Resilient Stormwater and Tidal Flooding BMP in Norfolk, Virginia

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Abstract

The City of Norfolk, like many coastal cities around the globe, is experiencing increased flooding due to more intense storm events combined with sea level rise, both a result of climate change. This report will outline the design of a series of Best Management Practices (BMPs) which will reduce both types of flooding in the South Brambleton neighborhood of Norfolk, VA. This BMP in series concept is known as a “treatment train,” a concept which will be expanded upon in a later section. The success of the design will be evaluated along the following criteria: attenuate stormwater peaks by 20% for a 100-year flood storm event, reduce sediment by 20%, create a plant community with a Shannon Diversity Index (SDI) of at least 2.5, and maintain a functional design life of 20 years given .41 meters of sea level rise and an associated increase in salinity.

This treatment train design was developed for a highly constrained site. Norfolk is a highly developed urban landscape, and adjacent infrastructure was abundant at our design site. This includes rail track, an overpass, light rail line, roads, existing culverts, among other things. A primary constraint of the design was to disrupt this existing infrastructure as little as possible. It must also stay within a $2 million budget and should abide by all relevant VA DEQ stormwater management codes. Also, the design was developed with longevity in mind. Creating a design that might adapt to changing hydrological, environmental, and social factors was a top priority for the design team. These constraints, criteria, goals, and objectives are summarized in the following, and a design solution will be presented. This includes a Civil 3D CAD drawing, estimates of pollutant reductions, wetland planting schedules, economic analysis, and a long-term maintenance plan.

Acknowledgements

We would like to thank our advisors, Dr. David Sample and Dr. Venkat Sridhar, for their enduring support, patience, and feedback; Ms. Shereen Hughes from Wetlands Watch for showing us the possibilities of green infrastructure; Mr. Justin Shafer from the City of Norfolk for taking the time to answer all the technical questions we had along the way; and finally, Dr. Cully Hession for his constant words of encouragement and for facilitating this whole project.

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Problem Statement

South Brambleton, a neighborhood in Norfolk, VA, is under threat from stormwater and tidal flooding. A plot of land in this area is being considered for redevelopment to address these challenges while providing community green space. This design must be resilient, capable of adapting to changing climatic and hydrologic conditions, while also preserving nearby infrastructure.

Background

The 21st century has seen an unprecedented rise in climate change tied to anthropogenic activities. Warming temperatures have expedited the recession of polar ice sheets and freshwater glaciers and have thereby caused sea levels to rise rapidly across the world (Church et al., 2008). Amid these climatic shifts, some regions have also experienced an uptick in storm severity and storm frequency. This combination of stormwater and tidal flooding poses significant risks to many communities along the Atlantic coastline, including the city of Norfolk in the Chesapeake Bay region of Virginia. In was reported that in 2023, Sewell's Point in Norfolk experienced the worst flooding in the past decade out of 34 sites surveyed on both coasts of the United States (EPA, 2023).

The neighborhood of South Brambleton in Norfolk, Virginia is located adjacent to the Elizabeth River, a tributary of the James River and the Chesapeake Bay. It holds special value due to its location in a historically black neighborhood dating back to the segregation era of the 20th century (Ringelstein, 2015). The tidally influenced Elizabeth River and the rising intensity in storms have placed the area under threat of flooding in recent years. Much of South Brambleton's existing stormwater infrastructure is easily overwhelmed during periods of seasonal high tide, while other structures have deteriorated in place due to negligence. The City of Norfolk has funded several redevelopment projects to combat these challenges, including a major overhaul of the nearby neighborhood of St. Paul (SOURCE). South Brambleton, however, is impacted by numerous obstacles that can restrict the placement of BMPs. The neighborhood and its important buildings and infrastructure are highlighted in Figure 1.

