A Comparative Cost Analysis of Ten Shore Protection Approaches at Three Sites Under Two Sea Level Rise Scenarios

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Hudson River Valley Greenway

Hudson River National Estuarine Research Reserve

As a part of:

The Hudson River Sustainable Shorelines Project

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About the Hudson River Estuary

The Hudson River Estuary is a narrow, 152 mile arm of the sea that extends from the southern tip of Manhattan, north to the Troy Dam. The maximum width of the river ranges from 3 miles in the Tappan Zee, to less than 0.5 miles near Albany; however most of the river ranges from 0.5 - 1 mile in width. The majority of the river is 20 - 50 feet deep with a 32 foot deep navigation channel extending to Albany. The river also contains extensive shallow-water areas that are less than 5 feet deep at low tide, many of which support wetlands or beds of submersed vegetation. Much of the river bottom is sand or mud, although patches of gravel, cobble, relict oyster reefs, and debris do exist. The average tidal range along the Hudson River is about 4 feet, peaking at around 5 feet at both ends of the estuary. In periods of normal freshwater flows, strong tidal currents (often greater than 2 feet per second) reverse the direction of water flow every six hours throughout the entire estuary, and are roughly 10 times as large as the downriver flow of fresh water. During extreme storm events however, the freshwater outflow can overwhelm the tidal variations, as was the case during Hurricane Irene. Water levels within the estuary are determined chiefly by tides, but can be strongly affected by high flows from upriver, including tributary flows, and by storm surges. The transition from fresh to saltwater occurs in the lower half of the river, with the exact location dependent on the prevailing flow conditions.

The shorelines of the Hudson River Estuary are constantly changing. The forces impinging on the Hudson's shores include wind-driven waves, wakes, currents, floating debris, and ice. Depending on their exposure to these forces, the geometry of the river including factors such as width, depth, distance to the navigation channel, and the presence of any protective shallows, different parts of the Hudson's shores receive very different inputs of physical energy. Likewise, land uses on the landward side of the shore and water-dependent uses on the riverward side of the shore are highly variable along the Hudson. As a result, different parts of the Hudson place very different demands on engineered structures constructed along the shore.

The shoreline has been dramatically altered over the last 150 years to support industry and other development, contain channel dredge spoils, and withstand erosion. About half of the shoreline has been conspicuously engineered with placed rip-rap, revetments, bulkheads, or timber cribbing. Many additional shorelines contain remnant engineered structures from previous human activities. The remaining "natural" shorelines, which have also been affected by human activities such as dredge spoil disposal and the introduction of invasive species and contaminants, include a mix of wooded, grassy, and unvegetated communities on mud, sand, cobbles, and bedrock. Miller et al. (2006) performed an inventory of Hudson River shorelines between the Tappan Zee Bridge and the federal dam at Troy, and proposed a five level classification scheme. Of the 250 miles of shorelines inventoried, 42% were hard engineered, 47% were natural, and 11% were natural with remnants of engineering structures. The most common shoreline structure was rip-rap (32%), followed by woody (29%) and unvegetated (16%) slopes. The dominant substrate found within the region was unconsolidated rock (52%), mud/sand (16%) and mixed soil/rock (12%).

About the Sustainable Shorelines Project

The Hudson River Sustainable Shorelines Project is a multi-year effort lead by the New York State Department of Environmental Conservation Hudson River National Estuarine Research Reserve in cooperation with the Greenway Conservancy for the Hudson River Valley. Partners in the project include Cary Institute for Ecosystem Studies, NYSDEC Hudson River Estuary Program and Stevens Institute of Technology. The Consensus Building Institute facilitates the project.

The project is supported by the National Estuarine Research Reserve System Science Collaborative, a partnership of the National Oceanic and Atmospheric Administration and the University of New Hampshire. The Science Collaborative puts Reserve-based science to work for coastal communities coping with the impacts of land use change, pollution, and habitat degradation in the context of a changing climate.

Disclaimer

The opinions expressed in this report are those of the authors and do not necessarily reflect those of the New York State Department of Environmental Conservation (NYSDEC) and the Greenway Conservancy for the Hudson River Valley or our funders. Reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Generic shoreline treatments for specific locations on the Hudson River Estuary are presented for the purpose of developing the relative cost analysis. Their use in this analysis does not imply regulatory approval of any such method at a particular site. The Hudson River is regulated by New York State under NYS Environmental Conservation Law (ECL) Article 15, Part 608 (Use and Protection of Waters), and associated wetlands and adjacent buffer areas may be regulated by ECL Article 24 Part 663 (Freshwater Wetlands) or Article 25, Part 661 (Tidal Wetlands). Individual project applications are evaluated on a case by case basis by NYSDEC, and each project must meet permit issuance standards. The United States Army Corps of Engineers also has regulatory jurisdiction of adjacent federally regulated wetlands and the Hudson River as a navigable waterway. Applicants should contact the USACOE and request a jurisdictional determination from that agency.

Terminology

There are many ways to describe both standard and innovative engineering methods to protect shoreline. The Hudson River Sustainable Shorelines Project uses the term ecologically enhanced engineered shoreline to denote innovative techniques that incorporate measures to enhance the attractiveness of the approach to both terrestrial and marine biota. Some documents and reports of the Hudson River Sustainable Shorelines Project may use other terms to convey this meaning, including: alternatives to hardening, bio-engineered, eco-alternatives, green, habitat-friendly, living, soft, or soft engineered shoreline.

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Introduction

The Hudson River Sustainable Shorelines Project is focused on bringing together community leaders, scientists, engineers, and natural resource managers to help people make decisions about how to manage community waterfronts, control erosion, and respond to increased flooding and projected higher water levels. The project is generating information about the performance, cost, and natural benefits of different shoreline management options, in the context of the Hudson River Estuary's human and natural setting. The project is being guided by the expressed needs and interests of local governments, experts and consultants, shoreline land owners, policy-makers, and regulators. The goal of this project is to protect shorelines and associated water quality, wildlife habitat, outdoor recreation, and community quality of life for future generations.

In support of the above objectives, this document describes the methodology and results of a comparative cost analysis of ten different shoreline stabilization approaches at three sites, under two sea level rise scenarios. The cost analysis was designed to compare the construction, long-term Maintenance, Damage, and Replacement Costs of ecologically-enhanced stabilization approaches to those of traditional approaches as sea levels rise. The ten approaches, the three sites, and the two sea level rise scenarios were selected in consultation with the Sustainable Shorelines Project Team. A 70 year time frame was selected for the analysis.

The ten approaches selected include: timber bulkhead, steel sheet pile bulkhead, bio-walls, revetments, rip-rap, joint planting, vegetated geogrids, timber cribbing, live crib walls, and sills (see the Glossary of Terms for descriptions of these methods). These approaches were described in detail by Rella and Miller (2012) in their review of engineering approaches for limiting erosion in sheltered waterways. A table, excerpted from Rella and Miller provides information on where each approach falls under the traditional coastal structure classification from "hard" to "soft", as well as information on initial costs, maintenance costs, and adaptability. It should be noted that in the literature review, biowalls were included under the discussion of green walls and joint planting was considered as a subset of live stakes. The approaches were selected based on their use or potential use at sites within the Hudson, and cover the spectrum from traditional approaches such as bulkheads and rip-rap, to more innovative approaches such as joint planting and sills. It should be noted that many of the approaches fall into a category of shore protection that others have previously defined as hybrid approaches due to their integration of structural and non-structural vegetated elements.

The three sites that were selected represent diverse shoreline types typical of those found along the Hudson and are a subset of those analyzed in a report prepared by Alden and ASA (2006) for the NYSDEC. The advantage to using these sites is that the majority of the required site information has already been collected, so the focus can be placed on developing the analysis methodology and preparing the cost analyses. The Henry Hudson Park site in Albany County, New York is a mild-moderately sloped site along a relatively narrow (~1000 ft), and shallow (~20 ft) section of the estuary. On the other hand, the Poughkeepsie site is located along the eastern bank abutting a relatively deep (~50 ft) section of the river. The side slopes at Poughkeepsie are steep, rising approximately 1 foot vertically for every 1.5 feet horizontally. Bowline Point Park in Upper Haverstraw Bay in Rockland County represents yet another common Hudson River shoreline type, with a mild sloping bank (~1 ft vertical for every 20 ft horizontal) which abuts a shallow (~10 ft) but wide (15,000 ft) reach of the river. For consistency, a 500 foot stretch of shoreline was considered at each site.

Table 1: Treatments selected for the cost analysis. Categorization taken from the Sustainable Shorelines literature review (Rella and Miller, 2012).

	Approach	Construction Cost	Maintenance Cost	Adaptability
Bulkhead	Soft ■■■■■ Hard	Low ■■■□□ High	Low ■□□□□ High	Low ■□□□□ High
Revetments	Soft ■■■■□ Hard	Low ■■■■■ High	Low ■■□□□ High	Low ■■■■□ High
Rip-rap	Soft ■■■□□ Hard	Low ■■□□□ High	Low ■□□□□ High	Low ■■■■□ High
Green Walls	Soft ■■■■□ Hard	Low ■■■■□ High	Low ■■□□□ High	Low ■■□□□ High
Timber Cribbing	Soft ■■■■□ Hard	Low ■■■□□ High	Low ■■■□□ High	Low ■■□□□ High
Live Crib Walls	Soft ■■■□□ Hard	Low ■■■■□ High	Low ■■■□□ High	Low ■■■■■ High
Vegetated Geogrid	Soft ■■■□□ Hard	Low ■■■■□ High	Low ■■■□□ High	Low ■■■□□ High
Live Stake	Soft ■■□□□ Hard	Low ■□□□□ High	Low ■■■□□ High	Low ■□□□□ High
Sills	Soft ■■□□□ Hard	Low ■■■□□ High	Low ■□□□□ High	Low ■■■□□ High

The Project Team selected two sea level rise scenarios for the analysis. The first is simply an extrapolation of the current rate over the next 70 years. The current rate was determined from the nearest long-term gauge maintained by NOAA, which places the rate of sea level rise at the Battery at 2.77 mm/yr, or roughly 10.9 inches per century (www.tidesandcurrents.noaa.gov/sltrends/index.shtml). Over the seventy year project period, this corresponds to approximately 7.6 inches of sea level rise. The second scenario is the rapid ice melt scenario considered by the New York City Panel on Climate Change (2009), which predicts 48 inches of sea level rise by 2080.

Unlike the first scenario in which the rate of sea level rise is constant, the rapid ice melt scenario assumes an increasing rate of sea level rise with dramatic changes towards the end of the century.

Methodology

Design Philosophy

The general characteristics of each site were obtained from the site profiles and descriptions presented in the 2006 report by Alden and ASA (Allen, et al., 2006). Supplementary information such as estimates of the wind wave heights for each site was obtained through additional analyses. This information was used to develop the basic design parameters from which a reliable "reconnaissance phase" cost analysis could be performed (USACE, 2008). Since the purpose of this analysis was to compare as many approaches at as many sites as possible, some designs were carried out at sites where their applicability may be questionable. Only in cases where a given approach was considered extremely unsuitable given the site conditions, was a design and cost analysis not performed. The shoreline stabilization designs, were developed expressly for estimating quantities for input to the cost analyses, and should not be considered complete for construction purposes. Simple sketches representing the basic designs are presented in the Appendices.

Cost Development

Cost estimates for each design were developed using one of two approaches. The first approach relies on bulk costs for similar projects collected from a variety of sources. All of the data used in developing the bulk cost estimates relied on local data for projects constructed within the past five years. Generally the bulk costs fall within a range from which an estimated cost was selected based on the complexity and anticipated energy at the site being considered. The second approach builds the costs from the ground up utilizing typical material and labor costs; however all cost estimates constructed in this manner were cross-checked with available bulk cost data for consistency. There are advantages and disadvantages to each approach. Utilizing bulk costs can be more straightforward particularly for a reconnaissance level analysis; however it is difficult to obtain bulk costs for many of the non-traditional approaches. Compiling the costs from the ground up offers more flexibility; however the lack of site specific details and the significant variability in unit costs and labor rates is problematic. Every effort was made to remain consistent throughout the analysis such that meaningful comparisons between the approaches could be made.

The cost estimates were developed using a lifecycle cost approach. The basic costs were separated into four main categories. The Initial Construction (IC) costs are the costs described above, associated with constructing each of the alternatives as designed. All other costs are formulated as a percentage of the Initial Cost so that a consistent and repeatable methodology could be used. An advantage of using this approach is that it facilitates modifications to the cost estimate if any of the underlying assumptions or unit costs are changed.

Maintenance and Repair Costs (MC) refer to the costs associated with inspecting and performing basic maintenance for each approach. Some structures such as bulkheads will only require minimal expenditures on maintenance and repairs while others, particularly those with a vegetative component, may engender higher costs. It is assumed that the MC for several of the approaches will increase under the rapid sea level rise scenario to account for the increased stress placed on the different components. MC for shoreline stabilization alternatives with a rooted vegetation (live crib walls, vegetated geogrids, joint planting) are assumed to increase by 10%, while MC for wooden structures (crib walls, wood bulkheads) are assumed to increase by 5%. The MC for the remaining structures (revetments, rip-rap, sills, steel sheet pile bulkhead), are assumed to remain the same. The percent increase is intended to be reflective of the increased stress placed on different materials by rising sea levels.

Damage Costs (DC) include costs outside of the typical MC created by storm impacts below the design level (50-year). These storms may have specific impacts that require significant modifications to restore the original function of the shoreline stabilization approach. Joint planting provides perhaps the clearest example. While a 10-year storm will have minimal impact on an adequately designed base structure (rip-rap slope or revetment), it will most likely displace the vegetation. The DC associated with a 10-year storm would be the cost to replace the vegetation to restore the original function of the stabilization approach. A 50-year storm on the other hand, may significantly damage both the base structure and the vegetation. The cost to restore the approach to its original function would therefore be the cost associated with replacing the vegetation in addition to the cost of repairing the base structure. DC are calculated on a probabilistic rather than an event basis. The total expected DC during any period is simply the DC associated with a single occurrence of an event multiplied by the most likely number of occurrences of that event during the period.

The fourth cost category is Replacement Cost (RC). Some structures, such as bulkheads, have a finite lifespan, and regardless of the storm conditions, will need to be replaced once or even twice with the seventy year analysis period. In most cases, replacement is driven by material degradation. For the purposes of this analysis, replacement assumes complete reconstruction of the original approach to the original design at the original cost (IC). The only adjustment made is to account for discounting and inflation according to the procedures outlined below.

In developing the above referenced cost categories, a relevant factor which has not been incorporated into the cost estimates, is the influence of vegetation on shoreline stability. When properly constructed and maintained, the root systems associated with shoreline vegetation can help stabilize the shoreline; however when not properly maintained, excessive growth can result in root systems that actually destabilize the shoreline by undermining the structural elements (rock/wood) designed to provide the primary erosion resistance. Miller (2006) identified a significant percentage (>10%) of Hudson River shoreline consisting of remnant engineering structures, many of which are in poor condition due to a lack of maintenance. Since it is impossible to know whether the vegetative alternatives considered here will be adequately maintained in the future, vegetation is assumed to have no net influence on shoreline/structure stability during storms. An example is provided below in the *Sensitivity Analysis* section of this report, which illustrates an approach that can be used to modify this assumption. Since no engineering benefits are assigned to the presence of the vegetation while additional costs are added for maintenance and the replacement of vegetation after moderate storms, the cost estimates are biased towards unvegetated treatments. This was done in order to remove a source of subjectivity, which could be used to call into question the results of the analysis.

Sea Level Rise

The two sea level rise scenarios are incorporated into the analysis by considering their impact on the probability of occurrence of significant floods as determined by flood elevations. The approach discussed below is a simplified method of treating return periods and probability. Additional information is presented in an Appendix.

Each shoreline stabilization approach is designed to resist the 50-year storm, where "50-year" refers to the return period (T_r) of the storm. The probability of the design storm occurring in any given year is:

$$p = 1/T_r$$

For the 50-year design storm, the annual probability of occurrence is 0.02. The probability that the design storm will occur over a period of n years is:

$$p_n = 1-(1-p)^n$$

Therefore, the probability that a 50-year storm (p = 0.02) will occur within the (n =) seventy year analysis period, is 0.757. The expected, or most likely number of occurrences (s), during a period of n years however, is:

$$s = n / T_r$$

For the 50-year design storm, the most likely number of occurrences over the seventy year analysis period is 1.4.

Sea level rise impacts the return period because it raises the base (non-storm) water level, making the number of exceedences of a specified water level increasingly likely. Put another way, in the future, smaller, more frequent storms become capable of generating water levels that reach or exceed the design storm thresholds. The results of an extreme value analysis performed on the Battery Park water level data are shown in Figure 1. The plot shows the relationship between water level measured above station datum (x-axis), and cumulative probability, $1\text{-}1/T_r$ (y-axis). The water level corresponding to the 10-year return period is approximately 12.25 feet. If the 10-year water level results in damage over a twenty five year period, that cost can be expected to be incurred 2.5 times, according to the formulas presented above. If sea levels rise 0.5 feet, the base elevation is increased and it no longer takes a 10-year storm (with an annual probability of occurrence of 0.1) to reach that elevation. In fact, a 5-year storm (with an annual probability of 0.2), reaches the same elevation (11.75 ft + 0.5 ft = 12.25 ft). Over a twenty five year period, the 5-year storm can be expected to occur 5 times, or twice as often, incurring associated DC each time. The present analysis uses this methodology to increase the frequency with which DC are incurred.

While climate change is expected to have additional impacts related to potential changes in the frequency and intensity of storms, and the duration and extent of ice cover, these impacts are not as well documented and are not considered here.

Under the first (current or historic) sea level rise scenario, the existing rate of change is assumed to continue into the future. Under the second, the rate accelerates, leading to a more rapid increase during the second half of the seventy year period under consideration. In order to simplify the analysis, the seventy year period is broken into three periods, P1 covering 2012-2037 (25 years), P2 covering 2037-2062 (25 years), and P3 covering 2062-2082 (20 years). The amount of sea level rise predicted at the midway point of each period is used to modify the return periods during that timeframe. This slightly overestimates the return periods during the first half of each period, and underestimates them during the second half, but simplifies the analysis. As the return periods are reduced, the expected number of occurrences of a given storm increase with time, as do the expected damages. Table 2 documents the expected sea level rise at the midpoint of each period, while Table 3 and Table 4 summarize the corresponding adjustments to the return periods and expected number of storms for each sea level rise scenario.

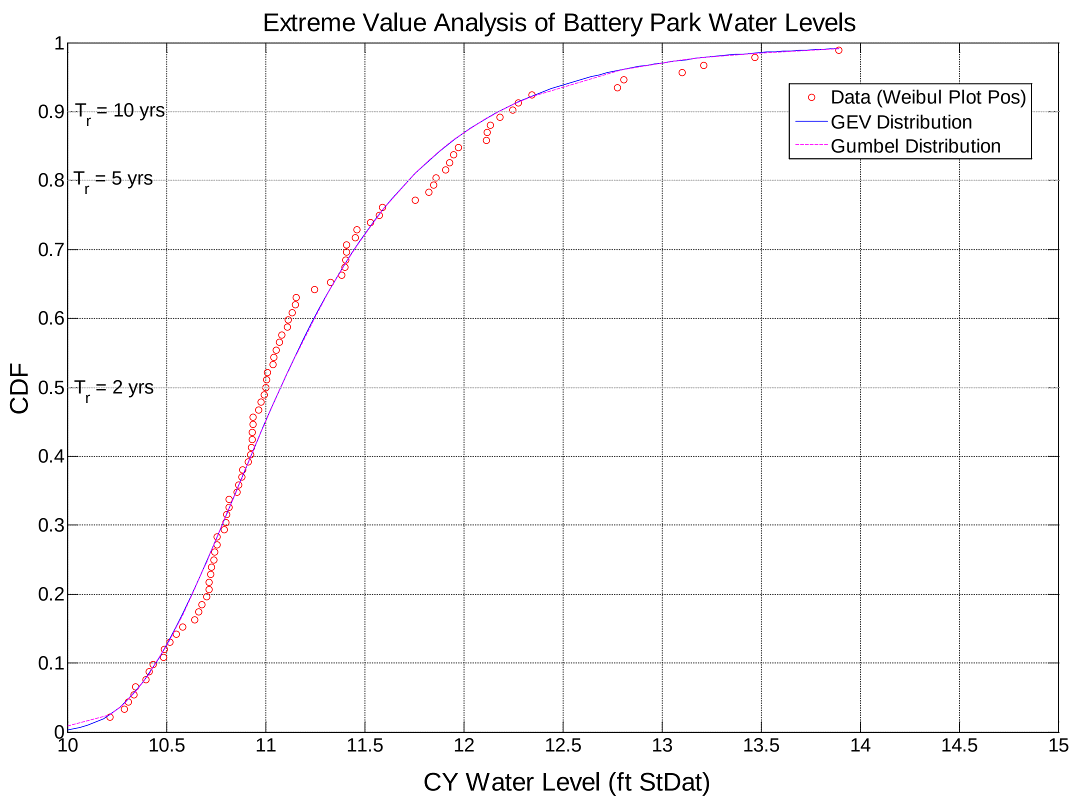

Figure 1 - Extreme Value Analysis of Water Level Data from Battery Park.

Table 2 - Sea Level Rise Increases.

Sea Level Rise at the Midpoint of Each Period		
Period	Current Rate (in)	Rapid Ice Melt (in)
P1 (2012-2037)	1.32	9.00
P2 (2037-2062)	3.96	24.00
P3 (2062-2082)	6.34	41.00

Table 3 - Storm Frequency Modification Based on Current Sea Level Trend.

	Current Rate of SLR					
	P1 (2012-2037)		P2 (2037-2062)		P3 (2062-2082)	
Current T_r	Modified T_r	# Storms	Modified T_r	# Storms	Modified T_r	# Storms
50	44.9	0.56	33.3	0.75	24.7	1.01
40	34.2	0.73	24.4	1.02	19.3	1.30
25	22.2	1.13	16.3	1.53	11.7	2.14
10	8.8	2.84	6.3	3.97	4.7	5.32

Table 4 - Storm Frequency Modification Based on Rapid Ice Melt Scenario.

	Rapid Ice Melt Rate of SLR					
	P1 (2012-2037)		P2 (2037-2062)		P3 (2062-2082)	
Current T_r	Modified T_r	# Storms	Modified T_r	# Storms	Modified T_r	# Storms
50	18.5	1.35	2.7	9.26	1.0	20.00
40	13.1	1.91	2.1	11.90	1.0	20.00
25	8.3	3.01	1.5	16.67	1.0	20.00
10	3.3	7.58	1.0	25.00	1.0	20.00

The rapid sea level rise scenario presents two analytical challenges that must be addressed. The first is that the water level increases so rapidly, that by period P2, the modified return period for a 10-year storm is reduced to less than 1. In other words, the 10-year water level is expected to be exceeded several times annually. By period P3, even the 50-year storm water elevation is expected to become an annual occurrence. For the purposes of this analysis, the minimum return period utilized is 1 year, even though during periods P2 and P3 the threshold water levels may be exceeded even more frequently. The second challenge relates to the physical characteristics of the sites selected. At all three sites, the difference between mean high water (MHW) and the "top of slope" based on the profiles in the Alden and ASA report (Allen, et al., 2006) is between 36 and 46 inches. Under the rapid sea level rise scenario, the existing bank at all three sites will be submerged at high tide at some point during the seventy year study period. While the analysis accounts for this by assuming the damages associated with even the smallest storms recur on a yearly basis, the likelihood is that a significant intervention beyond the scope of this report would be required. Options might include retreating inland, filling the adjacent area to raise the elevations, or constructing a floodwall or berm. When considering the results of the cost analysis under the rapid sea level rise scenario, consideration should be given to the fact that once a critical elevation is reached, likely near the start of period P3, key decisions will have to be made, and the possibility exists that all prior shoreline stabilization investments will be lost.

