics, water-borne particle transport, vegetation growth and infrastructure risk”. However, due to this level of detail, these models can be expensive and time-consuming to run. The Dynamic Interactive Vulnerability Assessment (DIVA) model integrates biophysical and socioeconomic consequences of sea-level rise and is able to assess the costs and benefits of adaptation to the predicted impacts. DIVA is designed to incorporate a large variety of factors and components at a global scale and size. Similarly, SimCLIM models the biophysical and socioeconomic impacts of climate change and variability. The tool estimates how future climate and sea-level changes impact sectors and associates a sensitivity analysis with the modeling. The tool can be applied to local and global scales, depending on the availability of data.

The final category of model used to predict and understand the impacts of SLR account for the social impact on coastal communities and economies. Hsiang et al. utilize SEAGLAS (Spatial Empirical Adaptive Global-to-Local Assessment System) to estimate the cost of climate change to the sectors of agriculture, crime, coastal storms, energy, human mortality, and labor using a “risk-based approach”, which is “grounded in empirical longitudinal analyses of nonlinear, sector-specific impacts”. The results suggest that climate change costs approximately 1.2% of the gross domestic product per +1 °C [21].

3. Methods

Building on existing methodologies, as well as new approaches developed for the current study, the current study employs a multi-step process incorporating climate projections, geoprocessing of detailed coastline flooding maps, the computational assessment of where coastline needed protection, and the calculation of the costs associated with this protection. The process developed for this estimation is based on previous climate impact work developed by the authors for infrastructure impacts locally, regionally, and globally [22–24].

3.1. SLR and Storm Surge Projections

The study utilized SLR and 1-year storm surge inundation projections from Climate Central through high-resolution datasets for the lower 48 states [25–27]. The datasets included analysis of the coastline at a 5 m × 5 m grid to ensure accurate capture of tidal inlets. Each geographic location provided information on whether the location was projected to be inundated and, if so, to what depth the inundation was expected.

The inundation dataset included alternative projections from the two lower projection Representative Concentration Pathways (RCP), RCP 2.6 and RCP 4.5. Based on the consid-

erations of [28] for our cost assessment, we focused on the two lower-end scenarios RCP 2.6 and RCP 4.5, while only presenting results for RCP 4.5, as the closest to the emission path followed so far, as well as to the trajectory determined by current mitigation policies up to 2040.

The inundation datasets provided for the study were derived from a Monte Carlo simulation set of 10,000 projections generated by Climate Central. Specifically, the 5th, 50th, and 95th percentile inundation projections for each of the two pathways from the overall dataset were selected for the current study. Three time periods were selected from the results for the impact analysis: 2040, 2060, and 2100. Additionally, inundation was included with and without 1-year storm surge projections to capture both the base SLR impact and the potential for regular flood impacts.

Similar to the projection data, Climate Central provided GIS files of infrastructure locations based on previous work and public database information [28]. This infrastructure included a broad range of public infrastructure including schools, hospitals, medical facilities, government buildings, airports, and all public horizontal infrastructure (roads, railways, and runways). Although the study does not consider private residences directly, the location of most residential areas can be determined through the location of public roads that are used to access residential areas. Therefore, by considering all areas that contain a road (both paved and unpaved), the majority of residential areas were considered. National parks and protected wildlife areas with limited access roads were not included in the study.

3.2. Geoprocessing

The first step in the impact assessment was the identification of areas where inundation and flooding propagated along the coastline and inland waterways. A transformation of the dataset was performed to reduce the information to indications of whether infrastructure was in a specific area, and whether that area was projected to be impacted by SLR or storm surge. Although the original climate dataset was provided at an ultra-high resolution, for processing speed, usability and accuracy, the dataset was condensed to a uniform grid size. Sensitivity analysis tests were performed to determine an appropriate grid size that would allow for the most accuracy in results while still maintaining computability speed. The sensitivity analysis focused on determining the largest grid size that would both retain the underlying inundation detail as well as accurate location information for the infrastructure being analyzed. Through a series of test runs of increasing grid sizes, the sensitivity analysis found that a horizontal grid system of 150 m would achieve the research objectives (Figure 1).

