Fells Point Flood Resiliency
Baltimore, Maryland

Prepared for
Environmental Engineering Design II
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1. EXECUTIVE SUMMARY AND INTRODUCTION

1.1 Executive Summary

Fells Point, a historical and culturally-rich neighborhood, is one of the lowest elevation areas in Baltimore City. This critically low elevation makes this neighborhood especially vulnerable to flooding from storm surges and heavy rainfall. On average, Fells Point receives 45 inches of rainfall per year and the community experiences an average of 2.67 floods each year. By 2050, the annual rainfall is expected to increase to 48.7 inches (by 3.7 inches), in addition to the mean sea level rising by 1 to 1.6 feet. This flooding problem is expected to grow in severity, and the intersection of Thames and South Wolfe Street is at particular risk of these exacerbated flood events. The intersection experiences storm surge flooding, rainfall flooding, and frequent nuisance flooding reports, highlighting the insufficient local flood mitigation infrastructure.

A Multi-Criteria Decision Analysis (MCDA) framework was used to evaluate alternative solutions for this design. Each solution was scored for each of the following ten criteria: rainfall flooding reduction, storm surge flooding reduction, construction difficulty, lifetime, sustainability, permitting requirements, historical preservation, maintenance, community acceptance, and cost. The most critical factors, rainfall flooding reduction and storm surge flooding reduction, were each weighted at 25%, emphasizing the project's primary goal of flood mitigation. Though other criteria were assigned lower weights, they ensured a balanced design that prioritizes long term resiliency over short term savings.

The results from the MCDA showed gray infrastructure improvements to be most effective in mitigating rainfall caused flooding, and coastal approaches such as seawalls are most effective in mitigating storm surge caused flooding. However, our team recognized that no single solution could adequately achieve all of our project goals, leading us to choose an integrative approach. The selected solution incorporates three walls of defense against flooding, collectively entitled 3D-Resiliency. To increase flood protection and climate resiliency, a multi-modal solution utilizing living seawalls, increased storm drainage, and bioswales will be implemented. The combined efforts of increased roadside storm drains and robust bioswales will effectively capture and reduce flooding in the streets from excess stormwater. Furthermore, a living seawall will mitigate property damages from storm surges, protecting the coast and promoting marine biodiversity.

The combined system is expected to have a lifespan of 25 years, though the seawall and gray infrastructure improvements have an expected lifespan of 50 years. While our presented solution requires high upfront costs, this investment is justified through long term prevention of flood damages and community protection, all accounting for climate intensification. If nothing is done to protect Fells Point, the frequency and intensity of these events will be beyond the neighborhood's current scope of resilience.

1.2 Introduction

This project is in collaboration with Baltimore Social Environmental Collaborative, University of Maryland Environmental Finance Center, Waterfront Partnership, Straughan Environmental, and the City of Baltimore. The Environmental Engineering Design Team at Johns Hopkins University was tasked with conducting a climate risk assessment for Fells Point and developing an effective climate resiliency and flood mitigation solution for the area.

Fells Point is a historic neighborhood located in Baltimore, Maryland on the north shoreline of the Baltimore Harbor and the Northwest Branch of the Patapsco River. Fells Point is one of Baltimore's oldest neighborhoods, initially established as a shipbuilding community back in 1761 before being annexed by the city later in 1773. As a historically and culturally-rich coastal community covering 75 acres, it is home to around 4,600 people and numerous historical, but old buildings and dated infrastructure. On top of this, Fells Point is one of the lowest elevation areas in the city, putting it at significant risk of climate-related hazards such as stormwater flooding, coastal storms/storm surges, and sea level rise.

The purpose of this project is to outline the major climate hazards impacting Fells Point, highlight the most vulnerable areas and outdated infrastructure in the area, and develop a comprehensive design utilizing gray and green infrastructure to reduce flooding, improve the neighborhood's climate resiliency, and protect the increasingly vulnerable community. A general summary of the site will be described to provide background information and a better understanding of the situation. The risks and hazards from climate change that are most devastating to Fells Point for the next several decades will be outlined. The vulnerabilities of the community associated with each hazard will be identified, with projections looking as far out as 2100 that represent the worst case scenarios. Potential adaptation measures will be listed and scored based on weighted criteria for a multi-criteria decision analysis (MCDA). The three highest scoring adaptation measures will be selected for the design of the solution to work in conjunction with one another to provide adequate flood reduction and property protection. A cost estimate and benefit analysis will be outlined for the proposed solution, along with a preliminary schedule for the construction and implementation of the design.

2. PROJECT SITE DESCRIPTION

2.1 Project Site Location - Wolfe and Thames St.

This project is located in one of the most well known, historical neighborhoods of Baltimore City, Fells Point. According to the United States 2024 Census, the City of Baltimore occupies about 52,000 acres and is home to about 586,000 individuals. Conversely, Fells Point accounts for approximately 75 acres and is home to roughly 4,600 people. Frequented daily for its businesses, historical sights, and community events, residents and local activists have fought to preserve this neighborhood from the forces of nature and man for nearly 300 years. This project was designed with the purpose of creating a solution to storm surge and overland precipitation events expected to continue affecting Fells Point. The solutions presented are intended to be scaled and adapted to meet the needs of other locations. This project will be piloted at the intersection of Wolfe and Thames Street.



Figure 1: *Wolfe Street and Thames Street Intersection.* Source: ArcGIS Pro

2.2 Hazard Risk Assessment at Project Site

Opening directly to the Patapsco River, a tributary of the Chesapeake Bay, the forces of nature threaten the communities that have formed along Baltimore's shore. In this section, an analysis of some of the most significant hazard sources that threaten the community of Fells Point will be identified and discussed. While each individual risk source may be easily resolved on its own, it is the compounding of each hazard in addition to unavoidable characteristics of Fells Point which intensifies the situation.

Setting the scene is the alarmingly low elevation of Fells Point. Travelling from the northern to the southern City limits, elevation relative to sea level decreases drastically. According to topological studies provided by the City of Baltimore, the average elevation of Fells Point is approximately 11-feet above sea level.

