Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources

By

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Abstract

This paper outlines a model for estimating the cost of elevating coastal seaport infrastructure in the United States to prevent potential damage from the effects of climate change. This estimation is a thought exercise to provoke consideration of the cumulative monetary and material demands of widespread adaptation of seaport infrastructure. This model estimates the combined cost of adding additional fill material to raise the working surface and reconstructing the yard to find an approximate unit area cost as a function of the necessary elevation increase for a generic port. The unit area cost is then combined with national estimates of storm surge increase by region and port area data to develop an estimate for the cost of elevating all United States commercial coastal ports in the World Port Index. Estimates of storm increase for the East Coast, Gulf Coast and West Coast are used to demonstrate anticipated variation in necessary port elevation between these regions and the resulting variation in cost. The use of a generic port model allows for the estimation of the material and monetary demands of entire regions, which would be infeasible if calculations were performed on an individualized port-by-port basis. Combined, these regional cost estimates predict a minimum of 62 billion to 88 billion dollars to elevate all United States commercial coastal ports in the World Port Index, as well as 495 million cubic meters of fill.

1. Introduction

In this paper we examine the cumulative regional and national costs of adapting all US ports from rising sea levels and storm surges through the elevation of infrastructure. As the impacts of climate change become an increasing reality, coastal ports are likely to be among the infrastructure hit first and hit hardest (Becker et al., 2012). The waterfront location intrinsic to coastal ports places many directly in the path of intense storms and rising sea levels. However, quantitative analysis of the potential cost to the shipping industry is lacking (Nicholls et al., 2010).

As hubs of commerce, significant damage to ports can cripple both local and regional economies, as well as have more far-reaching impacts. 99.4% by weight of imports into the United States are transported by ship and $3.8 billion dollars of goods travel through its seaports each day (American Association of Port Authorities, 2012). Infrastructure construction takes years to plan, design, and build. Often outliving a 30-50 year design life, much port infrastructure conceived of today will easily last into the end of the century. It is therefore important that government and port authorities examine methods of protecting infrastructure for environmental conditions. A number of options that may be employed to protect against climate change induced extreme events, such as the construction of dikes and the relocation or elevation of ports. This paper presents an estimate for the total cost of one such adaptation option. Through this research, we explore the strategy of elevating all coastal ports in the United States to a new height based on regional projections for sea level rise and storm surge expected by 2070. We do not advocate this as the right solution for any or all ports. Rather, we offer this estimation as a thought exercise to provoke consideration of the cumulative demands of widespread adaptation to maintain functioning seaports on the country's resources and as an "upper-bound estimate" of potential investment.

As noted by Nicholls et al. (2010), few assessments of regional port adaption to climate change have been conducted, largely due to a lack of comprehensive physical data. In their analysis of the cost of elevating port ground levels in countries classified by the World Bank as upper middle income, lower middle income, or low income, Nicholls et al compensated for this lack of data by applying a traffic-to area conversion. In their analysis Nicholls et al used the cost of 15 million US dollars per square kilometer to raise ground elevation by one meter based on a 1990 IPCC report. This value was "based on Dutch procedures including design, execution, taxes, levies and fees and the assumption that the operation would take place as one event (Nicholls et al., 2010)" but excluded the cost of adapting buildings and infrastructure (Delft Hydraulics , 1990). However, in our calculations we rely on port area data drawn from the Sebastian geodata system (Sebastian Database, 2012), a database with a Google Earth interface that allows us to create port polygons measuring the area of individual ports in the World Port Index. Additionally, we combine the costs of ground elevation and infrastructure reconstruction. Our estimate consists of the following components. First, we create a "generic port" model and calculate the average cost of infrastructure reconstruction per square meter. This is combined with the cost of land elevation per cubic meter to obtain an equation for calculating the cost of elevating a square meter of port area as a function of the meters of increased elevation. Next, we calculate the acreage of all coastal ports in the US through heads-up digitizing in Google Earth. Using regional climate projections and historical storm surge data, we find a recommended elevation necessary to raise port infrastructure out of the future floodplain for 2070 based on regional projections for sea level rise and storm surge. We then apply this cost estimate model to the East, Gulf and West Coasts of the contiguous United States as well as the coasts of Alaska and Hawaii to obtain regional cost estimates based on climate projections for each region. Finally, we aggregate our regional results for a final "upper bound estimate" to protect US seaports through an elevation strategy We believe that analyzing the cumulative demands will present a clearer picture of the difficulty involved in any strategy for protection, not only in the procurement of funds, but also in the procurement of materials such as fill.

2. Methods - GENPort

We propose a "generic port," hereafter referred to as GENPort, in order to examine the cost of elevating as a function of the area and height to which the port is elevated. This port is a 100 gross-acre two-berth marine container terminal[1]. In practice, every port is quite different. They handle different cargos, are of different sizes, and face a range of environmental conditions. The use of the GENPort model allows us to develop an estimate incorporating all commercial US ports without completing an in-depth assessment of each individual port and its infrastructure.