3.3. Protection Assessment

Once the flooding files were processed, the second step of the process required determining what areas of coastline needed protection to remove the threat of flooding. This determination requires a series of logic tests to understand if a flooded grid is directly impacted by flooding from adjacent waterways or if it is indirectly affected by other grids that are adjacent to waterways.

The first step in this process was to determine if any given gridded square is located within an area that is expected to flood, according to a specific climate scenario. This question is nuanced in that there must be a determination as to the minimum inundated fraction for a grid cell to be considered flooded. The need for this determination originates from the issue of how to limit the protection of coastal grids that appear in the study with minimal flooding along the edge of the coastline. For example, a grid covering an inlet which is indicated to have inundation over an area covering just a few yards onshore and does not include flooding of any infrastructure can be eliminated in terms of needing protection. The study adopted a threshold of 15% minimum inundation area to eliminate overprotection scenarios. The value of 15% was chosen based on engineering judgement upon inspection of protection patterns using 5%, 10%, 15%, and 20%.

Figure 1. The 150 m $\times$ 150 m grid used as the basis for analyzing the coastline is overlaid on the infrastructure and inundation zones. Each grid isolates information on the projected flooding and the infrastructure in that grid to determine length of protection required within each grid.

The second issue focused on whether a grid was flooded due to direct flooding or indirect flooding. The model works from the assumption that wherever flooding occurs, the shoreline directly impacting that flooded area needs to be protected. The case of direct flooding occurs when a grid is adjacent to a waterway and the scenario indicates that grid is flooded due to an overtopping of the adjacent waterway. In this case, the adjacent shoreline needs to be protected to prevent the grids from incurring flooding. The indirect case occurs when an inland grid is flooded due to being connected directly or indirectly to a water-facing grid. In this case, the model must trace the path of the flood back to its origin, which is the grid adjacent to the coastline. This tracing is accomplished by analyzing adjacent grids for flooding. Each time a grid with flooding is detected, adjacent grids are analyzed to determine which may be flooded. This process continues until a coastal grid is detected. The model then protects the coastline adjacent to the grid to eliminate the threat to the whole exposed area.

The identification of the flood areas provides the entry point for the final step in the process of calculating the length of coastline to be protected. The current study utilizes NOAA Medium Resolution Shoreline Data to determine what is considered shoreline. This dataset does not include Hawaii, Alaska, Puerto Rico, Guam, or other US territories. However, the dataset was selected to ensure that the results were consistent with the original dataset provided by Climate Central, which was based on the NOAA Medium Resolution Shoreline Data. As illustrated in the map of Charleston, South Carolina in Figure 1, detailed imaging of the inlets and tidal areas resulted in a high-resolution map where the actual length of coastline increased, in some cases significantly, from traditional coastline figures that emphasize only direct coastal exposure. Charleston is used as an example for two reasons: (1) the Charleston area was used as an initial benchmark of the methodology, as a comparison could be made with existing estimates and designs published for the Charleston area, and (2) the complexity of the Charleston coastline enabled the researchers to look at a complicated case as a foundational case. The methodology employed after this benchmarking effort is a notable advancement in understanding the

protection requirements for coastal communities as it gives a more accurate estimate of the protection requirements. This high resolution translated to a study length of approximately 217,000 km of potentially exposed coastline.

After completing the protection length calculation, the model analyzed the coastline for every grid that was determined to have a flooding impact on identified infrastructure. For each of the identified grids, the length of coastline in that grid was calculated to a linear meter (Figure 2).

Figure 2. The 150 m × 150 m grid overlaid on the infrastructure and inundation zones combined with the projected protection zones. Each red grid indicates an area requiring protection. The blue lines indicate shoreline.

