HIGH TIDE TAX

The Price to Protect Coastal Communities from Rising Seas

CENTER FOR CLIMATE INTEGRITY

The Center for Climate Integrity
Resilient Analytics

JUNE 2019

Lead Authors

Sverre LeRoy, PhD

Richard Wiles

Contributors

Paul Chinowsky, PhD

Jacob Helman

CENTER FOR CLIMATE INTEGRITY

About CCI

The Center for Climate Integrity is a project of the Institute for Governance and Sustainable Development. The Center for Climate Integrity supports litigation and advocacy to hold the fossil fuel industry accountable for their fair share of the escalating costs of adapting to climate change. Through community engagement, communications, and strategic legal support, CCI works to elevate the idea that taxpayers should not shoulder the burden of climate costs alone. Instead, those who contributed to the climate crisis — and who downplayed the monumental risks they knew their products would create — should help communities with those growing bills.

Executive Summary

The United States faces more than $400 billion in costs over the next 20 years, much of it sooner, to defend coastal communities from inevitable sea-level rise. This is approaching the cost of the original interstate highway system and will require the construction of more than 50,000 miles of coastal barriers in 22 states in half the time it took to create the nation's iconic roadway network. More than 130 counties face at least $1 billion in costs, and 14 states will see expenses of $10 billion or greater between now and 2040.

These costs reflect the bare minimum coastal defenses that communities need to build to hold back rising seas and prevent chronic flooding and inundation over the next 20 years. They represent a small portion, perhaps 10 to 15 percent, of the total adaptation costs these local and state governments will be forced to finance during that time and into the future.

The question is, will taxpayers be on the hook for all the costs of climate adaptation, or will polluters be forced to pay their fair share?

This looming climate and financial threat exists for every coastal community, regardless of size, population, or financial position, and includes large cities such as New York and Miami and small communities like Dames Quarter, MD and Topsail Beach, NC.

For hundreds of small coastal and tidal communities identified in the report, the costs will far outstrip their ability to pay, making retreat and abandonment the only viable option unless enormous amounts of financing emerge in a very short period of time. Yet even retreat comes at a substantial cost, as courts have begun to rule that governments that fail to protect private property must compensate property owners for the value of the property that is abandoned.

As just one example of the scope and gravity of this problem, in 19 small, mostly unincorporated communities, the cost of seawalls to protect property and infrastructure from a moderate amount of sea level rise by 2040 is more than $1,000,000 per person. It seems fair to say that these communities will not be defended, although those decisions will all be made locally. In 43 communities the cost is more than $500,000 per person, and in 178 communities the cost of basic coastal defenses is more than $100,000 per person.

In reality, the situation could be much worse. This analysis is based on modest sea-level rise projections that assume some reductions in carbon emissions (RCP 4.5, described below). Seas could easily rise more than we project in this study, but they are very unlikely to rise less. And we only assumed protections for a one-year storm (the event that is virtually certain to occur every year), even as one in 100 and one in 500-year storms strike the coast with alarming frequency.

This conservative approach is by design, and is intended to shine a light on near-term costs and choices that cannot be avoided. Unlike many studies that look at sea-level rise in the year 2100 and assume a higher level of ongoing emissions, we purposefully analyzed more moderate and immediate scenarios to direct the policy discussion toward decisions that need to be made right now.

In many states, including Florida, Virginia, and South Carolina among others, these discussions are well underway. But even where communities are beginning to plan for climate impacts, the statewide costs of basic coastal and tidal protection are most often not publicly known.

Florida is by far the most heavily impacted state, with costs reaching nearly $76 billion statewide, 23 counties facing at least $1 billion in seawall expenses alone (and often far greater price tags according to local estimates), and 24 communities where building just this rudimentary level of coastal protection will cost more than $100,000 per person.

Climate impacts do not respect partisan boundaries, with Republican and Democratic congressional districts hit roughly evenly by 2040: Republican congressional districts will incur $224 billion in seawall costs, while Democratic congressional districts will incur $192 billion. There are 71 districts facing more than $1 billion in seawall expenses by 2040: seven of the top 10 and 24 of the top 40 are currently represented by Republicans. Overall, 100 are represented by Democrats and 371 are represented by Republicans. Though Republican congressional districts make up only 27% of the congressional districts that will incur costs by 2040, they account for 54% of the total national cost.

For complete state, county, city and congressional district rankings, see our rankings webpage at climatecosts2040.org/rankings.

1 Including vacant seat NC-3, previously held by a Republican congressman.

Recommendations

The failure of the American public and its elected representatives to come to grips with the massive costs of climate adaptation (not to mention disaster recovery, which is not addressed here), is perhaps the most delusional form of climate denial we currently face.

Climate threats are real, they are here today, and the unaddressed financial costs of adaptation loom large and are unavoidable. Protecting America from climate change will be the most all-encompassing transformation of civil society ever undertaken, whether we engage the task wisely, or deny it and delay well past when we should act, as we are wont to do with all things climate related. Either way, climate adaptation will touch every sector of society and every citizen, requiring all the skills and resources we can muster ¬– in this case steel, cement, engineers, planners, road builders and much more – in an unprecedented reinvention of the world we live in.

And yet even then, none of this will come to pass unless everyone pays their fair share.