We derived the costs used in our GENPort calculations based on an assumption that each port would require the same area use types and in the same proportion. This differs from the CSI (Construction Specifications Institute) MasterFormat that is the typical standard when generating

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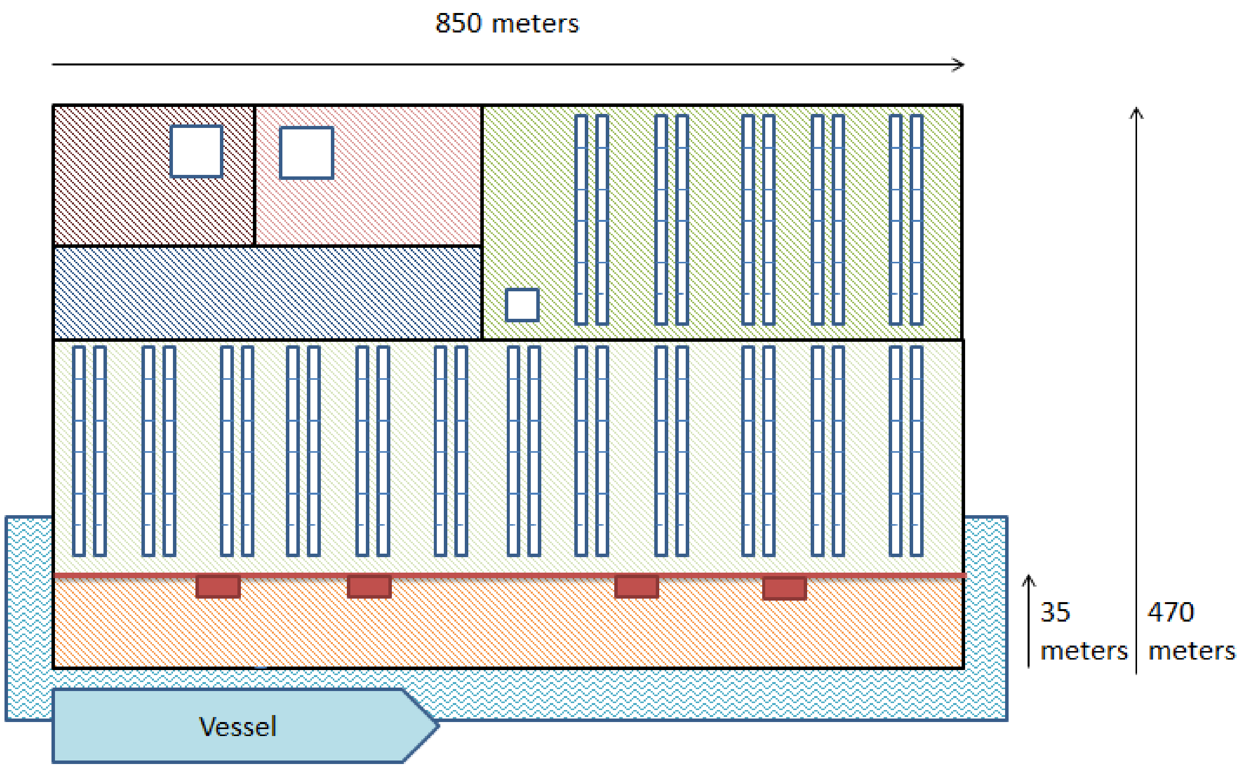
[1] Chosen based on correspondence with Tom Ward, the Chief Engineer at Ports America.

a construction cost estimate in the United States (Construction Specifications Institute, 2012), which breaks down construction costs into divisions of work. We diverged from the standard approach because the CSI MasterFormat is too case-specific for the purposes of GENPort, which is meant to be applicable across a wide range of ports. Instead of dividing the costs into construction categories such as earthwork and metals, we divided GENPort into general use areas and estimated the cost of reconstructing those areas, as well as the cubic meter cost of filling the port. These costs were then combined to find the average cost of raising one square meter as a function of the amount the land is raised.

Land Use at GENPort

We divided the land use into the categories of berth, apron, primary yard and secondary yard (Figure 1: The Schematic Layout of GENPort).



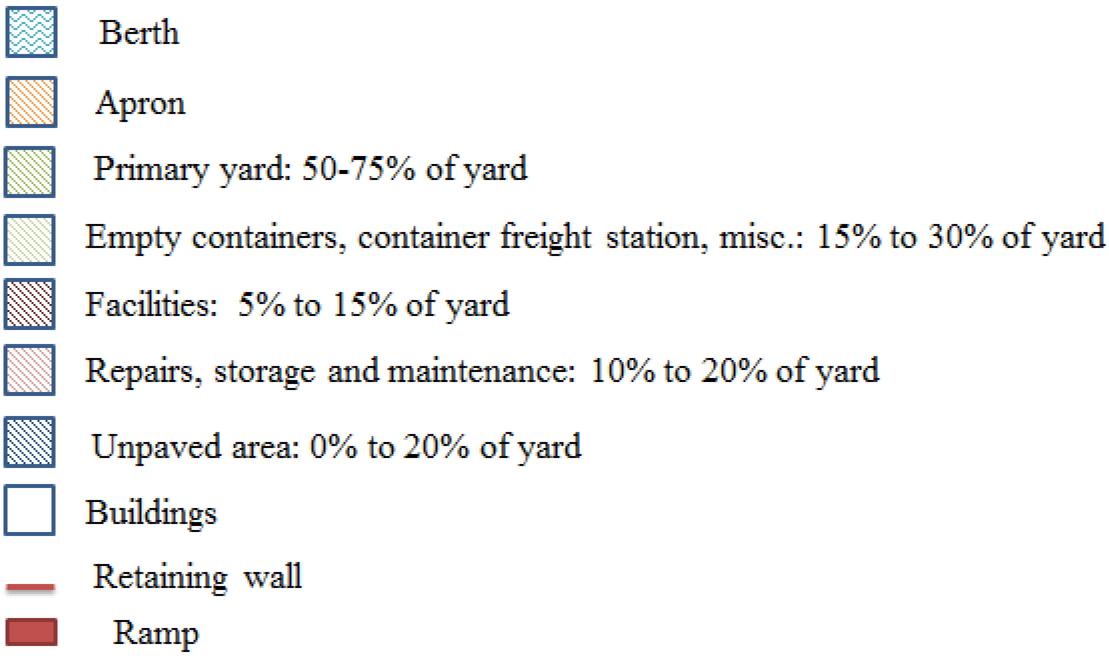


Figure 1: The Schematic Layout of GENPort, used to calculate the generic requirement of ports such that the aggregate of all ports will represent a holistic estimate of the cumulative requirements.