3.4. Costing

Costing assessments for the study were created using a combination of national cost data [29] and local estimates from seawall design and construction companies to establish localized per-meter costs. This combination provided a national baseline through the published data, as well as local specificity provided through individual project data. In this manner, the estimates were adjusted for location factor by state, based on the location of the sea wall.

The cost estimates are divided into two categories, coastal seawalls and inland seawalls. In terms of the former, coastal seawalls are comprised of armored revetments that are either adjacent to shore structures or serve as standalone offshore structures. The current study utilizes a typical design approach of using field stone to create an armored revetment on the shoreline. This design is utilized in the model wherever the coast exposure is direct to open water. Where the protection assessment determined that seawalls were required in an area that had direct ocean exposure, the linear meters of seawall required is multiplied by the per-meter cost of the revetment.

Inland seawalls, often referred to as bulkheads, focus on the protection of shoreline from an increased water level as well as from indirect wave action. Bulkheads are generally constructed of steel sheet piling, wood, or concrete where more permanent protection

is required. The primary cost factor in these solutions is the installation, which may vary depending on where the bulkhead is located. Similar to the revetments, where the protection assessment determined that inland protection was required, the per-meter cost of the bulkhead is multiplied by the total length of the protection required.

When the estimates for the two types of potential protection devices are combined, the overall costing Equation (1) can be written as follows:

$$C_T = ((C_R * L_R) * LF_R) + ((C_B * L_B) * LF_B) \quad (1)$$

where:

C_T = Cost Total (USD);

C_R = Cost Revetment (USD);

C_B = Cost Bulkhead (USD);

L_R = Local Cost Factor Revetment (change from national cost per meter);

LF_R = Linear Meters of Revetment;

L_B = Local Cost Factor Bulkhead (change from national cost per meter);

LF_B = Linear Meters of Bulkhead.

Returning to the Charleston, SC example, the costing methodology, when combined with the variance in model projections, results in a range of possible outcomes. Tables 1 and 2 detail the range of results for Charleston across the scenarios and time slices. Table 1 indicates the costs for SLR alone while Table 2 includes the additional costs when a one-year storm surge is considered. While the results presented in this paper emphasize the 2040 time slice with the 50th percentile from RCP 4.5, the full range of alternative projections were analyzed. The tables provide a representative example of the variance that exists for specific coastal locations with local variances occurring due to local geographic attributes.

Table 1. The cost in millions USD for protecting Charleston, SC under the different scenarios considered in the study. The variance is representative of that which exists for each location considered. The range of the variance is dependent on local conditions along the coastline.

Likelihood (in terms of percentiles)	RCP 2.6			RCP4.5		
	2040	2060	2100	2040	2060	2100
	Cost in Millions USD			Cost in Millions USD		
5th	945	960	977	948	968	1019
50th	969	1002	1028	972	1009	1043
95th	1005	1028	1047	1005	1029	1065

Table 2. The total cost for protection for the Charleston, SC example when the addition of a one-year storm surge is included in the protection cost. The incremental difference is representative of the increments experienced in locations throughout the study.

Likelihood (in terms of percentiles)	RCP 2.6			RCP4.5		
	2040	2060	2100	2040	2060	2100
	Cost in Millions USD			Cost in Millions USD		
5th	1027	1029	1032	1027	1030	1044
50th	1031	1036	1047	1031	1038	1059
95th	1038	1047	1064	1038	1048	1075

4. Results

In this section, the results of the SLR study are presented at the national, state, and city levels to emphasize the multi-jurisdictional impact of SLR. As detailed in the methodology section, the current study analyzed 36 different climate projections to determine the potential impacts of SLR and storm surge. The analysis presented in the following sections

is based on future projections of median floodwater depths, computed as the superposition of SLR and 1-year storm surge, targeting both 2040 and 2100 under RCP 4.5.

