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“Can seawalls help American cities adapt to coastal flooding?”

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Abstract

Purpose – This study aims to combine information about sea level rise (SLR), the probability distribution of storm surge, a flood damage function and the value of property by elevation along the coast of selected cities to measure expected flood damage. The selected six cities all have nearby long-term tidal stations that can be used to estimate the probability distribution of floods. The model is calibrated to each city. The study then compares the cost of building higher seawalls today along the coast versus the benefit of each wall (the reduction in expected flood damage).

Design/methodology/approach – The combination of coastal storms and SLR has led to extensive flood damage across American cities. This study creates a simple generic model that evaluates whether seawalls would be effective at addressing this flooding problem. The paper develops an approach that readily measures the expected flood benefits and costs of alternative coastal seawalls. The approach takes account of near term SLR and the probability distribution of storm surge. The model finds seawalls are effective only in cities where many buildings are in the 25-year flood plain.

Findings – Cities with many buildings built on land below 2 m in elevation (the 25-year flood plain) have high expected flood damage from storms and SLR. Cities which already have many buildings in this flood plain would benefit from seawalls. Assuming seawalls are built above the high tide line, the optimal wall height that maximizes net benefits is between 0.9 to 1.2 m. These relatively low seawalls block 70%–83% of expected flood damage in these cities. Fair flood insurance is the least cost strategy for handling the remaining damages that overtop the optimal seawalls.

Research limitations/implications – The analysis evaluates whether or not to build a seawall the length of each city at high tide lines. However, the analysis also finds several long stretches of coast in two cities where a wall is not warranted because there are few vulnerable buildings. Future analyses should consider seawalls in more spatially detailed sections of each city. Each section could then be analyzed independently. Whether or not more complex hydrodynamic models are needed to evaluate coastal resilience planning should also be explored. Alternative solutions such as planned retreat and nature-based solutions should be compared with seawalls in future studies as well.

Practical implications – Cities should be careful to avoid development in the 25-year flood plain because of high expected flood damage. Cities that have low elevation areas subject to frequent flooding should

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consider seawalls to reduce frequent flooding. Because they are very costly and have low expected benefits, high walls that can stop a one-hundred-year storm are generally not worth building.

Social implications – The analysis reveals that the most important factor determining the vulnerability of cities along the eastern coastline of the USA is the number of buildings built below 2 m in elevation (the 25-year flood plain). Cities should use zoning to discourage further development in the 25-year flood plain. Cities which already have many buildings in this flood plain would benefit from city-wide seawalls. Assuming these walls are built at mean high-high tide, the optimal height of current seawalls should be relatively modest – averaging about 0.9–1.2 m above ground. Using fair insurance for the remaining risk is less expensive than building taller walls. In particular, the cost of seawalls that protect against a major hurricane surge are over three times the expected benefit and should not be built. As decades pass and observed sea level progresses, seawalls and the boundary of the 25-year flood plain should be reevaluated.

Originality/value – This paper develops a coastal flood model that combines SLR and the probability distribution of storm surges with the value of property by elevation to estimate the expected damage from storm surge. The model is relatively easy to calibrate making it a practical tool to guide city flood planning. The authors illustrate what insights such a model gives about coastal resilience to flooding across six cities along the Eastern US coastline.

Keywords Storms, Sea level rise, Coastal resilience, Seawalls

Paper type Research paper

1. Introduction

This paper examines whether or not seawalls are effective at reducing the damage from storm surges along the Eastern coastal cities of the USA. It is well known that the damage from coastal floods in the USA is quite high. The premiums being charged for federal flood insurance are often not sufficient to pay for the outlays. After major storms, Congress is frequently asked to supplement the revenues of the federal flood insurance program to cover the cost of flood damage. Despite these high costs of annual flood damage, a very small fraction of the US coastline is protected by any kind of manmade barrier. Climate change is predicted to increase the rate of sea level rise (SLR) and to increase the intensity of storms (Intergovernmental Panel on Climate Change [IPCC], 2021). This increases the urgency of coastal barriers. This paper explores a model, based on available data, that can measure whether seawalls would effectively reduce storm surge damage. The available data makes it relatively easy to calibrate the model in different cities. We demonstrate the different results one gets with these models across six coastal cities spread along the East Coast of the USA (Dedekorkut-Howes *et al.*, 2020).

Society has three choices of how it could react to SLR and increased flood risk: protect, retreat or accommodate (Dedekorkut-Howes *et al.*, 2020). This study does not examine accommodation – such as raising buildings on stilts or building mangroves along shorelines. However, prior economic studies have carefully examined whether to protect or retreat (Yohe, 1991; Yohe *et al.*, 1995,1996; Yohe and Schlesinger, 1998; Bosello *et al.*, 2007; Anthoff *et al.*, 2010; Neumann *et al.*, 2010; Tebaldi *et al.*, 2012). These early studies assumed SLR is a steady increase of mean sea level that gradually but permanently inundates coastal properties forcing the coastline inward. These studies consistently found society should protect urban coasts and retreat along rural coasts.