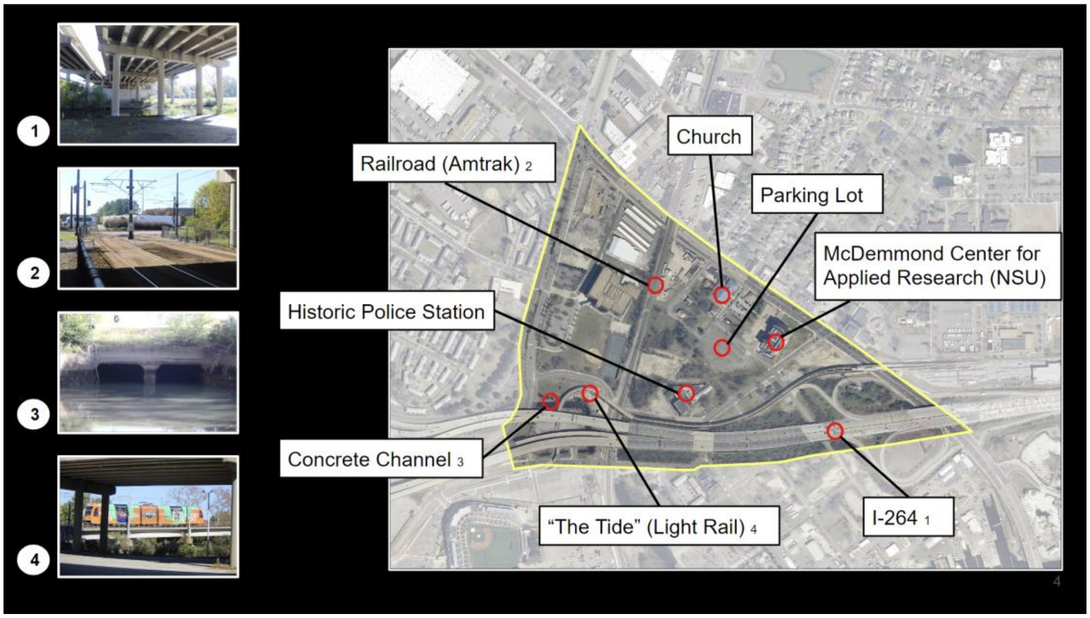

Figure 1. Existing infrastructure in South Brambleton neighborhood of Norfolk, VA

Goals and Objectives

Design a multi-use stormwater BMP;

- To reduce flooding from both stormwater and tidal inundation
- Contribute to the aesthetic value of the neighborhood
- Provide wildlife habitat
- Transition to a saltmarsh buffer zone after the design life of the project

Criteria and Constraints

There are multiple constraints that we need to take into consideration when planning the design. One of the biggest constraints is the physical constraints. As shown in Figure 1, there are a few buildings in the watershed that need to be worked around as well as the Amtrak railroad. The Amtrak railroad in particular creates some challenges since it prevents the possibility of a surface channel outlet and makes creating new culvert outlets extremely expensive. This leads us to the constraint of cost. The City of Norfolk gave us a budget of $2 Million for this project so we must keep our design within that range. The design must abide by the Virginia DEQ Stormwater Management Codes.

Our main criteria is to attenuate the stormwater and peak flows. It is important that our design reduces flooding on the existing infrastructure shown in Figure1. Some other criteria for our design is to reduce the pollutant loads on the creek it is draining into. The goal is to reduce sediment load by 20% and to reduce the nitrogen and phosphorus load by 45% and 20% respectively. It is also important to create a design that will be able to function for years to come. Our goal is for our design to maintain a functional life of 20 years.

Methodology

Analysis of Potential Solutions

The combination of tidal and stormwater flooding can easily overwhelm existing stormwater management infrastructure. In order to address these issues, a four-step treatment train composed of conveyance, storage, treatment and release was originally proposed. After analyzing a range of potential solutions for each of the four steps included within the treatment train, the most appropriate BMPs were selected accordingly based on the criteria highlighted and the respective decision matrices. River rock channels were chosen for treatment due to their effectiveness as slowing peak flow velocity and their aesthetic value. A lined retention pond was chosen over unlined retention pond and other BMPs for storage due to its higher pollutant removal rate, but also the ability to prevent bank erosion, seepage, and further contamination of stormwater runoff. Constructed wetlands were selected for the treatment stage for maintenance, habitat, aesthetics, and pollutant removal capacity when compared to swales. Finally, for the release mechanism, surface channels are most suitable due to their long service life and adaptability. The potential solutions were all ranked based on each criteria using decision matrices which can be found in Appendix A.