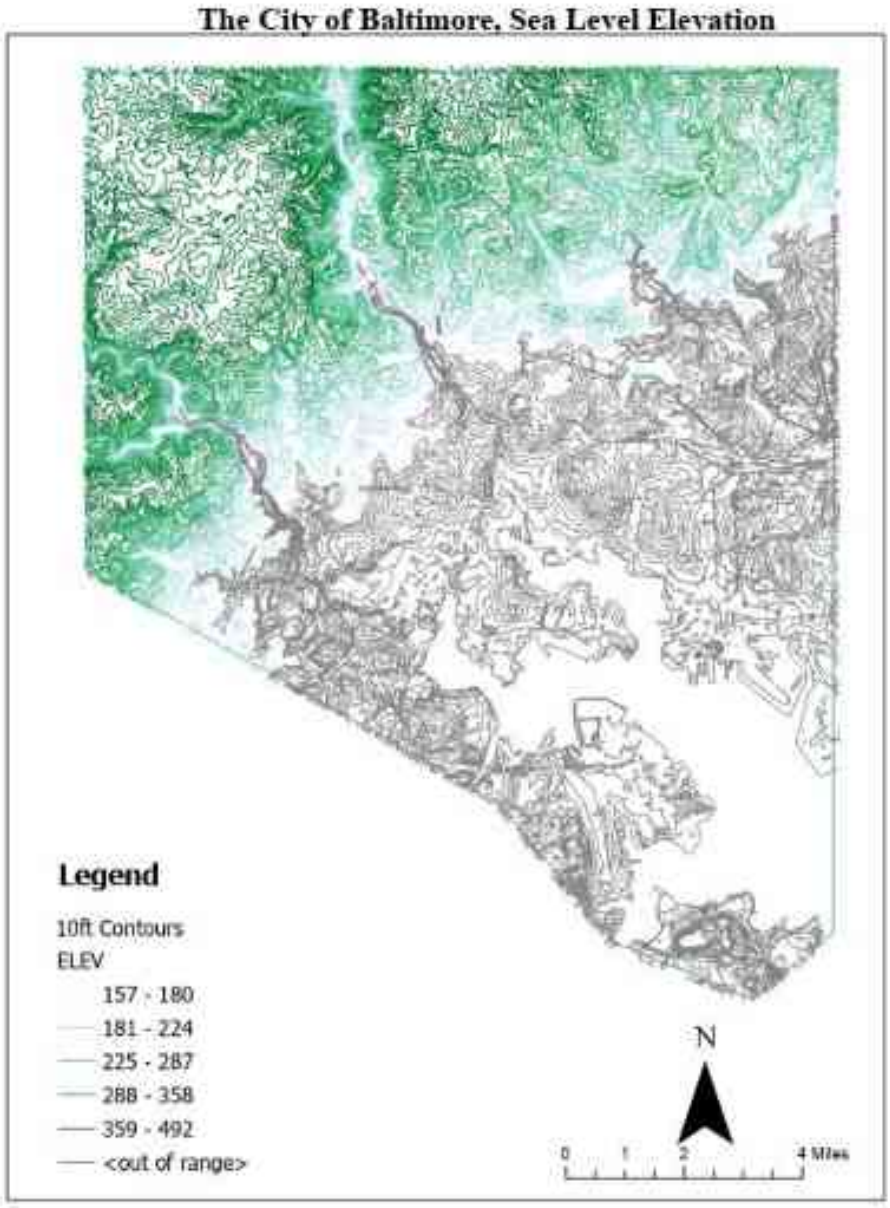


Figure 2: *Elevation relative to Sea Level, The City of Baltimore.* Source: ArcGIS Pro

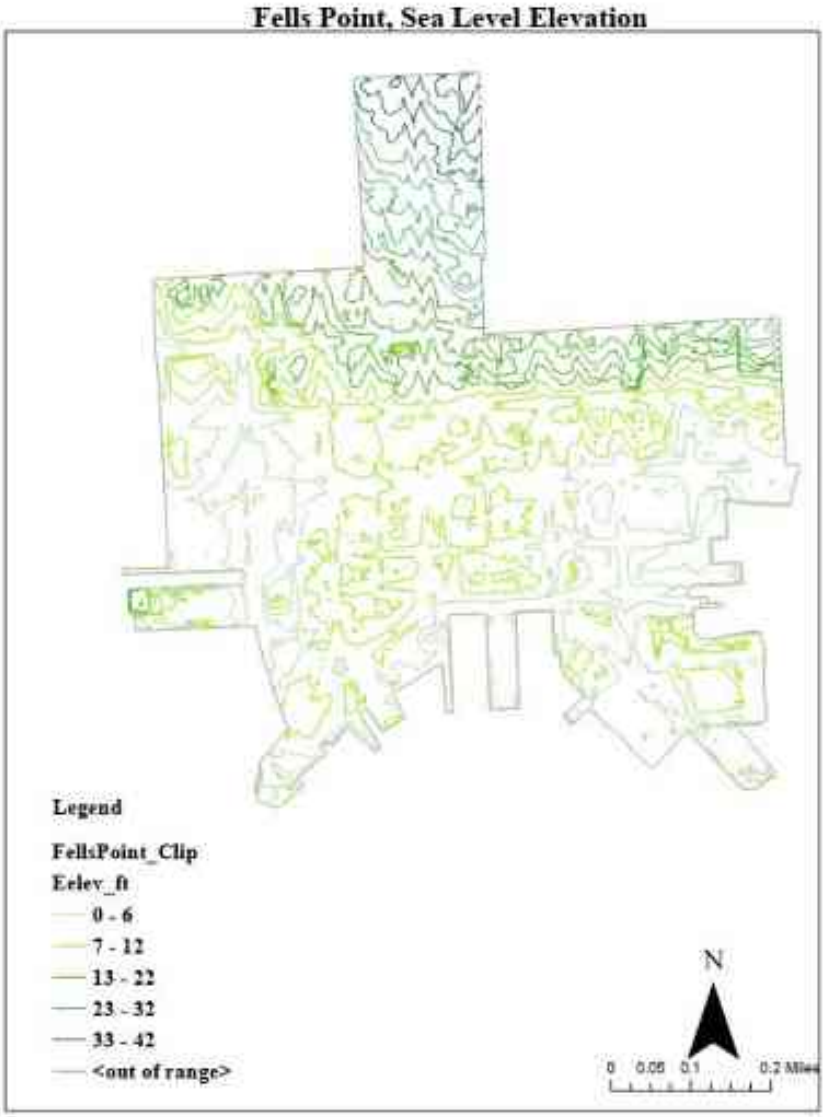


Figure 3: *Elevation relative to Sea Level, Fells Point.* Source: ArcGIS Pro

2.2.1 Rainfall and Stormwater Flooding

In addition to Baltimore City's proximity to a large body of water, roughly three percent of the City's land has been designated as a flood plain per Baltimore City's geospatial land declaration (*City of Baltimore, 2025*). These areas remain at a high risk of flooding and are depicted in **Figure 4**. As shown below, a significant portion of Fells Point is within the flood plain. While floods have the potential to severely damage property, they also pose a serious risk to public health and safety; with the potential to contaminate water sources, disrupt electrical systems, and create economic disruptions for individuals and businesses. In recent years, these disasters have increased in frequency as well as intensity. A 1-in-100 year flood would impact

about 35% of properties; however, in 30 years, a 100 year flood event would impact 59% of properties (*Fells Point, MD Flood Map and Climate Risk Report*, n.d.).