Inflation and Discounting

The lifecycle cost analysis uses a present value approach where all costs are converted into 2012 dollars. All historic cost information is scaled up using the methodology and data contained in the U.S. Army Corps of Engineers, Civil Works Construction Cost Index System (CCWIS) guide. Future costs are inflated using the CCWIS, but also discounted at a 4% annual rate according to the most recent federal guidance (USACE, 2012). The CCWIS tables only extend 15 years into the future. In order to cover the period of analysis, the rate (1.7%) used in the tables was held constant and projected through the seventy year project life. The following example illustrates the use of the inflation and discount rates in the cost estimates.

Assume the cost in 2012 of building a bulkhead is $100,000. The cost in 2012 dollars to reconstruct the bulkhead in 2072 is first adjusted to account for inflation according to:

$$IC_{2072} = \$100{,}000(1 + 0.017)^{(2072-2012)} = \$274{,}950$$

The inflated cost is the cost in 2072 to reconstruct the bulkhead; however the cost must also be adjusted to account for the discount rate if a present value analysis is used. This adjustment is as follows:

$$IDC_{2072} = \$274{,}950/(1 + 0.04)^{(2072-2012)} = \$26{,}251$$

The net result is the cost in 2012 dollars that takes into account the competing influences of inflation and discounting. Figure 2 illustrates that with the inflation set at 1.7% and the discount rate set at 4.0%, over time the discount rate has a more pronounced impact on the cost in terms of the present value.

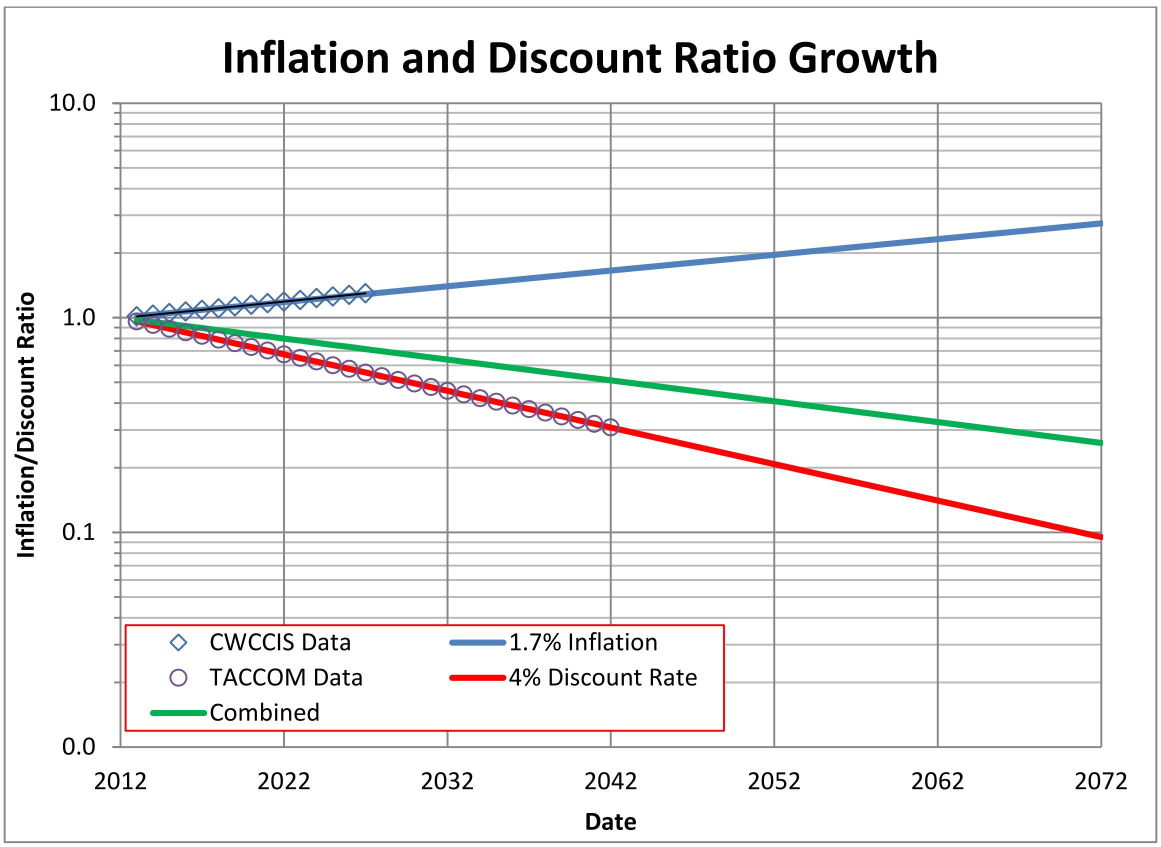

Figure 2 - Growth of the Inflation and Discount Terms with Time.

Anatomy of a Cost Analysis

An example of a completed cost analysis is provided in Figure 3. Every attempt was made to simplify the analysis and the presentation of the results. However, as the table suggests the complexity of the task necessitates some explanation of results. As discussed above, at each site, two cost analyses were performed for each shoreline stabilization alternative; one representing the current rate of sea level rise, and the other the accelerated, rapid ice melt scenario. The methodology used to develop the lifecycle costs is the same for both scenarios; therefore only a single example representing one of the sea level rise scenarios is dissected here.

A portion of Figure 3 is repeated in Figure 4, where the left-hand side of the table has been highlighted to identify the different costs that make up the total cost estimate. As indicated, the Initial Cost (IC) is the cost associated with constructing the specified shoreline stabilization approach in 2012 dollars. As discussed above, the IC is based on an analysis of the available data for each site, and takes into consideration factors like material and labor and bulk costs. The IC becomes the cost basis for all other costs (i.e. other costs are presented in terms of a percentage of the IC). As a direct, intended consequence, uncertainties in the IC propagate through the analysis, such that increasing or decreasing the IC by twenty-five or fifty percent increases or decreases the lifecycle cost by the same percentage.

As described above in the cost development section, the Damage Costs (DC) are costs associated with restoring the shoreline stabilization approach after storms of a specific magnitude. For the analysis, storms with return periods of 10, 25, 40, and 50 years were selected. Specific impacts such as scour, overtopping, and flanking, and an associated repair cost, are defined for each storm on each type of structure. In the example shown, a 10-year storm has minimal impact on the bulkhead, a 25-year storm was assumed to cause minor scour with an associated repair cost of 5% of the IC, a 40-year storm was assumed to cause no additional impact (beyond the scour), and a 50-year storm was assumed to cause moderate scour and overtopping and an additional repair cost equal to 10% of the IC. Because the 40-year storm is assumed to cause no additional impact over the 25-year storm, the DC incurred are the same as those for a 25-year storm. The DC are calculated in such a way that a 50-year storm will cause the incurrence of both the 25-year and 50-year DC.

Wood Bulkhead Cost Estimate											
Initial Cost (IC)		$ 171,500									
				Current Rate of SLR							
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)		
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final	
Damage Cost (DC)	50	10%	0.56	$ 7,220	0.75	$ 5,566	1.01	$ 4,537	$ 17,323	4.6%	
Damage Cost (DC)	25	5%	1.13	$ 7,302	1.53	$ 5,686	2.14	$ 4,789	$ 17,776	4.7%	
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 74,139	1.00	$ 44,825	$ 118,965	31.7%	
Maintenance Cost (MC)		20%	1.00	$ 25,935	1.00	$ 14,828	1.00	$ 8,965	$ 49,728	13.3%	
						Post-Construction Costs (DCs+RC+MC)			$ 203,792	54.3%	
								Initial Cost (IC)	$ 171,500	45.7%	
*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period								Total Cost	$ 375,292	100.0%	

				Rapid Ice Melt Rate of SLR						
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 17,524	9.26	$ 68,648	25.00	$ 112,063	$ 198,234	28.8%
Damage Cost (DC)	25	5%	3.01	$ 19,530	16.67	$ 61,783	25.00	$ 56,031	$ 137,344	20.0%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 74,139	1.00	$ 44,825	$ 118,965	17.3%
Maintenance Cost (MC)		25%	1.00	$ 32,419	1.00	$ 18,535	1.00	$ 11,206	$ 62,160	9.0%
						Post-Construction Costs (DCs+RC+MC)			$ 516,703	75.1%
								Initial Cost (IC)	$ 171,500	24.9%
*Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period								Total Cost	$ 688,203	100.0%

Figure 3 - Sample Output Illustrating a Final Cost Estimate.

The Replacement Cost (RC) as described above, is the cost associated with completely replacing a shoreline protection approach. RC are only incurred for structures such as bulkheads, which have a documented finite lifespan, which is typically related to limitations of the materials (wood/steel) used in construction.

Maintenance costs (MC) are the typical costs associated with the upkeep of a particular approach. MC are formulated as a percentage of the IC and are calculated on a per period basis.

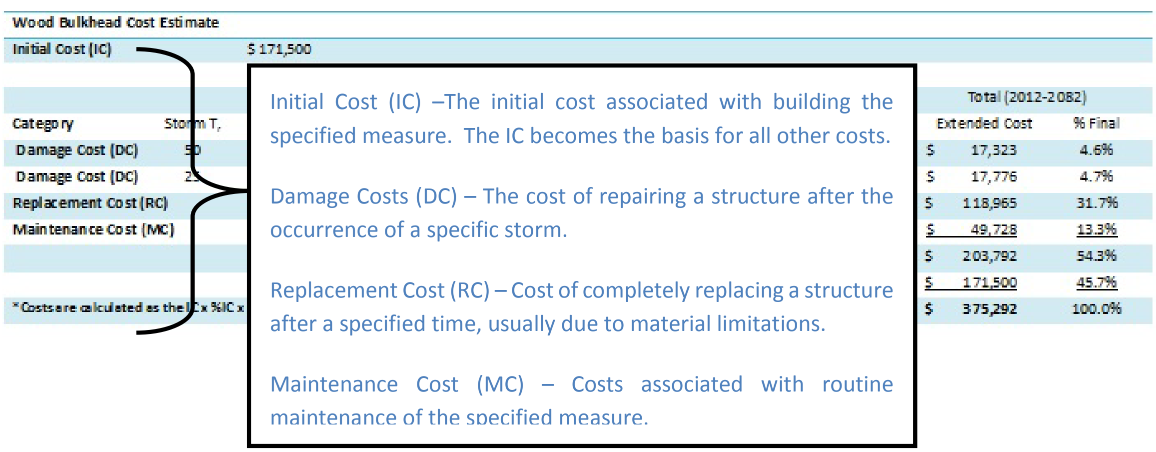

Figure 4 – Anatomy of a Cost Estimate (Part 1).

In Figure 5, the three discreet periods over which the costs are accrued are identified. Discounting and inflation are applied at the midpoint of each period. For example, all costs accrued during Period 2 (DC from a 50-year storm and a 25-year storm, RC, and MC in the example provided) are assumed to be incurred midyear in 2049.

As indicated, "# Events" refers to the number of times a specific cost is allocated during each period. For DC, "# Events" refers to the most likely number of storms of a given level during each period. The number increases with time as sea level rise makes it increasingly likely a given storm level will be exceeded in each period. As applied to RC, "# Events" is either zero (not replaced) or one (replaced) depending on whether complete replacement of the approach occurs during a given period. MC are calculated as periodic costs and thus are accrued once during each period.

Costs are calculated over discrete periods. For simplicity, inflation and discounting are applied at the midpoint of each period.

Wood Bulkhead Cost Estimate										
Initial Cost (IC)		$ 171,500								
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T.	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 7,220	0.75	$ 5,566	1.01	$ 4,537	$ 17,323	4.6%
Damage Cost (DC)	25	5%	1.13	$ 7,302	1.53	$ 5,686	2.14	$ 4,789	$ 17,776	4.7%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 74,139	1.00	$ 44,825	$ 118,965	31.7%
Maintenance Cost (MC)		20%	1.00	$ 25,935	1.00	$ 14,828	1.00	$ 8,965	$ 49,728	13.3%
							Post-construction Costs (DCs+RC+MC)		$ 203,792	54.3%
							Initial Cost (IC)		$ 171,500	45.7%
*Costs are							Total Cost		$ 375,292	100.0%

The number of events indicates the number of times a specific cost is incurred over a given period. For DC, this is related to the storm return period adjusted for sea level rise. RC are only incurred when a structure reaches its typical lifespan. The base MC is calculated on a per period basis, so MC are incurred once per period.

Costs are calculated as the IC times the % of the IC associated with damage or replacement times the number of events times the inflation rate times the discount

Figure 5 - Anatomy of a Cost Estimate (Part 2).

Periodic costs are calculated in the same way for each type of cost during each period. The periodic cost is calculated in 2012 dollars according to the following formula:

$$Cost = (IC)x(\%IC)x(\#\ Events)x\left[\frac{(1+IR)^{(Mid-2012)}}{(1+DR)^{(Mid-2012)}}\right]$$

Where IC is the initial cost, IR is the inflation rate, DR is the discount rate and Mid is the midpoint of the specified period. Essentially, the cost is the base cost (IC x %IC) multiplied by the number of occurrences (# Events) converted to present day dollars.

In Figure 6, the extended costs, subtotals and percent contribution to the final cost are highlighted. The extended cost is the total cost for each cost type summed over the three periods. The total post-construction cost is the sum of the DC, RC, and MC. The final cost is the post-construction cost plus the IC, and represents the true cost in 2012 dollars of protecting the identified shoreline with the specified treatment. The last column gives the percent contribution of each line to the total cost. In the example provided, the IC is 45.7% of the total, with the remainder being spread between RC, MC, and DC. Of these, replacement (31.7% of the total) and maintenance (13.3% of the total) are the major contributors.

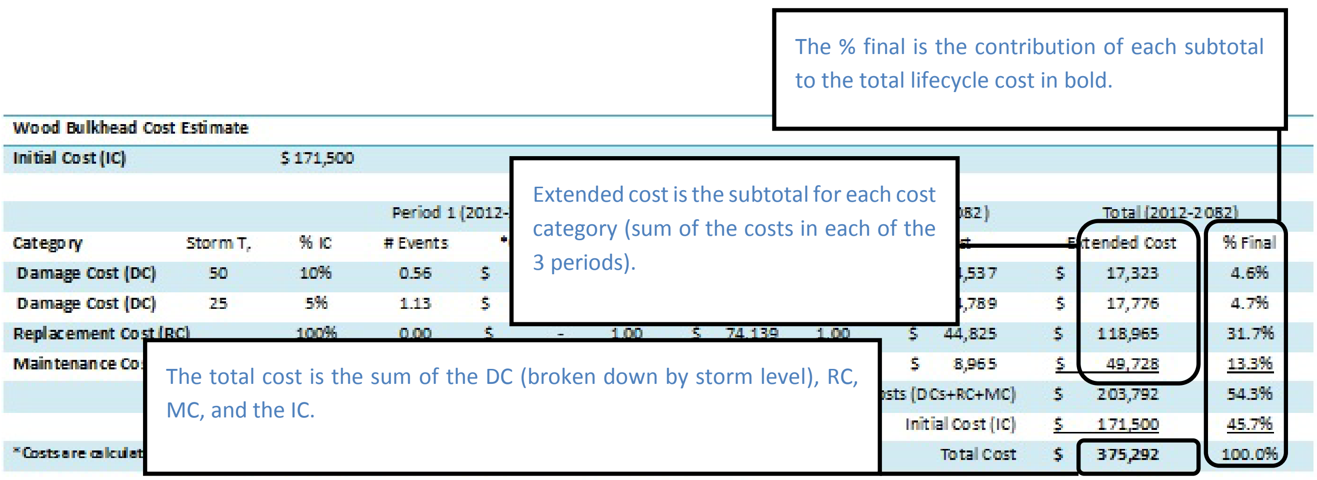

Figure 6 – Anatomy of a Cost Estimate (Part 3).

Sensitivity Analysis

Analyses were carried out to determine the sensitivity of the total costs to the modification of several of the assumptions used in the analyses. These sensitivity analyses could be used individually, or combined to produce confidence bands on the presented lifecycle costs; however it is beyond the scope of the simple analyses presented here.

Materials and Labor

The sensitivity of each cost estimate to individual costs (materials, labor, etc.) can be determined in a straightforward manner due to the way in which the analysis was constructed. All costs are scaled based on the Initial Cost (IC), such that if the IC is doubled, the final cost will double as well. The rationale used to develop the IC of each approach at each site is discussed in the text in sufficient detail, such that the interested reader can alter material costs, labor costs, etc. to derive a new IC. The following simple examples illustrate the concept. Consider an approach with an original Initial Cost (IC) of \$1,000,000 split evenly between material and labor costs:

$$Original\ IC = Labor(50\%) + Materials(50\%)$$

$$\$1{,}000{,}000 = \$500{,}000 + \$500{,}000$$

In the example, assume that the material costs are split evenly between stone, rock, and geotextile fabric:

$$Materials = Stone(33.3\%) + Rock(33.3\%) + Fabric(33.3\%)$$

$$\$500{,}000 = \$166{,}667 + \$166{,}667 + \$166{,}667$$

In the present example, for simplicity, assume the design called for 1,667 tons of rock at \$100/ton. As discussed previously, material costs are known to vary widely and an important question is what impact this ultimately has on the total cost. If a cost of 75\$/ton (75% of the original value) of rock had been used instead, the impact on the IC can be calculated as follows:

$$New\ Rock\ Cost = 1{,}667 tons\ \times\ \$75\ per\ ton = \$125{,}025$$

$$New\ Material\ Cost = \$166{,}667 + \$166{,}667 + \$125{,}025 = \$458{,}359$$

$$New\ IC = \$500{,}000 + \$458{,}359 = \$958{,}359$$

$$Percentage\ of\ IC = \frac{\$958{,}359}{\$1{,}000{,}000} \times\ 100 = 95.8\%$$

In the example provided, decreasing the unit cost of one of the components of the estimate by 25% reduces the IC by 4.2%. The same result can be determined directly from looking at the percentages:

$$Percentage\ of\ IC = 50\% + 50\%(33.3\% + (100\% - 25\%)(33.3\%) + 33.3\%) = 95.8\%$$

Again, because all of the costs scale with the IC, the net effect of reducing the unit cost of rock in the example by 25% will be an overall reduction in the lifecycle cost estimate by 4.2%.

Sea Level Rise/Storminess

A similar approach can be used to determine the sensitivity of the results to the sea level rise scenario considered. Sea level rise factors into the cost analyses in two ways. For vegetated techniques and wooden structures, it has been assumed that for the rapid sea level rise scenario, MC will increase by 10% and 5% respectively, compared to the base case (current rate of sea level rise). A simple example is used to illustrate the sensitivity of this assumption beginning with an

Original Total Cost (TC) estimate of $1,000,000 for which maintenance and repair costs account for 5% of the total.

$$Original\ \mathrm{TC} = Maintenance\ (5\%) + Other(95\%)$$

$$\$1{,}000{,}000 = \$50{,}000 + \$950{,}000$$

As with all costs, the MC are formulated as a certain percentage of the IC of the shoreline stabilization alternative. If the MC are modified due to sea level rise (or for any other reason), a ratio can be defined between the original and modified costs (as percentages of the IC). In the example, it is assumed that MC increase from 20% of the IC in the original estimate to 25% in the modified example.

$$Ratio = \frac{New\ Rate}{Old\ Rate} = \frac{25\%}{20\%} = 1.25$$

The modified total cost can then be calculated by replacing the original MC, by the modified MC which is just the original MC multiplied by the ratio.

$$\begin{aligned} New\ TC &= \{\, (5\% \times \mathrm{Original\ TC})\} \times \mathrm{Ratio} + (95\% \times \mathrm{Original\ TC}) \\ &= 101.25\% \times Original\ TC \end{aligned}$$

$$New\ \mathrm{TC} = \{\$50{,}000\} \times 1.25 + \$950{,}000 = \$1{,}012{,}500$$

Here we have assumed the initial total cost distribution is as given in the example (5% maintenance, 95% other). For a generic cost distribution where MC make up Y% of the total cost, the modified cost equation is

$$New\ \mathrm{TC} = (\mathrm{Y}\% \times \mathrm{Original\ TC}) \times \mathrm{Ratio} + \{(100 - \mathrm{Y})\% \times \mathrm{Original\ TC}\}$$

$$New\ \mathrm{T}C = \{100 + \mathrm{Y}(\mathrm{Ratio} - 1)\}\% \times \mathrm{Original\ TC}$$

Sea level rise also enters into the cost analysis through its influence on storm frequency and the resulting DC. Calculating the influence of this effect is less straightforward, since the influence of sea level rise is non-linear. In other words, if the assumed rate of sea level rise is doubled, the corresponding number of storms exceeding each of the pre-defined thresholds (10, 25, 40, and 50-year storms) does not follow suit. As discussed in the sea level rise section of this report, the sea level rise scenario is used to estimate the amount of sea level rise at the mid-point of each predefined period. This value is then used in conjunction with the extreme value analysis depicted in Figure 1 to adjust the return periods (i.e. a 50-year storm may become a 32.3-year storm) and hence the expected number of storms. In the following example it is assumed that altering the sea level rise scenario results in a doubling of the expected number of storms exceeding a specific storm threshold.

$$Original\ \mathrm{TC} = Damage\ (5\%) + Other(95\%)$$

$$\$1{,}000{,}000 = \$50{,}000 + \$950{,}000$$

If the expected number of storms doubles, the DC are adjusted as follows:

$$New\ \mathrm{TC} = \{\$50{,}000\} \times 2 + \$950{,}000 = \$1{,}050{,}000$$

$$New\ \mathrm{TC} = \{\mathrm{Damage}\ (5\%)\} \times 2 + \mathrm{Other}(95\%) = 105\%\ OC$$

Here we have assumed the initial total cost distribution is as given in the example (5% maintenance, 95% other). For a generic cost distribution where MC make up Z% of the total cost, the modified cost equation is:

$$New\ TC = (\mathrm{Z}\% \times \mathrm{Original\ TC}) \times \Delta_{storm} + \{(100 - \mathrm{Z})\% \times \mathrm{Original\ TC}\}$$

$$New\ TC = \{100 + \mathrm{Z}(\Delta_{storm} - 1)\}\% \times \mathrm{Original\ TC}$$

Since the Total Cost is simply the sum of the IC, the DC, the MC and the RC, and the overall influence of the two sea level rise impacts discussed above, can be combined in a linear fashion.