4.1. National Results

The national results focused on the lower 48 states are presented in terms of regional groups to ensure consistency with the underlying datasets utilized in the study. The first of these regions, the western states (California, Oregon, and Washington), see a combined impact of USD 53.5 billion by 2040, with Washington having the largest impact with a potential impact of USD 23.9 billion. While this region is not discussed as often as the Atlantic coast and Gulf coast states, the impact should not be minimized. Washington and California are ranked 7th and 8th, respectively, in terms of potential impacts from SLR and storm surge by 2040.

The Gulf coast states (Texas, Louisiana, Mississippi, Alabama, and Florida) see a combined impact of USD 142.9 billion by 2040, with Florida having the largest impact with a potential cost of USD 75.9 billion as the top ranked state for impact under this scenario. This region has received considerable focus for climate impact due to the potentially large impact on tourism and property values of coastal real estate [30]. However, the projected impact of SLR grows significantly larger when the cost of protecting assets beyond real estate to include infrastructure as a general category is considered.

The southern half of the Atlantic states (Virginia, North Carolina, South Carolina, and Georgia) account for USD 101.2 billion in costs by 2040. Notable among this group are North Carolina and Virginia, which rank 3rd and 4th in projected costs, respectively. This region is already incurring damage-related costs in the billions of dollars due to increased nuisance flooding, as well as from recent hurricanes. However, the projected impact from chronic SLR issues must not be overlooked. The long-term cost of chronic impacts will likely surpass those of one-time events.

Finally, the northern half of the Atlantic states (Maine, New Hampshire, New York, Massachusetts, Rhode Island, Connecticut, Delaware, Pennsylvania, New Jersey, Washington DC, and Maryland) account for the remaining USD 118.7 billion. This region is notable for having states with considerable coastal infrastructure that requires protection such as in Maryland and New Jersey. In these locations, as in many of the high-cost states, infrastructure has been constructed over time in low-lying areas that extends to the coast with little or no buffer areas to protect property and infrastructure.

4.2. State Results

As illustrated in Table 3, Florida, Louisiana, and North Carolina are the top three states in terms of projected protection costs and kilometers of protection required. Each of these states have extensive low-lying areas that exist together with the extensive infrastructure that has been built in the low-lying areas. While these vulnerabilities have been exposed in large events such as hurricanes, the potential risk from the topography is increased when the impact of SLR and storm surge is taken into account.

Table 3. Protection cost and kilometers of protection required per state at 2040 and 2100 using the RCP 4.5 scenario at 50% to provide a mid-range estimate.

State	2040 (Billions USD)	2040 (Kilometers)	2100 (Billions USD)	2100 (Kilometers)
Florida	75.9	14,875	109.4	20,543
Louisiana	38.4	10,885	42.3	11,915
North Carolina	34.8	8449	36.7	8696
Virginia	31.2	6538	37.7	7930
Maryland	27.4	4821	36.0	6160
New Jersey	25.0	4338	29.3	4842

Table 3. *Cont.*

State	2040 (Billions USD)	2040 (Kilometers)	2100 (Billions USD)	2100 (Kilometers)
Washington	23.9	2657	28.2	3159
California	22.0	2872	27.3	3611
South Carolina	20.1	5153	22.3	5436
Texas	19.3	4407	26.6	5845
Massachusetts	18.7	2077	24.0	2565
New York	17.4	2030	24.0	2774
Georgia	15.1	3958	15.8	4058
Maine	11.0	2039	13.8	2520
Delaware	9.4	1514	10.1	1612
Oregon	7.6	1105	9.8	1404
Alabama	6.0	963	7.7	1194
Connecticut	5.3	634	6.7	804
Mississippi	3.3	645	4.4	796
Rhode Island	2.9	397	4.0	553
New Hampshire	1.0	196	1.2	228
Pennsylvania	0.5	106	1.0	209
Washington DC	0.14	33	0.2	48
TOTAL	416.34	80,703	518.5	96,913

4.3. City Results

The results for individual cities are presented in this section in multiple formats, including the total costs and the costs per-capita. These multiple perspectives were created by translating the underlying grids from the study of the geographic boundaries specified by the Census Bureau (Data obtained from the US Census Bureau at <https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html>, accessed on 10 June 2019). Table 4 presents the top 20 cities in terms of total cost that are at risk from SLR and storm surge based on the medium projection scenario.