More recent studies have begun to take account of storms and SLR together in their analysis of urban coastlines. These studies also revealed one should retreat in undeveloped areas but protect urban coastlines. But most of these recent studies have simplified the risk from storms by looking only at the one-hundred-year storm (Nicholls *et al.*, 2008; Neumann *et al.*, 2015; Diaz, 2016). This effectively is a worst-case scenario analysis that takes a rare event and simply asks what happens when that event occurs. This approach does not measure the expected benefit of flood protection, and so it is a poor tool for choosing what surge protection to undertake.

Following the original suggestion by van Dantzig (1956), more recent economic studies have begun to take into account of the probability distribution of storm surge and SLR together (Mendelsohn *et al.*, 2020a; Mendelsohn *et al.*, 2020b). These examples use the entire probability distribution of storm surges. The studies also use spatially detailed descriptions of the coast that include the location, elevation and value of each vulnerable building. These studies also find that retreat is the best option when there are few low-lying buildings to protect. However, if there are sufficient vulnerable buildings per length of coastline, protection becomes the best choice. Although accurate, house-by-house analyses are expensive because they require extensive detailed data. They are consequently difficult to deploy across a national, much less international coastline.

This paper explores using a more generic description of what is in harm's way to develop a tool that is easier to deploy everywhere. The model measures the vulnerability of cities using the slope of the land near the coast, the elevation of the lowest lying buildings, the average density of the city and the average building value. All of these measurements are relatively easy to acquire. One feature of each city that the model measures carefully is the length of the coastline. Coastlines get longer, the more spatially refined the measurement (Mandelbrot, 1967). The length of the coastline is critical because the cost of the wall is proportional to the length of the coast. Modern geographic information system data sets make this measurement relatively easy to determine. We rely on Google Earth Pro to capture the actual peninsulas, points, inlets, riverways and wetlands of the coastline.

The most difficult task, however, is estimating the expected flood damage in each location. This study measures the relative SLR and the probability distribution of flood surge from long-standing tidal stations (National Oceanic and Atmospheric Administration [NOAA], 2021). The elevation of the lowest buildings and the slope of the vulnerable land that may be flooded are measured using satellite data from Google Earth Pro. Combined with the density and average housing values of each city, this information provides an estimate of the vulnerable building assets by elevation. Finally, a flood depth damage function is used to predict the percent of building value damaged given the depth of flooding at each building. Combining all of this information leads to an expected flood damage each year for each city depending on the height of the potential wall (including having no wall at all).

Note that the flooding algorithm is a simplistic hydrological simulator based solely on the height of the surge and elevation. It is important for future research to examine whether more complicated hydrodynamic models would lead to substantially different economic results. Note also that we are not considering whether to build walls in each segment of the coastline of each city. We are hoping to address this more spatially detailed question in the next version of this model.

2. Methodology

The study combines information about SLR, the probability distribution of storm surge, a flood damage function and the value of property by elevation along the coast of selected cities to measure expected flood damage. The model is then calibrated for six cities. The study then compares the cost of building higher seawalls along the coast versus the benefit of each wall (the reduction in expected flood damage).

The siting of the seawall is important for several reasons. A seawall exposed to active waves tends to deteriorate quickly and requires more frequent maintenance. However, a seawall built far into the interior leaves some buildings unprotected. We assume that the seawall will be built at high tide (more precisely Mean-Higher-High Water [MHHW]). By building above normal wave action, the maintenance cost associated with maintaining these walls is much lower. Building only above high tide lines also prevents seawalls from isolating salt marshes from ocean access. The white line shown in Figure 1 shows where each wall will be built. We also measure the nearest buildings to the coast. We use these nearby building measurements to determine the elevation of these lowest buildings in each city. The damage from coastal surges is very sensitive to the elevation of the lowest buildings (Mendelsohn *et al.*, 2020a; Mendelsohn *et al.*, 2020b). Flood damage increases nonlinearly as building elevation approaches MHHW because low elevation buildings are flooded by more cumulative storms and because the flood damage at each building increases proportionally with flood depth.

The analysis assumes walls should not be built in front of coastal wetlands, destroying the wetlands by blocking needed tidal flows. The potential walls analyzed in this paper do not go straight down the coast but rather weave inland around coastal wetlands and rivers. Even though the analysis does not explicitly measure environmental costs, by siting the walls carefully, the analysis has minimized one of the most serious environmental consequences of historic seawalls.

For each case study, we use Google Earth Pro to measure the coastal perimeter. Figure 1 displays the map for Wilmington, North Carolina. The maps of the remaining cities are shown in the Supplementary Materials. There are two continuous seawalls for Wilmington. On the western edge of the city is the Cape Fear River and on the eastern edge of the city is the Inland Waterway. Note the intricate pattern of the coast along the eastern edge of the city. This detail increases the length of the wall because the coast is a fractal set (Mandelbrot, 1967). For example, a straight-line distance along the water's edge suggests the coast in Wilmington is 25 km long, but the measured distance along the seawall is 49.4 km.