$$Original\ \mathrm{TC} = Maintenance\ (5\%) + Damage\ (5\%) + Other(90\%)$$

$$\$1{,}000{,}000 = \$50{,}000 + \$50{,}000 + \$900{,}000$$

$$New\ TC = \{\mathrm{Maintenance}(5\%)\} \times 1.25 + \{\mathrm{Damage}(5\%)\} \times 2 + \mathrm{Other}(90\%) = 106.25\%\ OC$$

$$\$1{,}062{,}500 = \$50{,}000 \times 1.25 + \$50{,}000 \times 2 + \$900{,}000$$

Or in general terms for MC making up Y% and DC making up Z% of the original total costs:

$$New\ \mathrm{TC} = (\mathrm{Y}\%\ \mathrm{x\ Original\ TC}) \times Ratio + (\mathrm{Z}\%\ \mathrm{x\ Original\ TC}) \times \Delta_{storm} + \{[100 - (\mathrm{Y} + \mathrm{Z})]\% \times \mathrm{Original\ TC}\}$$

$$New\ TC = \{100 - (\mathrm{Y} + \mathrm{Z}) + \mathrm{Y} \times \mathrm{Ratio} + \mathrm{Z} \times \Delta_{storm}\}\% \times \mathrm{Original\ TC}$$

Vegetation

As discussed above, properly maintained vegetation can have a significant stabilizing effect, but improperly maintained vegetation can have just as significant a destabilizing effect. Because of the uncertainties surrounding the quantification of the stabilizing/destabilizing effects of the vegetative components of the techniques considered, as well as the uncertainty of the future maintenance of these components, no monetary benefit has been assigned to vegetation in the cost analyses. It is possible, however, to examine the potential influence of vegetation through a sensitivity analysis similar to those carried out for material costs and sea level rise. The assumption is that the addition of properly maintained vegetation would reduce the damage associated with some of the smaller to moderate storms. For consistency with the examples above, a one million dollar total cost estimate is assumed, of which 5% is associated with DC from storms of a particular intensity.

$$Original\ \text{TC} = Damage\ (5\%) + Other(95\%)$$

$$\$1{,}000{,}000 = \$50{,}000 + \$950{,}000$$

In the example, it is assumed that the DC for storms of the intensity chosen are 10% of the initial construction cost. If it is assumed that well maintained vegetation has a stabilizing effect that reduces the damages from the selected storm from 10% to only 5% of the IC, the total cost is reduced by an amount relative to the ratio of between the new damage estimate and the old.

$$Ratio = \frac{New\ Rate}{Old\ Rate} = \frac{5\%}{10\%} = 0.5$$

$$New\ \text{TC} = \{\text{Damage (5\%)}\} \times \text{Ratio} + \text{Other(95\%)} = 97.5\%\ OC$$

$$New\ \text{TC} = \{\$50{,}000\} \times 0.5 + \$950{,}000 = \$975{,}000$$

Here it has been assumed that the initial total cost distribution is as given in the example (5% maintenance, 95% other). For a generic cost distribution where DC make up Y% of the total cost, the modified cost equation is:

$$New\ TC = (\text{Y\%} \times \text{Original TC}) \times \text{Ratio} + \{(100 - \text{Y})\% \times \text{Original TC}\}$$

$$New\ \text{T}C = \{100 + \text{Y}(\text{Ratio} - 1)\}\% \times \text{Original TC}$$

Poughkeepsie

The Poughkeepsie site is located just south of the Mid-Hudson Bridge along the eastern shore of the Hudson River as shown in Figure 7. A cross section illustrating the site conditions as of 2006 which was presented in the Alden and ASA (Allen, et al., 2006) report is reproduced here as Figure 8. The major site characteristics are summarized in Table 5. As illustrated in Figure 8, the existing shoreline is made up of bulkhead with a concrete cap. The Poughkeepsie shoreline is typical of many of the steep sloped shorelines which have traditionally been bulkheaded. The Alden report attributed the erosion of the Poughkeepsie shoreline to scour from ice, waves, and wakes. Run-off from behind the bulkhead was also cited as a problem. Wind wave heights were calculated using the methodology presented in Chapter 3, Section 6 of the Shore Protection Manual (USACE, 1977), assuming a wind speed of 50 mph and a constant depth of 50 feet. For the four fetches defined in Figure 7 the calculated wind wave heights are as shown in Table 6.

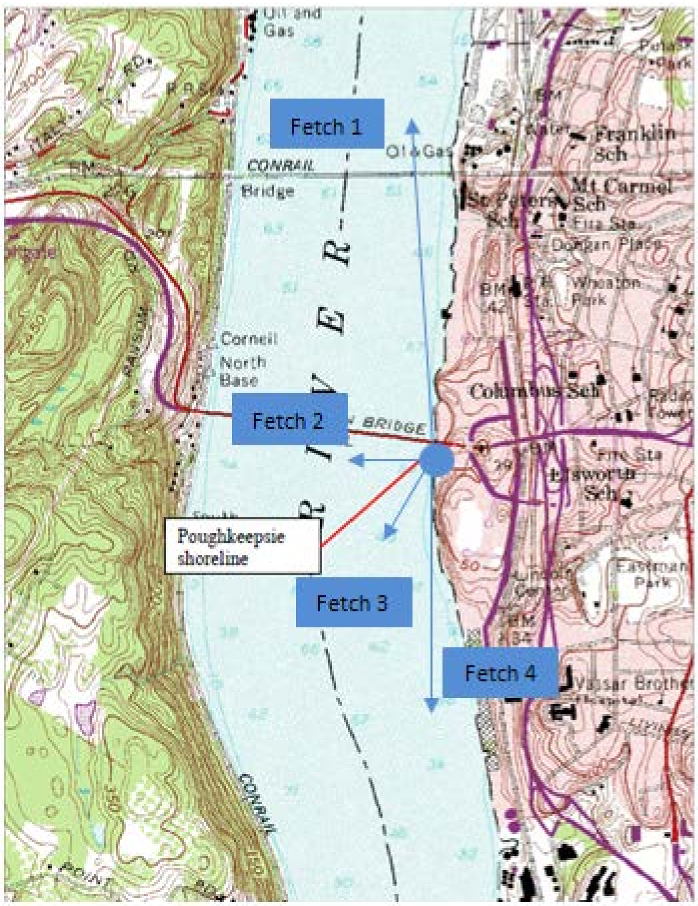

Figure 7 - Poughkeepsie Site and Fetch Delineations.

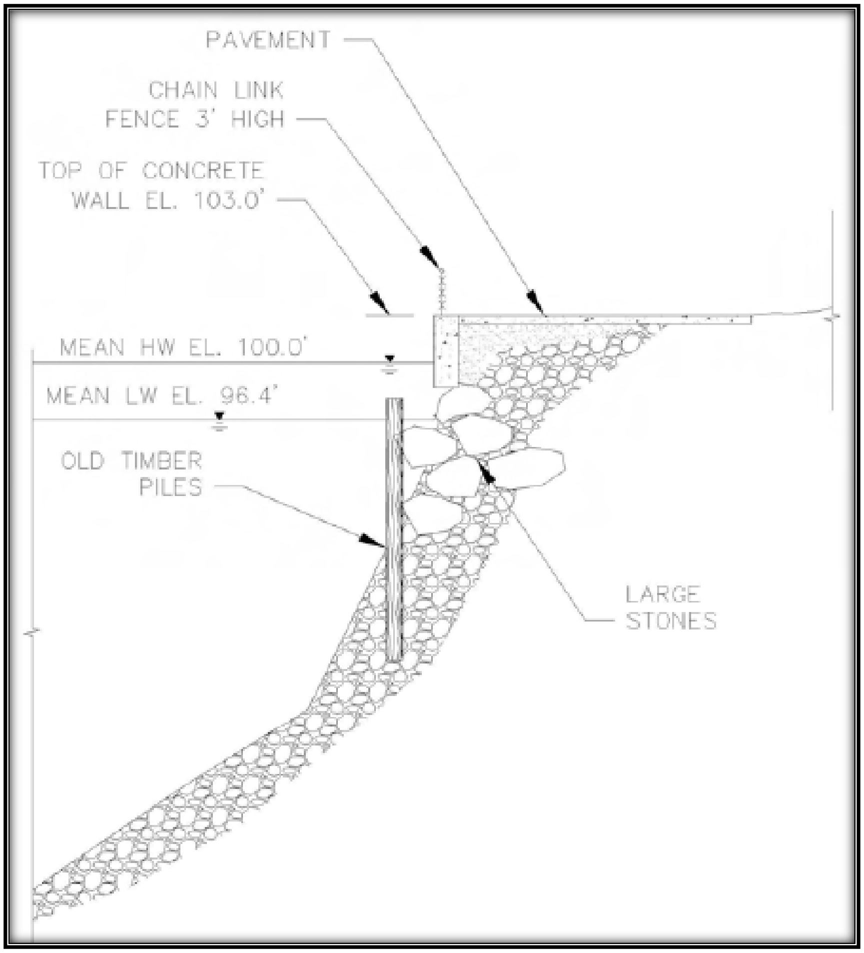

Figure 8 - Existing Cross-section at Poughkeepsie.

Table 5 - Poughkeepsie Site Characteristics and Dimensions.

General Characteristics	
Width of River	2,600 ft
Depth Range	30 – 125 ft
Average Depth	50 ft
Current Range	0-3 ft/s
Mean Current Velocity (Main Channel)	1 ft/sec
Mean Current Velocity (Shoreline)	1 ft/sec
Side Slope	1V:1.6H
Dimensions Above High Water Level	
Width	18 ft
Height	3.5 ft
Slope Length	18 ft

Surface Area	9,013 ft^2
Cross-section Area	31.5 ft^2
Volume	15,750 ft^3
Dimensions of Intertidal Zone	
Width	7 ft
Height	3.5 ft
Slope Length	7 ft
Surface Area	3,536 ft^2
Cross-section Area	12.25 ft^2
Volume	6,125 ft^3

Table 6 - Fetches and Related Wind Wave Heights at Poughkeepsie.

	Length (mi)	Wave Height (ft)
Fetch 1	2.00	2
Fetch 2	0.50	1.0
Fetch 3	0.75	1.3
Fetch 4	2.00	2.5

In addition to the costs described below within each section, there will be a cost associated with the removal of the existing bulkhead structure and rock. As this cost will be incurred regardless of the shoreline stabilization approach selected, it is not included in the cost analysis.

Shoreline Treatment Cost Analyses for Poughkeepsie

Bulkhead

Bulkheads are one of the more common shoreline stabilization approaches used along riverine and estuarine coastlines. Bulkheads are vertical soil retention structures designed to eliminate bank erosion by encapsulating the soil behind it. Bulkheads can take several forms, however the two most common types are cantilevered bulkheads and anchored bulkheads. Cantilevered bulkheads are used in relatively low height applications and simply rely on their embedment for support. Anchored bulkheads are similar to cantilevered bulkheads, only an anchoring system is added to provide additional lateral support.

Due to the relatively low grades at each of the Hudson River sites, cantilevered bulkheads were selected for each site. After balancing the loads and pressures acting on the front and rear faces of the bulkhead, the design parameters listed in Table 7 were obtained.

Table 7 - Bulkhead Design Summary.

Height of Wall Above Substrate	13.1 ft
Depth of Penetration	12.1 ft
Total Wall Height	25.2 ft

Bulkhead prices vary considerably depending on the material selected. Costs for wood, steel and concrete bulkheads are shown below in Table 8, and do not include labor costs.

Table 8 - Bulkhead Material Cost Comparison (Whalen, et al, 2011).

Material	Steel	Wood	Concrete
Cost Range/lf	$700-1,200	$ 116-$265	$500-$1000

Although not explicitly considered in this analysis, bulkheads can be modified to adapt to rising sea levels through the addition of a cap. The cap will normally consist of either wood secured to the face of the bulkhead, or concrete cast to raise the elevation of the structure. Such a modification must be carried out carefully however; as effectively increasing the unsupported length of the structure changes the pressure distributions on which the original design was based. Often the addition of an anchor will be necessary if the structure is retrofit. The cost associated with such modifications can be significant.

Wood Bulkhead

Given the steep side slopes, proximity to the navigation channel and exposure to relatively long fetches, an estimate of $265/lf or $132,500 was obtained for the material costs. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 400 man hours for construction, at $35/hr, an estimate of $14,000 for labor is obtained. In addition to the costs associated with the bulkhead construction, a lump sum cost of $25,000 is added to cover the cost of earthwork not directly related to the bulkhead construction. The total estimate of the IC associated with the construction of a wooden bulkhead at Poughkeepsie is $171,500.

In developing the lifecycle cost for wooden bulkheads, the following assumptions were made:

- Periodic maintenance and repairs will be necessary. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- It is assumed that maintenance and repair costs for wood structures will increase under the rapid sea level rise scenario. A 5% increase is applied.

- Wood bulkheads generally have a lifespan of between 25 and 40 years. For the purpose of this analysis, a 30 year lifespan is assumed.
- Wood bulkheads are resilient. The following damages are expected during significant storms:

Table 9 - Expected Damage – Wood Bulkhead.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Wood Bulkhead Cost Estimate										
Initial Cost (IC)		$ 171,500								
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 7,220	0.75	$ 5,566	1.01	$ 4,537	$ 17,323	4.6%
Damage Cost (DC)	25	5%	1.13	$ 7,302	1.53	$ 5,686	2.14	$ 4,789	$ 17,776	4.7%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 74,139	1.00	$ 44,825	$ 118,965	31.7%
Maintenance Cost (MC)		20%	1.00	$ 25,935	1.00	$ 14,828	1.00	$ 8,965	$ 49,728	13.3%
								Post-Construction Costs (DC+RC+MC)	$ 203,792	54.3%
								Initial Cost (IC)	$ 171,500	45.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 375,292**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 17,524	9.26	$ 68,648	25.00	$ 112,063	$ 198,234	28.8%
Damage Cost (DC)	25	5%	3.01	$ 19,530	16.67	$ 61,783	25.00	$ 56,031	$ 137,344	20.0%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 74,139	1.00	$ 44,825	$ 118,965	17.3%
Maintenance Cost (MC)		25%	1.00	$ 32,419	1.00	$ 18,535	1.00	$ 11,206	$ 62,160	9.0%
								Post-Construction Costs (DC+RC+MC)	$ 516,703	75.1%
								Initial Cost (IC)	$ 171,500	24.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 688,203**	100.0%

Steel Bulkhead

Given the steep side slopes, proximity to the navigation channel and exposure to relatively long fetches, a cost estimate of $1,200/lf or $600,000 which is on the higher end of the ranges obtained was selected. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/ publicViewPWChanges.do). Assuming 350 man hours for construction, at $35/hr, an estimate of $12,250 for labor is obtained. In addition to the costs associated with the bulkhead construction, a lump sum cost of $25,000 is added to cover the cost of earthwork not directly related to the bulkhead construction. The total estimate of the Initial Costs associated with the construction of a steel bulkhead at Poughkeepsie is $637,250.

In developing the lifecycle cost for steel bulkheads, the following assumptions were made:

- Maintenance and repair costs for steel bulkheads are generally minimal. An estimate of 5% of the IC is set aside for maintenance and repair during each.
- Steel bulkheads generally have a lifespan of between 25 and 40 years. For the purpose of this analysis, a 30 year lifespan is assumed.
- Steel bulkheads are resilient. The following damages are expected during significant storms:

Table 10 - Expected Damage - Steel Bulkhead.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Steel Bulkhead Cost Estimate

Initial Cost (IC) $ 637,250

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 26,829	0.75	$ 20,682	1.01	$ 16,858	$ 64,369	5.1%
Damage Cost (DC)	25	5%	1.13	$ 27,131	1.53	$ 21,126	2.14	$ 17,795	$ 66,051	5.3%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 275,483	1.00	$ 166,558	$ 442,042	35.2%
Maintenance Cost (MC)		5%	1.00	$ 24,092	1.00	$ 13,774	1.00	$ 8,328	$ 46,194	3.7%
						Post-Construction Costs (DC+RC+MC)			$ 618,656	49.3%
								Initial Cost (IC)	$ 637,250	50.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,255,906**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 65,114	9.26	$ 255,077	25.00	$ 416,396	$ 736,587	31.0%
Damage Cost (DC)	25	5%	3.01	$ 72,567	16.67	$ 229,569	25.00	$ 208,198	$ 510,334	21.5%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 275,483	1.00	$ 166,558	$ 442,042	18.6%
Maintenance Cost (MC)		5%	1.00	$ 24,092	1.00	$ 13,774	1.00	$ 8,328	$ 46,194	1.9%
						Post-Construction Costs (DC+RC+MC)			$ 1,735,157	73.1%
								Initial Cost (IC)	$ 637,250	26.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 2,372,407**	100.0%

Bio-Wall

The term bio-wall has been used generically to encompass a suite of shoreline stabilization approaches with similar characteristics. Most bio-walls are used in areas that have traditionally been protected by bulkheads. Bio-wall can refer to simple ecological enhancements used to modify traditional bulkheads such as hanging planter baskets, or more complex approaches which incorporate non-traditional materials and design layouts. For the purposes of this analysis a bio-wall will be defined as an ecologically enhanced concrete panel bulkhead which incorporates three precast tide pools. The enhancements used to modify the concrete panel include roughening the surface, and the use of low-PH concrete mix to maximize growth of aquatic organisms. The tide pools are pre-cast concrete structures that are designed to fill up during high tide and hold a reservoir of water once the water level has dropped. This maintains a wet environment that allows organisms to grow in a location that would normally be too dry (Perkol-Finkel, 2012).

Bio-walls are a fairly new concept and cost information is extremely limited. In general, ecologically enhanced concrete costs 7-15% more than regular Portland cement (Perkol-Finkel, 2012). Traditional concrete bulkheads cost between $500 and $1000 per linear foot (Devore, 2010); therefore an ecologically enhanced concrete bulkhead can be expected to cost between $575 and $1150 per linear foot. Tide pools for revetment habitat development generally cost between $1000 and $1500 each (Perkol-Finkel, 2012). At Poughkeepsie which is relatively high energy, the high end of these numbers is used to develop the estimated cost. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 400 man hours for construction, at $35/hr, an estimate of $14,000 for labor is obtained. An additional lump sum cost of $25,000 is added to the estimate to cover the cost of earthwork not directly related to the bio-wall. The total estimate of the Initial Costs associated with the construction of a bio-wall at Poughkeepsie is $618,500.

Table 11 – Bio-wall Cost Information.

Ecologically Enhanced Concrete Bulkhead per lf	$ 1,150
Total Cost of Enhanced Concrete Bulkhead	$ 575,000
Cost per Tide Pool	$1,500
Total Cost of Tide Pools	$4,500
Total Cost of Bio-wall	$579,500

In developing the lifecycle cost for a bio-wall, the following assumptions were made:

- Maintenance and repair costs for bio-walls are generally minimal. An estimate of 10% of the Initial Cost is set aside for maintenance and repair during each period
- Concrete bulkheads generally have a lifespan of between 20 and 50 years. For the purpose of this analysis, a 40 year lifespan is assumed for the bio-wall.
- Bio-walls are resilient. The following damages are expected during significant storms:

Table 12 - Expected Damage - Bio-wall.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Bio Wall Cost Estimate

Initial Cost (IC) $ 618,500

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 26,039	0.75	$ 20,073	1.01	$ 16,362	$ 62,475	5.7%
Damage Cost (DC)	25	5%	1.13	$ 26,332	1.53	$ 20,504	2.14	$ 17,271	$ 64,108	5.8%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 267,378	0.00	$ -	$ 267,378	24.3%
Maintenance Cost (MC)		10%	1.00	$ 46,767	1.00	$ 26,738	1.00	$ 16,166	$ 89,670	8.1%
							Post-Construction Costs (DC+RC+MC)		$ 483,631	43.9%
							Initial Cost (IC)		$ 618,500	56.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 1,102,131**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 63,198	9.26	$ 247,572	25.00	$ 404,144	$ 714,914	32.7%
Damage Cost (DC)	25	5%	3.01	$ 70,431	16.67	$ 222,815	25.00	$ 202,072	$ 495,318	22.7%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 267,378	0.00	$ -	$ 267,378	12.2%
Maintenance Cost (MC)		10%	1.00	$ 46,767	1.00	$ 26,738	1.00	$ 16,166	$ 89,670	4.1%
							Post-Construction Costs (DC+RC+MC)		$ 1,567,280	71.7%
							Initial Cost (IC)		$ 618,500	28.3%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 2,185,780**	100.0%

Revetment

A revetment is a sloped engineered shore protection method similar to rip rap; however the design is often more involved consisting of multiple layers and/or filter fabric, with the individual stones placed more precisely. Revetments tend to use larger stone falling in the boulder category according to the Wentworth scale. The median stone size (D_{50}) and weight (W_{50}) for the revetment armor stone were determined using the well-known Hudson formula (USACE, 1977). The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine an appropriate stone size. The largest wind wave height (2.5 ft) was selected as input into the Hudson formula. At the Poughkeepsie site, the calculated wind wave height is roughly consistent with type of wakes that would be expected (Bruno et al., 2002). The results from the Hudson formula recommend a median stone size (D_{50}) of 1.09 feet in diameter with a weight (W_{50}) of 217 pounds. Given the propensity for ice scour at the site, the recommended value was scaled up 20%, resulting in a D_{50} of 1.3 ft and a W_{50} of 363 lbs. Since revetments are constructed with uniformly sized stones, an underlayer, and geotextile filter layer are included to prevent the washout of the fine material. The table below summarizes the material costs for the two layer revetment. Each layer is assumed to be two stone diameters with an average porosity of 40%. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the revetment gives $1,395.

The placement of revetment stones is generally more precise and requires specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 400 man hours for construction, at $35/hr, an estimate of $14,000 for labor is obtained. An additional cost of $20,000 is added to the material and labor costs to account for general earthwork, not included in the estimate. This brings the final Initial Cost to $207,538.

Table 13 - Material Costs for Revetments (Bids).

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Weight (tons)	Rock Cost (per ton)	Total Cost
Armor	2.32	19,253	3,174,253	1587	$97	$153,939
Underlayer	0.11	2705	445,970	222	$82	$18,204

In developing the lifecycle cost for revetments, the following assumptions were made:

- Maintenance and repair costs for revetments are generally minimal. An estimate of 15% of the IC is set aside for maintenance and repair during each.
- Revetments are resilient. The following damages are expected during significant storms:

Table 14 - Expected Damage - Revetment.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	15%
40	Additional rock displacement	5%
25	Minor scour & rock displacement	10%

Although not explicitly considered in this analysis, revetments can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding stones to the crest of an existing structure would be relatively minimal.