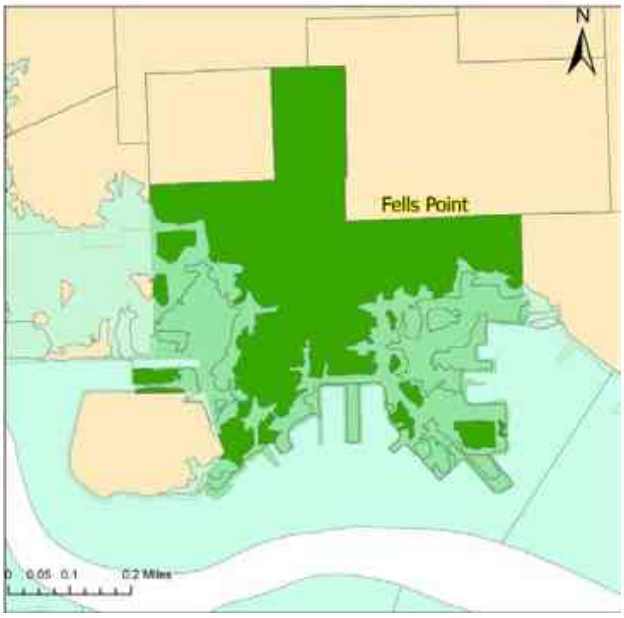


Figure 4 : *Fells Point and Flood Plains.* Source: ArcGIS Pro

Above, Fells Point is depicted as a green polygon while surrounding neighborhoods are beige. The City of Baltimore's flood plains are represented by the translucent blue that curves around the shoreline.

With the majority of Fells Point at risk for flooding, it is critical that infrastructure be in place to mitigate the intensity and frequency of flood damage. While flooding from casual rainfall events regularly creates transportation issues for pedestrians and vehicles, the gravity of this situation is more concerning as we project to the future. Since 1970, Baltimore City's average rainfall has increased by 5.4'' and is expected to increase by an additional 3.9'' by 2050 (*Baltimore, Maryland Climate Change Risks and Hazards*, n.d.).

The effects of precipitation events are felt and measured by their intensity and duration. As the expected volume of precipitation increases, the duration and intensity of events should also be expected to increase. According to Climate Central's NOAA analysis in **Figure 5**, this prediction is consistent with observed events.

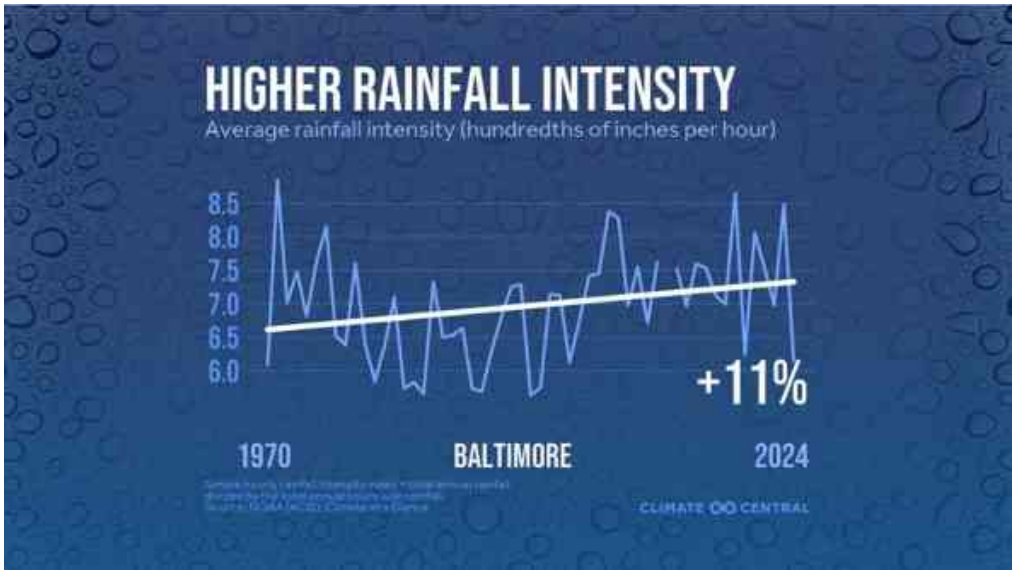


Figure 5 : *Rainfall Intensity Events.* Source: Climate Change in Baltimore, Maryland, n.d.

Due to the effects of climate change, the true value of these figures will only be observed with time. Despite potential variations in future rainfall accumulation, it is evident that for this community to be preserved, action must be taken to harden the infrastructure and increase its resilience against environmental hazards.

2.2.2 Coastal Storms and Storm Surge

In addition to a significant portion of Fells Point being part of the flood plain, it is directly affected by activity of the Patapsco River and Chesapeake Bay. With such low elevation and pervious ground, there is minimal infrastructure protecting Fells Point from coastal storms and storm surges. Today, it is estimated that a 1-in-100 year flood would impact about 35% of properties. In 30 years, a 1-in-100 year flood event would impact 59% of properties (*Fells Point, MD Flood Map and Climate Risk Report*, n.d.). This change is directly related to the increase in storm intensity as a result of climate change.

The National Hurricane Center (NHC) recognizes the increasing risks as climate change continues to affect storm systems. In **Figure 6,** the NHC's quantification of expected inundation from storm surge is depicted. Referencing this project site, the intersection of Wolfe Street and Thames Street, one may expect to find a minimum of three to six feet of water within public roadways after such an event. These projections have the potential to devastate communities and infrastructure, particularly when combined with other hazards (NOAA Coastal Flood Exposure Mapper).



Figure 6: *Fells Point Storm Surge Risk Map.* Source: Coastal Flood Exposure Mapper

2.2.3 Sea Level Rise

As sea levels continue to rise, the elevation of Fells Point becomes a pertinent consideration. As storms continue to form over rising bodies of water, their disastrous impacts will only be felt more intensely. From 1984 through 2020, Maryland recorded a loss of approximately 25,600 and 3,500 acres of forest and farmland, respectively, due to sea level rise. This land has been converted to tidal marshland and is a preview of what lays ahead. Based on the most up-to-date IPCC projections, Maryland is set to see between 1 and 1.6 feet of sea level rise by 2050 and up to a 3.6 foot increase by 2100. This means that an additional 216,000 acres of land could be inundated by the end of the century, severely impacting more than 100 local communities (*Sea-level Rise Projections for Maryland*, 2023).