As things stand, oil and gas companies and other climate polluters who knew their products caused climate change at least 50 years ago, and then masterminded an exquisitely effective denial campaign for 30 years, are paying none of these costs. And their position, as expressed in courtrooms across the country, is that they should continue to pay nothing at all.

That simply cannot stand. Regardless of your political persuasion or your views on energy policy or climate change, there is no avoiding the conclusion that the companies that made and promoted the products that they knew would irrevocably and radically alter the global climate, and then denied it, must pay their fair share to help the world deal with it. Failing to hold polluters to this basic responsibility would be to knowingly bankrupt hundreds of communities, standing idly by as they are slowly and inexorably swallowed up by the sea.

Introduction

Coastal communities worldwide are facing the daunting challenge of protecting their citizens and their infrastructure – roads, bridges, airports, rail lines, port facilities, sewage treatments systems, drinking water supply systems, storm drainage systems, and public utilities – from rising sea levels.

This study provides the first estimate for the contiguous United States of the costs associated with armoring areas of the coast that contain public infrastructure and that are projected to be flooded by sea-level rise. While a variety of infrastructures are at risk due to the impacts of climate change, the primary focus of this study is estimating the costs of ensuring that roads, rails, and other public infrastructure are protected from the predicted near-term and long-term impacts of sea-level rise under moderate, not worst case, emissions scenarios. The study did not specifically identify homes and other private property for protection, but instead relied on roads as a proxy for areas with developed private assets.

The Center for Climate Integrity partnered with Resilient Analytics, an engineering firm specializing in climate adaptation, to generate the estimated costs of constructing seawalls to protect public infrastructure in the contiguous United States from sea-level rise. By pairing a sophisticated sea-level rise model[2] with 1-year storm surge estimates,[3,4] as well as the NOAA Medium Resolution Shoreline dataset, we have produced planning-level cost estimates for different years (2040, 2060, 2100) under two different future emissions scenarios, with and without a 1-year storm surge for states, congressional districts, counties, as well as cities, towns, villages, and census designated places (unincorporated population centers), which we collectively refer to as *communities*. The complete dataset is available for download at www.climatecosts2040.org.

2 Kopp, Robert E., Robert M. DeConto, Daniel A. Bader, Carling C. Hay, Radley M. Horton, Scott Kulp, Michael Oppenheimer, David Pollard, and Benjamin H. Strauss. "Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections." *Earth's Future* 5, no. 12 (2017): 1217-1233.

3 Tebaldi, Claudia, Benjamin H. Strauss, and Chris E. Zervas. "Modelling sea level rise impacts on storm surges along US coasts." *Environmental Research Letters* 7, no. 1 (2012): 014032.

4 Buchanan, Maya, Kopp, Robert, Oppenheimer, Michael, Tebaldi, Claudia. "Allowances for evolving coastal flood risk under uncertain local sea level rise." *Climatic Change*, 137, 3-4, 347-362 (2016).

Sea-Level Rise

Since 1900, global mean sea-level has risen about 8 inches,[5] but this has not been a steady progression, nor has it been the same in every location. The rate of sea-level rise began to increase dramatically in the late 20th Century. Since 1990, the rate of sea-level rise has increased to about twice the rate of the last century and is continuing to accelerate.[6,7]

Global warming contributes to sea-level rise in several ways. As the oceans warm from rising air temperature, seawater expands, takes up more space, and the oceans rise to accommodate this physical expansion. This process is known as *ocean thermal expansion*, and accounts for about 50% of the increased volume of the world's oceans over the past 100 years. The remaining sea-level rise of the past century has been the result of melting mountain glaciers (about 25%) and Antarctic and Greenland ice sheet loss (about 25%).[8,9]

There is a delay between rising air temperatures and sea-level rise. Ocean thermal expansion and ice loss occur on timescales slower than the rate at which air temperature increases in response to rising atmospheric CO_2 concentrations. It can take over a thousand years for ocean thermal expansion to equilibrate with warmer air temperatures.[10] Even if there were huge reductions in fossil fuel use and CO_2 emissions, oceans would continue to rise for many centuries because of the slow nature of the processes governing sea-level rise.

5 Church, J., White, N., "Sea-level rise From the Late 19th to Early 21st Century", *Surveys in Geophysics*, 32, 4-5, 585-602 (2011).

6 Nerem, R. S., et al., "Climate-Change-Driven Accelerated Sea-Level Rise Detected in the Altimeter Era", *Proceedings of the National Academy of Sciences of the United States of America*, 115(9), 2022-2025 (2018).

7 Griggs, G, et al., "Rising Seas in California: An Update on Sea-Level Rise Science", California Ocean Science Trust (2017). http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf

8 Griggs, G, et al., "Rising Seas in California: An Update on Sea-Level Rise Science", *California Ocean Science Trust*, http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf

9 Church, J. A., et al., Chap. 13: "Sea Level Change", *Climate Change 2013: The Physical Science Basis* (2013).

10 Levermann, A., et al., "The Multimillennial Sea-Level Commitment of Global Warming", *Proceedings of the National Academy of Sciences*, 110(34), 13745-13750 (2013).