Revetment Cost Estimate

Initial Cost (IC)	$ 207,538									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	15%	0.56	$ 13,106	0.75	$ 10,103	1.01	$ 8,235	$ 31,445	9.2%
Damage Cost (DC)	40	5%	0.73	$ 5,736	1.02	$ 4,596	1.30	$ 3,513	$ 13,845	4.1%
Damage Cost (DC)	25	10%	1.13	$ 17,672	1.53	$ 13,761	2.14	$ 11,591	$ 43,023	12.6%
Maintenance Cost (MC)		15%	1.00	$ 23,539	1.00	$ 13,458	1.00	$ 8,137	$ 45,133	13.2%
								Post-Construction Costs (DC+RC+MC)	$ 133,446	39.1%
								Initial Cost (IC)	$ 207,538	60.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 340,984**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	15%	1.35	$ 31,809	9.26	$ 124,609	25.00	$ 203,416	$ 359,835	33.3%
Damage Cost (DC)	40	5%	1.91	$ 14,974	11.90	$ 53,404	25.00	$ 67,805	$ 136,183	12.6%
Damage Cost (DC)	25	10%	3.01	$ 47,267	16.67	$ 149,531	25.00	$ 135,611	$ 332,409	30.7%
Maintenance Cost (MC)		15%	1.00	$ 23,539	1.00	$ 13,458	1.00	$ 8,137	$ 45,133	4.2%
								Post-Construction Costs (DC+RC+MC)	$ 873,560	80.8%
								Initial Cost (IC)	$ 207,538	19.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,081,098**	100.0%

Rip-Rap

Rip-rap is a method of shore protection that uses well graded stones to armor the coast. The size of the stones generally falls within the cobble range according to the Wentworth scale. Rip-rap relies on its weight for stability and dissipates the incident energy on its slope. Estimates of rip-rap size based on current velocity generally lead to material much smaller than would be required to resist the potential wind and ship generated waves at the site. To calculate the required stone size, a rip-rap specific version of the Hudson formula (USACE, 1977) was utilized. The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine the appropriate size. The largest wave height (2.5 ft) calculated based on the fetches defined above for the Poughkeepsie site was used for input into the Hudson formula. At the Poughkeepsie site, the calculated wind wave height is roughly consistent with type of wakes that would be expected (Bruno, 2003). The results from the Hudson formula recommend a median stone size (D_{50}) of 1.0 foot in diameter with a weight (W_{50}) of 173 pounds. Given the propensity for ice scour at the site, the recommended value was scaled up 20%, resulting in a D_{50} of 1.2 ft and a W_{50} of 285 lbs. For the rip-rap slope protection, only a single layer (40% porosity) with a thickness equal to twice the median stone diameter is placed on top of a geotextile filter fabric. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the slope gives $1,395.

Table 15 - Cost Estimate for Rock Material to Build Rip-Rap.

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Rock Cost Per Ton	Total Cost
Armor	2.14	217,772	2,930,079	$97	$ 142,108

The placement of rip-rap stones is generally very quick and does not require specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 300 man hours for construction, at $35/hr, an estimate of $10,500 for labor is obtained. An additional cost of $20,000 is added to the material and labor costs to account for general earthwork, not included in the estimate thus far. This brings the final IC to $174,003.

In developing the lifecycle cost for rip-rap slopes, the following assumptions were made:

- Maintenance and repair costs for rip-rap are generally low. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- The following damages are expected during significant storms:

Table 16 - Expected Damages - Rip-rap.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%

Although not explicitly considered in this analysis, rip-rap slopes can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap to the crest of an existing structure would be relatively minimal.

Rip Rap Cost Estimate

Initial Cost (IC)	$ 174,003									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 14,651	0.75	$ 11,295	1.01	$ 9,206	$ 35,152	11.0%
Damage Cost (DC)	40	10%	0.73	$ 9,618	1.02	$ 7,707	1.30	$ 5,891	$ 23,216	7.3%
Damage Cost (DC)	25	10%	1.13	$ 14,816	1.53	$ 11,537	2.14	$ 9,718	$ 36,071	11.3%
Maintenance Cost (MC)		20%	1.00	$ 26,314	1.00	$ 15,044	1.00	$ 9,096	$ 50,454	15.8%
						Post-Construction Costs (DC+RC+MC)			$ 144,893	45.4%
								Initial Cost (IC)	$ 174,003	54.6%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 318,896**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 35,559	9.26	$ 139,299	25.00	$ 227,396	$ 402,255	35.5%
Damage Cost (DC)	40	10%	1.91	$ 25,108	11.90	$ 89,549	25.00	$ 113,698	$ 228,356	20.1%
Damage Cost (DC)	25	10%	3.01	$ 39,629	16.67	$ 125,369	25.00	$ 113,698	$ 278,696	24.6%
Maintenance Cost (MC)		20%	1.00	$ 26,314	1.00	$ 15,044	1.00	$ 9,096	$ 50,454	4.5%
						Post-Construction Costs (DC+RC+MC)			$ 959,761	84.7%
								Initial Cost (IC)	$ 174,003	15.3%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,133,764**	100.0%

Joint Planting

Live staking or joint planting involves planting live stakes or vegetation into the void spaces in a rip-rap slope or revetment. If the rip-rap slope or revetment already exists the only costs are related to the plant materials and the labor for installation. Table 17 provides some information on the typical costs of materials used in joint planting.

Table 17 - Cost for Stakes to be Coupled with Rip-Rap (NRPCVT, 2004).

Range	\$2.05 - \$4.78/ft^2
Surface Area of Site	9014 ft^2
Cost for Planting (@ \$3.00/sq. ft)	\$27,041
Cost	\$54.08/ft

Labor costs for joint planting are minimal as upwards of 100 stakes can be planted per hour depending on the work force (USACE, 2001). Assuming four cuttings per square yard (EPA, 1993), the Poughkeepsie Site would require upwards of 4000 plantings. Applying an average labor rate of \$25/hr, the following cost estimate for labor was obtained.

Table 18 - Labor Costs for Live Stakes.

Surface Area	1002 yd^2
Cutting Density	4/yd^2
Plants Required	4,008
Installation Rate	100/hr
Labor Rate	\$25/hr
Labor Cost	\$1,002

Taking into account the labor costs and the material costs, the cost estimate for joint planting at Poughkeepsie is \$28,043, or \$56/lf. It is assumed that the joint planting will be constructed in conjunction with the rip-rap slope discussed in the previous section. The total estimated cost for a rip rap protected slope with joint planting is \$202,046 or \$404/lf.

In developing the lifecycle cost for joint planting, the following assumptions were made:

- The rip-rap discussed in the previous section forms the base for the joint planting and the total cost is the cost of constructing the rip-rap slope plus the cost of the joint planting.
- Joint planting adds to the maintenance and repair costs associated with a rip-rap slope. An additional 5% of the IC is estimated for joint planting bringing the estimate for a rip-rap slope with joint planting to 25%.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.

- Joint plantings are not especially resilient. The following damages are expected during significant storms:

Table 19 - Expected Damage - Joint Planting.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%
10	Loss of plantings	10%

Although not explicitly considered in this analysis, rip-rap slopes with joint planting can usually be modified to adapt to rising sea levels by adding stones and vegetation to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap and vegetation to the crest of an existing structure would be relatively minimal.

Joint Planting Cost Estimate

Initial Cost (IC)	$ 202,046									

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 17,013	0.75	$ 13,115	1.01	$ 10,690	$ 40,817	8.3%
Damage Cost (DC)	40	10%	0.73	$ 11,168	1.02	$ 8,949	1.30	$ 6,841	$ 26,957	5.5%
Damage Cost (DC)	25	10%	1.13	$ 17,204	1.53	$ 13,396	2.14	$ 11,284	$ 41,884	8.5%
Damage Cost (DC)	10	10%	2.84	$ 43,401	3.97	$ 34,661	5.32	$ 28,090	$ 106,152	21.6%
Maintenance Cost (MC)		25%	1.00	$ 38,193	1.00	$ 21,836	1.00	$ 13,202	$ 73,232	14.9%
					Post-Construction Costs (DC+RC+MC)				$ 289,042	58.9%
								Initial Cost (IC)	$ 202,046	41.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 491,088**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 41,290	9.26	$ 161,749	25.00	$ 264,044	$ 467,084	25.6%
Damage Cost (DC)	40	10%	1.91	$ 29,155	11.90	$ 103,982	25.00	$ 132,022	$ 265,159	14.5%
Damage Cost (DC)	25	10%	3.01	$ 46,016	16.67	$ 145,574	25.00	$ 132,022	$ 323,612	17.7%
Damage Cost (DC)	10	10%	7.58	$ 115,737	25.00	$ 218,361	25.00	$ 132,022	$ 466,120	25.5%
Maintenance Cost (MC)		35%	1.00	$ 53,470	1.00	$ 30,571	1.00	$ 18,483	$ 102,524	5.6%
					Post-Construction Costs (DC+RC+MC)				$ 1,624,499	88.9%
								Initial Cost (IC)	$ 202,046	11.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,826,545**	100.0%

Vegetated Geogrid

A vegetated geogrid is constructed of successive layers of soil wrapped in a geotextile fabric. Each layer is stacked upon the previous at an inclined angle to resist any forward movement; while vegetation is added between each layer to promote a natural aesthetic and habitat development. The vegetation once established will also act to reinforce the strength of the structure. The number of layers and the amount of wrapping is determined by the height of the wall. The major material costs for vegetative geogrids consists of the geotextile fabric, the fill material, and the live vegetation. At Poughkeepsie it is assumed that the existing soil will be used to fill the geotextile wraps at a reduced cost of $25/ton. The costs for each element are summarized in Table 20. An additional $35,000 is added to the final cost to account for earthwork not directly related to filling each layer. Preparing a site of this width and length will require a significant amount of excavation.

Table 20 – Material Costs for Vegetated Geogrid at Poughkeepsie, NY.

Geotextile Costs (Haliburton Cooperative)	
Number of Layers	4
Wrap Length	7.15 ft
Length of geotextile per layer	23.45 ft
Total length	93.82 ft/lf
Total area of wrap	46,910 ft^2
Average Cost **(Storrar)**	$0.90/ yd^2
Total Geotextile Cost	$ 4,691
Sediment Costs (Swan River Trust)	
Volume of fill required (40% porosity)	15,600 ft^3
Unit weight of sediment fill	165 lb/ft^3
Weight of stone needed	2,574,000 lbs
Average Cost	$25/ton
Total Fill Cost	$ 32,175
Vegetation Costs (WSDT, 2002)	
6'x2' Pruned Live Willow Branches	5000
Unit Cost	$1.20
Total Vegetation Cost	$6000

Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 500 man hours for construction, at $35/hr, an estimate of $17,500 for labor is obtained. The total estimated cost for a vegetated geogrid structure at Poughkeepsie is $95,366.

In developing the lifecycle cost for vegetated geogrids, the following assumptions were made:

- Maintenance and repair costs for vegetated geogrids are generally minimal. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- Vegetated geogrids do not typically have a long lifespan. Although claims of as long as 120 years can be found, given the conditions along the Hudson, a 20 year lifespan is utilized in the analysis.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.
- The following damages are expected during significant storms:

Table 21 - Expected Damage - Vegetated Geogrid.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	20%
25	Loss of vegetation	10%

Although not explicitly considered in this analysis, vegetated geogrids can be modified to adapt to rising sea levels by adding additional layers to an existing structure. If additional layers are added, care must be taken to ensure that any new layers are secured to the existing structure and anchoring system such that the entire structure behaves as a single unit. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding an additional layer to a vegetated geogrid would be relatively minimal.

Vegetated Geogrid Cost Estimate

Initial Cost (IC)	$ 95,366

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 8,030	0.75	$ 6,190	1.01	$ 5,046	$ 19,266	6.4%
Damage Cost (DC)	25	10%	1.13	$ 8,120	1.53	$ 6,323	2.14	$ 5,326	$ 19,770	6.6%
Replacement Cost (RC)		100%	1.00	$ 72,109	1.00	$ 41,227	1.00	$ 24,926	$ 138,261	46.0%
Maintenance Cost (MC)		20%	1.00	$ 14,422	1.00	$ 8,245	1.00	$ 4,985	$ 27,652	9.2%
							Post-Construction Costs (DC+RC+MC)		$ 204,949	68.2%
							Initial Cost (IC)		$ 95,366	31.8%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 300,315**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 19,489	9.26	$ 76,346	25.00	$ 124,629	$ 220,464	34.0%
Damage Cost (DC)	25	10%	3.01	$ 21,720	16.67	$ 68,711	25.00	$ 62,315	$ 152,745	23.6%
Replacement Cost (RC)		100%	1.00	$ 72,109	1.00	$ 41,227	1.00	$ 24,926	$ 138,261	21.3%
Maintenance Cost (MC)		30%	1.00	$ 21,633	1.00	$ 12,368	1.00	$ 7,478	$ 41,478	6.4%
							Post-Construction Costs (DC+RC+MC)		$ 552,950	85.3%
							Initial Cost (IC)		$ 95,366	14.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 648,316**	100.0%

Crib Wall

Timber cribbing functions similar to a gravity bulkhead, in that its stability is directly related to its weight. This in turn is dependent upon its height to width ratio, which should be less than 3 (FEMA, 2000). The weight of the crib pushes perpendicularly upon the wooden posts that create the crib, and the allowable stress in the wood determines the capacity of each crib. Generally, the posts are 6 to 8 feet long (NRCS, 2007), with allowable stresses in the range of 200 to 1000 lb/in^2 depending on the species of wood (FEMA, 2000). Table 22 summarizes the crib design. A larger crib was selected for Poughkeepsie to combat the higher degree of wave energy at the site. Using 8 foot lengths, 63 cribs would be required along 500 ft of river frontage. The volume of each crib is $355ft^3$. When filled with stone with an average porosity of 40%, this requires nearly 1100 tons of stone and over 5,000 logs. A crib wall covering an area this large will require extensive excavation; however the soil and stone from the site could be recycled back into the project as fill for the cribs. The cost of the recycled fill material used to determine the material costs for the structure was $25/ton. The costs are summarized below in Table 24. An additional $35,000 is added to the final cost to account for earthwork not directly related to building and filling the cribs.

Table 22 - Selection of Log Criteria for Crib.

Log Length	8 ft
Log Cross Section	4.5 in x 4.5 in
Design Stress	750 lb/in^2
Crib Configuration	2 x 2
Capacity	60,750 lbs
Capacity per each contact	15,187 lbs

Table 23 - Determination of Weight of Filled Crib.

Area	44.44 ft^2
Volume	355.56 ft^3
Unit weight of stone	165 lbs/ft^3
Total Weight of Crib	29.31 tons
Total Number of Cribs	62.50 (500/8)
Weight of stone(40% Porosity)	1099 tons

Table 24 - Cost Summary for Timber Cribbing (Haliburton Cooperative).

Timber Cribbing (Based off Design of 6'wx6'hx500'l)			(WSDT, 2002)
Items	# of Units	Cost/Unit	Total
Logs, untreated D.Fir, Cedar or Hemlock	5,630 logs	$ 6.18/log	$34,782
Sediment Fill Material (Upper 6' of crib)	825 tons	$ 25/ton	$20,625
Stone Fill (Lower 2' of crib)	275 tons	$72/ton	$19,800
Total Cost			$75,207
Cost per Linear Foot			$150.40

The amount of labor required to construct a wooden crib wall will be roughly 1.5 times what is necessary for a wooden bulkhead. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 600 man hours for construction, at $35/hr, an estimate of $21,000 for labor is obtained. The total estimated cost for constructing a crib wall at the Poughkeepsie site is $131,207.

In developing the lifecycle cost for crib walls, the following assumptions were made:

- Maintenance and repair costs for crib walls are generally moderate. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- It is assumed that maintenance and repair costs for wood structures will increase under the rapid sea level rise scenario. A 5% increase is applied.
- Wooden cribs have a lifespan of approximately 25-40 years. For the purposes of this analysis, complete replacement is assumed after 30 years.
- Wooden crib walls are resilient. The following damages are expected during significant storms:

Table 25 - Expected Damage - Timber Cribbing.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
40	Damage to cribs	20%

Although not explicitly considered in this analysis, crib walls and live crib walls can be modified to adapt to rising sea levels through the construction of additional cribs. Such a modification must be carried out carefully however; as increasing the height of the structure changes the pressure distributions. In addition care must be taken to ensure that the additional weight doesn't cause the allowable stress in the timber and the bearing capacity of the earth supporting the structure to be exceeded. Assuming those conditions are met, the cost of adding an additional crib is relatively low.

Crib Wall Cost Estimate										
Initial Cost (IC)	$ 131,207									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 5,524	0.75	$ 4,258	1.01	$ 3,471	$ 13,253	4.3%
Damage Cost (DC)	40	20%	0.73	$ 14,504	1.02	$ 11,623	1.30	$ 8,884	$ 35,012	11.3%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 56,721	1.00	$ 34,294	$ 91,014	29.5%
Maintenance Cost (MC)		20%	1.00	$ 19,842	1.00	$ 11,344	1.00	$ 6,859	$ 38,045	12.3%
								Post-Construction Costs (DC+RC+MC)	$ 177,324	57.5%
								Initial Cost (IC)	$ 131,207	42.5%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 308,531**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 13,407	9.26	$ 52,519	25.00	$ 85,734	$ 151,660	19.8%
Damage Cost (DC)	40	20%	1.91	$ 37,866	11.90	$ 135,050	25.00	$ 171,468	$ 344,384	45.0%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 56,721	1.00	$ 34,294	$ 91,014	11.9%
Maintenance Cost (MC)		25%	1.00	$ 24,802	1.00	$ 14,180	1.00	$ 8,573	$ 47,556	6.2%
								Post-Construction Costs (DC+RC+MC)	$ 634,614	82.9%
								Initial Cost (IC)	$ 131,207	17.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 765,821**	100.0%

Live Crib Wall

Live crib walls are designed very similarly to timber cribbing; however only the base layer is filled with stone. The remainder of the crib is filled with alternating layers of sediment and live branches. The result is a box like structure that retains the structural integrity of a crib wall, but one that also promotes habitat growth. The design and cost of the cribs is as discussed above, with soil replacing the majority of the stone. At Poughkeepsie, it is assumed that the majority of the fill needs can be fulfilled using onsite material. Cost information is summarized in Table 26. An average price of $25/ton was utilized for the cost of recycled fill material. An additional $35,000 is added to the final cost to account for earthwork not directly related to building and filling the cribs.

Table 26 - Cost Summary for Vegetated Geogrid (Haliburton Cooperative).

Live Crib Wall **(Based off Design of 6'wx6'hx500'l)**			**(WSDT, 2002)**
Items	Units	Cost/Unit	Total
Logs, untreated D.Fir, Cedar or Hemlock	5,630	$6.18 /log	$34,782
Willow, pruned live branches (6'x2" diameter)	5,000	$1.74 /cutting	$8,721
Sediment Fill Material (Upper 6' of crib)	825 tons	$25 /ton	$20,625
Stone Fill(Lower 2' of crib)(40%Porosity)	275 tons	$72.00 /ton	$19,800
Total Cost			$83,928
Cost per linear foot			$167.86

The amount of labor required to construct a live crib wall will be the same as for a traditional crib wall with an added expense related to planting the vegetation. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). 600 man hours are allotted for constructing and filling the cribs, with an additional 50 hours added to account for planting. Using a rate of $35/hr, the labor costs are estimated at $22,750. Adding the labor costs to the material costs results in a total estimate of $141,678.

In developing the lifecycle cost for live crib walls, the following assumptions were made:

- Maintenance and repair costs for live crib walls are generally moderate. An estimate of 25% of the IC is set aside for maintenance and repair during each period.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.

- Wooden cribs have a lifespan of approximately 25-40 years. For the purposes of this analysis, complete replacement is assumed after 30 years.
- Live crib walls are resilient. The following damages are expected during significant storms:

Table 27 - Expected Damage - Live Crib Wall.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
40	Damage to cribs	20%
25	Loss of vegetation	10%

Although not explicitly considered in this analysis, crib walls and live crib walls can be modified to adapt to rising sea levels through the construction of additional cribs. Such a modification must be carried out carefully however; as increasing the height of the structure changes the pressure distributions. In addition, care must be taken to ensure that the additional weight doesn't cause the allowable stress in the timber and the bearing capacity of the earth supporting the structure to be exceeded. Assuming those conditions are met, the cost of adding an additional crib is relatively low.

Live Crib Wall Cost Estimate

Initial Cost (IC)	$	141,678

Current Rate of SLR										
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 5,965	0.75	$ 4,598	1.01	$ 3,748	$ 14,311	3.8%
Damage Cost (DC)	40	20%	0.73	$ 15,662	1.02	$ 12,551	1.30	$ 9,593	$ 37,806	10.1%
Damage Cost (DC)	25	10%	1.13	$ 12,064	1.53	$ 9,394	2.14	$ 7,912	$ 29,370	7.9%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 61,247	1.00	$ 37,030	$ 98,278	26.4%
Maintenance Cost (MC)		25%	1.00	$ 26,782	1.00	$ 15,312	1.00	$ 9,258	$ 51,351	13.8%
							Post-Construction Costs (DC+RC+MC)		$ 231,116	62.0%
							Initial Cost (IC)		$ 141,678	38.0%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 372,794**	100.0%

Rapid Ice Melt Rate of SLR										
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 14,477	9.26	$ 56,711	25.00	$ 92,576	$ 163,763	15.2%
Damage Cost (DC)	40	20%	1.91	$ 40,888	11.90	$ 145,827	25.00	$ 185,152	$ 371,868	34.6%
Damage Cost (DC)	25	10%	3.01	$ 32,267	16.67	$ 102,079	25.00	$ 92,576	$ 226,922	21.1%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 61,247	1.00	$ 37,030	$ 98,278	9.1%
Maintenance Cost (MC)		35%	1.00	$ 37,494	1.00	$ 21,437	1.00	$ 12,961	$ 71,892	6.7%
							Post-Construction Costs (DC+RC+MC)		$ 932,723	86.8%
							Initial Cost (IC)		$ 141,678	13.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 1,074,401**	100.0%

Sill

Sills are typically designed as low elevation structures and are constructed on flat or near flat bottoms in relatively shallow water. The steep side slopes at the Poughkeepsie site make the construction of a sill extremely impractical; therefore it was not considered in the cost analysis.

Bowline Point Park (Haverstraw Bay)

Bowline Point Park is located in Haverstraw Bay on the western bank of the Hudson between the oil dock for the Bowline Generating Station and the inlet to Bowline Pond as shown in Figure 9. A cross section illustrating the site conditions as of 2006 which was presented in the Alden and ASA (Allen, et al., 2006) report is reproduced here as Figure 10. The major site characteristics are summarized in Table 28. As illustrated in Figure 10, the existing shoreline at Bowline Point Park has been reinforced with rubble rip-rap. The Bowline Point Park shoreline is typical of many of the mild sloped shorelines fronting the wide, shallow sections of the Hudson. The Alden report attributed the erosion of the Bowline Point Park shoreline to wind and wake generated waves. Wind wave heights were calculated using the methodology presented in Chapter 3, Section 6 of the Shore Protection Manual (USACE, 1977), assuming a wind speed of 50 mph and a constant depth of 10 feet. For the four fetches defined in Figure 9, the estimated wind wave heights are as given in Table 29.