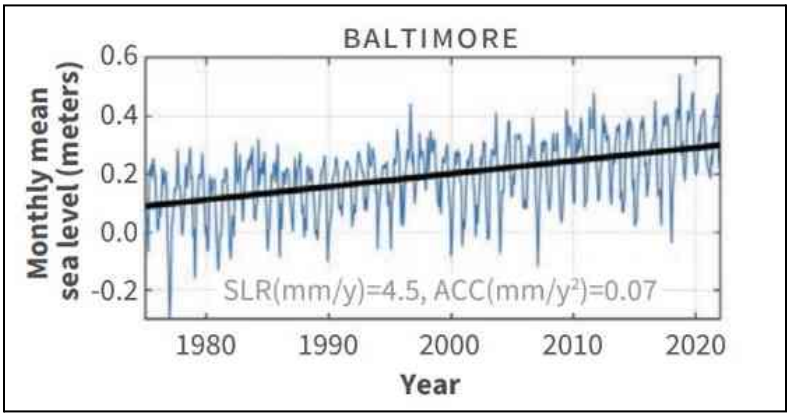


Figure 7: *Variations and Trends in Monthly Mean Sea Level from 1975-2021, measured at the Baltimore Tide Gauge.* Source: Ezer 2023

2.3 Conclusion

The above environmental hazards, while disastrous on their own, are only compounded by each other, making the risk of combined storm and rain events extremely dangerous for the Fells Point community. The only way to preserve Fells Point is to address these issues at the root of the problem; hardening the infrastructure of Fells Point and promoting a resilient response when met with the changing climate. By interweaving proven storm-resilience practices with water conveyance improvements and implementing green-forward infrastructure in a multifaceted mitigation approach, Fells Point will be expected to reduce inundation frequency even when facing the challenges of an intensified climate.

3. DESIGN ASSUMPTIONS

The following section describes assumptions made about the project site with respect to the design process. Specific design criteria described are based on the chosen storm and flood periods, precipitation periods and intensities, utilities assumptions, and upslope area discussion.

3.1 Storm and Flood Criteria

Fells Point is one of Baltimore's most flood-prone neighborhoods due to its waterfront exposure, low elevations, and outdated drainage infrastructure. Flooding occurs via the two primary pathways:

1) Coastal flooding caused by sea level rise and storm surge,
2) Pluvial flooding caused by intense rainfall that exceeds the capacity of the storm drainage system.

Climate change has led to an increase in storm severity and flood events. This is why the solution presented in this project was designed for both the 100-year storm as the primary design benchmark and the 500-year storm as the resiliency benchmark. Baltimore City and FEMA define these events to have annual probabilities of occurrence of 1% and 0.2%.

3.1.1 Flood Levels

FEMA's Baltimore flood mapping (as featured in **Figure 8**) shows that parts of the Fells Point waterfront fall within regulated coastal flood hazard areas, including the 1% annual-chance floodplain and nearby 0.2% annual-chance flood areas (also referred to as 100- and 500-year floodplains). Fells Point is especially concerning because elevated harbor levels can cause water to surge backward through the storm drainage system, even when heavy rainfall does not occur.



Figure 8: *FEMA Flood Insurance Rate Map (FIRM) Floodplains, with Regions of Interest Highlighted.* Source: FEMA NFHL

In the above image, the blue on-land area is classified as the 100-year floodplain, while the orange area is classified as the 500-year floodplain, as well as the "areas of 1 percent annual chance flood hazards with average depths of less than 1 foot or with drainage areas less than 1 square mile"(USDA & USGS). As can be seen from **Figure 8**, both South Caroline Street (left) and the intersection of Wolfe and Thames Street (right) are located in the 100-year floodplain, with most of the rest of Fells Point in the 500-year floodplain as well. This is cause for significant concern and further emphasizes the need for updated flood mitigation infrastructure.

3.1.2 Storm Precipitation

The NOAA Atlas 14 Point Precipitation Frequency website gives estimated precipitation frequency values at a 90% confidence interval for a variety of storm return intervals and durations. For the purposes of this report, the most relevant values from this data server are the 100-year 24-hour, 500-year 24-hour, and 50-year 10-minute storms, which are all used for various aspects of the proposed solutions later in this report. This is shown in **Figure 9**.

PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	**0.346** (0.313-0.382)	**0.414** (0.375-0.458)	**0.493** (0.445-0.544)	**0.550** (0.495-0.608)	**0.621** (0.556-0.687)	**0.674** (0.600-0.746)	**0.725** (0.643-0.805)	**0.775** (0.683-0.864)	**0.837** (0.730-0.937)	**0.884** (0.765-0.996)
10-min	**0.553** (0.500-0.610)	**0.663** (0.599-0.732)	**0.789** (0.713-0.872)	**0.879** (0.792-0.972)	**0.990** (0.886-1.10)	**1.07** (0.956-1.19)	**1.15** (1.02-1.28)	**1.23** (1.08-1.37)	**1.32** (1.15-1.48)	**1.39** (1.20-1.57)
15-min	**0.691** (0.625-0.762)	**0.833** (0.753-0.920)	**0.999** (0.902-1.10)	**1.11** (1.00-1.23)	**1.26** (1.12-1.39)	**1.36** (1.21-1.50)	**1.46** (1.29-1.62)	**1.55** (1.37-1.73)	**1.67** (1.45-1.87)	**1.75** (1.51-1.97)
30-min	**0.947** (0.857-1.04)	**1.15** (1.04-1.27)	**1.42** (1.28-1.57)	**1.61** (1.45-1.78)	**1.86** (1.66-2.06)	**2.05** (1.82-2.26)	**2.23** (1.98-2.48)	**2.41** (2.13-2.69)	**2.65** (2.31-2.97)	**2.83** (2.45-3.19)
60-min	**1.18** (1.07-1.30)	**1.44** (1.30-1.60)	**1.82** (1.64-2.01)	**2.10** (1.89-2.32)	**2.48** (2.22-2.74)	**2.77** (2.47-3.07)	**3.07** (2.73-3.41)	**3.38** (2.98-3.77)	**3.80** (3.32-4.26)	**4.13** (3.58-4.65)
2-hr	**1.42** (1.28-1.57)	**1.72** (1.56-1.90)	**2.18** (1.97-2.41)	**2.54** (2.28-2.80)	**3.03** (2.71-3.35)	**3.44** (3.06-3.80)	**3.86** (3.41-4.29)	**4.31** (3.77-4.80)	**4.94** (4.28-5.54)	**5.45** (4.67-6.14)
3-hr	**1.52** (1.38-1.70)	**1.86** (1.67-2.06)	**2.36** (2.12-2.62)	**2.75** (2.48-3.05)	**3.31** (2.94-3.67)	**3.77** (3.34-4.19)	**4.26** (3.74-4.74)	**4.77** (4.15-5.33)	**5.52** (4.73-6.20)	**6.12** (5.18-6.93)
6-hr	**1.90** (1.72-2.10)	**2.30** (2.09-2.54)	**2.91** (2.63-3.21)	**3.40** (3.07-3.76)	**4.14** (3.70-4.58)	**4.77** (4.22-5.27)	**5.45** (4.78-6.04)	**6.19** (5.36-6.88)	**7.28** (6.19-8.16)	**8.21** (6.88-9.25)
12-hr	**2.32** (2.09-2.60)	**2.81** (2.53-3.14)	**3.57** (3.21-4.00)	**4.23** (3.78-4.73)	**5.23** (4.62-5.84)	**6.11** (5.35-6.81)	**7.09** (6.12-7.93)	**8.19** (6.97-9.19)	**9.87** (8.20-11.2)	**11.3** (9.23-12.9)
24-hr	**2.68** (2.47-2.94)	**3.24** (2.99-3.56)	**4.17** (3.83-4.57)	**4.98** (4.57-5.46)	**6.24** (5.66-6.80)	**7.35** (6.62-7.98)	**8.61** (7.68-9.30)	**10.0** (8.84-10.8)	**12.2** (10.6-13.2)	**14.2** (12.1-15.2)