Climate Models and Sea-Level Rise Prediction

Representative Concentration Pathways (RCPs) are future climate scenarios that describe four alternative trajectories of CO_2 emissions and the resulting atmospheric CO_2 concentrations between the years 2000-2100 (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). These scenarios cover a range of possible climate policy outcomes based on different assumptions about energy consumption, energy sources, land use change, economic growth, and population. This limited set of scenarios ensures that researchers around the world, especially climate modelers, can conduct research that is comparable. The scenarios range from RCP2.6, the most aggressive in reducing carbon emissions, to RCP8.5, considered a "business as usual" scenario in which no effort is taken to reduce emissions.[11,12]

This study looks at projected sea-level rise under RCP2.6 and RCP4.5 combined with an annual, one-year storm event. We chose the two most conservative (most proactive) future scenarios in order to avoid worst-case assessments and focus the discussion on the baseline costs that will be required to protect our coastal communities against unavoidable, short-term sea-level rise. Under RCP2.6, the Intergovernmental Panel on Climate Change's Fifth Assessment Report projects that global mean sea level will likely rise 11–24 inches by 2100.[13,14] Under RCP4.5, global mean sea level is projected to likely rise 14–28 inches by 2100.[15,16] For RCP6.0 and RCP8.5, which are more plausible paths based on current policies, global mean sea level is projected to likely rise 15–29 inches and 20–39 inches, respectively, by 2100. Projections of sea-level rise that rely on these RCP scenarios generally provide conservative estimates because they do not account for the possibility that changing Antarctic ice sheet dynamics could dramatically increase sea levels by the end of the century.[17,18]

---

11 Jones, C., et al., "Twenty-First-Century Compatible CO_2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models Under Four Representative Concentration Pathways", *Journal of Climate*, 26, 4398-4413 (2013).

12 Collins, M., et al., Chap. 12: "Long-term Climate Change: Projections, Commitments and Irreversibility", *Climate Change 2013: The Physical Science Basis* (2013).

13 At least about 66% probability, according to Church, J. A., et al., Chap. 13: "Sea Level Change", *Climate Change 2013: The Physical Science Basis* (2013).

14 Relative to global mean sea level over 1986–2005.

15 At least about 66% probability, according to Church, J. A., et al., Chap. 13: "Sea Level Change", *Climate Change 2013: The Physical Science Basis* (2013).

16 Church, J. A., et al., Chap. 13: "Sea Level Change", *Climate Change 2013: The Physical Science Basis* (2013).

17 DeConto, R. & Pollard, D., "Contribution of Antarctica to Past and Future Sea-Level Rise", *Nature*, 531(7596): 591-597 (2016).

18 Shepherd, A., et al., "Mass Balance of the Antarctic Ice Sheet From 1992 to 2017, *Nature*, 556, 219-222 (2018).

The sea-level rise projections listed above are global means and do not account for regional differences, which can vary greatly. For example, the NOAA tide station in Chesapeake Bay indicates that local sea level is increasing at a rate of 5.92 mm per year, faster than nearly anywhere else in the United States. Conversely, sea-level in Crescent City, CA is *falling* at a rate of 0.78 mm per year due to local tectonic activity.[19,20] The future rate of sea-level rise is projected to be greater than the global average for the Northeast Atlantic (Virginia coast and northward) and the Western Gulf of Mexico coasts (Texas and Louisiana).[21] The effects of sea-level rise are already impacting some coastal communities: at many tide stations in the United States, the frequency of high-tide flooding has increased by an order of magnitude over the past few decades, moving from a rare event (once every 3 to 5 years) to a disruptive problem (once every 3 months).[22]

A *1-year storm surge* is the level to which coastal water rises in any given year during a typical storm according to historical sea-level data. It is an extremely common storm event, as opposed to a *100-year storm surge*, which represents a severe event that statistically occurs once every 100 years. This study relied on geographically specific storm surge predications based on work by Tebaldi et al. (2012) and Buchanan et al. (2016).

Methods

The methods employed by Resilient Analytics to assess the potential cost of protecting the coastline from the impacts of sea-level rise and 1-year storm surge entailed a multi-step process incorporating climate projections, processing detailed coastline flooding maps, a computational assessment of where tidal shorelines needed protection, and a calculation of the costs associated with this protection. The process developed for this estimation is based on previous climate impact work developed by Resilient Analytics and other scholars for

19 NOAA Center for Operational Oceanographic Products and Services, "U.S. Linear Relative Sea Level Trends," 2018, retrieved from https://tidesandcurrents.noaa.gov/sltrends/mslUSTrendsTable.html

20 Griggs, G, et al., "Rising Seas in California: An Update on Sea-Level Rise Science", *California Ocean Science Trust* (2017). http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf

21 Sweet, W., et al., "Global and Regional Sea Level Rise Scenarios for the United States," NOAA Technical Report NOS CO-OPS 083 (2017).

22 Sweet, W., et al., "Sea Level Rise and Nuisance Flood Frequency Changes Around the United States," NOAA Technical Report NOS CO-OPS 073 (2014).

infrastructure impacts locally, regionally, and globally.[23,24,25]

Sea-Level Rise Projections

Climate Central, a non-profit climate science and research organization, headquartered in Princeton, New Jersey, provided the research team with high-resolution maps for the contiguous United States coast based on published sea-level rise projections.[26] The maps provided projection data for all areas that will be impacted by sea-level rise as well as sea-level rise coupled with 1-year storm surge events. The maps include detailed analysis of the coastline down to a 5-meter x 5-meter grid to ensure accurate capture of tidal inlets. Each grid location indicated whether it was projected to be flooded and to what depth that flooding was expected to reach.