Berth

The berth is the waterfront portion of the port where ships tie up and cargo is loaded and unloaded.

Apron

The apron is the area immediately behind the berth where the cargo is loaded and unloaded. The apron typically has a width of 15 to 50 meters. The width varies due to the nature of the port (Thoresen, 2003). At a container port, the cranes sit on the apron and lift cargo on or off the ship to or from trucks which move the containers to other locations at the port or to an off-port destination.

Primary Yard

The primary yard is located behind the apron and is where containers or cargo is stored. The primary yard takes up 50 to 75 percent of the total yard area (Thoresen, 2003).

Secondary Yard

The secondary yard contains three main sections. The first is the area for empty containers and the container freight station, which takes up 15 to 30 percent of the total yard area. The second is the area for repairs, storage and maintenance, which takes up 10 to 20 percent of the total yard area. The third is the area for facilities such as office buildings, customs facilities and parking, which takes up 5 to 15 percent of the total area (Thoresen, 2003).

3. Cost Calculations

The calculations for the cost of filling the port to raise its elevation were made based on the assumption that the process would make use of dredged material from the surrounding area. Use of dredged material will often be more cost effective than trucking in fill due to the quantity of fill required and the transport distance. It should be noted that dredging will not always be possible due to lack of suitable dredging material or environmental restrictions. The unit cost of dredging was taken from the Army Corps of Engineers annual analyses of dredging costs. The 2009, 2010 and 2011 new work dredging costs were averaged to moderate year-to-year cost fluctuations and a twenty percent dozing and compaction factor was included to account for the cost of placing the fill. The calculated cost does not include the cost of erosion control or potential environmental protection requirements. **Error! Reference source not found.** shows the estimation components.

Table 1: Dredging fill cost calculations

Item	*Cost (\$/m^3)*
2009 New Work Dredging[2]	$24.16
2010 New Work Dredging[2]	$19.97
2011 New Work Dredging[2]	$22.98
3-year New Work Dredging Average	$22.37
Dozing & Compaction (20%)	$4.47
Total Cost	$26.84

Berth

For GENPort we assumed that the waterfront portion of the berth would remain at the existing elevation without alteration to maintain ship accessibility, as significantly raising its height over the existing sea level may impede the loading and unloading of cargo.

Apron

As with the berth, we assumed that the apron would not require additional elevation. As cargo is not stored in this portion of the port, cargo losses would not be expected during a storm event. It would be advisable to relocate any structures located within the apron to the elevated yard area. In addition to reducing construction costs, maintaining the existing apron and berth elevation would prevent possible difficulties in loading and unloading cargo. Ramps would allow vehicles access to the apron from the elevated portions of the port. This design is currently in use at the port of Gulfport, which uses a system of ramps to transport containers from sea level up to the new 15 foot elevation of the laydown area (Conn, 2010). However, some cranes, utilities and other waterfront port infrastructure would not be protected by this design and would be subjected

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[2] (Analysis of Dredging Costs, 2012)

to increased threat of flooding due to storm surge. In practical application it would be important to weigh the costs of these possible damages against the cost of elevating the berth and apron.

Our model assumes the construction of a retaining wall at the boundary between the apron and the primary yard as a means of holding back the fill in the elevated port area. To calculate the cost per linear foot of the retaining wall we used the cost of a cast-in-place level concrete retaining wall from RS Means. Because the square foot cost of the wall increased with the height of the wall, we treated the relationship between the height of the wall and the square foot cost of the wall as linear, as shown in Figure 2.

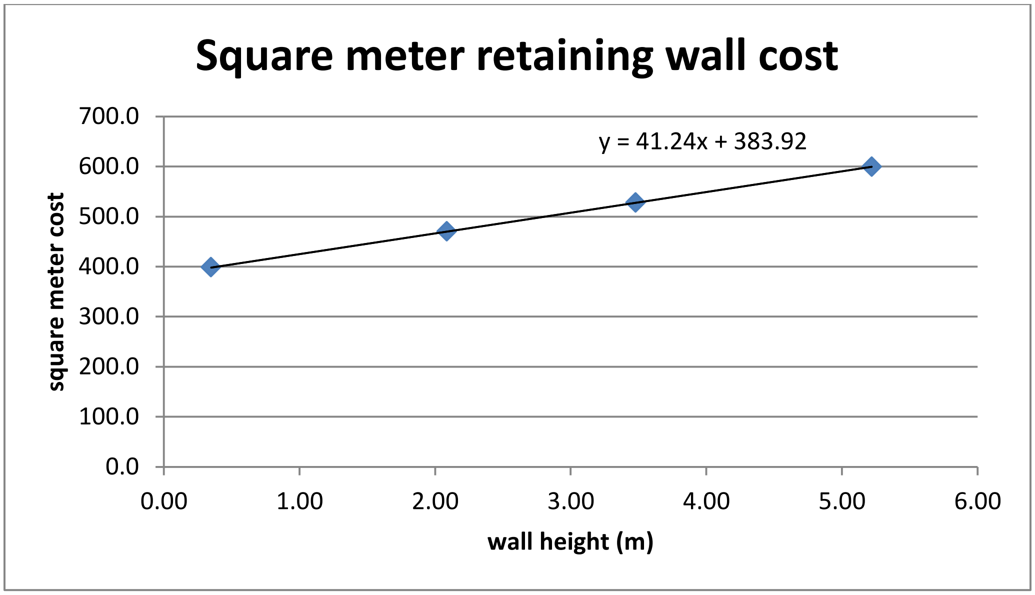

Figure 2: Square meter cost of the retaining wall as a function of wall height

We used this relationship to derive the cost estimate below, with wall height in meters.