Table 4. Protection cost for the Top 20 cities at 2040 using the RCP 4.5 scenario at 50%.

Rank	City	State	2040 (Millions USD)
1	Jacksonville	FL	3461
2	New York	NY	1974
3	Virginia Beach	VA	1717
4	Marathon	FL	1507
5	Fire Island	NY	1450
6	Galveston	TX	1058
7	Charleston	SC	1032
8	Bolivar Peninsula	TX	967
9	Tampa	FL	938
10	Barnstable Town	MA	889
11	Corpus Christi	TX	861
12	North Key Largo	FL	826
13	Poquoson	VA	821
14	Islamorada, Village of Islands	FL	811
15	St. Petersburg	FL	751
16	New Orleans	LA	725
17	North Topsail Beach	NC	724
18	Mobile	AL	718
19	Seattle	WA	716
20	Ocracoke	NC	708
	Total		22,654

The city ranking in Table 4 is critically affected by the inclusion of inland waterways in the assessment of coastal exposure, as demonstrated by the scores of Jacksonville, New York City, Virginia Beach, and Charleston. Cities that are located on islands (Marathon, FL, Fire Island, NY, and Galveston, TX) also occupy the top spots as a consequence of the significant extension of protection requirements.

The top 20 cities not only represent a diversity of geography, but also represent a diversity in costs per capita and costs per square area. Table 5 highlights a different perspective on the top twenty cities by highlighting those with the highest costs per capita. Many of these locations are either small towns located on islands, or beach towns located on coastal or inland waterways. These results highlight a challenge for policy makers as to where to prioritize limited protection funds. Should priority be given to popular tourist areas with small populations, but a large risk factor, or should priority be given to urban areas that provide a larger return-on-investment ratio in terms of the protection costs to area and population.

Table 5. Costs per capita at the city level in 2040 under the RCP 4.5 scenario at 50%. Minimum 100 population.

Rank.	City	State	2010 Population (US Census Bureau)	2040 Costs per Capita (Millions USD)
1	Fire Island	NY	246	5.89
2	Dames Quarter	MD	157	3.89
3	Frenchtown-Rumbly	MD	133	2.65
4	Gilgo	NY	146	1.99
5	Ocracoke	NC	404	1.75
6	Fairmount	MD	306	1.46
7	Napeague	NY	129	1.28
8	Bald Head Island	NC	225	1.09
9	Fishers Island	NY	230	0.97
10	St. George Island	FL	740	0.91
11	Cameron Parish	LA	222	0.87
12	North Key Largo	FL	1009	0.82
13	Topsail Beach	NC	366	0.74
14	North Topsail Beach	NC	1061	0.68
15	Deal Island	MD	465	0.66
16	Asharoken	NY	446	0.65
17	Aripeka	FL	111	0.62
18	Taylors Island	MD	201	0.61
19	Gwynn	VA	426	0.58
20	Strathmere	NJ	257	0.54

The projected costs per population highlight the challenge of small cities in terms of the cost of protection versus the size of the city. The same challenge exists in terms of the size of the town in comparison to the threats facing the location. Table 6 lists the 20 communities at least 2.6 square kilometers in size with highest costs per square kilometer. All but one of these communities is predicted to have costs that exceed USD 100 million to protect in 2040.

Table 6. Costs per square kilometer at the city level in 2040 under the RCP 4.5 scenario at 50%. Minimum 2.6 square kilometers in land area.