Future sea-level rise is dependent on the concentration of greenhouse gases in the atmosphere, so two RCPs were used to evaluate potential future scenarios. Specifically, the RCP2.6 and RCP4.5 pathways were used to capture a low-range and mid-range estimate of projected sea-level rise impacts. A suite of climate models, known as the CMIP5 GCM, were used to predict future sea-level rise. From this set of projections, the 5th, 50th, and 95th percentile results were selected for further analysis in this study. Three time periods were selected from the results for the impact analysis: 2040, 2060, and 2100. These data sets were provided with and without 1-year storm surge projections to capture both the base sea-level rise impact and the potential for regular flood impacts. These combinations resulted in a total of 36 different scenarios that were considered throughout the duration of the study.

Defining Infrastructure

In order to understand the impact that the projected flooding would have on public infrastructure, it was necessary to determine the location of infrastructure in the impacted

23 Cervigni, Raffaello, A. M. Losos, Paul Chinowsky, and J. L. Neumann. “Enhancing the Climate Resilience of Africa’s Infrastructure: The Roads and Bridges Sector.” *Publication* 110137 (2016): 1-0.

24 Chinowsky, Paul, Jacob Helman, Sahil Gulati, James Neumann, and Jeremy Martinich. “Impacts of climate change on operation of the US rail network.” *Transport Policy* (2017).

25 Schweikert, Amy, Xavier Espinet, and Paul Chinowsky. “The triple bottom line: bringing a sustainability framework to prioritize climate change investments for infrastructure planning.” *Sustainability Science* 13, no. 2 (2018): 377-391.

26 Kopp, R., et al., "Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections." *Earth’s Future* 5, no. 12 (2017): 1217-1233.

areas. Analysts at Climate Central provided this study with GIS files of the public infrastructure locations, based on previous work and public database information.[27] The infrastructure identification process emphasized 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 roads that are used to access residential areas. By considering all areas that contain a road (both paved and unpaved), the majority of residential areas were also considered. Areas that do not have any public infrastructure, such as national parks or protected wildlife areas, were not included in the study as pieces of infrastructure and were therefore not considered for protection.

The sea-level rise impacts and infrastructure locations were merged into one data set, and the results were placed into a gridded map (each grid square was 150 m^2).

Determining Where to Place Seawalls

The next step of the process was determining what areas of coastline needed protection from flooding. This determination requires a series of logic tests performed by a computer model 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 logic question determined 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 how much of a grid cell needs to be flooded for it to be considered a flooded grid. For the purposes of this study, grid squares are considered flooded if 15% or more of the land area within that grid is inundated. This 15% limit assisted in eliminating overprotection scenarios and was chosen based on engineering judgement upon inspection of protection patterns using 5%, 10%, 15% and 20%.

Next, the model determines whether a grid is flooded due to direct flooding or indirect flooding. Direct flooding occurs when a grid is adjacent to a waterway and the scenario indicates that the grid is flooded due to an overtopping of that adjacent waterway. In these cases, the adjacent shoreline needs to be protected to prevent the grids from incurring flooding. The indirect case

27 Strauss, B., et al., Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States, *Environmental Research Letters*, 7, 021001.

occurs when an inland grid is flooded due to being connected 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. The model then protects the coastline adjacent grid to eliminate the threat to the overall flood area.

In the next logic test, the model determined what portion of the identified flood area needs to be protected based on the presence of infrastructure. This eliminates the need for protection in areas such as nature preserves or remote areas that are uninhabited.

In the final logic test, the model calculates the length of coastline to be protected. This study utilizes the NOAA Medium Resolution Shoreline Data in order to determine what is considered shoreline. The model analyzed the coastline for every grid that was determined to require protection from flooding. For each of the identified grids, the length of coastline in that grid was calculated to the linear foot.

Seawall Cost Estimates

The estimated costs of seawall construction were created using a combination of nationally recognized construction cost estimates from the engineering community and local estimates from seawall design and construction companies to establish realistic localized per-foot costs. The location factor was important to ensure that costs reflected the rates at a local level since these rates can vary by over 10% depending on location.

The cost estimates are divided into two categories: coastal seawalls and inland seawalls. Coastal seawalls have been used to protect wave-impacted coastlines to stop or reduce the impacts of flooding. In this study, coastal seawalls are defined as retaining walls that are either adjacent to shore structures or serve as standalone offshore structures. This design is utilized wherever the coast is directly exposed to open water. Inland seawalls, often referred to as *bulkheads*, are used to protect property against rising inland water levels and indirect wave action.

Once the model determines whether a coastal or inland design is appropriate for the given grid location, the cost of that solution is multiplied by the linear feet of protection required to obtain a total cost. The results are presented as total cost and per capita cost, calculated using population estimates from the US Census Bureau's American Community Survey 5-year estimates.

Results

The data we report are from model run RCP4.5, the year 2040, with a 1-year storm surge, for the 50th percentile, unless otherwise specified.

The model predicts that by the year 2040 (2100), the contiguous US will need to construct 50,145 miles of seawall (60,213 miles), at a cost of $416 billion ($518 billion) to protect public infrastructure from predicted sea-level rise impacts (Table 1). Florida incurs the greatest state cost, facing over $75 billion in seawall defenses alone by 2040 (Table 1).