Equation 1: Cost of retaining wall per linear meter of berth

$$\mathbf{US\$\ per\ linear\ meter\ of\ berth} = \mathbf{41.24 \times height + 383.92 \times height}$$

Our calculations also include the cost of constructing ramps to allow access between the apron and the yard of the port. The ramps used in our calculations are 10 meters in width and have a 5 percent incline. We account for the construction of two ramps per berth, totaling 4 ramps per model port. We assumed the construction of the ramps from the same dredged fill material used to elevate the yard, topped with 15cm of crushed 2.5-1.3cm stone base and 10cm thick concrete paving, the costs of which are shown in Table 2.

Table 2: Unit cost of ramp materials

Ramp Materials		
Item	Unit Cost	Unit
Dredged fill	\$26.84	m^3
20cm concrete pavement	\$54.36	m^2
Crushed 2.5--1.3cm stone base, 15cm deep[3]	\$10.17	m^2

Using these costs, the price associated with constructing these ramps is shown in Equation 2: Cost of ramp construction per linear meter of berth as the cost per linear meter of berth as a function of the height of the retaining wall.

Equation 2: Cost of ramp construction per linear meter of berth

$$\text{US\$ per linear meter of berth} = 37.89 \times \text{height} \times (\text{height} - 0.15) + 187.08 \times \text{height}$$

Primary Yard

The primary yard requires paving. Concrete block pavers are a good choice when constructing port infrastructure because they function well in areas where heavy equipment is in use. Asphalt has a lower load capacity than concrete and there is a higher possibility of container supports penetrating asphalt, especially when its bearing capacity has been further reduced by warm

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[3] (Philip R. Waier, 2012)

weather (Thoresen, 2003). For our calculations we assumed that the subgrade soil condition is good because the new construction is taking place on the site of the existing port. The Port Designer’s Handbook recommends the use of 8-10cm thick inter-locking concrete pavers or 10-12cm thick rectangular concrete pavers (Thoresen, 2003). For our calculations we used a similar method to that employed by the Dundalk and Seagrit marine terminals in their repaving projects (Thomas J. Shafer, 2006). This design consists of concrete pavers on top of a bed of sand which in turn is placed on a layer of concrete pavement.

Table 3: Primary yard cost components

Primary Yard	
Item	Cost per m^2
100mm thick 100x200 rectangular concrete paver + 25mm sand + stabilizer[4]	$ 32.30
20cm concrete pavement	$ 54.36
Crushed 2.5--1.3cm stone base, 15cm deep[5]	$ 10.17
Total	**$ 96.82**

Secondary Yard

For the secondary yard paving costs we used the cost calculated previously for the primary yard to accommodate the average weight of trucks and equipment. For the portion of the secondary yard dedicated to repairs and maintenance, the cost of the maintenance building was calculated using the cost of a concrete block warehouse.

For the portion of the secondary yard dedicated to empty containers, container repair and freight handling we used the previously used square foot costs for warehouses and concrete paving.

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[4] (Thomas J. Shafer, 2006)

[5] (Philip R. Waier, 2012)

In calculating the cost of office space we used the cost of a one story EIFS on metal studs office building, $1,929.43 dollars per square meter (Balboni, 2012).

Table 4: Secondary yard cost components

Secondary Yard		
	Percent coverage[6,7]	Cost per m^2
Repairs, maintenance		
Concrete Block Warehouse[8]	10%	$ 1,051.63
Paving	90%	$ 96.82
Average		**$ 192.30**
Parking, office space, gate queuing, etc		
Administration Building[8]	15%	$1,929.43
Paving	85%	$ 96.82
Average		**$ 371.71**
Empty container storage		
Concrete Block Warehouse[8]	3%	$ 1,051.63
Paving	97%	$ 96.82
Average		**$ 125.47**

Other Possible Costs

Some costs were considered but not included in the cost calculations. One of these costs is the potential cost of dealing with the contamination of the area. Years of port activities would leave traces of fuels and other hazardous materials that would have to be remediated. Other potential costs include the necessary environmental permitting and changes to utilities as well as the cost of demolition and ruble removal if the original structures have to be removed. These costs were not included in the estimation.

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[6] (Thoresen, 2003)
[7] (Tom Ward, 2012)
[8] (Balboni, 2012)

Total Port Cost

Before combining these costs and the cost of the fill, we first consolidated the cost of the yard into a single average square foot cost for reconstructing the yard infrastructure, as shown in Table 5.

Table 5: Surface reconstruction cost components

Total Surface Reconstruction Cost		
	Percent of Yard[9,10]	Cost per m^2
Primary Yard	50% to 75%	\$98.56
Facilities	5% to 15%	\$326.88
Repairs, Storage and Maintenance	10% to 20%	\$182.81
Empty Containers, Container Freight Station, Misc.	15% to 30%	\$123.84
Unpaved Areas	20% to 0%	\$ -
Total Yard Cost		**\$102.48 to \$153.450**

This yard cost was combined with the retaining wall cost, ramp construction cost and fill cubic cost to generate cost estimation equation. The variable 'RWLC' represents the retaining wall linear cost equation and the variable 'RC' represents the ramp construction cost equation. In addition, 'FCC' represents fill cubic cost, and 'YC' represents the yard surface cost.

The final equation includes a multiplication factor of 1.1 to account for a ten percent engineering cost in addition to the previously calculated construction and material costs.