After working more on the project and analyzing the site the final design chosen was a wet pond for storage where the stormwater is conveyed and released by an existing concrete channel and existing stormwater pipes. The second part of the design is a riparian buffer on the tidal creek. The location of the wet pond was chosen because it is the low spot of the watershed. Although this area is wooded and would need to be cleared for our design, we noticed on our site visit that the vegetation was primarily invasives. We also decided to have the stormwater leave the pond through existing pipes because the railway prevents a surface channel.

Design Storm Modeling

In order to correctly size our BMP structures watershed modeling was conducted using HEC-HMS. This was done to obtain peak flow values as well as a total volume of water from a storm. There are multiple inputs needed to create a model. First a 10m DEM of the watershed was given to our team by our client Wetlands Watch. A curve number was calculated based on land use and hydrologic soil group (*HEC-RAS Manual*, 2024). Soil maps were found from Web Soil Survey. Most of the area was hydrologic soil group C and the rest had no data. The watershed was assumed to have C soils throughout. The land use and impervious area was defined visually by observations from our site visit as well as aerial imagery. The impervious area was estimated to be 53.4% of the watershed. The weighted curve number of the watershed was calculated using Equation B-1 came out to be 73.5

The lag time was calculated using the different methods laid out by Mehta et al. (2022). The Carter method was chosen to be the most accurate estimate for our watershed. The flow length was calculated using ArcGIS Pro with the Flow Length tool. This gave a flow length of 0.5299 km. Using this ArcGIS layer created with the Flow Length tool, the elevation of the beginning and end of the longest path were identified to be 9.465 m and 1.255 m. These elevations and length were used to calculate the slope: 0.0155 or 1.55%. These values were plugged into Equation B-2 and the Lag Time was found to be 13.98 minutes. The initial abstraction was assumed to be 5 mm due to the extent of pervious area.

These parameters discussed were used to run a HEC-HMS model of the watershed. This was done using a 10 year 24 hour storm obtained from NOAA precipitation frequency data. The model gave us a total volume of 11,500 m^3 and a peak value of 2 m^3/s.