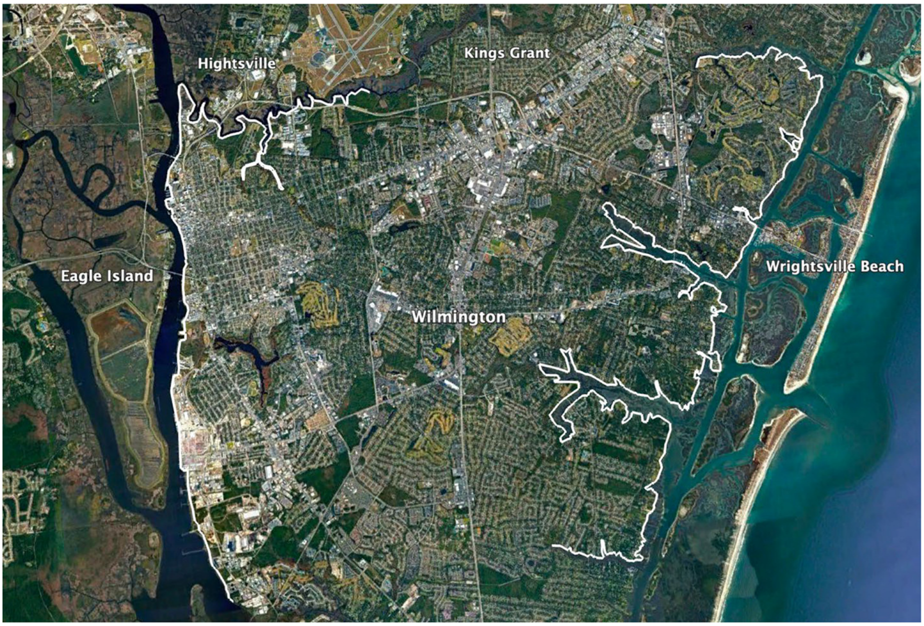

Figure 1. Map of east and west potential seawalls in Wilmington, NC

Note: White line of potential seawalls follows along the Cape Fear River in western Wilmington and the Inland Waterway in eastern Wilmington

2.1 Cost

The computation of the cost of hardened structures (which we will call "walls") follows the literature (Yohe *et al.*, 1995). The cost of constructing the wall rises with the volume of the wall. Coastal walls tend to have a triangular shape because the base must get wider as the wall gets taller to prevent it from falling over. The cost of walls, therefore, rise with the square of the height (H) times the length (L) of the wall. Following Yohe *et al.* (1995) but using updated estimates of Aerts (2018), the construction cost is estimated to be:

$$Construction\ \ Cost = 5200\ \ H^2L \tag{1}$$

A coastal wall is expected to last 30 years after which it will have to be replaced (Aerts, 2018). The maintenance cost over the lifetime of the wall is the present value of annual maintenance for 30 years. Annual maintenance is expected to be 0.5% of construction cost per year (Aerts, 2018). The interest rate used in this analysis is the current municipal bond rate, 2.5% (United States Treasury Department, 2019), which reflects the long-term interest rate that local towns and counties would face to finance these projects. Given these assumptions, the present value of maintenance is equal to 11% of construction costs. The present value of total cost (TC) of each wall (H) is, therefore:

$$TC(H:L) = 1.11 * 5200\ \ H^2L \tag{2}$$

2.2 Expected flood damage

We examine the area of land in each city that is protected by a wall of length, L, along coastal waterways. We assume that the wall is built at $MHHW$ so that it lies just above normal tides. We want to explore the cost and benefit of walls of different heights, H. Because the wall is built at $MHHW$, the elevation of the top of the wall is $H + MHHW$. We assume the wall will prevent all floods below the elevation of the top of the wall.

We calculate the ground elevation of the closest buildings to the water, e_{min}, in each city. These lowest buildings are the first to be damaged. We also measure the slope, α, of the land near the shore. Given that the wall is built at MHHW, the elevation, e, of the land at each distance, d, from the wall is $e(d) = ad + MHHW$.

We rely on a flood damage function, $D_i(h, d{:}\ a, V)$ per building that assumes the fraction of damage to a building of value, V, rises proportionally with flood depth (Federal Insurance Administration, 1974). The flood damage to each building, D_i, is proportional to the flood depth: $(h - \alpha d)$ and the value of that building, V:

$$D_i(h, d, \alpha, V) = (h - \alpha d + 1)/8 * V \tag{3}$$

The damage function assumes damage begins when the flood reaches 1 m below ground and is equal to 100% of the building value when the flood depth reaches 7 m. At 7 m, the building is assumed to be destroyed, and there is no additional damage to the building from additional flooding. We double this building damage to take account of the remaining damage from flooding (de Moel *et al.*, 2013). These other damages are roughly proportional to building damage and include damage to infrastructure, emergency services and cleanup.