These results are planning-level estimates only and should not take the place of a detailed engineering analysis.

Table 1: States Facing Costs to Protect Against Sea-Level Rise

Costs and seawall length by state for RCP4.5, with a 1-year storm surge, in 2040 and 2100.

2040				2100				
Cost Ranking	State	Cost (USD)	Seawall Length (miles)	Cost Ranking	State	Cost (USD)	Seawall Length (miles)	% Cost Increase
17	AL	$5,997,821,000	599	17	AL	$7,648,923,000	741	28%
8	CA	$21,999,799,000	1,785	8	CA	$27,339,843,000	2,243	24%
18	CT	$5,339,664,000	394	18	CT	$6,672,956,000	500	25%
23	DC	$138,316,000	21	23	DC	$197,817,000	30	43%
15	DE	$9,415,208,000	941	15	DE	$10,123,742,000	1,002	8%
1	FL	$75,898,048,000	9,243	1	FL	$109,397,491,000	12,765	44%
13	GA	$15,060,564,000	2,460	13	GA	$15,773,720,000	2,522	5%
2	LA	$38,431,868,000	6,764	2	LA	$42,258,710,000	7,404	10%
11	MA	$18,731,965,000	1,291	10	MA	$24,000,218,000	1,594	28%
5	MD	$27,414,762,000	2,996	5	MD	$36,033,205,000	3,828	31%
14	ME	$10,897,440,000	1,267	14	ME	$13,761,299,000	1,566	26%
19	MS	$3,273,800,000	401	19	MS	$4,369,649,000	494	34%
3	NC	$34,838,128,000	5,250	4	NC	$36,722,499,000	5,404	5%

[Table 1, continued]

2040 Cost Ranking	State	Cost (USD)	Seawall Length (miles)	2100 Cost Ranking	State	Cost (USD)	Seawall Length (miles)	% Cost Increase
21	NH	$1,032,541,000	122	21	NH	$1,197,839,000	141	16%
6	NJ	$24,985,408,000	2,696	6	NJ	$29,315,494,000	3,009	17%
12	NY	$17,388,527,000	1,262	11	NY	$23,959,435,000	1,724	38%
16	OR	$7,550,580,000	687	16	OR	$9,731,336,000	873	29%
22	PA	$482,927,000	66	22	PA	$950,117,000	130	97%
20	RI	$2,872,550,000	247	20	RI	$3,935,942,000	344	37%
9	SC	$20,061,030,000	3,202	12	SC	$22,321,331,000	3,378	11%
10	TX	$19,279,011,000	2,738	9	TX	$26,578,972,000	3,631	38%
4	VA	$31,207,175,000	4,063	3	VA	$37,714,317,000	4,928	21%
7	WA	$23,892,865,000	1,651	7	WA	$28,196,185,000	1,963	18%
	TOTAL	**$416,189,998,000**	**50,145**		TOTAL	**$518,201,041,000**	**60,213**	

Table 2: Counties Facing Costs Greater Than $1 Billion

This study identifies 132 counties that will face costs greater than $1 billion (Table 2).

Ranking	County	State	Cost (USD)
1	Suffolk County	NY	$11,373,203,000
2	Monroe County	FL	$11,087,377,000
3	Barnstable County	MA	$7,039,036,000
4	Dorchester County	MD	$6,531,735,000
5	Charleston County	SC	$6,319,023,000
6	Beaufort County	SC	$6,127,015,000
7	Cumberland County	NJ	$5,789,911,000
8	Cameron Parish	LA	$5,527,708,000
9	Dare County	NC	$5,479,912,000
10	Accomack County	VA	$4,913,390,000
11	Terrebonne Parish	LA	$4,731,861,000

[Table 2, continued]

Ranking	County	State	Cost (USD)
12	Ocean County	NJ	$4,601,543,000
13	St. Mary Parish	LA	$4,547,520,000
14	Cape May County	NJ	$4,246,506,000
15	Chatham County	GA	$4,200,013,000
16	Plaquemines Parish	LA	$4,006,559,000
17	Carteret County	NC	$3,980,168,000
18	Taylor County	FL	$3,969,756,000
19	Sussex County	DE	$3,960,716,000
20	Galveston County	TX	$3,902,091,000
21	Collier County	FL	$3,847,124,000
22	Franklin County	FL	$3,794,895,000
23	Lee County	FL	$3,530,371,000
24	Duval County	FL	$3,519,456,000
25	Lafourche Parish	LA	$3,291,630,000
26	Hyde County	NC	$3,275,386,000
27	Salem County	NJ	$3,254,307,000
28	Grays Harbor County	WA	$3,252,516,000
29	Miami-Dade County	FL	$3,187,877,000
30	Somerset County	MD	$3,103,594,000
31	Mobile County	AL	$3,023,233,000
32	Pinellas County	FL	$3,001,555,000
33	Baldwin County	AL	$2,974,587,000
34	Camden County	GA	$2,951,842,000
35	Glynn County	GA	$2,944,328,000
36	Matagorda County	TX	$2,842,992,000
37	Beaufort County	NC	$2,807,684,000
38	Clallam County	WA	$2,804,153,000
39	Kent County	DE	$2,803,336,000
40	Georgetown County	SC	$2,779,912,000
41	Vermilion Parish	LA	$2,752,922,000
42	Levy County	FL	$2,735,896,000