Figure 9: *NOAA Atlas 14 Point Precipitation Frequency Estimates for Baltimore, MD, with 100-year 24-hour, 500-year 24-hour, and 50-year 10-minute storms highlighted.* Source: NOAA

Additionally, for stormwater infrastructure guidance in particular, the Maryland Stormwater Design Manual 2025 Draft features a table with both Atlas 14 and climate-adjusted precipitation depth values. This is seen in **Figure 10**.

Table 2.2 Rainfall Depths (P) for Design Storms in Maryland

County		Water Quality Storm	Rainfall Depth (P) (inches)					
			1 yr, 24 hr		10 yr, 24 hr		100 yr, 24 hr	
			Atlas 14	Adjusted[1]	Atlas 14	Adjusted[1]	Atlas 14	Adjusted[1]
			Pre	Post	Pre	Post	Pre	Post
Allegany		1.0	2.07	2.50	3.64	4.38	5.96	7.17
Anne Arundel		1.5	2.64	3.14	4.94	5.73	8.53	9.89
Baltimore[2]		1.5	2.70	3.21	5.01	5.81	8.65	10.03
Calvert		1.5	2.73	3.30	5.17	6.12	8.93	10.57
Caroline		1.5	2.70	3.19	5.13	6.07	8.84	10.46
Carroll		1.5	2.54	3.00	4.69	5.57	8.06	9.56
Cecil		1.5	2.66	3.09	4.87	5.73	8.10	9.53
Charles		1.5	2.67	3.23	5.04	5.96	8.70	10.30
Dorchester		1.5	2.77	3.13	5.27	6.01	9.08	10.35
Frederick	Catoctin	1.5	2.54	2.92	4.51	5.31	7.44	8.75
	Frederick	1.5	2.54	2.92	4.63	5.31	7.94	8.75
Garrett		1.0	2.13	2.41	3.69	4.22	5.99	6.85
Harford		1.5	2.70	3.19	5.00	5.85	8.57	10.03
Howard		1.5	2.64	2.98	4.91	5.65	8.47	9.74
Kent		1.5	2.66	3.01	5.01	5.91	8.63	10.18
Montgomery		1.5	2.57	3.01	4.77	5.52	8.23	9.52
Prince George's		1.5	2.63	3.02	4.92	5.74	8.49	9.91
Queen Anne's		1.5	2.67	3.12	5.06	5.97	8.72	10.29
St. Mary's		1.5	2.77	3.19	5.24	6.13	9.04	10.58
Somerset		1.5	2.65	3.02	5.01	5.81	8.64	10.02
Talbot		1.5	2.74	3.12	5.19	6.00	8.97	10.38
Washington	East	1.0	2.52	2.85	4.41	5.19	7.30	8.59
	West	1.0	2.37	2.68	4.11	4.19	6.40	8.59
Wicomico		1.5	2.13	3.23	5.34	6.14	9.22	10.60
Worcester			2.70	3.32	5.34	6.25	9.23	10.80

1. 1, 10, and 100-year, 24-hour design storms from NOAA Atlas 14 and adjusted to reflect climate change using the MARISA tool county climate change factors for the 100-year median confidence level for the 8.5 Representative Concentration Pathway (RCP) and 2050-2100 time period
2. Includes Baltimore City and Baltimore County

Figure 10: *Maryland Stormwater Design Manual 2025 Draft Rainfall Depths Table, with Baltimore City highlighted.* Source: MDE

This provided table is beneficial for designing climate-resilient flood solutions because it accounts for future predictions adjusted for climate change, which is key for creating long-lasting, effective infrastructure.

3.2 Additional Criteria

3.2.1 Soil Assumptions

Due to Fells Point being a largely impervious area with limited green spaces, there is limited availability of soil data barring a select few, broad datasets. One dataset available from MD imap, the state's official GIS data portal is titled "Maryland SSURGO Soils - SSURGO Soils", which contains information such as hydrologic soil group, depth to nearest water table, and surface texture (MD IMAP). For Fells Point, the only data available is within a generalized block group that contains the majority of downtown Baltimore, Canton, and Federal Hill, as shown below in **Figure 11**.



Figure 11: *Maryland SSURGO Data, with Thames Street Region Highlighted.* Source: Maryland.gov

Although the available information is overly generalized across most of downtown Baltimore City, it is the only soil information available, and will therefore be sufficient enough for basic soil assumptions. Per the Maryland SSURGO map, Fells Point seems to be approximately 200 feet from the nearest water table and has soil from hydrologic soil group D, which makes sense considering the unnatural fill makeup (Maryland.gov). Per the Natural

Resources Conservation Service National Engineering Handbook: Hydrologic Soil Groups chapter, in a section about group D soil: "For soils that are deeper than 100 centimeters [40 inches] to a restriction or water table, the saturated hydraulic conductivity of all soil layers within 100 centimeters [40 inches] of the surface is less than or equal to 0.40 micrometers per second (0.06 inches per hour)" (USDA, 2009). This indicates that for soil near the surface in this region, it likely possesses a hydraulic conductivity (K) value of 0.06 $\frac{in}{hr}$ or less, which strongly limits natural infiltration capabilities in the area. In practice, this information must be evaluated and certified by a geotechnical engineer through various in-situ soil tests.