The number of buildings at each slice of distance, Δd, depends on the area ΔdL times the density of buildings, η. The damage $D(h,d)$ from a surge of h at each distance d is:

$$D(h, d : \alpha, V, L, \ \eta) = \left(\frac{h - \alpha d + 1}{8} V\right) \eta L \Delta d \quad (4)$$

The total damage, *AD*(*h*), from each surge of height *h* is the summation from e_{min}/α to $(h + 1)/\alpha$:

$$AD(h) = \int_{e_{min}/\alpha}^{(h+1)/\alpha} \left(\frac{h - \alpha d + 1}{8} V\right) \eta L \Delta d \quad (5)$$

$$AD(h) = \frac{\eta L V}{16\alpha} (h + 1 - e_{min})^2 \quad (6)$$

To assess expected outcomes, we need to measure the probability of surges of different heights. We estimate the probability distribution of surges at each city using the maximum annual tidal data from each station and a generalized extreme value function:

$$F(h : \mu, \ \sigma, k) = \exp\left\{-\left[1 + k\frac{(h - \mu)}{\sigma}\right]^{-\frac{1}{k}}\right\} \quad (7)$$

where μ is the location parameter (mean height), σ is the scale parameter and *k* is the shape parameter. Figure 2 displays the probability distribution of surges in each city. Bridgeport has the highest surges of all the cities because of the narrowing effects of Long Island Sound, whereas Norfolk and Wilmington have the lowest surges because they are somewhat protected from surges by their locations.

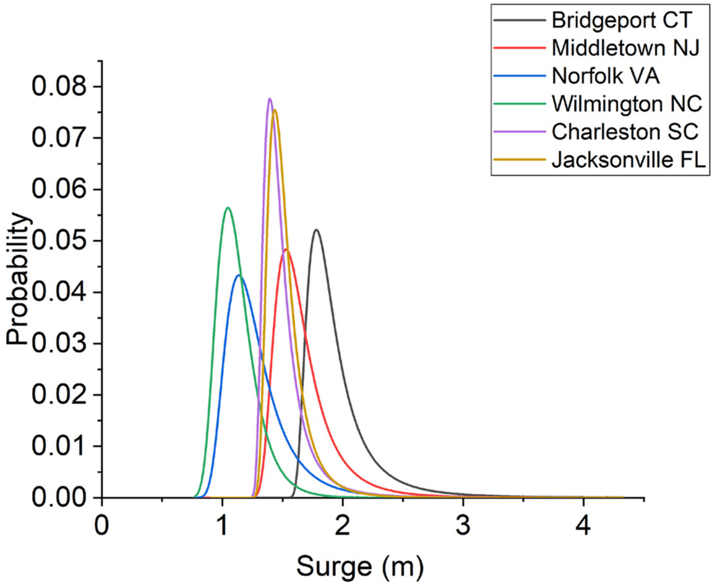

Figure 2.
Probability distribution of surges by city

Source: Mendelsohn and Zheng (2020) estimated from NOAA (2021)

Given the probability distribution of surges, $Pr(h)$, the expected annual damage of flooding with no protection is:

$$E[AD(h)] = \int_{e_{min}}^{\infty} \Pr(h)AD(h)dh \tag{8}$$

2.3 Benefits of walls

The benefit of walls is that they block surges below the elevation of the top of the wall. The elevation of the top of a wall of height H built on land of elevation $MHHW$ is $MHHW + H$. The total expected benefit $E[B(H)]$ of a wall of height H is the sum of the flood damages eliminated from all surges below $H + MHHW$.

$$E[B(H)] = \int_{e_{min}}^{H+MHHW} \Pr(h)AD(h)dh \tag{9}$$

There remains a flood risk from surges that go over the top of the wall. The expected value of this residual damage, $E[RD(H)]$, with the wall is:

$$E[RD(H)] = \int_{H+MHHW}^{\infty} \Pr(h)AD(h)dh \tag{10}$$

Because the wall will last for 30 years, we must calculate the flood benefits for the lifetime of the wall. We take account of SLR by increasing the height of every surge by the amount relative sea level increases each year. A surge of initial height h would, therefore, have a height of $h + SLR$ the next year and $h + tSLR$ in year t. We rely on National Oceanic and Atmospheric Administration (NOAA) (2022) estimates of the relative SLR at all six sites, which are also reported in Table 1. Relative SLR varies slightly from place to place from 2–5 mm/year as the ocean rises but also as land subsides. Figure 3 shows the observed rate of SLR in Bridgeport over time. However, projections of SLR into the far future suggest that SLR rates will likely increase (IPCC, 2021). The corresponding SLR figures for the remaining sites are in the Supplementary Materials.