[Table 2, continued]

Ranking	County	State	Cost (USD)
43	Plymouth County	MA	$2,733,209,000
44	Hillsborough County	FL	$2,701,224,000
45	Worcester County	MD	$2,677,970,000
46	Brunswick County	NC	$2,665,667,000
47	Onslow County	NC	$2,660,449,000
48	Solano County	CA	$2,651,660,000
49	New Castle County	DE	$2,651,156,000
50	St. Mary's County	MD	$2,580,370,000
51	Pamlico County	NC	$2,547,038,000
52	Humboldt County	CA	$2,543,754,000
53	Dixie County	FL	$2,527,310,000
54	Essex County	MA	$2,478,393,000
55	Brazoria County	TX	$2,436,894,000
56	Pacific County	WA	$2,421,406,000
57	McIntosh County	GA	$2,384,361,000
58	Talbot County	MD	$2,376,301,000
59	Mendocino County	CA	$2,304,753,000
60	Northumberland County	VA	$2,282,367,000
61	Jefferson County	TX	$2,226,575,000
62	Currituck County	NC	$2,225,353,000
63	Skagit County	WA	$2,198,549,000
64	Mathews County	VA	$2,169,506,000
65	Volusia County	FL	$2,164,314,000
66	Dukes County	MA	$2,161,128,000
67	San Juan County	WA	$2,145,603,000
68	Wakulla County	FL	$2,138,965,000
69	Gloucester County	VA	$2,131,285,000
70	Atlantic County	NJ	$2,126,117,000
71	Citrus County	FL	$2,114,361,000
72	Island County	WA	$2,085,436,000
73	Manatee County	FL	$2,022,544,000

[Table 2, continued]

Ranking	County	State	Cost (USD)
74	Brevard County	FL	$2,016,984,000
75	Santa Barbara County	CA	$2,007,493,000
76	Jefferson County	WA	$1,988,324,000
77	St. Johns County	FL	$1,976,528,000
78	Lancaster County	VA	$1,910,896,000
79	Pasco County	FL	$1,902,080,000
80	Nassau County	NY	$1,898,430,000
81	Hancock County	ME	$1,897,524,000
82	Anne Arundel County	MD	$1,885,389,000
83	Washington County	RI	$1,877,044,000
84	Gulf County	FL	$1,822,844,000
85	Queen Anne's County	MD	$1,817,082,000
86	Jackson County	MS	$1,790,400,000
87	Bristol County	MA	$1,771,597,000
88	Craven County	NC	$1,728,854,000
89	Northampton County	VA	$1,722,736,000
90	York County	ME	$1,720,259,000
91	Virginia Beach city	VA	$1,716,510,000
92	Calcasieu Parish	LA	$1,706,849,000
93	Lincoln County	OR	$1,702,086,000
94	Washington County	ME	$1,696,260,000
95	New Haven County	CT	$1,676,482,000
96	Charlotte County	FL	$1,648,130,000
97	Liberty County	GA	$1,618,356,000
98	Bay County	FL	$1,592,755,000
99	Clatsop County	OR	$1,583,660,000
100	New Hanover County	NC	$1,577,112,000
101	St. Tammany Parish	LA	$1,569,754,000
102	Chambers County	TX	$1,566,687,000
103	New London County	CT	$1,540,954,000
104	Kent County	MD	$1,538,213,000

[Table 2, continued]

Ranking	County	State	Cost (USD)
105	Jefferson Parish	LA	$1,492,583,000
106	Nantucket County	MA	$1,489,874,000
107	Fairfield County	CT	$1,426,282,000
108	Monmouth County	NJ	$1,405,033,000
109	Berkeley County	SC	$1,377,966,000
110	Iberia Parish	LA	$1,369,525,000
111	Cumberland County	ME	$1,368,080,000
112	Sonoma County	CA	$1,361,121,000
113	Whatcom County	WA	$1,332,840,000
114	Sagadahoc County	ME	$1,315,125,000
115	Middlesex County	VA	$1,303,959,000
116	Jasper County	SC	$1,282,418,000
117	Tillamook County	OR	$1,272,835,000
118	Wicomico County	MD	$1,266,722,000
119	King County	WA	$1,257,733,000
120	St. Bernard Parish	LA	$1,245,843,000
121	Knox County	ME	$1,230,140,000
122	Westmoreland County	VA	$1,194,001,000
123	Sarasota County	FL	$1,155,486,000
124	Charles County	MD	$1,151,405,000
125	Lincoln County	ME	$1,144,820,000
126	Marin County	CA	$1,136,640,000
127	St. Martin Parish	LA	$1,125,893,000
128	Colleton County	SC	$1,114,143,000
129	Snohomish County	WA	$1,112,754,000
130	San Joaquin County	CA	$1,027,678,000
131	Nassau County	FL	$1,002,791,000
132	Kitsap County	WA	$1,001,277,000

Table 3: Communities Facing Costs Greater Than $1 Billion

This study identifies seven communities that will face costs greater than $1 billion (Table 3). Note that "communities" includes self-governing cities, towns, and villages, as well as their unincorporated counterparts, known as Census Designated Places.