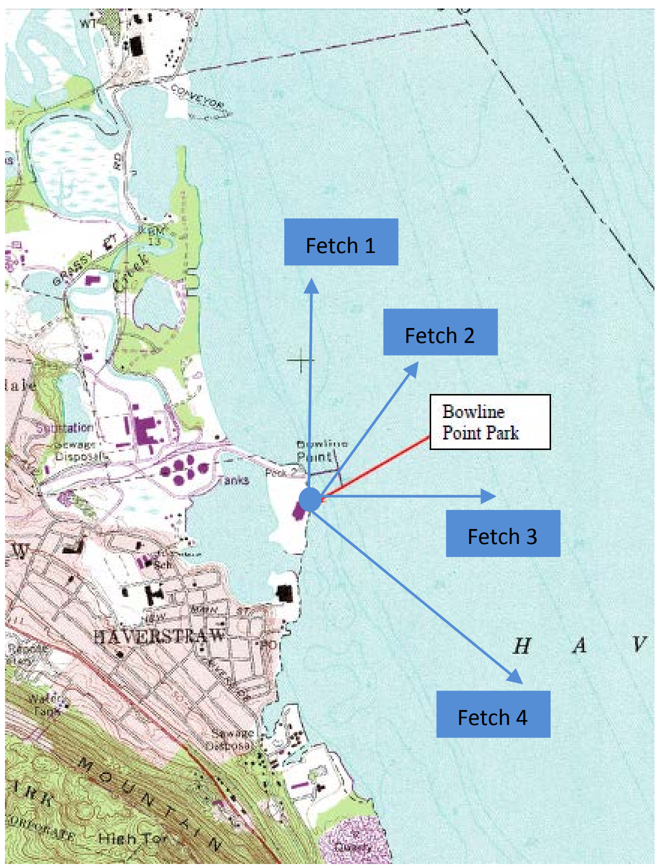

Figure 9 - Bowline Point Park Site and Fetch Delineations.

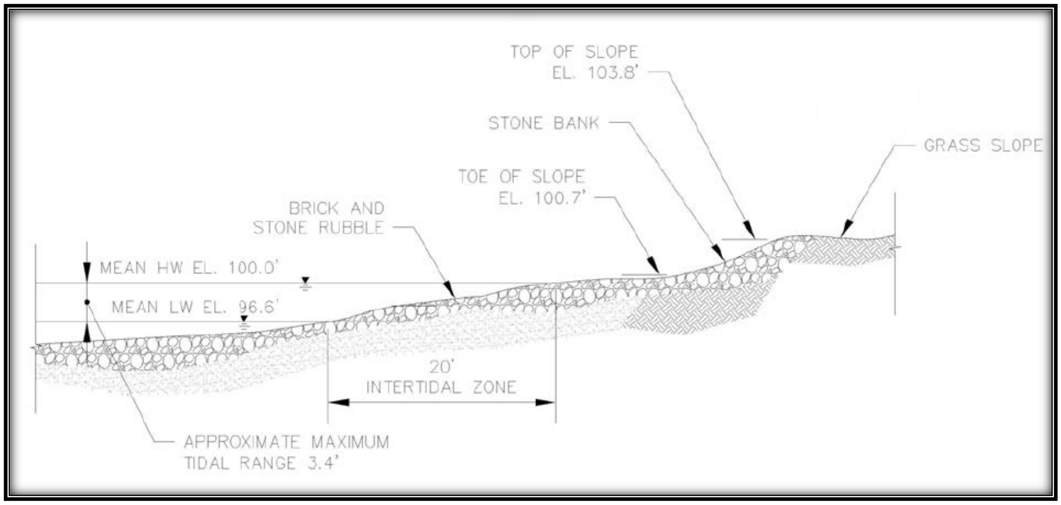

Figure 10 - Existing Cross-section at Bowline Point Park.

Table 28 - Bowline Point Park Site Characteristics and Dimensions.

General Characteristics	
Width of River	14,700 ft
Average Depth	10 ft
Depth at Shoreline	< 10 ft
Mean Current Velocity (Main Channel)	1.2 ft/sec
Mean Current Velocity (Shoreline)	0.5 ft/sec
Tidal Flow	130,000 ft^3/sec
Max Tidal Fluctuation	2.9 ft
Side Slope	1V:20H
Dimensions of Above High Water Level	
Width	25 ft
Height	4 ft
Slope Length	25 ft
Surface Area	12,510 ft^2
Cross-section Area	44 ft^2
Volume	21,875 ft^3
Dimensions of Intertidal Zone	
Width	20 ft
Height	3.5 ft
Slope Length	20 ft
Surface Area	10,012 ft^2
Cross-section Area	35 ft^2
Volume	17,500 ft^3

Table 29 - Fetches and Related Wind Wave Heights at Bowline Point Park.

	Length (mi)	Wave Height (ft)
Fetch 1	3.10	2.10
Fetch 2	2.50	2.00
Fetch 3	3.50	2.25
Fetch 4	6.00	2.50

Shoreline Treatment Cost Analyses for Bowline Point Park

Bulkhead

Bulkheads were not considered a viable alternative at the Bowline Point Park site. The extremely mild slope of the existing shoreline makes the construction of vertical or near vertical retaining structures (bulkheads, bio-walls, timber cribbing, live crib walls, and vegetated geogrids) impractical. The nearly horizontal nature of the Bowline Point Park site does not provide enough natural relief to make these structures cost-efficient without adding a significant amount of fill. Doing so would change the project from a shoreline protection project to a land reclamation project, negating any useful information that could be obtained from the cost analysis. It should be noted that this suggestion is consistent with the conclusions reached in the Alden and ASA (Allen, et al., 2006) report.

Bio-Wall

Bio-walls were not considered a viable alternative at the Bowline Point Park site. The extremely mild slope of the existing shoreline makes the construction of vertical or near vertical retaining structures (bulkheads, bio-walls, timber cribbing, live crib walls, and vegetated geogrids) impractical. The nearly horizontal nature of the Bowline Point Park site does not provide enough natural relief to make these structures cost-efficient without adding a significant amount of fill. Doing so would change the project from a shoreline protection project to a land reclamation project, negating any useful information that could be obtained from the cost analysis. It should be noted that this suggestion is consistent with the conclusions reached in the Alden and ASA (Allen, et al., 2006) report.

Revetment

A revetment is a sloped engineered shore protection method similar to rip rap; however the design is often more involved consisting of multiple layers and/or filter fabric, with the individual stones placed more precisely. Revetments tend to use larger stone falling in the boulder category according to the Wentworth scale. The median stone size (D_{50}) and weight (W_{50}) for the revetment armor stone were determined using the well-known Hudson formula (USACE, 2006). The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine an appropriate stone size. The largest wind wave height (2.5 ft) calculated based on the fetches defined above for Bowline Point Park was used for input into the Hudson formula. At the Bowline site, the calculated wind wave height is roughly consistent with type of wakes that might be expected (Bruno). The results from the Hudson formula recommend a median stone size (D_{50}) of 0.59 feet in diameter with a weight (W_{50}) of 34 pounds. Given the propensity for ice scour at the site, the recommended value was scaled up 20%, resulting in a D_{50} of 0.7 ft and a W_{50} of 56 lbs. Since revetments are constructed with uniformly sized stones, an underlayer, and geotextile filter layer are included to prevent the washout of the fine material. The table below summarizes the material costs for the two layer revetment. Each layer is assumed to be two stone diameters with an average porosity of 40%. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the revetment gives $2,252.

The placement of revetment stones is generally more precise and requires specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 300 man hours for construction, at $35/hr, an estimate of $10,500 for labor is obtained. An additional cost of $10,000 is added to the material and labor costs to account for general earthwork, not included in the estimate. This brings the final IC to $190,896.

Table 30 - Material Costs for Revetments (Bids).

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Weight (tons)	Rock Cost Per Ton	Total Cost
Armor	1.25	18,810	3,101,096	1,550	$97	$150,350
Underlayer	0.106	2,643	435,811	217	$82	$17,794

In developing the lifecycle cost for revetments, the following assumptions were made:

- Maintenance and repair costs for revetments are generally minimal. An estimate of 15% of the IC is set aside for maintenance and repair during each period.
- Revetments are resilient. The following damages are expected during significant storms:

Table 31 - Expected Damage – Revetments.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	15%
40	Additional rock displacement	5%
25	Minor scour & rock displacement	10%

Although not explicitly considered in this analysis, revetments can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding stones to the crest of an existing structure would be relatively minimal.

Revetment Cost Estimate

Initial Cost (IC)	$	190,896

Current Rate of SLR

Category	Storm T_r	% IC	Period 1 (2012-2037) # Events	Period 1 (2012-2037) *Cost	Period 2 (2037-2062) # Events	Period 2 (2037-2062) *Cost	Period 3 (2062-2082) # Events	Period 3 (2062-2082) *Cost	Total (2012-2082) Extended Cost	Total (2012-2082) % Final
Damage Cost (DC)	50	15%	0.56	$ 12,055	0.75	$ 9,293	1.01	$ 7,575	$ 28,924	9.2%
Damage Cost (DC)	40	5%	0.73	$ 5,276	1.02	$ 4,228	1.30	$ 3,232	$ 12,735	4.1%
Damage Cost (DC)	25	10%	1.13	$ 16,255	1.53	$ 12,657	2.14	$ 10,661	$ 39,573	12.6%
Maintenance Cost (MC)		15%	1.00	$ 21,651	1.00	$ 12,379	1.00	$ 7,484	$ 41,514	13.2%
								Post-Construction Costs (DC+RC+MC)	$ 122,746	39.1%
								Initial Cost (IC)	$ 190,896	60.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 313,642**	100.0%

Rapid Ice Melt Rate of SLR

Category	Storm T_r	% IC	Period 1 (2012-2037) # Events	Period 1 (2012-2037) *Cost	Period 2 (2037-2062) # Events	Period 2 (2037-2062) *Cost	Period 3 (2062-2082) # Events	Period 3 (2062-2082) *Cost	Total (2012-2082) Extended Cost	Total (2012-2082) % Final
Damage Cost (DC)	50	15%	1.35	$ 29,258	9.26	$ 114,617	25.00	$ 187,105	$ 330,980	33.3%
Damage Cost (DC)	40	5%	1.91	$ 13,773	11.90	$ 49,122	25.00	$ 62,368	$ 125,263	12.6%
Damage Cost (DC)	25	10%	3.01	$ 43,476	16.67	$ 137,541	25.00	$ 124,737	$ 305,754	30.7%
Maintenance Cost (MC)		15%	1.00	$ 21,651	1.00	$ 12,379	1.00	$ 7,484	$ 41,514	4.2%
								Post-Construction Costs (DC+RC+MC)	$ 803,511	80.8%
								Initial Cost (IC)	$ 190,896	19.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 994,407**	100.0%

Rip-Rap

Rip-rap is a method of shore protection that uses well graded stones to armor the coast. The size of the stones generally falls within the cobble range according to the Wentworth scale. Rip-rap relies on its weight for stability and dissipates the incident energy on its slope. Estimates of rip-rap size based on current velocity generally lead to material much smaller than would be required to resist the potential wind and ship generated waves at the site. To calculate the required stone size, a rip-rap specific version of the Hudson formula (USACE, 1977) was utilized. The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine the appropriate size. The largest wind wave height (1.8 ft) calculated based on the fetches defined above for the Bowline Point Park site was used for input into the Hudson formula. At the Henry Hudson Park site, the calculated wind wave height is roughly consistent with the type of wakes that would be expected (Bruno, 2003). The results from the Hudson formula recommend a median stone size (D_{50}) of 0.57 feet in diameter with a weight (W_{50}) of 30 pounds. Given the propensity for ice scour at the site, the recommended value was scaled up 20%, resulting in a D_{50} of 0.68 ft and a W_{50} of 52 lbs. For the rip-rap slope protection, only a single layer (40% porosity) with a thickness equal to twice the median stone diameter is placed on top of a geotextile filter fabric. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the revetment gives $2,252.

Table 32 - Cost Estimate for Rock Material to Build Rip-Rap.

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Rock Cost Per Ton	Total Cost
Armor	1.2	18,272	3,012,494	$97	$146,105

The placement of rip-rap stones is generally very quick and does not require specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 200 man hours for construction, at $35/hr, an estimate of $7,000 for labor is obtained. An additional cost of $10,000 is added to the material and labor costs to account for general earthwork, not included in the estimate thus far. This brings the final IC to $165,357.

In developing the lifecycle cost for rip-rap slopes, the following assumptions were made:

- Maintenance and repair costs for rip-rap are generally low. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- The following damages are expected during significant storms:

Table 33 - Expected Damage- Rip-rap.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%

Although not explicitly considered in this analysis, rip-rap slopes can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap to the crest of an existing structure would be relatively minimal.

Rip Rap Cost Estimate

Initial Cost (IC) $ 165,357

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 13,923	0.75	$ 10,733	1.01	$ 8,749	$ 33,405	10.3%
Damage Cost (DC)	40	20%	0.73	$ 18,279	1.02	$ 14,648	1.30	$ 11,197	$ 44,124	13.6%
Damage Cost (DC)	25	10%	1.13	$ 14,080	1.53	$ 10,964	2.14	$ 9,235	$ 34,279	10.5%
Maintenance Cost (MC)		20%	1.00	$ 25,006	1.00	$ 14,297	1.00	$ 8,644	$ 47,947	14.7%
								Post-Construction Costs (DC+RC+MC)	$ 159,756	49.1%
								Initial Cost (IC)	$ 165,357	50.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 325,113**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 33,792	9.26	$ 132,378	25.00	$ 216,097	$ 382,267	35.5%
Damage Cost (DC)	40	10%	1.91	$ 23,861	11.90	$ 85,100	25.00	$ 108,049	$ 217,009	20.1%
Damage Cost (DC)	25	10%	3.01	$ 37,660	16.67	$ 119,140	25.00	$ 108,049	$ 264,848	24.6%
Maintenance Cost (MC)		20%	1.00	$ 25,006	1.00	$ 14,297	1.00	$ 8,644	$ 47,947	4.5%
								Post-Construction Costs (DC+RC+MC)	$ 912,072	84.7%
								Initial Cost (IC)	$ 165,357	15.3%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,077,429**	100.0%

Joint Planting

Live staking or joint planting involves planting live stakes or vegetation into the void spaces in a rip-rap slope or revetment. If the rip-rap slope or revetment already exists the only costs are related to the materials used and the labor for installation. Table 34 provides some information on the typical costs of the materials used in joint planting.

Table 34 - Cost for Stakes to be Coupled with Rip-Rap (NRPCVT, 2004).

Range	$2.05 - $4.78/ft^2
Surface Area of Site	12,510 ft^2
Cost for Planting (@ $3.00/sq. ft)	$37,530
Cost per linear foot	$75.06

Labor costs for joint planting are minimal as upwards of 100 stakes can be planted per hour depending on the work force (USACE, 2001). Assuming four cuttings per square yard (EPA, 1993), the Bowline site would require upwards of 5500 plantings. Applying an average labor rate of $25/hr, the following cost estimate for labor was determined.

Table 35 - Labor Costs for Live Stakes.

Surface Area	1,390 yd^2
Cutting Density	4/yd^2
Plants Required	5,560
Installation Rate	100/hr
Labor Rate	$25.00/hr
Labor Cost	$1,390

Taking into account the labor costs and the material costs, the cost estimate for joint planting at the Bowline Park site is $38,920, or $77/lf. It is assumed that the joint planting will be constructed in conjunction with the rip-rap slope discussed in the previous section. The total estimated cost for a rip rap protected slope with joint planting is $204,277 or $408/lf.

In developing the lifecycle cost for joint planting, the following assumptions were made:

- The rip-rap discussed in the previous section forms the base for the joint planting and the total cost is the cost of constructing the rip-rap slope plus the cost of the joint planting.
- Joint planting adds to the maintenance and repair costs associated with a rip-rap slope. An additional 5% of the IC is estimated for joint planting bringing the estimate for a rip-rap slope with joint planting to 25%.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.

- Joint plantings are not especially resilient. The following damages are expected during significant storms:

Table 36 - Expected Damage - Joint Planting.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%
10	Loss of plantings	10%

Although not explicitly considered in this analysis, rip-rap slopes with joint planting can usually be modified to adapt to rising sea levels by adding stones and vegetation to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap and vegetation to the crest of an existing structure would be relatively minimal.

Joint Planting Cost Estimate

Initial Cost (IC)	$	204,277

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 17,200	0.75	$ 13,260	1.01	$ 10,808	$ 41,268	8.3%
Damage Cost (DC)	40	10%	0.73	$ 11,291	1.02	$ 9,048	1.30	$ 6,916	$ 27,255	5.5%
Damage Cost (DC)	25	10%	1.13	$ 17,394	1.53	$ 13,544	2.14	$ 11,409	$ 42,347	8.5%
Damage Cost (DC)	10	10%	2.84	$ 43,881	3.97	$ 35,043	5.32	$ 28,400	$ 107,324	21.6%
Maintenance Cost (MC)		25%	1.00	$ 38,615	1.00	$ 22,077	1.00	$ 13,348	$ 74,040	14.9%
							Post-Construction Costs (DC+RC+MC)		$ 292,234	58.9%
							Initial Cost (IC)		$ 204,277	41.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 496,511**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 41,746	9.26	$ 163,535	25.00	$ 266,960	$ 472,241	25.6%
Damage Cost (DC)	40	10%	1.91	$ 29,477	11.90	$ 105,130	25.00	$ 133,480	$ 268,087	14.5%
Damage Cost (DC)	25	10%	3.01	$ 46,524	16.67	$ 147,182	25.00	$ 133,480	$ 327,186	17.7%
Damage Cost (DC)	10	10%	7.58	$ 117,015	25.00	$ 220,773	25.00	$ 133,480	$ 471,267	25.5%
Maintenance Cost (MC)		35%	1.00	$ 54,061	1.00	$ 30,908	1.00	$ 18,687	$ 103,656	5.6%
							Post-Construction Costs (DC+RC+MC)		$ 1,642,437	88.9%
							Initial Cost (IC)		$ 204,277	11.1%

***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**	Total Cost	**$**	**1,846,714**	100.0%

Vegetated Geogrid

Vegetated geogrids were not considered a viable alternative at the Bowline Point Park site. The extremely mild slope of the existing shoreline makes the construction of vertical or near vertical retaining structures (bulkheads, bio-walls, timber cribbing, live crib walls, and vegetated geogrids) impractical. The nearly horizontal nature of the Bowline Point Park site does not provide enough natural relief to make these structures cost-efficient without adding a significant amount of fill. Doing so would change the project from a shoreline protection project to a land reclamation project, negating any useful information that could be obtained from the cost analysis. It should be noted that this suggestion is consistent with the conclusions reached in the Alden and ASA (Allen, et al., 2006) report.

Crib Wall

Crib walls were not considered a viable alternative at the Bowline Point Park site. The extremely mild slope of the existing shoreline makes the construction of vertical or near vertical retaining structures (bulkheads, bio-walls, timber cribbing, live crib walls, and vegetated geogrids) impractical. The nearly horizontal nature of the Bowline Point Park site does not provide enough natural relief to make these structures cost-efficient without adding a significant amount of fill. Doing so would change the project from a shoreline protection project to a land reclamation project, negating any useful information that could be obtained from the cost analysis. It should be noted that this suggestion is consistent with the conclusions reached in the Alden and ASA (Allen, et al., 2006) report.

Live Crib Wall

Live crib walls were not considered a viable alternative at the Bowline Point Park site. The extremely mild slope of the existing shoreline makes the construction of vertical or near vertical retaining structures (bulkheads, bio-walls, timber cribbing, live crib walls, and vegetated geogrids) impractical. The nearly horizontal nature of the Bowline Point Park site does not provide enough natural relief to make these structures cost-efficient without adding a significant amount of fill. Doing so would change the project from a shoreline protection project to a land reclamation project, negating any useful information that could be obtained from the cost analysis. It should be noted that this suggestion is consistent with the conclusions reached in the Alden and ASA (Allen, et al., 2006) report.

Sill

Stone sills have been used extensively in areas like the Chesapeake Bay since the mid 1980's to protect low to medium energy shorelines, and to promote the growth of marshland. Research has shown that a typical cross-section developed by the Maryland Department of Natural Resources (DNR, 1993), has worked well both within Maryland and when applied elsewhere. The typical cross-section is reproduced below in Figure 11Figure 11 Typical Cross Section for Sill (DNR, 1993). The recommended stone sizes for low and medium energy sites determined by Hardaway and Byrne (1999) are summarized in Table 37. For the low energy Bowline Park site, a stone size of 400 pounds was selected. Using the Maryland cross section as a guide, the design parameters shown in Table 38 were used to develop the cost for a sill at the Bowline Point Park site. The suggested dimensions result in a sill with a total cross-sectional area of 47ft^2/ft. Over 500 ft, the sill has a total volume of 23,540 ft^3. The cost estimate was developed assuming a porosity of 40% for the structure and an average rock price of $97 per ton.

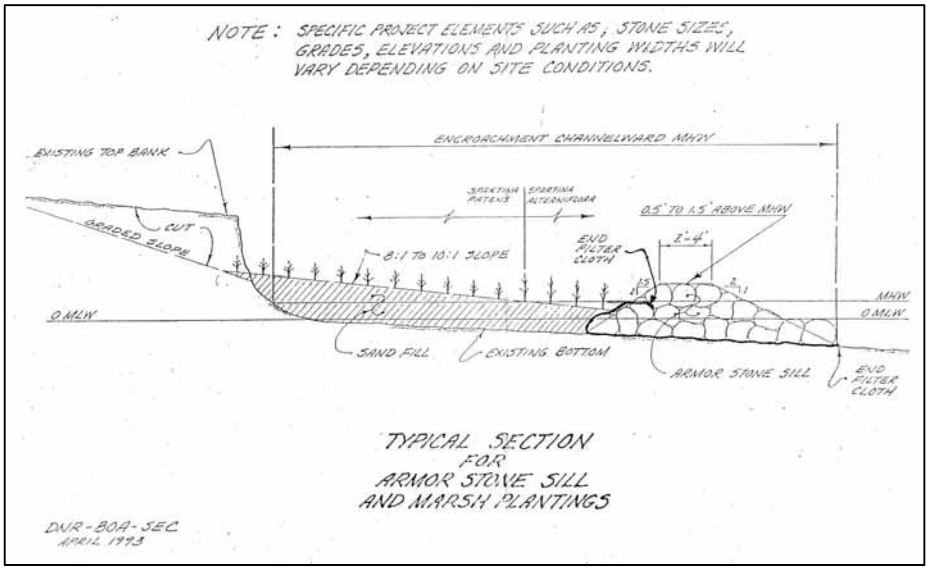

Figure 11 Typical Cross Section for Sill (DNR, 1993).

Table 37 – Weights for Varying Energy Regimes (Virginia Institute of Marine Science).

Energy Regime	Suggested Stone Size
Low (0-2 feet)	300 - 900 lbs
Medium (2-4 feet)	400 - 1200 lbs

Table 38 – Selected Sill Dimensions for Bowline Park.

Seaward Slope	1V : 2.0H
Shoreward Slope	1V : 1.5H
Crest Width	5 ft
Sill Height	5.5 ft

Table 39 – Material Costs - Sill.