We calculate the present value of the benefits, $TB(H)$, over the lifetime of the wall, which we assume is 30 years using a discount rate of r equal to the current municipal bond rating of 2.5% (United States Treasury Department, 2019).

$$TB(H) = \int_{0}^{30} \left\{ \int_{e_{min}}^{H+MHHW} \Pr(h)AD(h, SLR)dh \right\} e^{-rt}dt \tag{11}$$

2.4 Cost-benefit analysis

The cost-benefit analysis examines the present value of cost [equation (2)] and the present value of expected benefits [equation (11)]. The net benefit of the wall is the difference between the present value of benefits minus costs, $TB(H) - TC(H)$. The wall height, H, that maximizes net benefits is the preferred choice, but the model calculates the net benefits for all relevant wall heights. When the preferred choice of wall height is 0, the model is suggesting no wall be built. That is, the cost of all walls is higher than the benefit.

Table 1.
Physical flood parameters by city

City	Coast length (km)	Building density (#/km^2)	Building value (Thousand $)	Min elevation (m)	Relative sea level rise (mm/yr)	Present value of damage (Million $)	PV damage/length (Million $/km)
Bridgeport	31.5	1,218	210	2.7	3.1	44	1.4
Middletown	41 (88)	223	250	1.5	4.2	582	14.4 (6.6)
Norfolk	180.9	629	225	2.4	4.7	61	0.3
Wilmington	49.4	385	316	1.2	2.6	581	11.8
Charleston	35.2	195	321	2.4	3.4	27	0.8
Jacksonville	431 (491)	173	225	1.2	2.2	4292	10.0 (8.7)

Note: Values in parenthesis include a long length of coast with few buildings at risk

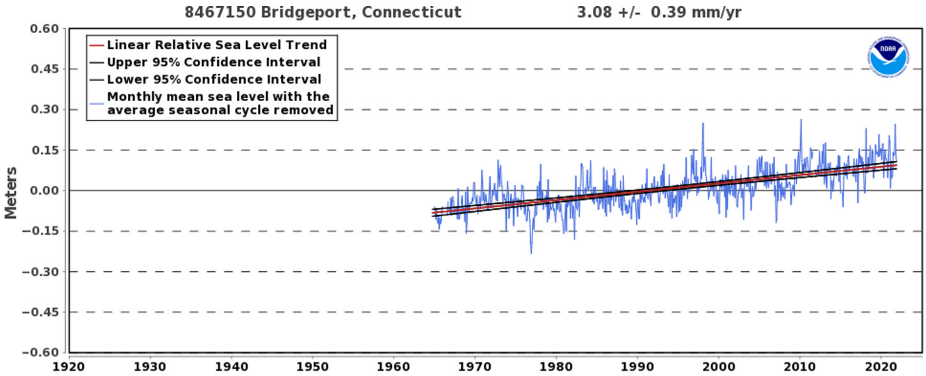

Figure 3. Relative sea level trend at Bridgeport, CT

Source: NOAA (2022)

2.5 Study area

The six cities studied were chosen because they are proximate to a long-standing NOAA tidal station. The nearby tidal station is helpful because it allows an accurate measurement of both local relative SLR and the probability distribution of surge heights. Bridgeport, Norfolk and Wilmington were modeled using the formal city limits. Only the historic island is modeled for Charleston. For Middletown Township and Jacksonville, we added coastal towns between the city limits and the Atlantic Ocean.

There are a few long sections in Middletown and Jacksonville where a wall is likely not needed because there are almost no buildings in these sections. We consequently explore including and excluding these large sections in the analysis. The potential excluded segments in Middletown include a long thin barrier island (Sandy Hook) with few buildings and a high elevation section along the Navesink River's edge. The excluded section in Jacksonville is the western edge of the Intracoastal Waterway from Palm Valley Road to Pablo Creek. We evaluate both cities with and without these additional walls.

3. Results

3.1 Flooding parameters of each city

Table 1 presents some basic physical facts related to coastal flooding in each city. The length of the coastline of each city is quite different. Jacksonville is much larger than the other cities in the sample and Jacksonville has more coastal rivers running through it, giving it a much longer coastline. Provided there is constant density, both the benefit and the cost of the wall is proportional to length. However, Middletown and Jacksonville have long sections of coast which would be costly to protect with virtually no buildings at risk. We present two cases for these cities, with and without these extra coastlines being considered.

Table 1 also presents the density of housing and the average value of housing. We assume that the damage to buildings is about one-half of all flood damage (de Moel *et al.*, 2013). The remaining damage is likely proportional to density and includes damage to infrastructure, emergency services and cleanup. As the value of what is in harm's way rises, the benefit of protection rises proportionally. Table 1 also presents the ground elevation of the lowest buildings in each city. Note that Wilmington, Jacksonville and Middletown have more low elevation buildings. Damage rises more than proportionally at lower elevations, so cities with many low-lying buildings have higher expected flood damage.