3.2.2 Utilities Assumptions

In Fells Point and the greater Baltimore area, information on the location and depth of stormwater, gas, and electric utility lines, is limited at the preliminary design stage. The limitation on available information makes excavation-based solutions difficult to navigate from the perspective of construction design and planning. Based on project planning discussions with Kimberly Grove, division manager at Baltimore City's Department of Public Works (DPW), it was determined that within the boundaries of Fells Point, the majority of utilities can be assumed to reside at approximately 4 feet below grade, or street level, while stormwater main lines may be as shallow as 2 feet below grade. These assumptions were used in attempts to determine excavation limits, particularly for solutions requiring the construction of bioretention bodies. In further design stages, these assumptions are required to be verified by pot holing prior to excavation.

In coordination with Baltimore DPW, geospatial data for the main stormwater channels and inlets was also obtained and is depicted in **Figure 12**.

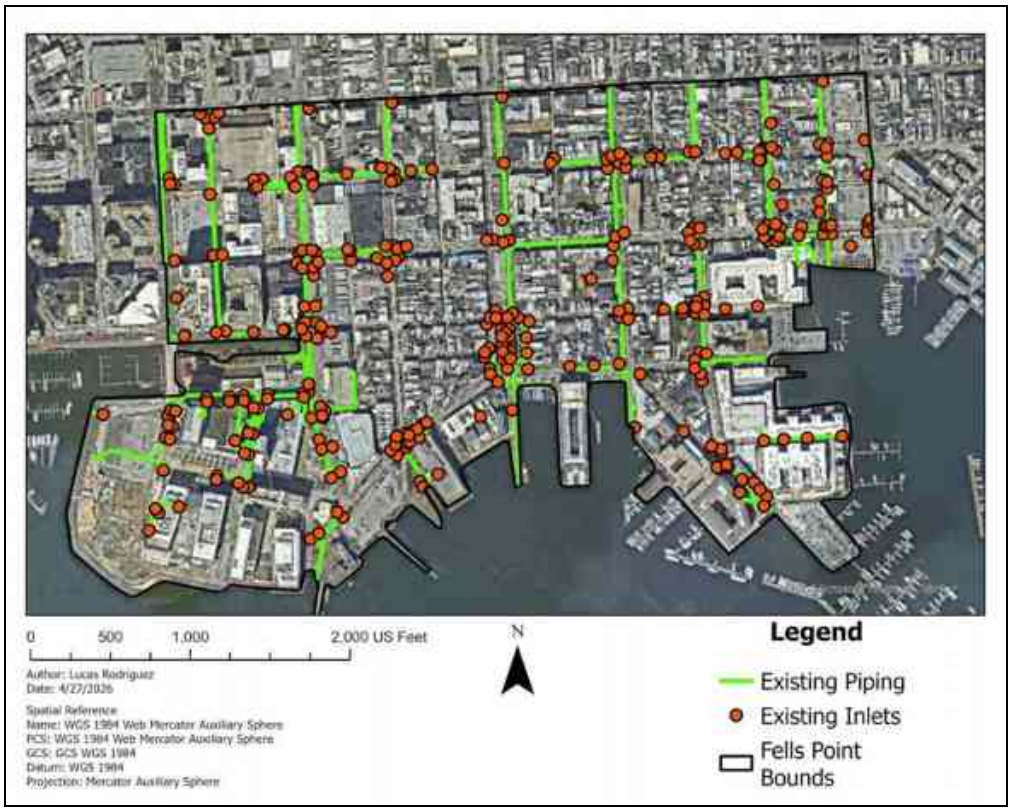


Figure 12: *Fells Point Stormwater Pipes and Inlets, with Thames Street zoomed in.* Source: Baltimore City, Department of Public Works

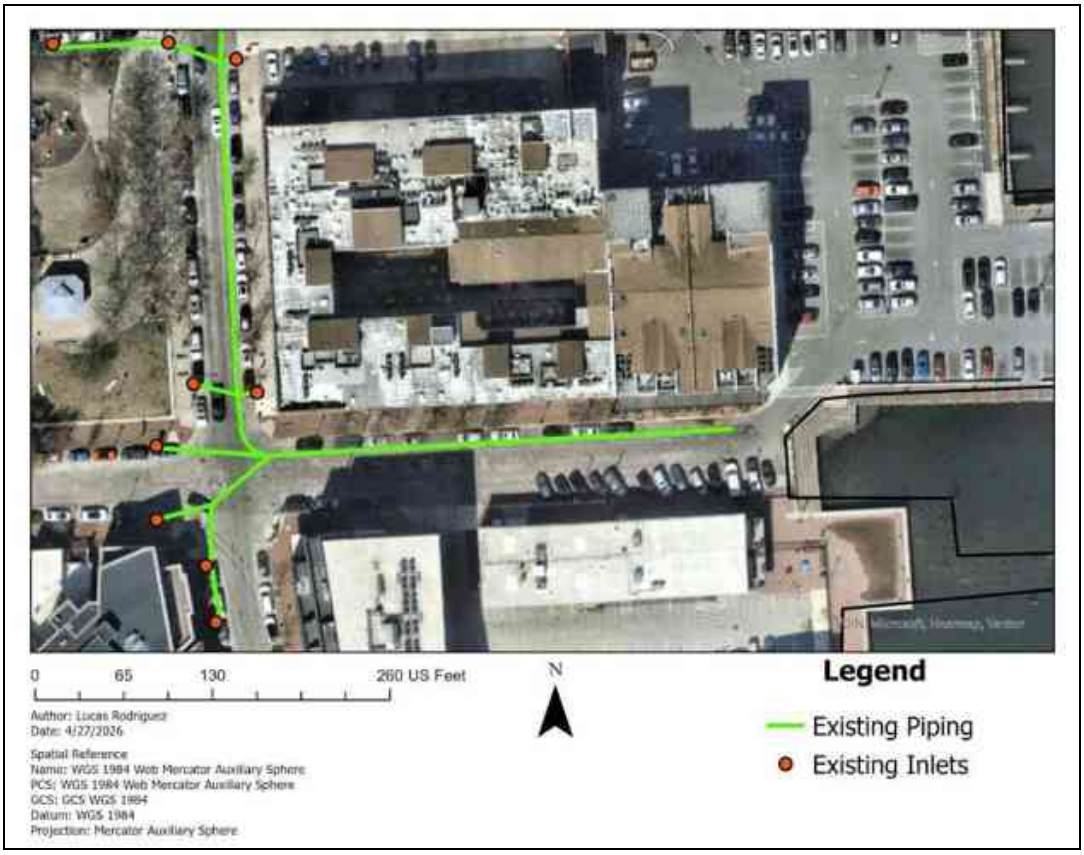


Figure 13: *Thames Street Corridor Stormwater Pipes and Inlets.* Source: Baltimore DPW

3.2.3 Catchment Assumptions

In order to understand the stormwater runoff volume entering Thames Street, the catchment area had to be analyzed. The catchment area was delineated by our report to include the entire area of Fells Point where stormwater would eventually flow to the harbor through Thames Street. This was done by analyzing the existing pipes and inlets, elevation data, and roof slopes. Each area on the map was evaluated to determine which way it would likely flow. Any area where stormwater would likely flow into the upstream SWM pipes that empty out at Thames Street was included. The result is in **Section 5.1**, specifically **Figure 23**, where it is discussed further. The percent of the area that is impervious was determined to be 92.5%, as this is a very urban and developed neighborhood.