Unit weight of stone	165 lbs/ft^3
Size of stone (D_{n50})	2.43 ft
Volume required	14,124 ft^3
Tons of Stone	1,164
Cost of Sill	$112,908
Cost of Sill per linear foot	$225

The placement of sill stones is generally more precise and requires specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 500 man hours for construction, at $35/hr, an estimate of $17,500 for labor is obtained. An additional cost of $5,000 is added to the material and labor costs to account for general earthwork, not included in the estimate. This brings the final IC to $135,408.

In developing the lifecycle cost for sills, the following assumptions were made:

- Maintenance and repair costs for sills are generally minimal. An estimate of 10% of the IC is set aside for maintenance and repair during each period.
- Sills are resilient. The following damages are expected during significant storms:

Table 40 - Expected Damage – Sill.

T_r	Expected Impacts	Damage Costs (% IC)
40	Some stone replacement	10%

Although not explicitly considered in this analysis, sills can usually be modified to adapt to rising sea levels by adding stone to build up the crest elevation. With rapid sea level rise however, it is unlikely that sediment accumulation and marsh growth will occur naturally. The cost associated with adding stone to a sill will generally be higher than for similar land based structures due to the additional costs related to marine construction.

Sill Cost Estimate

Initial Cost (IC)	$ 135,408									
Current Rate of SLR										
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	40	10%	0.73	$ 7,484	1.02	$ 5,998	1.30	$ 4,584	$ 18,066	10.4%
Maintenance Cost (MC)		10%	1.00	$ 10,239	1.00	$ 5,854	1.00	$ 3,539	$ 19,631	11.3%
								Post-Construction Costs (DC+RC+MC)	$ 37,698	21.8%
								Initial Cost (IC)	$ 135,408	78.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 173,106**	100.0%

Rapid Ice Melt Rate of SLR										
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	40	10%	1.91	$ 19,539	11.90	$ 69,687	25.00	$ 88,479	$ 177,705	53.4%
Maintenance Cost (MC)		10%	1.00	$ 10,239	1.00	$ 5,854	1.00	$ 3,539	$ 19,631	5.9%
								Post-Construction Costs (DC+RC+MC)	$ 197,337	59.3%
								Initial Cost (IC)	$ 135,408	40.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 332,745**	100.0%

Henry Hudson Park (Albany County)

Henry Hudson Park lies along the west bank of the Hudson River in Albany County as shown in Figure 12. A cross section illustrating the site conditions as of 2006 which was presented in the Alden and ASA (Allen, et al., 2006) report is reproduced here as Figure 13. The major site characteristics are summarized in Table 41. As illustrated in Figure 13, the existing shoreline at Henry Hudson Park has been armored with a shore parallel timber and rock crib structure with a concrete cap. The Henry Hudson Park shoreline is typical of many of the moderately sloped shorelines along the Hudson, where a variety of stabilization alternatives could be applied. The Alden report attributed the erosion of the Henry Hudson Park shoreline to a combination of wakes from ships transiting the navigation channel, large ice floes during the winter months, and surface runoff from the park. Wind wave heights were calculated using the methodology presented in Chapter 3, Section 6 of the Shore Protection Manual (USACE, 1977), assuming a wind speed of 50 mph and a constant depth of 20 feet. For the four fetches defined in Figure 12, the estimated wind wave heights are as given in Table 42.

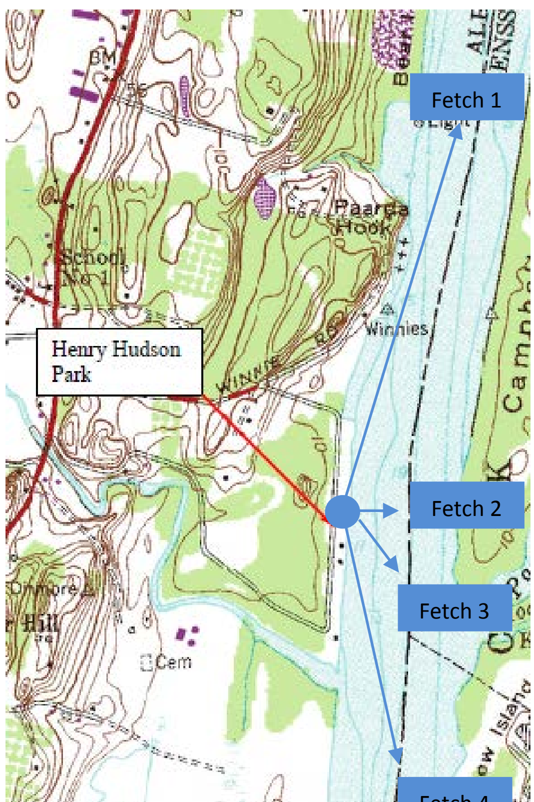

Figure 12: Henry Hudson Park site and fetch delineation.

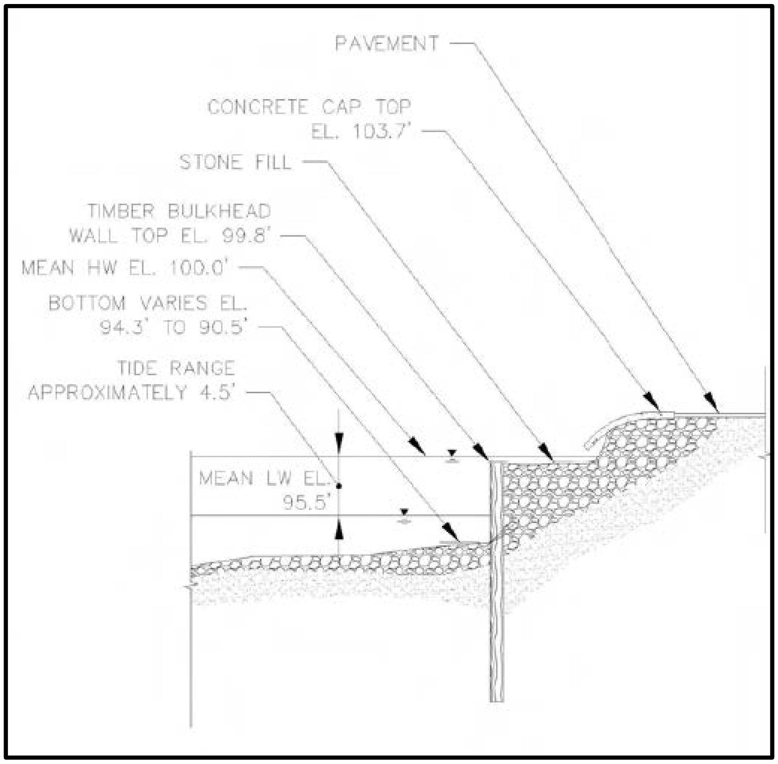

Figure 13 - Existing Cross-section at Henry Hudson Park.

Table 41 - Henry Hudson Park Site Characteristics and Dimensions.

General Characteristics	
Width of River	1,000 ft
Average Depth	15-20 ft
Depth at Shoreline	3 - 10 ft
Mean Current Velocity (Main Channel)	1.2 ft/sec
Maximum Current Velocity (Main Channel)	2.2 ft/sec
Tidal Flow	10,000 ft^3/sec
Max Tidal Fluctuation	4.5 ft
Side Slope	1V:15H
Dimensions Above High Water Level	
Width	11 ft
Height	3.5 ft
Slope Length	11 ft
Surface Area	5,523 ft^2
Cross-section Area	19 ft^2

Volume	9,625 ft^3
Dimensions of Intertidal Zone	
Width	7 ft
Height	4 ft
Slope Length	7 ft
Surface Area	3,536 ft^2
Cross-section Area	14 ft^2
Volume	7,000 ft^3

Table 42 - Fetches and Related Wind Wave Heights at Henry Hudson Park.

	Length (mi)	Wave Height (ft)
Fetch 1	1.55	1.8
Fetch 2	0.20	0.7
Fetch 3	0.33	0.9
Fetch 4	0.85	1.3

In addition to the costs described below within each section, there will be a cost associated with the removal of the existing deteriorated bulkhead structure. As this cost will be incurred regardless of the shoreline stabilization approach selected, it is not included in the cost analysis.

Shoreline Treatment Cost Analyses for Henry Hudson Park

Bulkhead

Bulkheads are one of the more common shoreline stabilization approaches used along riverine and estuarine coastlines. Bulkheads are vertical soil retention structures designed to eliminate bank erosion by encapsulating the soil behind it. Bulkheads can take several forms, however the two most common types are cantilevered bulkheads and anchored bulkheads. Cantilevered bulkheads are used in relatively low height applications and simply rely on their embedment for support. Anchored bulkheads are similar to cantilevered bulkheads, only an anchoring system is added to provide additional lateral support.

Due to the relatively low grades at each of the Hudson River sites, cantilevered bulkheads were selected for each site. After balancing the loads and pressures acting on the front and rear faces of the bulkhead, the design parameters listed in Table 43 were obtained.

Table 43 - Bulkhead Design Summary.

Height of Wall above Substrate	11.40 ft
Depth of Penetration	10.68 ft
Total Height of Wall	22.08 ft

Bulkhead prices vary considerably depending on the material selected. Costs for wood, steel and concrete bulkheads obtained from local bids on projects with similar dimensions are shown below in Table 44 and include material and labor costs.

Table 44 - Bulkhead Material Cost Comparison (Whalen, et al., 2011).

Material	Steel	Wood	Concrete
Cost Range/lf	$700-1,200	$116-265	$500-$1000

Although not explicitly considered in this analysis, bulkheads can be modified to adapt to rising sea levels through the addition of a cap. The cap will normally consist of either wood secured to the face of the bulkhead, or concrete cast to raise the elevation of the structure. Such a modification must be carried out carefully however; as effectively increasing the unsupported length of the structure changes the pressure distributions on which the original design was based. Often the addition of an anchor will be necessary if the structure is retrofit. The cost associated with such modifications can be significant.

Wood Bulkhead

Given the moderate side slopes, proximity to the navigation channel and exposure to modest fetches, a cost estimate of $190/lf or $95,000 which is in the middle of the ranges obtained was selected. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 400 man hours for construction, at $35/hr, an estimate of $14,000 for labor is obtained. In addition to the costs associated with the bulkhead construction, a lump sum cost of $15,000 is added to cover the cost of earthwork not directly related to the bulkhead construction. The total estimate of the IC associated with the construction of a wooden bulkhead at Henry Hudson Park is $124,000.

In developing the lifecycle cost for wood bulkheads, the following assumptions were made:

- Periodic maintenance and repairs will be necessary. An estimate of 20% of the IC is set aside for maintenance and repair during each period.

- It is assumed that maintenance and repair costs for wood structures will increase under the rapid sea level rise scenario. A 5% increase is applied.
- Wood bulkheads generally have a lifespan of between 25 and 40 years. For the purpose of this analysis, a 30 year lifespan is assumed.
- Wood bulkheads are resilient. The following damages are expected during significant storms:

Table 45 - Expected Damage - Wood Bulkhead.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Wood Bulkhead Cost Estimate

Initial Cost (IC) $ 124,000

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 5,220	0.75	$ 4,024	1.01	$ 3,280	$ 12,525	4.6%
Damage Cost (DC)	25	5%	1.13	$ 5,279	1.53	$ 4,111	2.14	$ 3,463	$ 12,853	4.7%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 53,605	1.00	$ 32,410	$ 86,015	31.7%
Maintenance Cost (MC)		20%	1.00	$ 18,752	1.00	$ 10,721	1.00	$ 6,482	$ 35,955	13.3%
							Post-Construction Costs (DC+RC+MC)		$ 147,348	54.3%
								Initial Cost (IC)	$ 124,000	45.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 271,348**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 12,670	9.26	$ 49,634	25.00	$ 81,025	$ 143,330	28.8%
Damage Cost (DC)	25	5%	3.01	$ 14,120	16.67	$ 44,671	25.00	$ 40,512	$ 99,304	20.0%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 53,605	1.00	$ 32,410	$ 86,015	17.3%
Maintenance Cost (MC)		25%	1.00	$ 23,440	1.00	$ 13,401	1.00	$ 8,102	$ 44,944	9.0%
							Post-Construction Costs (DC+RC+MC)		$ 373,593	75.1%
								Initial Cost (IC)	$ 124,000	24.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 497,593**	100.0%

Steel Bulkhead

Given the moderate side slopes, proximity to the navigation channel and exposure to modest fetches, a cost estimate of $950/lf or $475,000 which is in the middle of the ranges obtained was selected. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 350 man hours for construction, at $35/hr, an estimate of $12,250 for labor is obtained. In addition to the costs associated with the bulkhead construction, a lump sum cost of $15,000 is added to cover the cost of earthwork not directly related to the bulkhead construction. The total estimate of the Initial Costs associated with the construction of a wooden bulkhead at Henry Hudson Park is $502,250.

In developing the lifecycle cost for steel bulkheads, the following assumptions were made:

- Maintenance and repair costs for steel bulkheads are generally minimal. An estimate of 5% of the IC is set aside for maintenance and repair during each period.
- Steel bulkheads generally have a lifespan of between 25 and 40 years. For the purpose of this analysis, a 30 year lifespan is assumed.
- Steel bulkheads are resilient. The following damages are expected during significant storms:

Table 46 - Expected Damage - Steel Bulkhead.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Steel Bulkhead Cost Estimate

Initial Cost (IC) $ 502,250

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 21,145	0.75	$ 16,301	1.01	$ 13,287	$ 50,732	5.1%
Damage Cost (DC)	25	5%	1.13	$ 21,383	1.53	$ 16,651	2.14	$ 14,025	$ 52,059	5.3%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 217,123	1.00	$ 131,273	$ 348,396	35.2%
Maintenance Cost (MC)		5%	1.00	$ 18,988	1.00	$ 10,856	1.00	$ 6,564	$ 36,408	3.7%
								Post-Construction Costs (DC+RC+MC)	$ 487,595	49.3%
								Initial Cost (IC)	$ 502,250	50.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 989,845**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 51,320	9.26	$ 201,040	25.00	$ 328,184	$ 580,543	31.0%
Damage Cost (DC)	25	5%	3.01	$ 57,194	16.67	$ 180,936	25.00	$ 164,092	$ 402,221	21.5%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 217,123	1.00	$ 131,273	$ 348,396	18.6%
Maintenance Cost (MC)		5%	1.00	$ 18,988	1.00	$ 10,856	1.00	$ 6,564	$ 36,408	1.9%
								Post-Construction Costs (DC+RC+MC)	$ 1,367,568	73.1%
								Initial Cost (IC)	$ 502,250	26.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,869,818**	100.0%

Bio-walls

The term bio-wall has been used generically to encompass a suite of shoreline stabilization approaches with similar characteristics. Most bio-walls are used in areas that have traditionally been protected by bulkheads. Bio-wall can refer to simple ecological enhancements used to modify traditional bulkheads such as hanging planter baskets, or more complex approaches which incorporate non-traditional materials and design layouts. For the purposes of this analysis a bio-wall will be defined as an ecologically enhanced concrete panel bulkhead which incorporates three precast tide pools. The enhancements used to modify the concrete panel include roughening the surface, and the use of low-PH concrete mix to maximize growth. The tide pools are pre-cast concrete structures that are designed to fill up during high tide and hold a reservoir of water once the water level has dropped. This maintains a wet environment that allows organisms to grow in a location that would normally be too dry.

Bio-walls are a fairly new concept and cost information is extremely limited. In general, ecologically enhanced concrete costs 7-15% more than regular Portland cement (Shimrit Perkol-Finkel, 2012). Traditional concrete bulkheads cost between $500 and $1000 per linear foot (Devore); therefore an ecologically enhanced concrete bulkhead can be expected to cost between $575 and $1150 per linear foot. Tide pools for revetment habitat development generally cost between $1000 and $1500 each (Shimrit Perkol-Finkel, 2012). At the Henry Hudson Park site which is relatively low energy, the low end of these numbers is used to develop the estimated cost. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/ publicViewPWChanges.do). Assuming 400 man hours for construction, at $35/hr, an estimate of $14,000 for labor is obtained. An additional lump sum cost of $15,000 is added to the estimate to cover the cost of earthwork not directly related to the bio-wall. The total estimate of the Initial Costs associated with the construction of a bio-wall at Henry Hudson Park is $319,500.

Table 47 – Bio-wall Cost Information.

Ecologically Enhanced Concrete Bulkhead per lf	$575/lf
Total Cost of Enhanced Concrete Bulkhead	$287,500
Cost of Tide Pools	$3,000
Total Cost	$290,500

In developing the lifecycle cost for a bio-wall, the following assumptions were made:

- Maintenance and repair costs for bio-walls are generally minimal. An estimate of 10% of the IC is set aside for maintenance and repair during each period.

- Concrete bulkheads generally have a lifespan of between 20 and 50 years. For the purpose of this analysis, a 40 year lifespan is assumed for the bio-wall.
- Bio-walls are resilient. The following damages are expected during significant storms:

Table 48 - Expected Damage – Bio-wall.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
25	Minor scour	5%

Bio Wall Cost Estimate

Initial Cost (IC) $ 319,500

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 13,451	0.75	$ 10,369	1.01	$ 8,452	$ 32,273	5.7%
Damage Cost (DC)	25	5%	1.13	$ 13,603	1.53	$ 10,592	2.14	$ 8,922	$ 33,116	5.8%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 138,120	0.00	$ -	$ 138,120	24.3%
Maintenance Cost (MC)		10%	1.00	$ 24,158	1.00	$ 13,812	1.00	$ 8,351	$ 46,321	8.1%
								Post-Construction Costs (DC+RC+MC)	$ 249,830	43.9%
								Initial Cost (IC)	$ 319,500	56.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 569,330**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 32,646	9.26	$ 127,889	25.00	$ 208,770	$ 369,305	32.7%
Damage Cost (DC)	25	5%	3.01	$ 36,383	16.67	$ 115,100	25.00	$ 104,385	$ 255,868	22.7%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 138,120	0.00	$ -	$ 138,120	12.2%
Maintenance Cost (MC)		10%	1.00	$ 24,158	1.00	$ 13,812	1.00	$ 8,351	$ 46,321	4.1%
								Post-Construction Costs (DC+RC+MC)	$ 809,614	71.7%
								Initial Cost (IC)	$ 319,500	28.3%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,129,114**	100.0%

Revetment

A revetment is a sloped engineered shore protection method similar to rip rap; however the design is often more involved consisting of multiple layers and/or filter fabric, with the individual stones placed more precisely. Revetments tend to use larger stone falling in the boulder category according to the Wentworth scale. The median stone size (D_{n50}) and weight (W_{50}) for the revetment armor stone were determined using the well-known Hudson formula (USACE, 2006). The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine an appropriate stone size. The largest wind wave height (1.8 ft) calculated based on the fetches defined above for Henry Hudson Park was used for input into the Hudson formula. At the Henry Hudson site, the calculated wind wave height is roughly consistent with type of wakes that might be expected (Bruno et al., 2003). The results from the Hudson formula recommend a median stone size (D_{50}) of 0.47 feet in diameter with a weight (W_{50}) of 16 pounds. The Rock Manual (CIRIA, CUR, CETMEF, 2007) suggests that in ice prone areas, the minimum stone size used in a revetment is at least as large as the thickness of the anticipated ice. Ice reports collected by the U.S. Coast Guard generally indicate ice thicknesses on the order of 1 foot during the winter. Given the propensity for ice scour at the site, the recommended value was scaled up resulting in a D_{50} of 1.2 ft and a W_{50} of 285 lbs. Since revetments are constructed with uniformly sized stones, an underlayer, and geotextile filter layer are included to prevent the washout of the fine material. The table below summarizes the material costs for the two layer revetment. Each layer is assumed to be two stone diameters with an average porosity of 40%. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the revetment gives $906.

The placement of revetment stones is generally more precise and requires specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 350 man hours for construction, at $35/hr, an estimate of $12,250 for labor is obtained. An additional cost of $15,000 is added to the material and labor costs to account for general earthwork, not included in the estimate. This brings the final IC to $192,289.

Table 49 - Material Costs for Revetments (Bids).

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Weight (tons)	Rock Cost Per Ton	Total Cost
Armor	2.15	14,877	2,452,720	1226	$97	$118,955
Underlayer	0.98	6,818	1,124,163	562	$82	$46,084

In developing the lifecycle cost for revetments, the following assumptions were made:

- Maintenance and repair costs for revetments are generally minimal. An estimate of 15% of the IC is set aside for maintenance and repair during each period.
- Revetments are resilient. The following damages are expected during significant storms:

Table 50 - Expected Damage – Revetments.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	15%
40	Additional rock displacement	5%
25	Minor scour & rock displacement	10%

Although not explicitly considered in this analysis, revetments can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding stones to the crest of an existing structure would be relatively minimal.

Revetment Cost Estimate

Initial Cost (IC)	$ 192,289									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	15%	0.56	$ 12,143	0.75	$ 9,361	1.01	$ 7,630	$ 29,135	9.2%
Damage Cost (DC)	40	5%	0.73	$ 5,314	1.02	$ 4,259	1.30	$ 3,255	$ 12,828	4.1%
Damage Cost (DC)	25	10%	1.13	$ 16,373	1.53	$ 12,749	2.14	$ 10,739	$ 39,862	12.6%
Maintenance Cost (MC)		15%	1.00	$ 21,809	1.00	$ 12,469	1.00	$ 7,539	$ 41,817	13.2%
								Post-Construction Costs (DC+RC+MC)	$ 123,641	39.1%
								Initial Cost (IC)	$ 192,289	60.9%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 315,930**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	15%	1.35	$ 29,472	9.26	$ 115,454	25.00	$ 188,470	$ 333,396	33.3%
Damage Cost (DC)	40	5%	1.91	$ 13,874	11.90	$ 49,480	25.00	$ 62,823	$ 126,177	12.6%
Damage Cost (DC)	25	10%	3.01	$ 43,794	16.67	$ 138,544	25.00	$ 125,647	$ 307,985	30.7%
Maintenance Cost (MC)		15%	1.00	$ 21,809	1.00	$ 12,469	1.00	$ 7,539	$ 41,817	4.2%
								Post-Construction Costs (DC+RC+MC)	$ 809,375	80.8%
								Initial Cost (IC)	$ 192,289	19.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 1,001,664**	100.0%

Rip-Rap

Rip-rap is a method of shore protection that uses well graded stones to armor the coast. The size of the stones generally falls within the cobble range according to the Wentworth scale. Rip-rap relies on its weight for stability and dissipates the incident energy on its slope. Estimates of rip-rap size based on current velocity generally lead to material much smaller than would be required to resist the potential wind and ship generated waves at the site. To calculate the required stone size, a rip-rap specific version of the Hudson formula (USACE, 2006) was utilized. The Hudson formula uses the balance between the stabilizing (i.e. weight) and destabilizing (i.e. shear stresses) forces acting on the stone to determine the appropriate size. The largest wind wave height (1.8 ft) calculated based on the fetches defined above for the Henry Hudson Park site was used for input into the Hudson formula. At the Henry Hudson Park site, the calculated wind wave height is roughly consistent with the type of wakes that would be expected (Bruno, 2002). The results from the Hudson formula recommend a median stone size (D_{50}) of 0.45 feet in diameter with a weight (W_{50}) of 15 pounds. Given the propensity for ice scour at the site, the recommended value was scaled up 20%, resulting in a D_{50} of 0.54 ft and a W_{50} of 26 lbs. For the rip-rap slope protection, only a single layer (40% porosity) with a thickness equal to twice the median stone diameter is placed on top of a geotextile filter fabric. Geotextile costs were calculated using a unit cost of $0.90/sy, which when multiplied by the total surface area of the revetment gives $906.