Equation 3: Square meter cost of port adaptation as a function of elevation increase

$$US\$\ per\ m^2\ of port\ area = \frac{1.1}{435m}(RWLC + RC + \ \ FCC * height\ \ * 435m + YC * 435m)$$

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[9] (Thoresen, 2003)

[10] (Tom Ward, 2012)

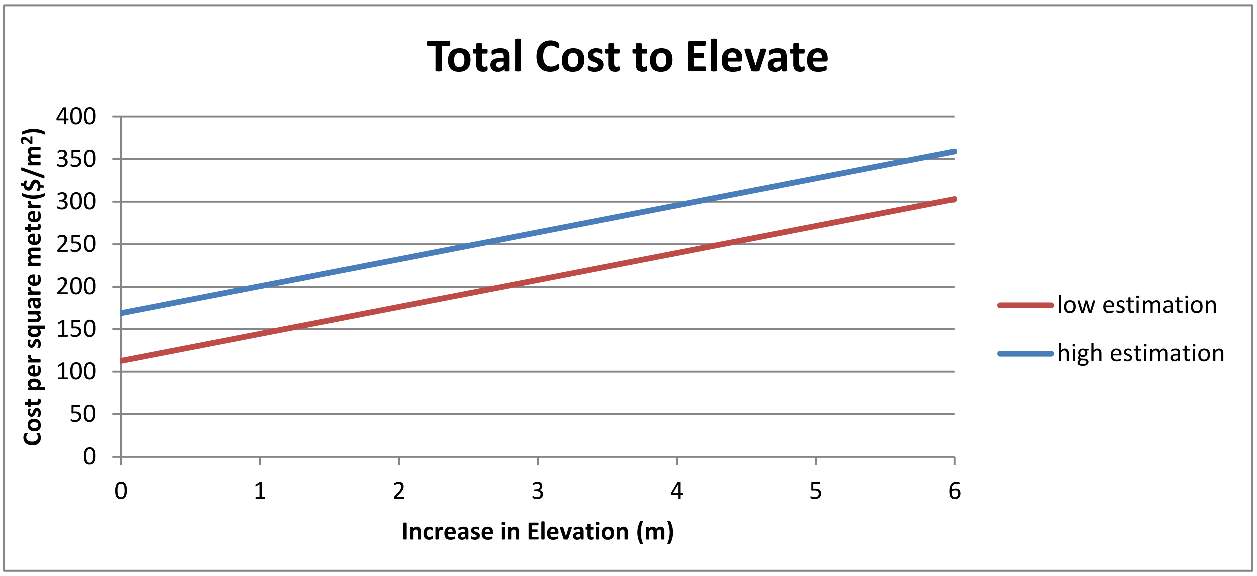

Figure 3: High and low esimation of the cost per square meter to elevate as a function of elevation increase

Figure 3 shows the upper and lower cost estimations. The slope of the lines is fairly shallow, so it may be financially sound to raise a port more than the predicted minimum required to avoid storm surge due to the modest increase in cost per square foot with an increase in elevation. This is supported by Figure 4 below, which shows that the cost of yard reconstruction dominates even if the port is elevated as much as 2 meters.

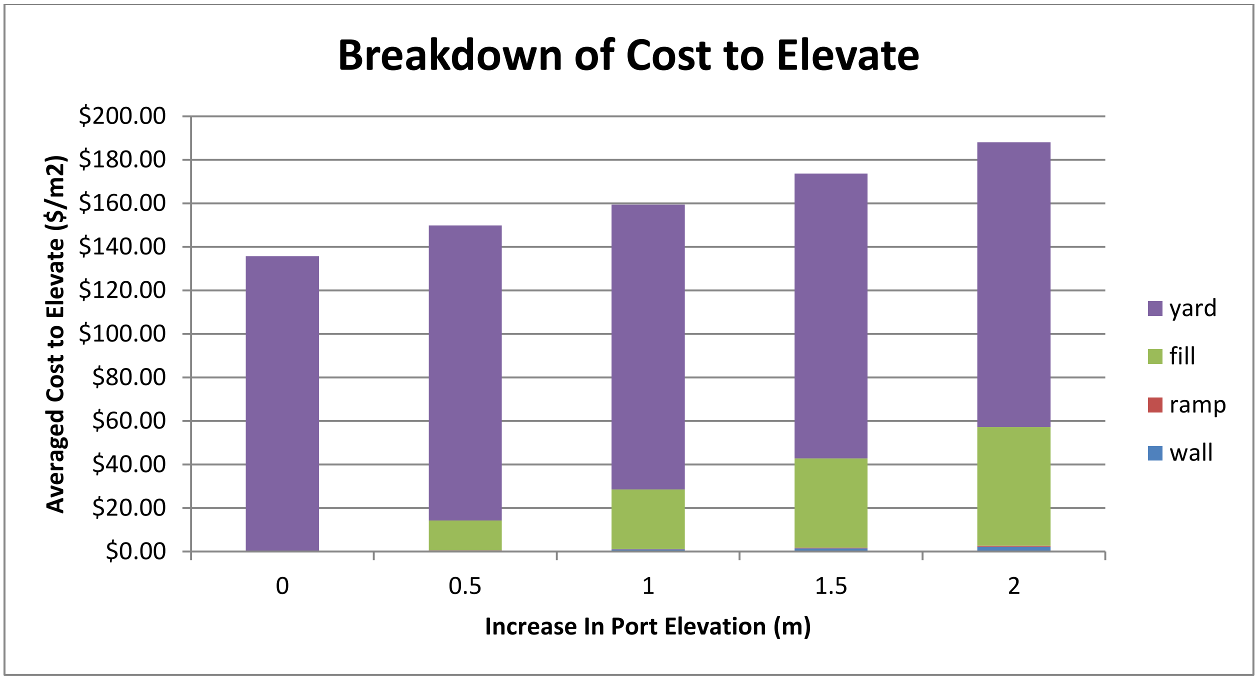

Figure 4: Breakdown of elements of the average cost per square meter to elevate GENport as a function of the increase in elevation

4. New elevation for conditions in 2070

If the elevation of a port is to be considered as a preventative measure against the impacts of climate change, both sea level rise and the increased height of storm surges must be taken into account. We utilize the method for estimating changes in future storm surges proposed by Nicholls et al. (2008). We estimate historical 100-year storm surges from the SURGEDAT database (Needham, 2011). We apply these estimates to all United States commercial coastal ports listed in the World Port Index (World Port Index, 2012).