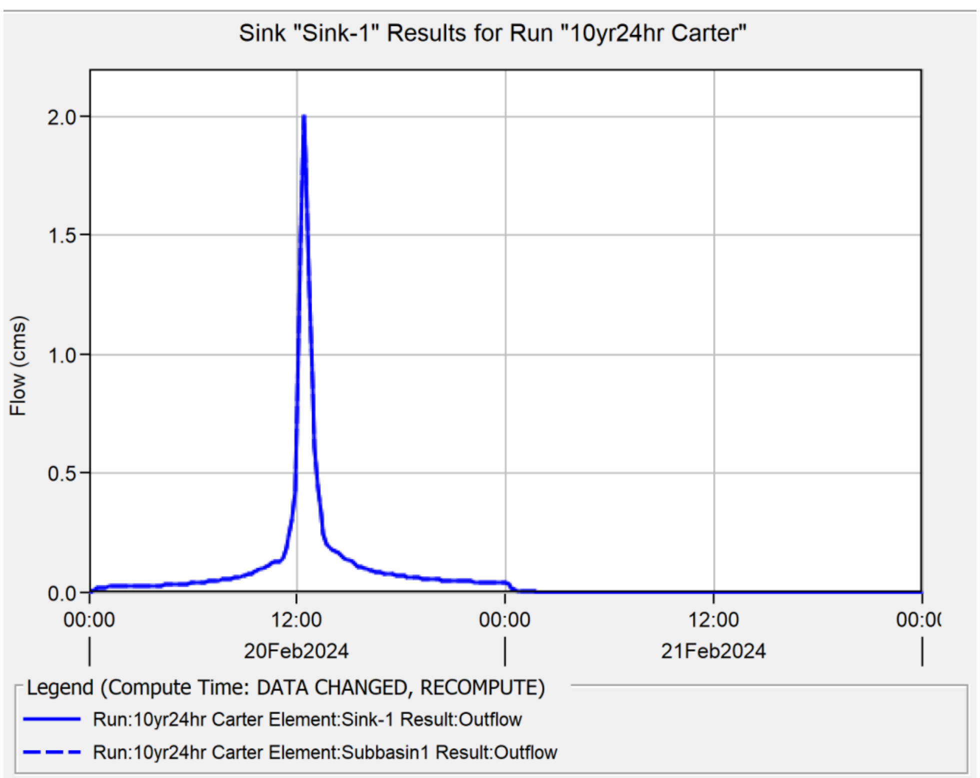

Figure 2. HEC-HMS 10 year 24 hour storm model

Final Design

Wet Pond

Using the results of the modeling, the total storage volume needed for our design was calculated to also include a margin of safety between 5-10%. Our total storage volume came out to 12,388 m^3, with a 7.2% excess storage volume. Within this total design footprint, we allocated significant portions of the design to a variety of elevations based on the existing elevation, so as to both minimize the amount of excavation, and to maximize the different habitat classifications within our design. The permanent ponded area was designed to meet the following criteria:

- Expose the existing stormwater pipes under the site to serve as the primary inputs
- Express the high water table in the low-lying coastal site to provide base storage
- Cover between 1-3% of the contributing watershed area

The final design included a ponded area of 31,397 sqft (2.4% of drainage area) that was at an elevation of –5 ft below the existing ground. From there, the additional storage required for the site was accomplished through the design of an emergent wetland terrace and a shallow grade to the south providing a route for wetland migration. The design areas of each are detailed in table 1, and the profile grade through the site is shown in figure 3.

Figure 3. Wet pond contours within the existing design site.

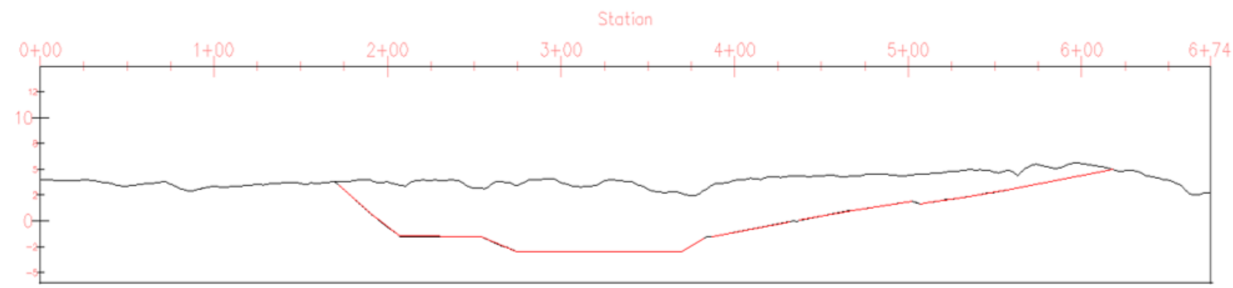

Figure 4: Cross section of the wet pond along the alignment shown in Figure 3.

Classification	Area (ft^2)	Storage Volume (m^3)
Open Water	31,397	1,334
Emergent	18,666	450
Freshwater Marsh	22,226	10,604
Upland	59,502	-
Total	-	12,388

Table 1: Storage volumes and surface area of the different habitat classifications.

Riparian Buffer Area

To address some of the tidal flooding concerns on our site, our primary focus was on the tidal creek connecting the southern edge of the site with the Elizabeth River. This was the source of much of the tidal influence in the site, from the backwards flow of creek water up storm sewers, to the flooding of roads and other infrastructure near the creek channel. By expanding the channel to provide extra storage and including plantings to increase surface roughness and dissipate tidal energy, the design will protect critical infrastructure while also providing a variety of habitats.

Using an adjusted tidal datum for the Norfolk/Portsmouth area, the mean sea level was established as the baseline for design geometry. An intertidal zone with slope of 4.8% provides the necessary conditions for the formation of a low marsh zone experiencing the full daily tidal regime. A grade break to a steeper 6.3% grade serves to limit the extent of current daily tidal activity, but will allow for the gradual upwards migration of the marsh as the mean sea level rises. At the top of the marsh slope, just before the road is an existing depression that will serve as the salt panne. Here excess tidal water will pool during storms and high tide events but will be prevented from returning to the channel through surface flow. Evaporation will concentrate salts in the soil, forming another habitat and further protecting the road.