Rank	City	State	Land Area (Sq. Kms.)	2040 Per Sq. Km (Millions USD)
1	Fire Island	NY	23.8	61.1
2	Holden Beach	NC	7.1	60.1
3	Holmes Beach	FL	4.4	59.6
4	Wrightsville Beach	NC	3.6	59.5
5	North Beach Haven	NJ	4.7	57.3
6	St. George Island	FL	12.3	54.8

Table 6. *Cont.*

Rank	City	State	Land Area (Sq. Kms.)	2040 Per Sq. Km (Millions USD)
7	Old Field	NY	5.36	51.8
8	Nahant	MA	2.7	49.8
9	Piney Point	MD	4.0	48.6
10	Islamorada, Village of Islands	FL	16.7	48.6
11	Big Coppitt Key	FL	3.0	45.6
12	North Topsail Beach	NC	16.1	45.1
13	Rehoboth Beach	DE	3.1	42.6
14	Dauphin Island	AL	16.2	42.5
15	Gwynn	VA	6.1	40.7
16	Duck	NC	6.3	40.7
17	Tavernier	FL	6.5	40.1
18	Deal Island	MD	7.9	39.1
19	Westbrook Center	CT	4.4	39.1
20	Belford	NJ	3.3	37.0

5. Discussion

The protection of the coastline across 23 states with coastal exposure is a significant task that will require the cooperation of national, regional, and local entities. An intermediate climate scenario in 2040 projects that every coastal-facing state is threatened by sea level rise and storm surge at a national cost conservatively placed at USD 416 billion. This estimate grows to USD 518 billion dollars when the same scenario is extended to 2100. This projection does not include maintenance costs, future replacement costs, or potential inflationary pressures due to a limitation of material or personnel resources.

This exposure elevates the SLR issue from a local problem that places the burden on local officials to a national issue that requires collaboration at all levels. This study highlighted a middle-of-the-road projection in 2040 and 2100 to emphasize a likely scenario of costs that jurisdictions will face by 2040. As illustrated in this study, the majority of states incur the primary protection costs by 2040, and only a few see significant increases in 2100.

Complementing the focus on states is a deeper focus on coastal cities. Whereas cities such as New York City, San Francisco, and Miami are often the focus of SLR concerns, the risks of SLR go beyond these limited examples. The current study addresses this oversight by specifically addressing coastal cities of all sizes. The analysis highlights the particular concern for the small islands and coastal areas that either line the coast or lie adjacent to the mainland in areas along the Atlantic coast in particular. These areas often have small populations, but are popular tourist destinations, have individuals with longstanding family ties to the area, or may be small communities of very wealthy individuals. Protecting these areas, in particular the islands, can translate to significant costs when put in the context of the size of the area.

The following sections focus on three specific issues that emerge from the current study: the response timeline, the urban versus rural challenge, and the protection options challenge.

5.1. Response Timeline

A key message developed in this study is that the timeline for responding to the threat of sea level rise and storm surge begins now. The data for all alternative projections included within this study indicates that SLR and storm surge will have a national impact by 2040 in the majority of locations. In addition to the projected cost factor, there is considerable effort required to plan and design for protective barriers. Issues such as environmental impacts, site-specific engineering solutions, and the availability of expertise will extend the time required to implement protection solutions.

Given that additional cost and time will be required for almost all of the protection projects, consideration must be given to initiating discussions on this issue if they are not already started. The study indicates that within 20 years, approximately 80% of the protection needed by 2100 to protect infrastructure from the SLR risk will already be required. In terms of the number of kilometers of protection required by 2040, there is a projected need for over 80,000 km of protection. This projection only increases by 15% to just over 96,000 by 2100. This increase reduces to 10% or less in states including Delaware, Louisiana, New Jersey, North Carolina, South Carolina, and Georgia.

The overall message being that the timeline for decision making is sooner rather than later. The majority of impacts to infrastructure will occur by 2040.