Sea Level Rise Adjustment

Regional variations in sea level rise may prove to be significant in the future. However, because these variations are difficult to predict with any accuracy (Nicholls, et al., 2008), we used a single sea level rise value for all port locations. Though there has been a range of estimated sea level rise values published, we used data from the software code accompanying Vermeer and Rahmstorf's article "Global sea level linked to global temperature" (Vermeer & Rahmstorf, 2009). We chose to assume a 61.8 cm increase in sea level over 1990 levels, a value based on the B1 IPCC emission scenario. This is an optimistic emission scenario that describes a world with a "global population that peaks in midcentury and declines thereafter" and "rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies (Intergovernmental Panel on Climate Change, 2000)."

Storm Surge Height Adjustment

In addition to an increase in global sea level rise, the heights of storm surges are also predicted to increase with climate change due to an increase in storm intensity. Changes in storm surge height are dependent on a variety of factors, such as the local bathymetry, the geography of the local coastline and the shifting of storm tracks with climate change (Weisse & Storch, 2010). Therefore, the change in storm surge height could vary significantly along a fairly short distance of coastline (Shepard, et al., 2012) (Tebaldi, et al., 2012).

Because of the lack of comprehensive coastal analysis, for the general analysis of a coastline it is simpler to use the method used by the OECD's analysis of port vulnerability (Nicholls, et al., 2008). Their calculations assumed a linear relationship between the increase in storm intensity and the increase in 100-year storm surge height based on a study on cyclones done in North East Australia (Nicholls, et al., 2008). Because they assumed a ten percent increase in the intensity of tropical cyclones by 2070, they assumed that the height of storm surges in ports exposed to tropical cyclones would also increase ten percent from current 100-year levels. In addition, they assumed a ten percent increase in storm surge height in ports in the 45 to 70 degree latitude range that currently experience extratropical cyclones. Ports outside of that latitudinal range were either not expected to see an increase in the severity of extratropical cyclones or not to experience these storms at all (Nicholls, et al., 2008).

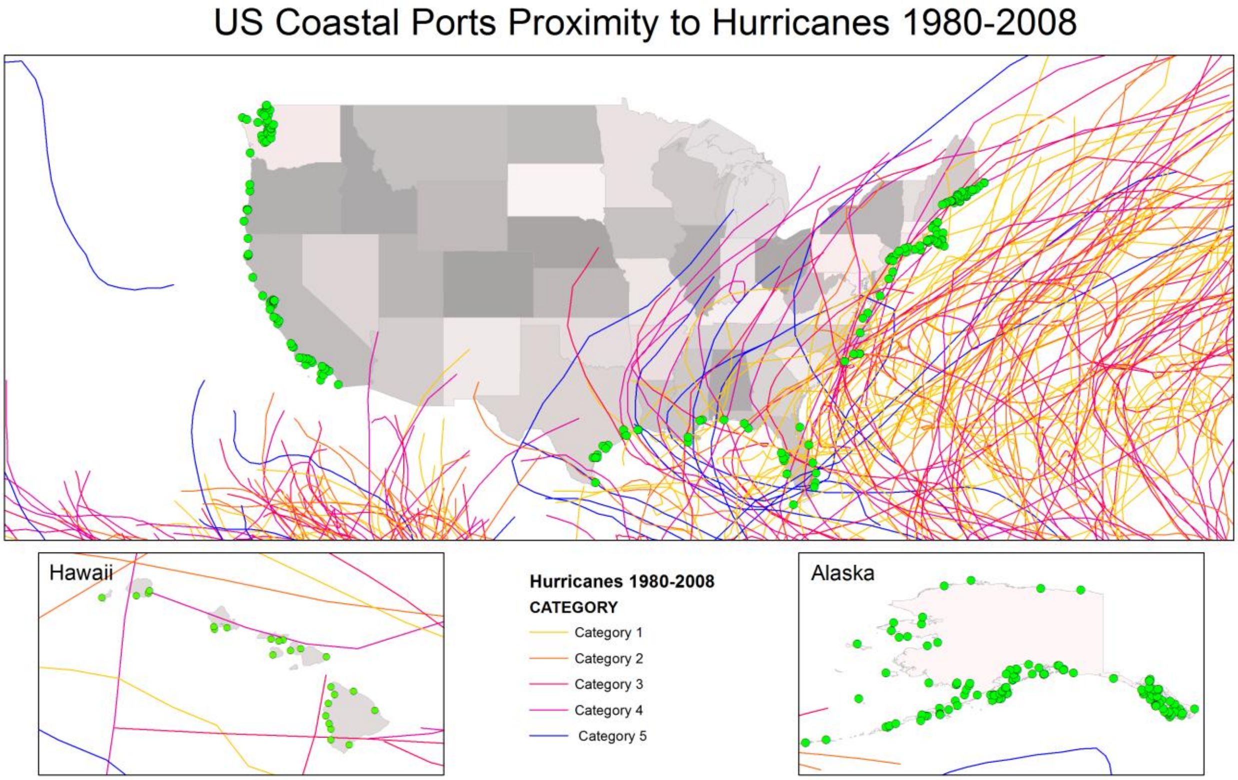

Figure 5 - US Coastal Ports Proximity to Hurricanes 1980-2008. (I. B. T. A. f. C. Stewardship, 2010), (National Geospatial-Intelligence Agency, 2011).