Table 1 also presents an important initial result, the calculation of expected damage if no walls are built. The present value of expected flood damage is larger the longer the length of the vulnerable coastline. So, Jacksonville has the largest expected damage because of its exceptional coastal length.

However, the key factor that determines whether or not to build seawalls depends on the expected flood damage per unit of length. If the expected flood damage per unit of length is high (low), it generally does (does not) make sense to build seawalls. However, expected damage per unit of length is larger for cities with many buildings at low elevations. The expected damage per length for Wilmington, Jacksonville and Middletown are relatively high, between \$10 and \$14m per km, because they have many buildings at lower than 2 m in elevation. In contrast, buildings in Bridgeport, Norfolk and Charleston are mostly built at elevations well above 2 m, and so these cities have low expected damages of \$0.3 to \$1.4m per km. The fact that Middletown, Wilmington and Jacksonville all allowed buildings to be built at low elevations along the coast has led them to be more vulnerable to coastal flooding. Coastal flood damage to buildings occurs on ground below 4 m (12 feet) in elevation, but the damage per building really escalates for buildings on ground lower than 2 m (seven feet) in elevation. This is the 25-year floodplain. Buildings in the 25-year flood plain are highly vulnerable to flooding.

3.2 Optimal seawall height

The focus of this analysis is upon building seawalls to protect against flood damage. The value of the seawalls depends upon the benefit of the wall, $TB(H)$ minus the cost, $TC(H)$. With three of the cities, the optimal height of the wall is zero. For Bridgeport, Norfolk and Charleston, the cost of the city-wide wall exceeds the benefit of the wall for every possible height. City-wide seawalls do not make sense in these cities because they have few, if any buildings, in the 25-year flood plain.

However, the net benefit is positive for city-wide walls in Wilmington and Jacksonville. Both have enough vulnerable low-lying buildings that the benefit of a seawall exceeds the cost. Table 2 presents the effects of a wall of optimal height that maximizes net benefits. One interesting result is that the optimal height of city-wide seawalls is relatively low, ranging from 0.9 to 1.2 m above ground. Nonetheless, the wall blocks a high fraction of expected damage. The optimal-height seawall blocks 70% of the damage in Middletown, 83% of the damage in Wilmington and 79% of the expected damage in Jacksonville.

3.3 Optimal seawall length

Another experiment conducted in Middletown and Jacksonville was to identify whether a coastal wall was needed for the entire city. Middletown has two sections with relatively few

Table 2.
Net benefit of optimal height walls

City	Height (m)	Cost (Million \$)	Benefit (Million \$)	Net benefit (Million \$)	Benefit/cost
Middletown*	1.20	336	403	67	1.2
Middletown all	1.00	507	246	−261	0.5
Wilmington	0.92	240	480	240	2.0
Jacksonville*	0.89	1,946	3,470	1,524	1.8
Jacksonville all	0.87	2,116	3,379	1,263	1.6

Notes: All costs and benefits are present values for the lifetime (30 years) of the wall. *These estimates assume walls were not built along extensive sections of the city where there were few vulnerable buildings vulnerable buildings. The barrier island (Sandy Hook) has few buildings, and a long stretch of the Navesink River has steep embankments. Dropping these two sections reveals that the rest of Middletown, the entire mainland coastline along the Atlantic Ocean, should be protected by a seawall. In Jacksonville, the western edge of the Intercoastal Waterway has virtually no buildings nearby. No wall should be built along this section. When this wall is removed from the analysis, the remaining city-wide wall is more effective. The cost goes down because the length is shortened and yet the benefits hardly change. The net benefits are higher with the shorter length wall, and the benefit/cost ratios improve as well. The results suggest one can improve over a uniform city-wide wall by dropping walls in sections with few buildings at risk.

3.4 Future sea level rise

The analysis assumes that historic rates of SLR continue for the next 30 years, but it does not take account of forecasts of faster future rates of SLR. But climate change may well increase near term SLR from 3 to 4 mm/year (IPCC, 2021). We conduct a sensitivity analysis by increasing the relative rate of SLR by 1 mm/year above the historic relative rate for each city. With the higher SLR and the ineffective walls removed, we reexamine the economics of the seawall for all six cities. Bridgeport, Norwalk and Charleston still do not currently need seawalls even with the faster SLR. The seawall is slightly more beneficial in Middletown, Wilmington and Jacksonville. The optimal height of the seawall increases 1 cm and the net benefit of the seawall increases by $11m in Middletown, $48m in Wilmington and $5m in Jacksonville. The optimal height and the net benefits of a seawall increase as future rates of SLR rise, but the near-term change is relatively small. In the long run, however, these changes can become quite large.