In addition to this, one important value determined from the catchment area sizing is the water quality volume, which is designed as the first 1.5 inches of water (for Eastern Maryland, see Stormwater Design Manual) falling over the catchment area. This value and its implications are further explained in **Section 5.2.2**.

4. ALTERNATIVE ANALYSIS

The environmental hazards and site priorities, as described in **Section 2**, served as a baseline for determining potential solutions. Any solution that would address the challenges presented must be evaluated on the basis of multiple relevant criteria. In order to quantify the effectiveness of these potential solutions, a Multi-Criteria Decision Analysis (MCDA) was conducted. This presented the solutions in terms of the criterion identified to align best with the objectives and priorities of the project. The MCDA process is outlined as follows: Listing and description of potential solutions, listing and description of scoring criteria and weight, criteria rating explanation per solution, and full MCDA breakdown.

4.1 MCDA Potential Solutions

Preliminary research and brainstorming led to the development of the following potential solutions:

4.1.1 Permeable Roads

Permeable Roads are a common flood-mitigation strategy particularly in dense, urban areas. This solution would have consisted of changing the filling in between the belgian blocks in the streets to be a more permeable material. This way, the history and the culture of Fells Point are preserved without compromising on flood mitigation. An image of a permeable road surface is shown in **Figure 14**.

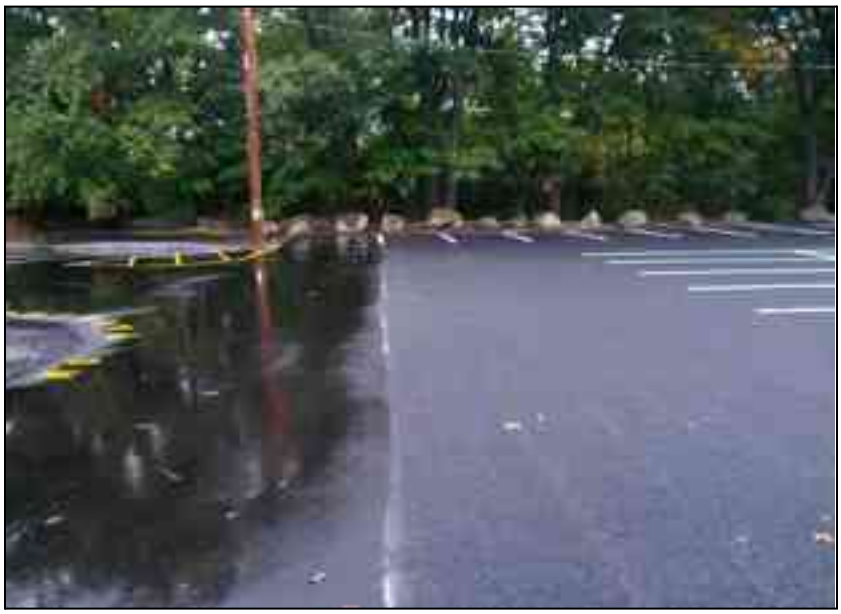


Figure 14: *Traditional vs. Permeable Road.* Source: United States Environmental Protection Agency

4.1.2 Living Sea Wall

Seawall structures are a staple of gray flood prevention infrastructure, protecting coastal communities by effectively blocking, absorbing, and deflecting wave energy. However, they do not have much of an effect on inland, overland flooding from intense rainfall, and are very costly solutions. For the "living" seawall aspect, seawalls may be retrofitted with ecological panels, enhancing marine structures and ecosystems (International Coalition for Sustainable Infrastructure, 2023). A sample living seawall can be seen in **Figure 15.**



Figure 15: *Living Seawall Example.* Source: NSW Government

4.1.3 Living Shoreline Extension

Living shorelines are engineered structures that mimic the effects of natural shoreline elements, from water quality enhancement to wave energy dispersal and coastline buffering. Living shorelines may include local plants, sills, breakwaters (stone structures), and artificial marshes (Maryland Department of Natural Resources; Alliance for the Chesapeake Bay). An image of a living shoreline can be seen in **Figure 16.**



Figure 16: *Living Shoreline Example.* Source: Delaware Living Shorelines Committee

4.1.4 Floating Wetlands

Floating wetlands are a common green infrastructure flood mitigation strategy that mimic the functions of natural wetlands. These floating wetlands absorb excess water, improve water quality, and provide habitats for fish species such as sunfish and bluegill (Gallagher, 2025). Floating wetlands are relatively low in cost and less demanding of maintenance than alternative flood mitigation techniques. An image of floating wetlands already in Fells Point can be seen in **Figure 17**.



Figure 17: *Floating Wetlands in front of Bond Street Wharf.* Source: Habits of a Travelling Archaeologist

4.1.5 Gray Infrastructure Improvements

Gray infrastructure improvements involve increasing the capacity and efficiency of stormwater systems. These upgrades may include increasing pipe diameter, additional stormwater piping or inlets, expanded underground storage capacity, or added pumping measures. These systems can be incredibly effective at capturing and conveying overland runoff, but are quite costly to install and maintain. An example of gray infrastructure improvements can be seen in **Figure 18**.



Figure 18: *Gray Infrastructure Example.* Source: HR Green

4.1.6 Green Roofs

Green roofs are environmentally friendly infrastructure additions to existing buildings, and consist of a rooftop vegetated layer supported by drainage layers and water-proofing membranes. Green roofs are effective in mitigating rooftop storm runoff, improving local aesthetics, providing energy efficiency through insulation, and reducing the urban heat island effect (Green Roofs for Healthy Cities). One example of a green roof is displayed in **Figure 19**.



Figure 19: *Green Roof Example.* Source: Zinco-greenroof

4.1.7 Bioswales

Bioswales are a type of bioretention system that involves a gently sloping trapezoidal or triangular vegetated structure conveying water to infiltrate through the center of the practice. Bioswales are designed to treat, infiltrate, and capture stormwater runoff, utilizing natural processes and low impact development. Bioretention practices may or may not include an underdrain, which can assist with stormwater conveyance in project sites with low hydraulic conductivity soils, such as Fells Point. An example of a bioretention swale is shown below in Figure 20.



Figure 20: *Bioswale Example.* Source: Sustainable Technologies Wiki

4.1.8 No Solution

The "No Solution" represents the scenario where no changes are made to the existing Fells Point. This acts as the baseline for the other alternative solutions to scored off of.