5.2. *Urban versus Rural*

The second challenge arising from the current study is the issue of where to prioritize protection from SLR and storm surge. As documented previously, depending on the perspective chosen, the cities at greatest risk will change in terms of cost. Smaller, remote island communities can be viewed as significantly higher in cost when viewed from a perspective of per-square-kilometer costs. In contrast, coastal cities such as Jacksonville, Florida have a much smaller investment when viewed on a per-square-kilometer basis. This would indicate that the relative cost of protecting the infrastructure in Jacksonville is less than that facing a small coastal island community. When viewed from a perspective of population, small coastal cities are a much more significant investment than larger coastal communities, especially when placed in the context of a costs per capita investment. Finally, from a total cost perspective, the perspective changes with cities such as Miami, which are spread along the coast rather than having a compact waterfront. Each of these perspectives is valid but requires a different prioritization of funding.

5.3. *Protection Feasibility and Options*

The final issue that is highlighted here is the issue of whether defensive seawalls are the appropriate approach to protecting communities, in particular smaller communities. With 80,000 km of seawall to construct by 2040, the issue arises as to the feasibility of constructing this volume of protection in time and whether this is the correct approach. The issue of feasibility gives rise to multiple concerns, including those for the availability of design and construction personnel, for the availability of materials, and for potential price increase due to micro-inflationary pressures. However, an overriding question exists as to whether every community should undertake such a defensive endeavor.

This study focuses on the potential to protect infrastructure from SLR and storm surge. However, the remaining two options, retreat and accommodate, cannot be discounted as viable options. Significant attention is currently being placed on the concepts of managed retreat where communities strategically move away from vulnerable locations along the coastline [31–33]. These strategies emphasize the advantage of placing communities in safer locations rather than expending large amounts of resources on protection which may not be sufficient in the long-term.

In contrast to retreating, accommodating focuses on utilizing topography and water channeling efforts to manage the rising sea around an urban area. This approach focuses on considering options such as canals and raised structures to coexist with the rising sea level [34–36]. The argument for this approach being those examples such as Venice and Amsterdam which have demonstrated over centuries that accommodation can be effective given the planning and strategic management of the solution. Additionally, the solution can be implemented over an extended period of time rather than a large investment that is required for protection.

The ultimate decision as to which approach to take will likely be made at a local level. While each approach has advantages and disadvantages, the underlying focus remains consistent that a strategy is required to address the real threat of SLR.

5.4. Limitations

The cost estimates presented here are considered conservative in that they are estimated construction costs that may increase due to specific conditions in local areas. The costs also do not include long-term maintenance costs or the potential for cost increases due to inflationary pressures. Thus, the actual costs incurred by municipalities is likely to be higher than the costs presented in this study.

6. Conclusions

The current study is intended to open a new conversation on the impact of sea level rise and storm surge. It is not focused on the science behind the SLR risks, nor does it intend to add to the scientific question of whether there will be SLR or how much SLR there might be. Rather, the current study addresses the critical question of what the potential impact of the projected SLR and storm surge is. In the same manner that public officials plan for earthquakes, hurricanes, floods, and tornadoes, SLR is a natural hazard that deserves a complete range of discussions including how to minimize the damage if and when such an event occurs. At a conservative projection of a USD 400 billion impact by 2040, SLR can no longer be ignored or treated as a purely theoretical argument by public officials responsible for the health and safety of the general public.

In addition to encouraging public officials to include SLR in planning discussions, this study should encourage communities of all sizes to consider the monetary commitment required for protection against SLR. Whether the community is limited in physical area and population or is one of the larger cities such as San Francisco, the impact of SLR will have significant financial impact.

The decision to address SLR is only the first step in addressing this complex issue. A single property owner, or even a single community, is not enough to address the overall threat from SLR. While a single owner may choose to retreat from the coastal area, or a community may elect to aggressively address SLR, this is an issue that requires cooperation and collaboration at the state, regional, and national levels. The successful implementation of a protection system requires neighboring communities and states to work together to ensure that engineered or natural systems work seamlessly along the coastline.

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