3.5 Hurricane seawalls

Of course, it is physically possible to build seawalls that are higher than the optimal-height wall. The US Corps of Engineers, US Department of Homeland Security (FEMA) and the National Flood Insurance Program all encourage the top of seawalls to be 12 ft in elevation (3.66 m) which is enough to stop the surge of most hurricanes. Table 3 presents the cost and benefit of this much higher wall. The TC of these tall walls far outweighs the expected flood benefit. The tall walls make the flooding problem worse, not better. None of these tall walls should be built. One needs several billions of dollars of vulnerable buildings for each km of wall to justify tall walls. Given how rare major hurricanes are, the expected additional flood damage avoided by these taller walls is not worth the additional cost. The additional cost of these tall walls is between 9 to 25 times the expected additional damage avoided. In other words, the taller walls cost 9 to 25 times the cost of simply relying on fair insurance. It is far cheaper to build an optimal height wall and rely on fair insurance to cover the residual damage than to build these massive 12-foot seawalls.

Table 3. Net benefit when the top of the wall is 12 feet in elevation

City	Cost (Million $)	Benefit (Million $)	Net benefit (Million $)
Middletown*	1,987	578	−1,410
Wilmington	2,590	571	−2,019
Jacksonville*	19,797	4,287	−15,510

Note: Height relative to ground (MHHW). *These estimates assume walls were not built along extensive sections of the city where there were few vulnerable buildings

4. Discussion

This analysis examines whether coastal cities should protect their coastlines with walls, how these walls should be sited and how high these walls should be. The analysis reveals that there are undeveloped shorelines even within cities. These coastlines should not be protected with walls. But how exactly should these unprotected coasts be managed? Should cities simply retreat from these coasts as the ocean rises or should they try to accommodate the changes? Accommodation and retreat options within urban areas should be studied further.

A major drawback of this generic analysis is that it examines a city-wide wall. A simple experiment identified some walls in Middletown and Jacksonville that protected only a few buildings. Dropping these sections of wall improved the economics of the city-wide walls. Previous studies suggest that analysis of more spatially detailed segments of walls is worthwhile (Mendelsohn *et al.*, 2020a; Mendelsohn *et al.*, 2020b). An important extension of this research involves asking more spatially detailed questions. What walls make the most sense for each neighborhood?

There are also some natural science issues that the study raises. Would the results change if one used more complicated dynamic hydrological models to model flooding? How carefully do we need to measure the precise elevation and location of buildings? What are the flood damages associated with floods of various depths and buildings of various types?

Finally, how should coastal defense develop as climate change proceeds. This study examines the immediate question of whether or not to defend coastlines right now. But as sea level progresses and storms possibly evolve, how does that change future decisions to protect? How should coastal resilience change as climate change progresses?

5. Conclusion

The analysis reveals how to calculate the expected cost and benefit of seawalls using available data. The model is calibrated to six cities along the US coastline to illustrate its flexibility and insights. One innovation of the study is to site walls so that they circle coastal streams, rivers and wetlands, rather than abruptly cutting them off from the ocean. This protects wetlands and allows rivers to remain unimpeded, but it also makes the length of the coastline and, therefore, the length of the seawall considerably longer.

Another innovation of the analysis is that expected flooding is a function of the entire probability distribution of surges. This reveals that a large fraction of the expected storm damage in highly vulnerable cities comes from frequent storms and not the more catastrophic but rare major hurricane. This implies that relatively low walls (0.9–1.2 m above ground) that eliminate the effect of common surges are highly effective in these vulnerable cities. These low walls eliminated 70%–83% of the expected flood damage in each city.

In none of the six cities studied, did it make any sense to build a seawall high enough to prevent surge damage from a major hurricane. Twelve-foot seawalls, promoted by the Corps of Engineers, Homeland Security and the National Flood Insurance Program, are a maladaptation. The tall walls eliminate a relatively small amount of expected damage by spending 10 to 20 times more on a tall wall.

The study also revealed that the cities (Middletown, NJ; Wilmington, NC; and Jacksonville, FL) that allowed buildings at low elevation, all had very high expected damage per unit of coastline length. The low elevation buildings have very high expected annual flood damage because even common surges cause damage. The results suggest that cities should be more careful about allowing development in the 25-year flood plain.

The purpose of this paper is to illustrate a model that could be applied to study seawalls in urban settings along the East Coast of the USA. We show the model works for six cities spread along that coastline. The model could readily be adopted along the West Coast as well. A more challenging question involves calibrating the model for cities around the world. The geographic data required to calibrate the model is available for most coastal cities. Economic data about housing density and value should also be available for coastal cities, but the spatial detail of this data is likely limited. Long-standing tidal stations may not be available everywhere, so future research is needed to determine the probability distribution of surges across all coastal cities. Cities need to understand where to site seawalls and how tall they should be to get the most benefit from this particular coastal resilience tool.

References

Aerts, J.C. (2018), "A review of cost estimates for flood adaptation", *Water*, Vol. 10 No. 11, pp. 1-33, doi: 10.3390/w10111646.