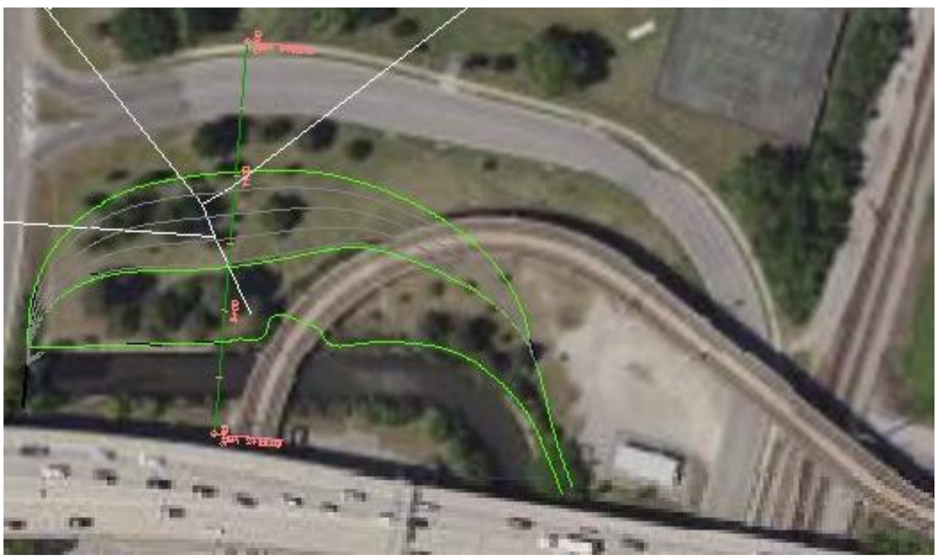

Figure 5. Riparian buffer area design contours with the existing design site.

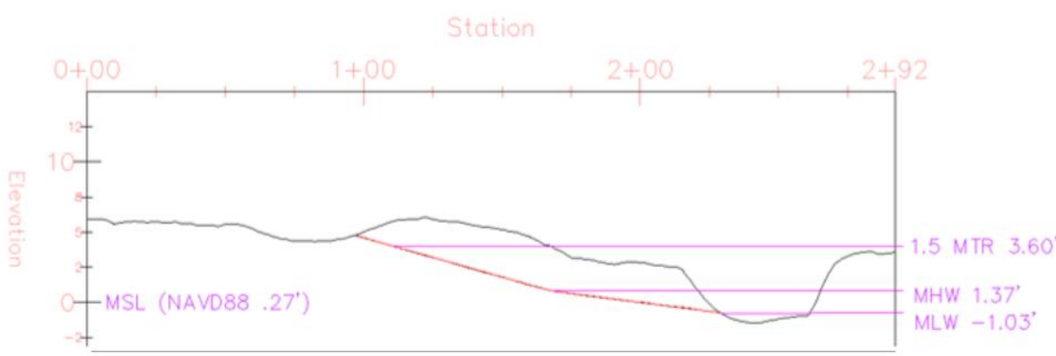

Figure 6. Cross section of the wet pond along the alignment shown in Figure 5.

Planting Zones

While regrading provides much of the flood mitigation benefits of this design, the nutrient treatment, habitat creation, and greenspace aspects of this project are a function of the planting plan. For this project, the wet pond and the riparian buffer area were each split into three sections, each corresponding to a different inundation regime. For the wet pond, those zones were designated as “emergent”, “peripheral”, and “upland.” For the riparian buffer area, those zones were designated as “low marsh,” “high marsh,” and “salt panne.” The total area of each of these six zones is summarized in the chart below.

Habitat Zone	Planting Area (ft^2)
Emergent	18,666
Peripheral	22,226
Upland	59,502
Low Marsh	25,915
High Marsh	10,571
Salt Panne	8,512

Table 2. Planting zone categories and areas

The emergent planting zone consists of predominantly freshwater plants growing beneath 0-6in of water. They will be planted along the perimeter of the permanently ponded area and provide habitat for birds, reptiles, and amphibians, among other species. The peripheral planting zone will be above the emergent planting zone in terms of elevation and features many shrubs-like vegetation that will provide pollinator habitat. The upland planting zone for the wet pond will feature mostly trees and will be a shaded area that will provide both wildlife habitat and community green space. To increase the biodiversity of the upland planting area, a native grass seed mix will be used between tree plantings.