Figure 5 shows coastal ports and historical storm tracks in the United States since 1980. Many ports on the East Coast, Gulf Coast, and in Hawaii are regularly hit or come very close to hurricanes each decade. As the model used by the OECD only predicts an increase in storm surge in those areas already impacted by tropical and extratropical cyclones, in some locations we only considered sea level rise when calculating the necessary increase in port elevation.

For current storm surge levels we used data from the SURGEDAT database compiled by Needham (2011). SURGEDAT is a comprehensive database of storm surges with records dating back to 1886 (Needham, 2011). Using these data we selected the highest recorded storm surge per region for use as the approximate regional 100-yr storm surge.

This method was used for a number of reasons. Firstly, it allowed us to analyze an entire coastline using a single storm surge value. Additionally, there are gaps in data for 100-year storm surge data along these coastlines and this method allows the separation of storm surge caused by cyclones from storm surge caused by other varieties of extreme weather. Also, because it is our desire to develop an aggregate estimate, we need tools like SURGEDAT to develop the regional condition for the design. **Error! Reference source not found.** shows the national distribution of the data catalogued in SURGEDAT.

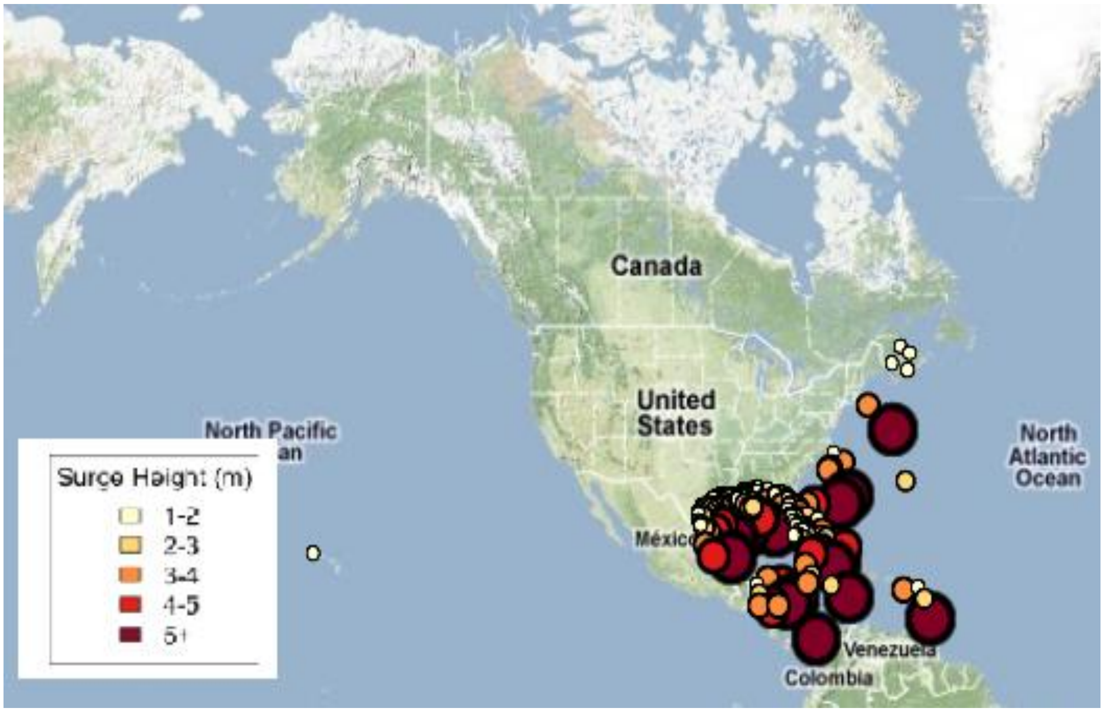

Figure 6: SURGEDAT data points used in the estimation of 100-yr storm surge

(Needham, 2011)

Subsidence

Another factor that should be considered in certain cases is subsidence, the settling of a land mass. For some ports, future subsidence may pose a more significant threat than sea level rise. While some port areas are experiencing uplift, which would lessen the impact of climate change, others are experiencing significant subsidence. In some locations the natural subsidence is exacerbated by anthropogenic subsidence, which can lead to the rapid sinking of ground level. One significant cause of anthropogenic subsidence is the draining of groundwater. Subsidence should be considered on a port-by-port basis; for example, the Long Beach/Los Angeles port experienced at least 2 meters of subsidence due to oil pumping in the past century (Subsidence History, 2012). However, for our calculations we chose not to include subsidence because anthropomorphic subsidence will vary depending on future human activity in the area, and we wanted to keep the focus of the estimations on climate change. However, port managers should be aware of subsidence in their area and factor it into their planning when considering climate change prevention plans.

5. Calculation of Port Area

We calculated the port area values by heads-up digitizing individual ports using Google Earth. Figure 7 below shows an example for Port Manatee (Florida). The red polygon indicates the area recorded as coastal port infrastructure.

Figure 7: Heads-up digitization of the area of Port Manatee in Google Earth

Each United States port listed in the World Port Index (World Port Index, 2012) was considered, but only commercial coastal ports handling freight were included. Marinas and fishing harbors were excluded, as was surrounding infrastructure not directly tied to port activities.