Ranking	City	State	Cost (USD)
1	Jacksonville	FL	$3,460,516,000
2	New York	NY	$1,973,735,000
3	Virginia Beach	VA	$1,716,510,000
4	Marathon	FL	$1,506,927,000
5	Fire Island	NY	$1,449,948,000
6	Galveston	TX	$1,057,849,000
7	Charleston	SC	$1,031,923,000

Table 4: Communities Facing Per Capita Costs Greater Than $500,000

This study identifies 43 communities that will face per capita costs greater than $500,000 (Table 4).

Ranking	City	State	Cost per Capita (USD)
1	Junction City	WA	$7,155,000
2	Fire Island	NY	$5,894,000
3	Popponesset Island	MA	$3,966,000
4	Dames Quarter	MD	$3,894,000
5	Quintana	TX	$3,439,000
6	Oak Beach-Captree	NY	$3,359,000
7	Pawleys Island	SC	$3,211,000
8	Frenchtown-Rumbly	MD	$2,651,000
9	Pine Island	FL	$2,546,000
10	Marineland	FL	$2,249,000
11	Hat Island	WA	$2,102,000
12	Gilgo	NY	$1,992,000
13	Ocracoke	NC	$1,753,000
14	Moss Landing	CA	$1,552,000
15	Fairmount	MD	$1,461,000
16	West Hampton Dunes	NY	$1,362,000
17	Napeague	NY	$1,281,000
18	Saltaire	NY	$1,241,000
19	Bald Head Island	NC	$1,092,000
20	Dering Harbor	NY	$973,000
21	Fishers Island	NY	$972,000
22	Elliott	MD	$969,000
23	Sanford	VA	$950,000
24	Hobucken	NC	$948,000
25	St. George Island	FL	$912,000
26	Seconsett Island	MA	$901,000
27	Cameron	LA	$870,000

[Table 4, continued]

Ranking	City	State	Cost per Capita (USD)
28	Bayport	FL	$820,000
29	North Key Largo	FL	$819,000
30	Topsail Beach	NC	$739,000
31	North Topsail Beach	NC	$682,000
32	Deal Island	MD	$664,000
33	Asharoken	NY	$653,000
34	Aripeka	FL	$621,000
35	Altoona	WA	$613,000
36	Taylors Island	MD	$609,000
37	Gwynn	VA	$583,000
38	Sekiu	WA	$573,000
39	Strathmere	NJ	$544,000
40	Dauphin Island	AL	$543,000
41	Fenwick	CT	$538,000
42	Horseshoe Beach	FL	$519,000
43	Slaughter Beach	DE	$507,000

Table 5: Congressional District Cost Rankings

This study identifies 137 congressional districts that will incur costs to protect their shoreline against sea-level rise by 2040 (Table 5).

Ranking	Congressional District		Cost (USD)
1	NC	3	$28,184,617,000
2	MD	1	$20,492,822,000
3	FL	2	$19,013,483,000
4	NJ	2	$18,124,997,000
5	LA	3	$17,498,287,000
6	VA	1	$15,472,328,000
7	LA	1	$15,394,584,000
8	GA	1	$15,060,564,000
9	MA	9	$13,857,355,000
10	FL	26	$12,906,485,000
11	SC	1	$11,298,192,000
12	VA	2	$11,195,012,000
13	WA	6	$10,037,982,000
14	DE	(at Large)	$9,415,208,000
15	NY	1	$9,059,599,000
16	TX	14	$8,639,534,000
17	WA	2	$7,456,997,000
18	CA	2	$7,303,127,000
19	ME	1	$6,803,346,000
20	TX	27	$6,105,658,000
21	AL	1	$5,997,821,000
22	FL	19	$5,789,968,000
23	FL	4	$5,647,118,000
24	SC	6	$5,008,135,000
25	MD	5	$4,925,217,000
26	NC	7	$4,910,089,000

[Table 5, continued]

Ranking	Congressional District		Cost (USD)
27	ME	2	$4,094,094,000
28	FL	6	$3,923,020,000
29	LA	6	$3,846,989,000
30	SC	7	$3,754,703,000
31	FL	16	$3,527,392,000
32	MS	4	$3,273,800,000
33	CA	3	$3,113,328,000
34	WA	3	$3,075,147,000
35	FL	11	$3,030,741,000
36	FL	1	$3,028,569,000
37	OR	5	$2,974,921,000
38	TX	36	$2,952,301,000
39	CA	24	$2,816,183,000
40	FL	17	$2,795,206,000
41	FL	12	$2,721,312,000
42	CT	2	$2,562,678,000
43	MA	6	$2,465,678,000
44	FL	8	$2,438,881,000
45	NJ	3	$2,435,729,000
46	OR	4	$2,286,648,000
47	OR	1	$2,199,679,000
48	FL	13	$2,182,323,000
49	VA	3	$2,145,779,000
50	RI	2	$2,030,097,000
51	VA	4	$1,900,473,000
52	NY	2	$1,809,784,000
53	FL	18	$1,797,435,000
54	NC	1	$1,743,421,000
55	LA	2	$1,643,332,000
56	CT	3	$1,587,843,000

[Table 5, continued]