Like the wet pond, the planting zones for the riparian buffer area were delineated based on the corresponding inundation regime. However, because this part of the design site experiences tidal dynamics (it is an arm of the Elizabeth River), the inundation status of each zone is slightly more complicated. Instead of being based simply on permanent inundation status (like the wet pond) the planting zones for the riparian buffer area are based on inundation *frequency.* For example, the low marsh zone will experience a full range of tidal inundation daily. At high tide, it will be completely submerged, and at low tide it will be dry. The high marsh zone will largely be dry but will be fully inundated twice per day at high tide. The salt panne zone will remain dry throughout the year but will be inundated during a storm surge.

The following tables summarize the plants used for each of the six planting zones.

Riparian Buffer Vegetation	Habitat Type
Juncus roemerianus	Low Marsh
Scirpus robustus	Low Marsh
Spartina alterniflora	Low Marsh
Spartina cynosuroides	Low Marsh
Atriplex patula	Salt Meadow
Distichlis spicata	Salt Meadow
Limonium spp.	Salt Meadow
Spartina patens	Salt Meadow
symphyotrichum tenuifolium	Salt Meadow
Baccharis halimifolia	Salt Panne
Borrichia frutescens	Salt Panne
Hibiscus moscheutos	Salt Panne
Iva frutescens	Salt Panne
Kostelezkya virginica	Salt Panne
Panicum virgatum	Salt Panne
Salicornia spp.	Salt Panne
Solidago sempervirens	Salt Panne
Quercus phellos (tree)	Upland
Native Short Grass Seed mix	Upland

Table 3. Riparian Buffer Vegetation

Retention Pond Vegetation	Habitat Type
Cephalanthus occidentalis (shrub)	Emergent
Ilex glabra (shrub)	Emergent
Alnus 9errulate (tree)	Emergent
Azalea viscosum (shrub)	Emergent
Rosa palustris (shrub)	Emergent
Nyssa biflora (Tree)	Emergent

Juncus spp. (sedge)	Emergent
Carex spp. (rush)	Emergent
Sambucus canadensis	Peripheral
Ilex verticillatta	Peripheral
Magnolia virginiana (tree)	Peripheral
Platanus occidentalis (tree)	Peripheral
Acer rubrum (tree)	Upland
Liquidambar styraciflua (tree)	Upland
Quercus nigra (tree)	Upland

Table 4. Retention Pond Vegetation

Filterra® Units

The team also proposes the replacement of two Contech Filterra® units adjacent to the McDemmond Center parking lot. Filterra® units function primarily as bioretention systems, with the capacity to remove nitrogen, phosphorus, and heavy metals through a combination of microbial degradation, sedimentation, and plant uptake (Coffman & Siviter, 2009). This is especially relevant for urban settings where heavy metal contamination occurs more frequently. A set of properly functioning Filterra® units can achieve total suspended solids (TSS) removal efficiencies of over 90%, as well as total phosphorus (TP) and total Kjeldahl nitrogen (TKN) removal of efficiencies of over 50% and 20%, respectively (Yu & Stanford, 2007).

The two former units located near the parking lot have likely fallen into neglect and are in a state of disrepair; however, retaining their current position allows for stormwater capture near the impervious lot and for treatment to occur earlier in the BMP series. While the bases of the structures remain, the concrete box and tree grate presently occupy vacant units. This problem is exacerbated by downstream flooding that can force water to back up the underdrain system and up towards the tree grate. Despite the present concrete curb and Filterra® containers being compatible with our design, it is probable that any old mulch and underdrain systems will need to be completely replaced. A replanting of vegetation and replacement of the soil-microbe complex can be conducted once the previous elements have been successfully excavated and removed.