Anthoff, D., Nicholls, R.J. and Tol, R.S.J. (2010), "The economic impact of substantial sea-level rise", *Mitigation and Adaptation Strategies for Global Change*, Vol. 15 No. 4, pp. 321-335, doi: 10.1007/s11027-010-9220-7.

Bosello, F., Roson, R. and Tol, R.S.J. (2007), "Economy-wide estimates of the implications of climate change: sea level rise", *Environmental and Resource Economics*, Vol. 37 No. 3, pp. 549-571, doi: 10.1007/s10640-006-9048-5.

de Moel, H., Botsen, W. and Aerts, J. (2013), "Economic and direct losses from hurricane sandy", *Annals New York Academy Sciences*, Vol. 1294, pp. 80-89.

Dedekorkut-Howes, A., Torabi, E. and Howes, M. (2020), "When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding", *Journal of Environmental Planning and Management*, Vol. 63 No. 12, pp. 2102-2143.

Diaz, D. (2016), "Estimating global damages from sea level rise with the coastal impact and adaptation model (CIAM)", *Climatic Change*, Vol. 137 Nos 1/2, pp. 143-156, doi: 10.1007/s10584-016-1675-4.

Federal Insurance Administration (1974), *Depth-Percent Damage Curves*, US Department of Housing and Urban Development, Washington, DC.

Intergovernmental Panel on Climate Change (IPCC) (2021), Climate Change 2021 Synthesis Report, Sixth Assessment Report.

Mandelbrot, B.B. (1967), "How long is the Coast of Britain: statistical self-similarity and fractional dimension", *Science*, Vol. 156 No. 3775, pp. 636-638.

Mendelsohn, R. and Zheng, L. (2020), "Coastal resilience against storm surge from tropical cyclones", *Atmosphere*, Vol. 11 No. 7, p. 725.

Mendelsohn, R., Rajaoberison, A. and Yoo, J. (2020a), "A coastal resilience analysis of a heterogeneous landscape", *Journal of Environmental Protection*, Vol. 11 No. 6, pp. 441:456.

Mendelsohn, R., Schiavo, J. and Felson, A. (2020b), "Are American coasts underprotected?", *Coastal Management*, Vol. 48 No. 1, pp. 23-37.

National Oceanic and Atmospheric Administration (NOAA) (2021), "Extreme water levels", available at: https://tidesandcurrents.noaa.gov/est/ (accessed 15 October 2021).

National Oceanic and Atmospheric Administration (NOAA) (2022), "Relative sea level trends", available at: https://tidesandcurrents.noaa.gov/sltrends/ (accessed 1 February 2022).

Neumann, J.E., Emanuel, K., Ravela, S., Ludwig, L., Kirshen, P., Bosma, K. and Martinich, J. (2015), "Joint effects of storm surge and sea-level rise on US coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy", *Climatic Change*, Vol. 129 Nos 1/2, pp. 337-349, doi: 10.1007/s10584-014-1304-z.

Neumann, J.E., Hudgens, D.E., Herter, J. and Martinich, J. (2010), "The economics of adaptation along developed coastlines", *WIREs Climate Change*, Vol. 2 No. 1, pp. 89-98, doi: 10.1002/wcc.90.

Nicholls, R.S., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Château, J. and Muir-Wood, R. (2008), "Ranking port cities with high exposure and vulnerability to climate extremes", OECD Environment Working Papers No. 1, OECD Publishing, Paris, doi: 10.1787/011766488208.

Tebaldi, C., Strauss, B. and Zervas, C. (2012), "Modelling sea-level rise impacts on storm surges along US coasts", Environmental Research Letters 7, 14032.

United States Treasury Department (2019), "Daily treasury long term rate data", available at: www.treasury.gov/resource-center/data-chart-center/interest-rates/pages/textview.aspx?data=longtermrate (accessed 15 June 2019).

van Dantzig, D. (1956), "Economic decision problems for flood prevention", *Econometrica*, Vol. 24 No. 3, pp. 276-287.

Yohe, G., Neumann, J.E. and Ameden, H. (1995), "Assessing the economic cost of greenhouse-induced sea level rise methods and application in support of a national survey", *Journal of Environmental Economics Management*, Vol. 29, pp. 78-97, doi: 10.1006/jeem.1995.1062.

Yohe, G., Neumann, J.E., Marshall, P. and Ameden, H. (1996), "The economic cost of greenhouse-induced sea-level rise for developed property in the United States", *Climatic Change*, Vol. 32 No. 4, pp. 387-410, doi: 10.1007/BF00140353.

Yohe, G. (1991), "The cost of not holding back the sea – toward a national sample of economic vulnerability", *Coastal Management*, Vol. 18 No. 4, pp. 403-431.

Yohe, G. and Schlesinger, M. (1998), "Sea level change: the expected economic cost of protection or abandonment in the United States", *Climatic Change*, Vol. 38 No. 4, pp. 447-472.

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