Ranking	Congressional District		Cost (USD)
57	NJ	6	$1,573,643,000
58	TX	34	$1,530,128,000
59	FL	14	$1,519,734,000
60	NY	3	$1,485,736,000
61	CA	9	$1,453,100,000
62	MA	8	$1,393,685,000
63	FL	25	$1,386,518,000
64	WA	1	$1,257,506,000
65	CT	4	$1,189,142,000
66	CA	5	$1,172,505,000
67	FL	27	$1,141,970,000
68	FL	3	$1,110,929,000
69	WA	7	$1,107,054,000
70	NJ	1	$1,036,855,000
71	NH	1	$1,032,541,000
72	CA	20	$907,494,000
73	NY	4	$893,421,000
74	MD	3	$869,978,000
75	RI	1	$842,452,000
76	MD	2	$840,701,000
77	NY	19	$837,610,000
78	CA	18	$737,899,000
79	CA	48	$701,102,000
80	NJ	9	$630,289,000
81	NY	11	$622,736,000
82	FL	23	$620,478,000
83	CA	14	$598,176,000
84	NJ	4	$553,596,000
85	WA	9	$536,379,000
86	NY	5	$519,670,000

[Table 5, continued]

Ranking	Congressional District		Cost (USD)
87	NY	16	$471,008,000
88	CA	52	$470,027,000
89	CA	17	$460,578,000
90	FL	22	$458,383,000
91	MA	4	$454,989,000
92	NY	17	$453,181,000
93	WA	10	$421,801,000
94	CA	11	$404,389,000
95	NJ	8	$377,707,000
96	FL	5	$347,346,000
97	MA	5	$332,183,000
98	CA	49	$327,095,000
99	CA	26	$286,586,000
100	MD	4	$283,163,000
101	NY	18	$260,492,000
102	NY	10	$252,661,000
103	CA	51	$251,925,000
104	VA	11	$249,931,000
105	NY	8	$249,638,000
106	CA	47	$246,333,000
107	VA	8	$240,101,000
108	CA	12	$221,175,000
109	CA	13	$217,938,000
110	MA	7	$215,361,000
111	FL	21	$186,252,000
112	NY	14	$176,637,000
113	FL	7	$163,742,000
114	CA	44	$151,831,000
115	NJ	10	$149,753,000
116	DC	(at Large)	$138,316,000

[Table 5, continued]

Ranking	Congressional District		Cost (USD)
117	CA	33	$125,360,000
118	NY	20	$125,228,000
119	FL	24	$109,899,000
120	NJ	12	$100,024,000
121	OR	3	$89,333,000
122	NY	12	$74,933,000
123	LA	5	$48,676,000
124	TX	29	$46,857,000
125	NY	7	$37,864,000
126	CA	15	$33,649,000
127	NY	15	$29,186,000
128	FL	20	$28,010,000
129	NY	13	$26,275,000
130	FL	15	$22,855,000
131	MA	3	$12,715,000
132	VA	7	$3,551,000
133	MD	7	$2,881,000
134	NY	9	$2,869,000
135	NJ	5	$2,815,000
136	TX	18	$2,301,000
137	TX	22	$2,233,000

Discussion

These cost estimates represent a small fraction of total costs associated with protecting our coastal communities against sea-level rise. First, this study only considers relatively conservative estimates of future sea-level rise. Second, it does *not* account for many line items that must be included in city resilience plans. For example, in New York City's comprehensive plan to defend the city against predicted sea-level rise, coastal protection amounts to only 16-20% of the total estimated cost. Other resilience considerations include: elevating buildings, insurance, utilities, liquid fuels, healthcare and community preparedness, telecommunications, transportation, environmental protection and remediation, and water and wastewater.[28]

Furthermore, this study only takes into account a 1-year storm surge. Experts recommend that communities prepare for more than 6.5 ft of sea-level rise by 2100.[29] Hurricane Sandy was statistically between a 103 – 260-year storm. Sandy pummeled New York's coastal communities with a 13 ft storm surge. Mounting evidence indicates that Sandy-sized storms will become more prevalent as climate change worsens.[30,31,32]

This study does not attempt to answer any questions that could be considered policy decisions. Some regions will be able to reduce their protective costs in exchange for relinquishing some land to the sea. In areas where the costs to protect their communities are greater than the cost to relocate, community members may be forced to consider managed retreat. This study identified many small communities where the costs of protection exceed $100,000 per person, and hundreds where the costs of protection exceed $10,000 per person. Managed retreat may become an option in these locations but is controversial due to the social and psychological difficulties associated with removing people from their homes. Additional research is needed to understand the conditions under which managed retreat should be implemented.

28 NYC Special Initiative for Rebuilding and Resiliency: https://www1.nyc.gov/site/sirr/report/report.page

29 Bamber, J., et al. Ice sheet contributions to future sea-level rise from structured expert judgement. *Proceedings of the National Academy of Sciences*, 113(43), 12071-12075 (2016).

30 Lopeman, M., et al. Extreme storm surge hazard estimation in Lower Manhattan. *Natural Hazards*, 78, 1, 355-391 (2015).

31 Orton, P., et al. A validated tropical-extratropical flood hazard assessment for New York Harbor. *Journal of Geophysical Research: Oceans*, 121, 8904 – 8908 (2016).

32 Lin, N., et al., Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *Proceedings of the National Academy of Sciences*, 116(23), 11195-11200 (2019).