Cost Estimate

A cost analysis was performed to assess the monetary requirements to implement and maintain our design, which is laid out in Table 5. This cost analysis can be separated into three main sections: cost of materials and equipment, cost of vegetation, and cost of maintenance. Unit quantities for area and volume, such as for each of the vegetation types or for excavation, are taken from zone areas and excavation volumes that were calculated earlier in the design process. These were then paired with unit costs to provide total costs for each category. Vegetation costs were calculated by finding pricing for plug sets or for individual pots (larger trees/shrubs) on websites of native nurseries in the region, including Delmarva Native Plants, Mid Atlantic Native Plant Farm, and Wetland Plants, Inc. as recommended by our advisor Justin Shafer of the City of Norfolk. The prices of individual plants used in our design were then multiplied using an evenly spaced planting regime occupying each planting zone. Costs for labor are estimates based on a recent project cost analysis generously provided to the team by advisor Shereen Hughes of Wetlands Watch. Our total cost to construct the team's design, excluding recurring maintenance costs, is $269,906.68, which is well within the current $2 million budget.

Materials & Equipment	**Unit Cost**	**Unit**	**Quantity**	**Total Cost**
Clearing Existing Vegetation	$3,500	/AC	1.84	$6,440
Excavation	$10	/CY	16,322	$163,220
Erosion & Sediment Control	$1,053.17	/200 FT	200	$1,053.17
Standpipe/ Riser	$501.80	/U	1	$501.80
Filterra® Unit	$25,500	/U	2	$51,000
Vegetation (Riparian Buffer Area)				
Low Marsh	$6.38	/SY	2,879 SY	$18,370.86
Salt Meadow	$4.41	/SY	1,175 SY	$5,179.79
Salt Panne	$5.97	/SY	946 SY	$5,646.29
Vegetation (Wet pond)				
Emergent	$4.62	/SY	2,074 SY	$9,581.88
Peripheral	$1.28	/SY	2,470 SY	$3,161.03
Upland	$.87	/SY	6,611 SY	$5,751.86
Maintenance	**Rate**		**Basis**	**Cost / year**

Landscaping	$27	/HR/person	2	$54
Plant Checkup (annual)	$27	/HR/person	4	$108
Culvert / Inlet Debris Removal	$27	/HR/person	4	$108
Total				$269,906.68

Table 5. Cost Analysis

Conclusion

Norfolk, VA, like many coastal cities, is experiencing a worsening situation with respect to flooding. This is happening not only because of climate change, but also land subsidence. As a result, the ocean is rising at a rate of approximately 5.4mm/yr (Malmquist, 2023). To make matters worse, the sea level rise happening in Norfolk is occurring in a highly urbanized area, obfuscating simple solutions to the problem. This report summarized one possible solution to this looming threat.

Given the above, it should be no surprise that the primary objective of this design project was to reduce flooding in and around the site. The project design, however, had other objectives as well. A green infrastructure project like this one is an opportunity to create both wildlife habitat and community greenspace, both things that are sorely missing from the current urban landscape of the Hampton Roads area. In addition, green infrastructure can serve to reduce nutrient pollution entering our river systems. Taken together, these three objectives form the backbone of the design project summarized in the report: reduce flooding, provide nutrient treatment, create wildlife habitat and community green space.

The design for this project was created for a highly constrained site. The site was constrained not only by its hydrological characteristics (high water table, for example) but also by infrastructure constraints. In the immediate vicinity of the project site was a parking lot, a historical building, a rail track, a lite rail, and an overpass, along with additional roads. The design solution presented here interfered with that infrastructure as little as possible.

After considering multiple potential design solutions, the design team settled on a three-step treatment train. The first step of the treatment train is to replace two defunct filterra units adjacent to the parking lot on site. Next, the existing stormwater infrastructure system would be used to transport stormwater from up in the water shed into a wet pond. Our wet pond design followed the guidelines laid out in the Virginia Department of Environmental Quality Clearinghouse BMP Standards. A peak flow and total storage volume were calculated using the HEC-HMS modeling software and assuming a 10-year, 24-hour storm event. The pond was appropriately sized to hold this volume of runoff. A CAD model was created for the wet pond using Civil 3D, and schematics from that CAD drawing can be found in Figure 3. A planting guide was created for the wet pond to provide nutrient treatment. According to the VA DEQ Standards, the wet pond can be classified as a Level 1 design in the coastal plain, meaning there is an expected 45% reduction in total phosphorus, and a 20% reduction in total nitrogen. Once this nutrient treatment has occurred, the excess stormwater will leave the wet pond through a riser. It will then be conveyed to a redesigned concrete channel which hold a tidal arm of the Elizabeth River. This channel was redesigned to include a buffer area, which will reconnect that arm of the river to the floodplain.