Table 51 - Cost Estimate for Rock Material to Build Rip-Rap.

Layer	Thickness (ft)	Volume (ft^3)	Weight (lbs)	Rock Cost Per Ton	Total Cost
Armor	0.96	6,694	1,103,724	$97	$53,530

The placement of rip-rap stones is generally very quick and does not require specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 250 man hours for construction, at $35/hr, an estimate of $8,750 for labor is obtained. An additional cost of $15,000 is added to the material and labor costs to account for general earthwork, not included in the estimate thus far. This brings the final IC to $78,186.

In developing the lifecycle cost for rip-rap slopes, the following assumptions were made:

- Maintenance and repair costs for rip-rap are generally low. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- The following damages are expected during significant storms:

Table 52 - Expected Damage- Rip-rap.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%

Although not explicitly considered in this analysis, rip-rap slopes can usually be modified to adapt to rising sea levels by adding stones to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap to the crest of an existing structure would be relatively minimal.

Rip Rap Cost Estimate

Initial Cost (IC)	$ 78,186

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 6,583	0.75	$ 5,075	1.01	$ 4,137	$ 15,795	11.0%
Damage Cost (DC)	40	10%	0.73	$ 4,322	1.02	$ 3,463	1.30	$ 2,647	$ 10,432	7.3%
Damage Cost (DC)	25	10%	1.13	$ 6,658	1.53	$ 5,184	2.14	$ 4,367	$ 16,208	11.3%
Maintenance Cost (MC)		20%	1.00	$ 11,824	1.00	$ 6,760	1.00	$ 4,087	$ 22,671	15.8%
								Post-Construction Costs (DC+RC+MC)	$ 65,106	45.4%
								Initial Cost (IC)	$ 78,186	54.6%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 143,292**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 15,978	9.26	$ 62,592	25.00	$ 102,178	$ 180,748	35.5%
Damage Cost (DC)	40	10%	1.91	$ 11,282	11.90	$ 40,238	25.00	$ 51,089	$ 102,609	20.1%
Damage Cost (DC)	25	10%	3.01	$ 17,807	16.67	$ 56,333	25.00	$ 51,089	$ 125,229	24.6%
Maintenance Cost (MC)		20%	1.00	$ 11,824	1.00	$ 6,760	1.00	$ 4,087	$ 22,671	4.5%
								Post-Construction Costs (DC+RC+MC)	$ 431,256	84.7%
								Initial Cost (IC)	$ 78,186	15.3%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 509,442**	100.0%

Joint Planting

Live staking or joint planting involves planting live stakes or vegetation into the void spaces in a rip-rap slope or revetment. If the rip-rap slope or revetment already exists the only costs are related to the materials used and the labor for installation. Table 53 provides some information on the typical costs of the materials used in joint planting.

Table 53 - Cost for Stakes to be Coupled with Rip-Rap (NRPCVT, 2004).

Range	\$2.05 - \$4.78/ft^2
Surface Area of Site	5,522 ft^2
Cost for Planting (@ \$3.00/sq. ft)	\$16,568
Cost per linear foot	\$33.14

Labor costs for joint planting are minimal as upwards of 100 stakes can be planted per hour depending on the work force (USACE, 2001). Assuming four cuttings per square yard (EPA, 1993), the Henry Hudson Site would require upwards of 2400 plantings. Applying an average labor rate of \$25/hr, the following cost estimate for labor was determined.

Table 54 - Labor Costs for Live Stakes.

Surface Area	614 yd^2
Cutting Density	4/yd^2
Plants Required	2,455
Installation Rate	100/hr
Labor Rate	\$25.00/hr
Labor Cost	\$614

Taking into account the labor costs and the material costs, the cost estimate for joint planting at the Henry Hudson Park site is \$17,182, or \$34/lf. It is assumed that the joint planting will be constructed in conjunction with the rip-rap slope discussed in the previous section. The total estimated cost for a rip rap protected slope with joint planting is \$95,368 or \$191/lf.

In developing the lifecycle cost for joint planting, the following assumptions were made:

- The rip-rap discussed in the previous section forms the base for the joint planting and the total cost is the cost of constructing the rip-rap slope plus the cost of the joint planting.
- Joint planting adds to the maintenance and repair costs associated with a rip-rap slope. An additional 5% of the IC is estimated for joint planting bringing the estimate for a rip-rap slope with joint planting to 25%.

- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.
- Joint plantings are not especially resilient. The following damages are expected during significant storms:

Table 55 - Expected Damage - Joint Planting.

T_r	Expected Impacts	Damage Costs (% IC)
50	Significant overtopping & scour	20%
40	Moderate scour	10%
25	Minor scour	10%
10	Loss of plantings	10%

Although not explicitly considered in this analysis, rip-rap slopes with joint planting can usually be modified to adapt to rising sea levels by adding stones and vegetation to the crest of the structure. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding rip-rap and vegetation to the crest of an existing structure would be relatively minimal.

Joint Planting Cost Estimate

Initial Cost (IC)	$ 95,368									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 8,030	0.75	$ 6,190	1.01	$ 5,046	$ 19,266	8.3%
Damage Cost (DC)	40	10%	0.73	$ 5,271	1.02	$ 4,224	1.30	$ 3,229	$ 12,724	5.5%
Damage Cost (DC)	25	10%	1.13	$ 8,121	1.53	$ 6,323	2.14	$ 5,326	$ 19,770	8.5%
Damage Cost (DC)	10	10%	2.84	$ 20,486	3.97	$ 16,360	5.32	$ 13,259	$ 50,105	21.6%
Maintenance Cost (MC)		25%	1.00	$ 18,028	1.00	$ 10,307	1.00	$ 6,232	$ 34,566	14.9%
						Post-Construction Costs (DC+RC+MC)			$ 136,431	58.9%
								Initial Cost (IC)	$ 95,368	41.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 231,799**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 19,489	9.26	$ 76,347	25.00	$ 124,632	$ 220,469	25.6%
Damage Cost (DC)	40	10%	1.91	$ 13,762	11.90	$ 49,080	25.00	$ 62,316	$ 125,158	14.5%
Damage Cost (DC)	25	10%	3.01	$ 21,720	16.67	$ 68,713	25.00	$ 62,316	$ 152,749	17.7%
Damage Cost (DC)	10	10%	7.58	$ 54,629	25.00	$ 103,069	25.00	$ 62,316	$ 220,014	25.5%
Maintenance Cost (MC)		35%	1.00	$ 25,239	1.00	$ 14,430	1.00	$ 8,724	$ 48,393	5.6%
						Post-Construction Costs (DC+RC+MC)			$ 766,782	88.9%
								Initial Cost (IC)	$ 95,368	11.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 862,150**	100.0%

Vegetated Geogrid

A vegetated geogrid is constructed of successive layers of soil wrapped in a geotextile fabric. Each layer is stacked upon the previous at an inclined angle to resist any forward movement; while vegetation is added between each layer to promote a natural aesthetic and habitat development. The vegetation once established will also act to reinforce the strength of the structure. The number of layers and the amount of wrapping is determined by the height of the wall. The major material costs for vegetative geogrids consists of the geotextile fabric, the fill material, and the live vegetation. At Henry Hudson Park it is assumed that the existing soil will be used to fill the geotextile wraps at a reduced cost of $25/ton. The costs for each element are summarized in Table 56. An additional $20,000 is added to the final cost to account for earthwork not directly related to filling each layer. Preparing a site of this width and length will require a significant amount of excavation.

Table 56 – Material Costs for Vegetated Geogrid at Henry Hudson Park.

Geotextile Costs (Haliburton Cooperative)	
Number of Layers	3
Wrap Length	7.40 ft
Length of geotextile per layer	24.28 ft
Total length	72.85 ft/lf
Total area of wrap	36424.15 ft^2
Average Cost **(Storrar)**	$0.90/ yd^2
Total geotextile cost	$ 3,642
Sediment Costs (Swan River Trust)	
Volume of fill required	18,581 ft^3
Unit weight of sediment fill	165 lbs/ft^3
Weight of stone needed	3,065,832 lbs
Average Cost	$25/ton
Total Fill Cost	$ 38,323
Vegetation Costs (WSDT, 2002)	
6'x2' Pruned Live Willow Branches	5000
Unit Cost	$1.20
Total Vegetation Cost	$6,000

Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 500 man hours for construction, at $35/hr, an estimate of $17,500 for labor is obtained. The total estimated cost for a vegetated geogrid structure at Henry Hudson Park is $85,465.

In developing the lifecycle cost for vegetated geogrids, the following assumptions were made:

- Maintenance and repair costs for vegetated geogrids are generally minimal. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- Vegetated geogrids do not typically have a long lifespan. Although claims of as long as 120 years can be found, given the condition along the Hudson, a 20 year lifespan is utilized in the analysis.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.
- The following damages are expected during significant storms:

Table 57 - Expected Damage – Geogrid.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	20%
25	Loss of vegetation	10%

Although not explicitly considered in this analysis, vegetated geogrids can be modified to adapt to rising sea levels by adding additional layers to an existing structure. If additional layers are added, care must be taken to ensure that any new layers are secured to the existing structure and anchoring system such that the entire structure behaves as a single unit. In this case, the original design calls for armoring the bank to the top of the existing slope; therefore additional means such as infilling would be required to continue to elevate the crest. Normally the cost associated with adding an additional layer to a vegetated geogrid would be relatively minimal.

Vegetated Geogrid Cost Estimate										
Initial Cost (IC)	$ 85,465									

Current Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	0.56	$ 7,196	0.75	$ 5,548	1.01	$ 4,522	$ 17,266	6.4%
Damage Cost (DC)	25	10%	1.13	$ 7,277	1.53	$ 5,667	2.14	$ 4,773	$ 17,717	6.6%
Replacement Cost (RC)		100%	1.00	$ 64,622	1.00	$ 36,947	1.00	$ 22,338	$ 123,907	46.0%
Maintenance Cost (MC)		20%	1.00	$ 12,924	1.00	$ 7,389	1.00	$ 4,468	$ 24,781	9.2%
								Post-Construction Costs (DC+RC+MC)	$ 183,671	68.2%
								Initial Cost (IC)	$ 85,465	31.8%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 269,136**	100.0%

Rapid Ice Melt Rate of SLR

			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	20%	1.35	$ 17,466	9.26	$ 68,420	25.00	$ 111,690	$ 197,575	34.0%
Damage Cost (DC)	25	10%	3.01	$ 19,465	16.67	$ 61,578	25.00	$ 55,845	$ 136,887	23.6%
Replacement Cost (RC)		100%	1.00	$ 64,622	1.00	$ 36,947	1.00	$ 22,338	$ 123,907	21.3%
Maintenance Cost (MC)		30%	1.00	$ 19,387	1.00	$ 11,084	1.00	$ 6,701	$ 37,172	6.4%
								Post-Construction Costs (DC+RC+MC)	$ 495,542	85.3%
								Initial Cost (IC)	$ 85,465	14.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 581,007**	100.0%

Crib Wall

Timber cribbing functions similar to a gravity bulkhead, in that its stability is directly related to its weight. This in turn is dependent upon its height to width ratio, which should be less than 3 (FEMA, 2000). The weight of the crib pushes perpendicularly upon the wooden posts that create the crib, and the allowable stress in the wood determines the capacity of each crib. Generally, the posts are 6 to 8 feet long (NRCS, 2007), with allowable stresses in the range of 200 to 1000 lb/in^2 depending on the species of wood (FEMA, 2000). Table 58 summarizes the crib design. A smaller crib was selected for Henry Hudson Park due to the lower energy at the site. Using 6 foot lengths, 83 cribs would be required along 500 ft of river frontage. The volume of each crib is 131ft^3. When filled with stone with an average porosity of 40%, this requires nearly 897 tons of stone and over 5,000 logs. A crib wall covering an area this large will require extensive excavation; however the soil and stone from the site could be recycled back into the project as fill for the cribs. The cost of the recycled fill material used to determine the material costs for the structure was $25/ton. The costs are summarized below in Table 60. An additional $20,000 is added to the final cost to account for earthwork not directly related to building and filling the cribs.

Table 58 - Selection of Log Criteria for Crib.

Log Length	6 ft
Log Cross-Section	3.5 in x 3.5 in
Design Stress	500 lb/in^2
Crib Configuration	2 x 2 ft x ft
Capacity	24,500 lbs
Capacity per each contact	6,125 lbs

Table 59 - Determination of Weight of Filled Crib.

Area	21.78 ft^2
Volume	130.67 ft^3
Unit weight of stone	165 lbs/ft^3
Total Weight of Crib	10.77 tons
Total Number of Cribs (500/6)	83.33
Weight of Stone (40% Porosity)	538 tons

Table 60 - Cost Summary for Timber Cribbing (Haliburton Cooperative).

Timber Cribbing (Based off Design of 6'wx6'hx500'l)			(WSDT, 2002)
Items	# of Units	Cost/Unit	Total
Logs, untreated D.Fir, Cedar or Hemlock	5,630	$ 6.18/log	$34,782
Sediment Fill Material (Upper 6' of crib)	538	$ 25/ton	$13,450
Stone Fill (Lower 2' of crib)	134	$72/ton	$9,648
Total Cost			$57,880
Cost per Linear Foot			$115.76

The amount of labor required to construct a wooden crib wall will be roughly 1.5 times what is necessary for a wooden bulkhead. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 600 man hours for construction, at $35/hr, an estimate of $21,000 for labor is obtained. The total estimated cost for constructing a crib wall at the Henry Hudson Park site is $98,880.

In developing the lifecycle cost for crib walls, the following assumptions were made:

- Maintenance and repair costs for crib walls are generally moderate. An estimate of 20% of the IC is set aside for maintenance and repair during each period.
- It is assumed that maintenance and repair costs for wood structures will increase under the rapid sea level rise scenario. A 5% increase is applied.
- Wooden cribs have a lifespan of approximately 25-40 years. For the purposes of this analysis, complete replacement is assumed after 30 years.
- Wooden crib walls are resilient. The following damages are expected during significant storms:

Table 61 - Expected Damage - Wooden Crib.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
40	Damage to cribs	20%

Although not explicitly considered in this analysis, crib walls and live crib walls can be modified to adapt to rising sea levels through the construction of additional cribs. Such a modification must be carried out carefully however; as increasing the height of the structure changes the pressure distributions. In addition, care must be taken to ensure that the additional weight doesn't cause the allowable stress in the timber and the bearing capacity of the earth supporting the structure to be exceeded. Assuming those conditions are met, the cost of adding an additional crib is relatively low.

Crib Wall Cost Estimate

Initial Cost (IC)	$ 98,880									
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 4,163	0.75	$ 3,209	1.01	$ 2,616	$ 9,988	4.3%
Damage Cost (DC)	40	20%	0.73	$ 10,931	1.02	$ 8,759	1.30	$ 6,695	$ 26,386	11.3%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 42,746	1.00	$ 25,844	$ 68,590	29.5%
Maintenance Cost (MC)		20%	1.00	$ 14,953	1.00	$ 8,549	1.00	$ 5,169	$ 28,671	12.3%
								Post-Construction Costs (DC+RC+MC)	$ 133,635	57.5%
								Initial Cost (IC)	$ 98,880	42.5%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 232,515**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 10,104	9.26	$ 39,579	25.00	$ 64,611	$ 114,294	19.8%
Damage Cost (DC)	40	20%	1.91	$ 28,537	11.90	$ 101,776	25.00	$ 129,222	$ 259,534	45.0%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 42,746	1.00	$ 25,844	$ 68,590	11.9%
Maintenance Cost (MC)		25%	1.00	$ 18,691	1.00	$ 10,686	1.00	$ 6,461	$ 35,839	6.2%
								Post-Construction Costs (DC+RC+MC)	$ 478,257	82.9%
								Initial Cost (IC)	$ 98,880	17.1%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 577,137**	100.0%

Live Crib Wall

Live crib walls are designed very similarly to timber cribbing; however only the base layer is filled with stone. The remainder of the crib is filled with alternating layers of sediment and live branches. The result is a box like structure that retains the structural integrity of a crib wall, but one that also promotes habitat growth. The design and cost of the cribs is as discussed above, with soil replacing the majority of the stone. At Henry Hudson Park, it is assumed that the majority of the fill needs can be fulfilled using onsite material. Cost information is summarized in Table 62. An average price of $25/ton was utilized for the cost of recycled fill material. An additional $20,000 is added to the final cost to account for earthwork not directly related to building and filling the cribs.

Table 62 - Cost Summary for Live Crib Wall (Haliburton Cooperative).

Live Crib Wall **(Based off Design of 6'wx6'hx500'l)**			**(WSDT, 2002)**
Items	# of Units	Cost/Unit	Total
Logs, untreated D.Fir, Cedar or Hemlock	5,630	$6.18 /log	$34,782
Willow, pruned live branches (6'x2" diameter)	5,000	$1.74 /cutting	$8,721
Sediment Fill (upper 4.5’)	538	$ 25/ton	$13,450
Stone Fill (lower 1.5’, 40% porosity)	134	$72/ton	$9,648
Total Cost			$66,601
Cost per linear foot			$133.20

The amount of labor required to construct a live crib wall will be the same as for a traditional crib wall with an added expense related to planting the vegetation. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). 600 man hours are allotted for constructing and filling the cribs, with an additional 50 hours added to account for planting. Using a rate of $35/hr, the labor costs are estimated at $22,750. Adding the labor costs to the material costs results in a total estimate of $109,351.

In developing the lifecycle cost for live crib walls, the following assumptions were made:

- Maintenance and repair costs for live crib walls are generally moderate. An estimate of 25% of the IC is set aside for maintenance and repair during each period.
- It is assumed that maintenance and repair costs for living structures will increase significantly under the rapid sea level rise scenario. A 10% increase is applied.

- Wooden cribs have a lifespan of approximately 25-40 years. For the purposes of this analysis, complete replacement is assumed after 30 years.
- Live crib walls are resilient. The following damages are expected during significant storms:

Table 63 - Expected Damage - Live Crib Wall.

T_r	Expected Impacts	Damage Costs (% IC)
50	Moderate overtopping & scour	10%
40	Damage to cribs	20%
25	Loss of vegetation	10%

Although not explicitly considered in this analysis, crib walls and live crib walls can be modified to adapt to rising sea levels through the construction of additional cribs. Such a modification must be carried out carefully however; as increasing the height of the structure changes the pressure distributions. In addition care must be taken to ensure that the additional weight doesn't cause the allowable stress in the timber and the bearing capacity of the earth supporting the structure to be exceeded. Assuming those conditions are met, the cost of adding an additional crib is relatively low.

Live Crib Wall Cost Estimate										
Initial Cost (IC)	$	109,351								
					Current Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	0.56	$ 4,604	0.75	$ 3,549	1.01	$ 2,893	$ 11,046	3.8%
Damage Cost (DC)	40	20%	0.73	$ 12,088	1.02	$ 9,687	1.30	$ 7,404	$ 29,180	10.1%
Damage Cost (DC)	25	10%	1.13	$ 9,311	1.53	$ 7,250	2.14	$ 6,107	$ 22,669	7.9%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 47,272	1.00	$ 28,581	$ 75,854	26.4%
Maintenance Cost (MC)		25%	1.00	$ 20,671	1.00	$ 11,818	1.00	$ 7,145	$ 39,634	13.8%
						Post-Construction Costs (DC+RC+MC)			$ 178,382	62.0%
								Initial Cost (IC)	$ 109,351	38.0%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 287,733**	100.0%

					Rapid Ice Melt Rate of SLR					
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	50	10%	1.35	$ 11,173	9.26	$ 43,771	25.00	$ 71,453	$ 126,397	15.2%
Damage Cost (DC)	40	20%	1.91	$ 31,559	11.90	$ 112,553	25.00	$ 142,906	$ 287,018	34.6%
Damage Cost (DC)	25	10%	3.01	$ 24,905	16.67	$ 78,787	25.00	$ 71,453	$ 175,145	21.1%
Replacement Cost (RC)		100%	0.00	$ -	1.00	$ 47,272	1.00	$ 28,581	$ 75,854	9.1%
Maintenance Cost (MC)		35%	1.00	$ 28,939	1.00	$ 16,545	1.00	$ 10,003	$ 55,488	6.7%
						Post-Construction Costs (DC+RC+MC)			$ 719,901	86.8%
								Initial Cost (IC)	$ 109,351	13.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**								Total Cost	**$ 829,252**	100.0%

Sill

Stone sills have been used extensively in areas like the Chesapeake Bay since the mid 1980's to protect low to medium energy shorelines, and to promote the growth of marshland. Research has shown that a typical cross-section developed by the Maryland Department of Natural Resources (cite), has worked well both within Maryland and when applied elsewhere. The typical cross-section is reproduced below in Figure 14. The recommended stone sizes for low and medium energy sites determined by Hardaway and Byrne (1999) are summarized in Table 64. For the low energy Henry Hudson Park site, a stone size of 300 pounds was selected. Using the Maryland cross section as a guide, the design parameters shown in Table 65 were used to develop the cost for a sill at the Henry Hudson Park site. The suggested dimensions result in a sill with a total cross-sectional area of 69 ft^2/ft. Over 500 ft, the sill has a total volume of 34,719 ft^3. The cost estimate was developed assuming a porosity of 40% for the structure and an average price of $97 per ton of rock.

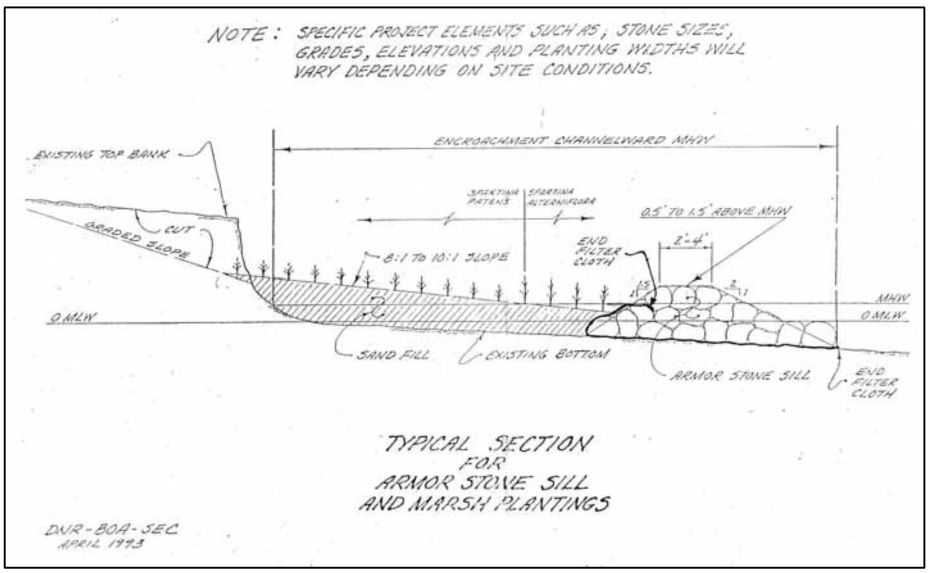

Figure 14 - Typical Cross Section for Sill (DNR, 1993)

Table 64 – Weights for Varying Energy Regimes (Virginia Institute of Marine Science).