6. Regional Costs

The SURGEDAT data was divided into the four sub-regions of Hawaii, West Coast, Gulf Coast and East Coast. We used the highest recorded storm surge value for each port as the approximate 100-year storm surge level for that region. Table 6 shows the expected storm surge increase calculated from the SURGEDAT data for the sub-regions of the United States as well as the unit cost to elevate ports in those regions to the necessary height. A port on the West Coast, which is not likely to see a significant increase in storm surge height, would have to spend approximately ten percent less on port elevation than a port of the same size on the Gulf Coast. This relatively small difference in cost between coasts is due to the large fraction of the total expenditure that goes into the reconstruction of port infrastructure.

The costs in Table 6 are comparable to those reported by the Port of Gulfport. The Port of Gulfport spent approximately 250 dollars per square meter on raising the western wharf 4.6 meters (Conn, 2010). It should be noted that our calculations assume that existing port infrastructure is currently at an elevation that protects it from current storm surge and sea levels. For some ports, as was the case in Gulfport, an additional increase in elevation will be necessary if the port infrastructure is currently located at an elevation within the reach of the 100-year storm surge.

Using the SURGEDAT data we were able to create approximate 100-year storm surge levels for United States regions impacted by tropical cyclones. We combined this with port area data from Google Earth. By sorting ports into the sub-regions created for storm surge data, we calculated the cost to elevate the ports in each region and the total cost of elevating all United States ports in the Sebastian database. Table 6 shows the results.

Table 6: Cumulative regional cost breakdown

Region	Sea Rise (m)	Surge Height Increase (m)	Necessary Rise (m)	Cost to Elevate ($/m^2)	Total Port Area[11] (km^2)	Total Regional Cost to Elevate
Hawaii	0.681	0.183	0.9	131.57 to 188.99	5.70	$749,716,686 to 1,076,908,349
West Coast	0.681	0.0	0.7	126.34 to 183.76	115.87	$14,639,899,680 to $21,293,361,438
Gulf Coast	0.681	0.85	1.5	150.61 to 208.03	167.38	$25,207,760,091 to $34,818,474,302
East Coast	0.681	0.61	1.3	143.80 to 201.22	151.10	$21,728,604,046 to $30,405,008,2709
Total					**440.05**	**$62,325,980,503 to $87,593,752,359**

The total cost of elevating all of commercial coastal ports comes to a cost between $62 billion and $88 billion dollars.

7. Discussion

The per-acre cost of elevating the ports stays within a relatively close range, with only approximately a fourteen percent difference in per acre cost between the Gulf Coast and the West Coast of the United States. This is because the most costly part of the construction is the reconstruction of the port once the land has been elevated, not the process of elevating the land. It may therefore be advisable to raise a port more than the minimum amount required, as a greater level of protection can be achieved through a relatively small increase in unit price.

Port elevation is one of a number of preventative measures that can be taken against the damages associated with climate change. Other alternatives include the construction of seawalls and the

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[11] (Sebastian Database, 2012)

relocation of the port. The complete relocation of ports is unlikely to be the most economical adaptation strategy as it requires the acquisition of a large area of land and the restructuring of the surrounding transportation network. However, particularly in areas where the largest concern is the increase in storm surge rather than sea level rise, the construction of a seawall may be a valid alternative to elevation of the port infrastructure. The cost and feasibility of constructing a seawall will vary significantly depending on a number of factors, such as the geography of the surrounding coastline, the local bathymetry and the environmental restrictions that must be considered during planning and construction. Therefore, the decision of whether elevating or constructing a seawall is the more economical option must be determined on a case-by-case basis.

In reality, many ports are likely to elevate their infrastructure more gradually as old structures reach the end of their useful lives and are replaced. This will lessen the blow of the roughly 62 to 88 billion dollar national price tag calculated above, as the reconstruction of the infrastructure will already be included in the anticipated operating cost of the port and the only additional cost will be in the filling of the area to increase the elevation. While this approach may be possible in locations such as the West Coast where the main concern is sea level rise alone, in other regions such as the Gulf Coast where storm surge increase is likely to be a major concern, a large portion of infrastructure is likely to be endangered before the end of its useful life. It would be possible to apply this estimation model to regions expected to see storm surge and sea level rise increase at rates that will begin to threaten infrastructure within 30 years to more closely predict the necessary increase in anticipated spending to maintain the functioning of the nation’s port system.

According to American Association of Port Authorities, U.S. ports currently anticipate spending 2.1 billion dollars on capital upgrades annually (American Association of Port Authorities, 2008). Even if the majority of this budget were put toward climate change adaptation, funding is likely to be insufficient. It is likely that the cumulative demand of protecting coastal port infrastructure will exceed state and federal funding capabilities. This becomes far more likely when the additional costs not included in this rough cost estimation are factored in. While this model includes the bare minimum requirements for port operation, actual port elevation would involve many additional costs, including but not limited to permitting and environmental remediation. Elevating a port is a huge undertaking, and its environmental impacts are compounded by the immediate location of sensitive aquatic habitats. Environmental costs alone are likely to contribute significantly to the final price tag.

Obtaining the necessary fill required to raise infrastructure is likely to be in itself a limiting factor, as the total national adaptation outlined in Table 6 would require 441 million cubic meters of dredged fill, roughly 35.8 times more than the volume of material generated through new work dredging in the United States by the Army Corps of Engineers in 2011 and 2.8 times more than all material dredged my the Army Corps of Engineers in 2011, including maintenance and emergency dredging (Analysis of Dredging Costs, 2012). The lack of sufficient dredged material of adequate quality would likely lead to an increasing demand for fill trucked in over land. This would drive up costs and tax inland resources. In the event of increased port damage due to rising sea levels and storm surges, it is unlikely that there will be the resources available to enable the universal adaptation of United States ports if all adaptation is attempted in a short time frame. However, a combination of port elevation and dike construction may be feasible if implemented in a staged manner over an extended period of time. It is therefore essential that government and port authorities begin the development of adaptation strategies rather than assuming the future availability of financial and material resources.

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