For the wet pond and riparian buffer area, a planting guide was created to promote wildlife habitat, considering salinity level, inundation regime, and desired ecosystem benefits. The project is within budget, with an expected cost of $269,906. The bulk of that cost comes from the significant amount of excavation that will be required to construct the wet pond and riparian buffer area. Regular maintenance of the BMP systems and upkeep of riparian vegetation in all planting zones is essential for optimal performance.

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Appendix A: Decision Matrices

Conveyance:

		Concrete Drainage Channel		Vegetated Drainage Channel		River Rock Lined Channels	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product
Functionality	0.3	1	0.3	2	0.6	3	0.9
Design Life and Adaptability	0.25	2	0.5	1	0.25	2	0.5
Cost	0.2	1	0.2	3	0.6	2	0.4
Maintenance	0.1	3	0.3	2	0.2	1	0.1
Aesthetics	0.1	1	0.1	2	0.2	3	0.3
Habitat	0.05	0	0	3	0.15	2	0.1
Total			1.4		2		2.3

Storage:

		Lined Retention		Unlined Retention		Dry Detention		In Ground Storage	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product	Rank	Product
Functionality	0.3	3	0.9	2	0.6	1	0.3	0	0

		Lined Retention		Unlined Retention		Dry Detention		In Ground Storage	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product	Rank	Product
Design Life and Adaptability	0.25	3	0.75	2	0.5	2	0.5	1	0.25
Cost	0.2	2	0.4	2	0.4	3	0.6	1	0.2
Maintenance	0.1	2	0.2	3	0.3	3	0.3	3	0.3
Aesthetics	0.1	3	0.3	3	0.3	2	0.2	3	0.3
Habitat	0.05	3	0.15	3	0.15	1	0.05	0	0
Total			2.7		2.25		1.95		1.05

Treatment:

		Constructed Wetland		Wet Swale		Dry Swale	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product
Functionality	0.3	3	0.9	2	0.6	1	0.3
Design Life and Adaptability	0.25	3	0.75	3	0.75	1	0.25
Cost	0.2	1	0.2	2	0.4	2	0.4
Maintenance	0.1	3	0.3	2	0.2	1	0.1
Aesthetics	0.1	3	0.3	2	0.2	1	0.1
Habitat	0.05	3	0.15	2	0.1	1	0.05
Total			2.6		2.25		1.2

Release:

		Surface channel		Existing stormwater infrastructure		New culvert	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product
Functionality	0.3	3	0.9	1	0.3	3	0.9
Design Life and Adaptability	0.25	3	0.75	1	0.25	2	0.5

		Surface channel		Existing stormwater infrastructure		New culvert	
Criteria	Weight	Rank	Product	Rank	Product	Rank	Product
Cost	0.2	1	0.2	3	0.6	1	0.2
Maintenance	0.1	1	0.1	3	0.3	3	0.3
Aesthetics	0.1	3	0.3	0	0	0	0
Habitat	0.05	3	0.15	0	0	0	0
Total			2.4		1.45		1.9

Appendix B: Hydraulic Analysis

Equation B-1. Weighted Curve Number

$$CN_{weighted} = \frac{\sum A_i CN_i}{\sum A_i} \tag{1}$$

where,

A_i = The drainage area of subdivision i

CN_i = The curve number of subdivision i

Equation B-2. Carter Method for Time of Concentration (Mehta, 2022)

$$t_c = 0.0977 L_{LF}^{0.6} S_C^{-0.3} \tag{2}$$

where,

L_{LF} = The length of main channel/length of flow (km)

S_C = The average slope of the main channel or longest flow path (m/m) or (ft/ft)

Table B-1. 10 year Precipitation Frequency from NOAA

Duration	**Depth (in)**
15 minutes	1.29
30 minutes	1.87
1 hour	2.44
2 hours	2.99
3 hours	3.24
6 hours	3.92
12 hours	4.67
1 day	5.54