Energy Regime	Suggested Stone Size
Low (0-2 feet)	300 - 900 lbs
Medium (2-4 feet)	400 - 1200 lbs

Table 65 – Selected Sill Dimensions for Henry Hudson Park.

Seaward Slope	1V : 2.0H
Shoreward Slope	1V : 1.5H
Crest Width	3 ft
Sill Height	5.5 ft

Table 66 – Material Costs - Sill.

Unit weight of stone	165 lbs/ft^3
Size of stone (D_{n50})	1.82 ft
Volume required	20,831 ft^3
Tons of Stone	1,718
Cost of Sill	$166,700
Cost of Sill per linear foot	$333

The placement of sill stones is generally more precise and requires specialized labor. Labor costs were estimated based on the prevailing wage for marine construction in the State of New York (http://wpp.labor.state.ny.us/wpp/publicViewPWChanges.do). Assuming 500 man hours for construction, at $35/hr, an estimate of $17,500 for labor is obtained. An additional cost of $5,000 is added to the material and labor costs to account for general earthwork, not included in the estimate. This brings the final IC to $189,200.

In developing the lifecycle cost for sills, the following assumptions were made:

- Maintenance and repair costs for sills are generally minimal. An estimate of 10% of the IC is set aside for maintenance and repair during each period.
- Sills are resilient. The following damages are expected during significant storms:

Table 67 - Expected Damage – Sill.

T_r	Expected Impacts	Damage Costs (% IC)
40	Some stone replacement	10%

Although not explicitly considered in this analysis, sills can usually be modified to adapt to rising sea levels by adding stone to build up the crest elevation. With rapid sea level rise however, it is unlikely that sediment accumulation and marsh growth will occur naturally. The cost associated with adding stone to a sill will generally be higher than for similar land based structures due to the additional costs related to marine construction.

Sill Cost Estimate

Initial Cost (IC)	$ 189,200									
			Current Rate of SLR							
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	40	10%	0.73	$ 10,458	1.02	$ 8,380	1.30	$ 6,406	$ 25,243	10.4%
Maintenance Cost (MC)		10%	1.00	$ 14,306	1.00	$ 8,179	1.00	$ 4,945	$ 27,430	11.3%
							Post-Construction Costs (DC+RC+MC)		$ 52,674	21.8%
							Initial Cost (IC)		$ 189,200	78.2%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 241,874**	100.0%

			Rapid Ice Melt Rate of SLR							
			Period 1 (2012-2037)		Period 2 (2037-2062)		Period 3 (2062-2082)		Total (2012-2082)	
Category	Storm T_r	% IC	# Events	*Cost	# Events	*Cost	# Events	*Cost	Extended Cost	% Final
Damage Cost (DC)	40	10%	1.91	$ 27,301	11.90	$ 97,370	25.00	$ 123,628	$ 248,300	53.4%
Maintenance Cost (MC)		10%	1.00	$ 14,306	1.00	$ 8,179	1.00	$ 4,945	$ 27,430	5.9%
							Post-Construction Costs (DC+RC+MC)		$ 275,730	59.3%
							Initial Cost (IC)		$ 189,200	40.7%
***Costs are calculated as the IC x %IC x #Events with inflation and discounting applied mid period**							Total Cost		**$ 464,930**	100.0%

Summary

Cost analyses were conducted to compare the relative costs of stabilizing five hundred linear feet of shoreline at three different locations over a seventy year period. The three different sites are representative of the diverse shorelines found within the Hudson River Estuary and include a narrow deep section, a wide shallow section, and something in between. Ten stabilization alternatives were considered at each site and two different sea level rise scenarios were applied. The ten approaches selected include: timber bulkheads, steel sheet pile bulkheads, bio-walls, revetments, rip-rap, joint planting, vegetated geogrids, timber cribbing, live crib walls, and sills. The two sea level rise scenarios represent the persistence of the existing trend, and the so-called rapid ice melt scenario. Overall, a total of forty cost estimates were prepared. All of the cost estimates were developed using a lifecycle cost approach in present day (2012) dollars, with the costs separated into four main categories:

- Initial Construction (IC) cost – the up-front costs associated with constructing each of the shoreline stabilization alternatives as designed,
- Maintenance and Repair (MC) costs - costs associated with inspecting and performing basic maintenance for each approach,
- Damage costs (DC) - costs directly attributable to specific storm impacts such as scour and overtopping,
- Replacement costs (RC) – costs to replace structures that have reached the end of their useful life.

The results of the analysis are summarized in Table 68. At the Poughkeepsie site, six of the nine alternatives had a cost of between $300,000 and $400,000 under the current sea level rise scenario. Given the uncertainties related to prices, inflation, discounting, performance, etc. the cost of each of these approaches is essentially the same. The group of six similarly priced alternatives includes a combination of traditional as well as ecologically enhanced structures. The cost of the joint planting alternative is driven up by the RC associated with replanting the vegetation after every 10-year storm, while the higher costs for bio-walls and steel sheet pile bulkheads are driven by the higher IC and the RC associated with material degradation.

At the Henry Hudson Park site under the current sea level rise scenario, all of the alternatives were generally cheaper due to the moderate slope and more sheltered location. While the cost analysis showed that rip-rap was the cheapest alternative, other factors such as the likelihood of ice suggest that rip-rap may not represent the best alternative. A second group of five alternatives were estimated to cost between $200,000 and $300,000. Once again, this grouping includes both traditional structures such as wooden bulkheads, as well as ecologically enhanced alternatives such as sills and vegetated geogrids.

At Bowline Point Park a majority of the vertical alternatives were excluded from the analysis due to the lack of natural relief at the site. Of the four alternatives that were considered, the sill was found to be the cheapest. The primary reason is that during large storms, sills have been found to be remarkably stable. Typically, the storm surge submerges the structure thereby protecting it from the damaging waves and currents. Revetments and rip-rap were once again found to be similar in cost with revetments being slightly cheaper due to their enhanced stability in bigger storms.

Table 68 - Summary of Cost Estimate.

Current Sea Level Rise Scenario			
	Poughkeepsie	Henry Hudson Park	Bowline Point Park
Wooden Bulkhead	$ 375,292	$ 271,348	N/A
Steel Bulkhead	$ 1,255,906	$ 989,845	N/A
Revetment	$ 340,984	$ 315,930	$ 313,642
Rip rap	$ 318,896	$ 143,292	$ 325,113
Crib Wall	$ 308,531	$ 232,515	N/A
Live Crib Wall	$ 372,794	$ 287,733	N/A
Joint Planting	$ 491,088	$ 231,799	$ 496,511
Vegetated Geogrid	$ 300,315	$ 269,136	N/A
Bio Wall	$ 1,102,131	$ 569,330	N/A
Sill	N/A	$ 241,874	$ 173,106
Rapid Sea Level Rise Scenario			
	Poughkeepsie	Henry Hudson Park	Bowline Point Park
Wooden Bulkhead	$ 688,203	$ 497,593	N/A
Steel Bulkhead	$ 2,372,407	$ 1,869,818	N/A
Revetment	$ 1,081,098	$ 1,001,664	$ 994,407
Rip rap	$ 1,133,764	$ 509,442	$ 1,077,429
Crib Wall	$ 765,821	$ 577,137	N/A
Live Crib Wall	$ 1,074,401	$ 829,252	N/A
Joint Planting	$ 1,826,545	$ 862,150	$ 1,846,714
Vegetated Geogrid	$ 648,316	$ 581,007	N/A
Bio Wall	$ 2,185,780	$ 1,129,114	N/A
Sill	N/A	$ 464,930	$ 332,745

Costs rise significantly under the rapid sea level rise scenario primarily because the number of damaging storms and therefore the DC increase markedly. Under the rapid sea level rise scenario, Maintenance Costs (MC), Damage Costs (DC), and Replacement Costs (RC) typically make up 75% of the total cost; a significant increase from approximately 50% under the current sea level rise scenario. At Poughkeepsie, three of the nine alternatives considered have lifecycle costs less than one million dollars, while three more have costs just over one million dollars. Both groupings contain at least one ecologically enhanced approach. At Henry Hudson Park, five of the ten approaches have cost estimates ranging from $400,000 to $600,000. While this group includes vegetated geogrids and sills, other ecologically advanced techniques were found to cost significantly more. This is primarily due to the fact that under the rapid sea level rise scenario, the vegetation needs to be replaced much more frequently. At Bowline Point Park, the sill remains the cheapest alternative. Since sills are submerged structures, they sustain minimal damage during storms; however they also lose their effectiveness with time.

Within the limitations of the analysis, the results show that at most sites there is a suite of alternatives for which the lifecycle costs are relatively similar. Given the uncertainties associated with many aspects of the economic valuations, the error bands on the results are such that many of the costs are functionally equivalent. Generally, these groups of similarly priced alternatives contain at least one alternative that has been ecologically enhanced. This finding is consistent with a recent NOAA report entitled *Weighing Your Options* (Seachange Consulting, 2011) that determined the costs of many "living shorelines" stabilization approaches was on par with bulkheads. While ecologically enhanced structures may not be the cheapest overall, this analysis confirms that over a seventy year period under both the current and rapid sea level rise scenarios, several of the ecologically enhanced approaches are cost competitive with some of the traditional approaches.

Glossary of Terms

Bio-wall - Walls or barriers that incorporate living plants or stakes into their design. This term is used to refer to a collection of approaches, all of which attempt to soften a traditionally hard edge through the introduction of ecologically friendly modifications.

Bulkhead – Traditionally, the most common shoreline hardening technique used to protect vulnerable and eroding shorelines. Used at the base of bluffs or steep shorelines, bulkheads are vertical walls which prevent the loss of soil and the further erosion of the shore.

Crib Wall – Box-like arrangement of interlocking logs, timbers, precast concrete or plastic structural members are used to form a crib, which is then filled with broken rock.

Live Crib Wall - A live crib wall is a three-dimensional, box-like chamber that is constructed out of untreated log or timber and is placed at the streams base flow level. The interior of the structure has alternating layers of soil and/or fill material and live branches that are meant to root themselves inside the box and eventually extend into the slope of the bank.

Joint Planting - Joint planting consists of adding live stakes or vegetation into open spaces or joints in an already existing or to be constructed rip-rap, or rock covered slope. As the stakes mature, they create a living root mat beneath the structure that binds the soil and prevents additional soil erosion.

Revetment - Revetments are shore attached structures built to protect natural sloping shorelines against wave energy and erosion. Revetments use large rocks (or other materials) on the front of a dune or stream bank to dissipate wave and/or current energy to prevent further recession of the backshore.

Rip-rap - A rip-rap slope functions similar to a revetment; however they are constructed from small rocks, cobble and gravel, instead of large stones. Rip-rap structures armor the shoreline by providing a base layer, which is stable under normal stream flow conditions.

Sill – Low-profile, shore parallel mounds placed offshore with the purpose of retaining sediment and elevating the nearshore profile. Sills can be constructed of natural (stone, soil, etc.) or synthetic (geotextile rolls) materials and are typically used as part of a perched beach system.

Vegetated Geogrid - A vegetated geogrid is a terraced wall consisting of alternating horizontal layers of soil wrapped in synthetic fabric and live branch cuttings. The live branch cuttings serve to both reduce the wave energy and shear stress on the wall and bind the geogrid together, as the vegetation matures.

References

Allen, G., Cook, T., Taft, E., Young, J., and D. Mosier, 2006. *Hudson River Shoreline Restoration Alternatives Analysis*. Prepared by Alden Research Laboratory, Inc. and ASA Analysis and Communications, Inc.

Allen, H.H. and J.R. Leech, 1997. *Bioengineering for Streambank Erosion Control, Report 1: Guidelines*. U.S. Army Engineer Waterways Experiment Station, TR-EL-97-8.

Army Budget Office, Budget Formulation Division, 2002. *Inflation and Real Growth Handbook.*

Blankenship, Tim K., 2004 *To Repair or Replace a Bulkhead: That is the Question*. Coastal Systems International, Inc. <http://www.coastalsystemsint.com/media/ pop_marina_dock_age.htm>.

Bruno, M., Fullerton, B., and R. Datla, 2002. *Ferry Wake Wash in NY/NJ Harbor.* Hoboken: Davidson Laboratory-TR SIT-DL-02-9-2812.

Caulk, A.D., Gannon, J.E, Shaw, J.R. and J.H. Hartig, 2000. *Best Management Practices for Soft Engineering of Shorelines*. Greater Detroit American Heritage River Initiative, Detroit, Michigan.

Center for Sustainable Design, 1999. *Water Related Best Management Practices in the Landscape*. Mississippi State University.

CIRIA, CUR, CETMEF, 2007. *The Rock Manual. The Use of Rock in Hydraulic Engineering (2nd edition)*. C683, CIRIA, London, 1268 pp.

City of Rockville Department of Public Works, 2003. *Standard Prices for Cost Estimating and Permit Applications*.

Committee on Mitigating Shore Erosion along Sheltered Coasts, National Research Council, 2007. *Mitigating Shore Erosion on Sheltered Coasts*. National Research Council of the National Academies, The National Academies Press, Washington, D.C. 174 pp.

Cramer, M., Bates, K., Miller, D. and K. Boyd, 2002. *Integrated Streambank Protection Guidelines*. Washington State Aquatic Habitat Guidelines Program

Davis, J. E. and S.T. Maynord, 1998. *Shoreline and Channel Erosion Protection: Overview of Alternatives*. Wetlands Research Program Technical Notes Collection (WRP Technical Note HS-RS-4.1), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Davis, J. E. and S.T. Maynord, 1998. *Wetland Shoreline Protection and Erosion Control: Design Considerations*, Wetlands Research Program Technical Notes Collection (WRP Technical Note HS-RS-3.1), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

DCR, 2012. *The Virginia Stream Restoration and Stabilization Best Management Practices Guide, Workshop*. Department of Conservation and Recreation.

DCR, 2004. *The Virginia Stream Restoration and Stabilization Best Management Practices Guide.* Division of Soil and Water Conservation, Richmond, Virginia.

Devore, D., 2010. *Cost and Maintenance of Living Shorelines.* South Florida Ecological Services Office, Vero Beach, Florida.

DNR, 2005. *Shore Erosion Control, The Natural Approach.* Maryland Department of Natural Resources.

Douglass, S., and J. Chen, 2004. *Overview of Coastal Engineering II Revetment Design*. Presentation given at FHWA National Hydraulics Conference, Asheville, NC.

Erdle, S., Davis, J.L.D., and K.G. Sellner, eds. 2008. *Management, Policy, Science and Engineering of Nonstructural Erosion Control in the Chesapeake Bay*: *Proceedings of the 2006 Living Shoreline Summit*. CRC Publ. No. 08-164, Gloucester Point, VA. 136 pp.

EPA, 1993. *Management Guidance, Streambank and Shoreline Erosion Managment Measure.*

FEMA, 2000. *FEMA National US&R Response System Structural Collapse Technician, Modula 2a Shoring Basics.*

Finkel, Shimrit, 2011. *EcoConcrete: Concrete Ecological Solutions*.

Fischenich, J.C., 2001. *Impacts of Stabilization Measures.* EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-32), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Fischenich, C., 2001. *Stability Thresholds for Stream Restoration Materials.* EMRRP Technical Notes Collection (ERDC TNEMRRP-SR-29), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

GeoSyntec Consultants, 2006. *Massachusetts Nonpoint Source Pollution Management Manual*. Prepared for the Massachusetts Department of Environmental Protection.

Haliburton Cooperative, 2008. *Solutions to Riverbank Erosion: A Summary of Current Shoreline Stabilization Techniques for the Gull River In Minden, Ontario.*

Hardaway, C. C., and R.J. Byrne, 1999. *Shoreline Management in Chesapeake Bay VSG-99-11.* Virginia Sea Grant. Virginia Institute of Marine Science, Gloucester Point, VA.

Hardaway, C.S., Milligan, D. and K. Duhring, 2010. *Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments.* Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Herrington, T.O., Datla, R., and R. Royce, 2005. *Alternative Shoreline Stabilization Structures: Physical Model Tests*. Davidson Laboratory, TR SIT-04090284.

Hoag, J.C., 2000. *Costs and Considerations of Streambank Bioengineering Treatments*. Riparian/Wetland Project Information Series No. 15. USDA- Natural Resources Conservation Service.

Iowa Department of Natural Resources, 2006. *How to Control Streambank Erosion*. <http://www.ctre.iastate.edu/erosion/manuals/streambank_erosion.pdf>

Jefferson Patterson Park & Museum, 2006. *Site #4 – Sills, Living Shorelines Tour*. Maryland Department of Planning.

Maryland Department of the Environment, 2000. *Maryland's Waterway Construction Guidelines*. Water Management Administration.

MD Eastern Shore RC&C Council Inc. *Stream Restoration, Using Bioengineering Techniques "A Demonstration Project"*, Rock Creek Park, Frederick City.

Michael Kosiw, K. P., 2008. *Solutions to riverbank erosion: A summary of current shoreline stabilization techniques for the Gull River in Minden, Ontario*.

Miller, D., 2006. *Understanding and Managing Hudson River Shorelines*. Presentation given at Hudson River Estuary Shorelines Workshop, Soft Engineering Solutions to Shoreline Stabilization.

Miller, D., C. Bowser, J. Eckerlin, 2006. *Shoreline Classification in the Hudson River Estuary*. Unpublished, NYSDEC Hudson River National Estuarine Research Reserve.

National Oceanic and Atmospheric Administration. *Living Shorelines*. NOAA Restoration Portal. <http://www.habitat.noaa.gov/restoration/techniques/lsimplementation.html>.

National Resource Conservation Service, 2007. *National Engineering Handbook*. United States Department of Agriculture, USACE.

New York City Panel on Climate Change, 2009. *Climate Risk Information*.

New York State Soil and Water Conservation Committee, 2005. *New York State Standards and Specifications for Erosion and Sediment Control*. New York State Department of Environmental Conservation.

North Carolina Division of Coastal Management, 2008. *Coastal Hazards & Storm Information :: Estuarine Shoreline Stabilization Options*. http://dcm2.enr.state.nc.us/Hazards/estuarinestabilization %20options.htm>.

Northwest Regional Planning Commision, 2003. *The Shoreline Stabilization Handbook for Lake Champlain and Other Inland Lakes.* National Sea Grant Library Publication LCSG-04-03.

NSP, 2006. *Live Stakes Fact Sheet, NSP Management Manual.* Nonpoint Source Pollution, Massachusetts.

NSP. 2006. *Vegetated Geogrid Fact Sheet, NSP Management Manual.* Nonpoint Source Pollution, Massachusetts.

Lee, T., 2012. *Riprap Revetments*. Ohio Stream Management Guide, Fact Sheet 16. Ohio Department of Natural Resources, Divisions of Engineering.

Partnership for the Delaware Estuary, 2012. *Final Report, Delaware Living Shoreline Possibilities*.

Perkol-Finkel, Shirmrit. *Personal Communication.* June 15, 2012.

Rich, B., 2012. *Living Shorelines: The Natural Alternative.* North Carolina Coastal Federation, 2012.

Rich, B., 2012. *Living Shorelines Require Careful Planning.* North Carolina Coastal Federation, 2012.

Seachange Consulting, 2011. *Weighing Your Options, How to Protect Your Property from Shoreline Erosion: A Handbook for Estuarine Property Owners in North Carolina*. Center for Coastal Fisheries and Habitat Research.

Shafer, D. J., Roland, R., and S.L. Douglass, 2003. *Preliminary Evaluation of Critical Wave Energy Thresholds at Natural and Created Coastal Wetlands.* WRP Technical Notes Collection (ERDC TN-WRP-HS-CP-2.2), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Smylnycky, N., 2012. *2012 Discounting Guide*. TACOM LCMC Cost and Systems Analysis, TP 2012-027.

Sotir, R. B., and J. C. Fischenich. 2007. *Live Stake and Joint Planting for Streambank Erosion Control*. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-35), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Stormwater Management Resource Center. *Stream Restoration: Bank Protection Practices*. <http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Restoration/bank_protection.htm>

Storrar, C., 2007. *Alternatives for Addresing Pheasant Branch Creek "Mini-Hemble" Slope Failure.*

Swan River Trust, 2008. *Best Management Practices, Chapter 8: Rock Revetments.*

Thom, R.M., Shreffler, D. and K. Macdonald, 1994. *Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington*. Coastal Erosion Management Studies, Volume 7. Washington State Department of Ecology

Urban Creeks Council, 2006. *Live Staking and Joint Planting*. Contra Costs Clean Water Program

U.S. Army Corps of Engineers (USACE), 1977. *Shore Protection Manual*. Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C.

U.S. Army Corps of Engineers (USACE), 1981. *Low Cost Shore Protection…a Guide for Engineers and Contractors*. A Report of the Shoreline Erosion Control Demonstration Program (Section 54 Program).

U.S. Army Corps of Engineers (USACE), 1993. *Review of Recent Geotextile Coastal Erosion Control Technology.* Department of the Army, Washington, D.C.

U.S. Army Corps of Engineers (USACE), 2000. *A Guide to Developing and Documenting Cost Estimates During the Feasibility Study.* OSWER No. 9355.0-75. SUPERFUND Program.

U.S. Army Corps of Engineers (USACE), 2001. *Plant Material Acquisition, Layout, and Handling for Flood Control Projects. ERDC TR-01-14.* Flood Damage Reduction Research Program.

U.S. Army Corps of Engineers (USACE), 2002. *Coastal Engineering Manual*. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, D.C. (in 6 volumes).

U.S. Army Corps of Engineers (USACE), 2006. *Coastal Engineering Manual, Chapter VI, Design of Coastal Project Elements.* Coastal Engineering Manual.

U.S. Army Corps of Engineers (USACE), 2008. *Construction Cost Estimating Guide for Civil Works*. CECW-EC- Technical Letter No. 1110-2-573. Department of the Army, Washington, D.C.

U.S. Army Corps of Engineers (USACE), 2012. *Economic Guidance Memorandum, 12-01, Federal Interest Rates for Corps of Engineers Projects for Fiscal Year 2012.* Memorandum for Planning Community of Practice.

U.S. Army Corps of Engineers (USACE). *Revetments*. Fact Sheets, Low Cost Shore Protection, St. Paul District.

U.S. Department of Agriculture, 1996. *Engineering Field Handbook, Chapter 16: Streambank and Shoreline Protection*. Natural Resources Conservation Service.

U.S. Environmental Protection Agency, 2012. *Climate Ready Estuaries 2012 Progress Report.* EPA Office of Water, Oceans and Coastal Protection Division.