4.2 MCDA Scoring Criteria and Solution Ranking

The following criteria were selected to rank each solution based on a score of 1 - 5; 1 would mean (1 = poor, 5 = excellent). Criteria definitions and importance are explained below, followed by solutions rankings and reasoning in each category.

- ***Criterion SC1–Rainfall Flooding Reduction:*** How effective is this solution at reducing the severity and/or frequency of flooding caused by rainfall?

Proposed Solution	Score	Reasoning
Permeable Roads	4	Reasonable benefit to absorb stormwater.
Living Seawall	1	Solution has no or minimal benefit.
Living Shoreline	1	Solution has no or minimal benefit.
Floating Wetlands	1	Solution has no or minimal benefit.
Gray Infrastructure Improvements	5	Proven and high benefit to handle stormwater.
Green Roofs	3	Some benefit from reducing runoff from buildings.
Bioswales	4	Reasonable benefit to absorb stormwater.
No Solution	1	Solution has no or minimal benefit.

- ***Criterion SC2–Storm Surge Flooding Reduction:*** How effectively will the solution reduce the severity and/or frequency of flooding caused by storm surge?

Proposed Solution	Score	Reasoning
Permeable Roads	2	Minimal benefit.
Living Seawall	5	Proven and high benefit to prevent storm surge flooding.
Living Shoreline	3	Some benefit from reducing wave force.
Floating Wetlands	1	Solution has no or minimal benefit.
Gray Infrastructure Improvements	3	Some benefit from removing surge from the street.
Green Roofs	1	Solution has no or minimal benefit.
Bioswales	2	Minimal benefit.
No Solution	1	Solution has no or minimal benefit.

- ***Criterion SC3–Construction Difficulty:*** How difficult is it to physically implement this solution? How difficult is it to design?

Proposed Solution	Score	Reasoning
Permeable Roads	3	Straightforward construction, but disruption to traffic.
Living Seawall	2	Difficult construction.
Living Shoreline	2	Difficult construction.
Floating Wetlands	3	Straightforward construction.
Gray Infrastructure Improvements	2	Straightforward construction, but disruption to traffic.
Green Roofs	2	Difficult construction due to owner permission.
Bioswales	4	Relatively simple construction.
No Solution	5	No implementation or design needed.

- ***Criterion SC4–Lifetime:*** How long will the solution function effectively without major repairs or renovations?

Proposed Solution	Score	Reasoning
Permeable Roads	3	Lifetime can be around 20+ years.
Living Seawall	4	Lifetime can be 50+ years with proper care
Living Shoreline	4	Lifetime can span 15-20 years
Floating Wetlands	3	Lifetime can be 10+ years
Gray Infrastructure Improvements	5	Lifetime can span 50-100 years.
Green Roofs	4	Lifetime can be around 40 years.
Bioswales	3	Lifetime around 25 years.
No Solution	1	Solution has no or minimal benefit.

- ***Criterion SC5–Sustainability:*** Defined as how the solution impacts the local environment during project construction and lifetime.

Proposed Solution	Score	Reasoning
Permeable Roads	2	Neutral sustainability, similar to any construction project.
Living Seawall	3	Neutral sustainability, similar to any construction project, but possible living sea wall habitats.
Living Shoreline	5	Creates habitats for local wildlife, promoting ecological development. Can help improve water quality.
Floating Wetlands	5	Creates habitats for local wildlife, promoting ecological development. Can help improve water quality.
Gray Infrastructure Improvements	3	Neutral sustainability, similar to any construction project.
Green Roofs	4	Utilizes local flora to capture and filter stormwater.
Bioswales	4	Utilizes local flora to capture and filter stormwater.
No Solution	1	Solution has no or minimal benefit.

- ***Criterion SC6–Permitting Requirements:*** Defined as how complicated it is to obtain permission from governing bodies to construct and operate the practice.

Proposed Solution	Score	Reasoning
Permeable Roads	4	Permits required from the city.
Living Seawall	2	Construction in a waterway requires several permits from federal, state, and local governments.
Living Shoreline	1	Construction extending into the harbor requires several federal-level, state-level, and local-level permits. Potentially impossible due to maritime traffic.
Floating Wetlands	4	Waterway permits required by the state government.
Gray Infrastructure Improvements	4	Stormwater management permits required by county and state.
Green Roofs	5	Construction permit needed.

Bioswales	5	Permits for erosion and sediment control from the city.
No Solution	5	No permitting requirements.

- ***Criterion SC7–Historical Preservation:*** How will the solution impact the cultural and historical value of Fells Point during project construction and lifetime?

Proposed Solution	Score	Reasoning
Permeable Roads	2	Low preservation due to disruption of the Belgian block.
Living Seawall	3	Changes existing harbor walk's design.
Living Shoreline	3	Changes existing harbor walk's design.
Floating Wetlands	4	Adds greenery and matches existing floating wetlands.
Gray Infrastructure Improvements	2	Possibility of Belgian block disruption during construction.
Green Roofs	4	Out of sight from the street level.
Bioswales	3	Adds greenery and beautifies the neighborhood.
No Solution	3	Leaves historic architecture vulnerable to flood damage, but no initial impact.

- ***Criterion SC8–Maintenance:*** How difficult will it be to keep the solution in a properly maintained condition?

Proposed Solution	Score	Reasoning
Permeable Roads	3	Regular clearing of pores.
Living Seawall	3	Regular inspections and repairs.
Living Shoreline	4	Occasional removal of debris and replanting of vegetation.
Floating Wetlands	2	Remove weeds and cut crowns of plants periodically. Repairs and technical maintenance is difficult due to the mass of the wetlands and having

		to remove from water.
Gray Infrastructure Improvements	3	Relatively simple maintenance on pipes & inlets. Regular pump station inspections.
Green Roofs	3	Regular maintenance of vegetation, drainage, and roof.
Bioswales	2	Regular debris removal, inspection, vegetation management, and inlet clearing.
No Solution	1	Will result in the most flood- related damages.

- ***Criterion SC9–Community Acceptance:*** How receptive will the local community be towards proposed solutions?

Proposed Solution	Score	Reasoning
Permeable Roads	3	Lower acceptance due to belgian block removal.
Living Seawall	3	Lower acceptance due to construction disruptions.
Living Shoreline	2	Lower acceptance due to construction disruptions.
Floating Wetlands	4	High acceptance due to greenery provided.
Gray Infrastructure Improvements	2	Lower acceptance due to construction disruptions.
Green Roofs	3	Lower acceptance due to necessity of owner involvement.
Bioswales	2	Lower acceptance due to unfamiliarity or risk of losing sidewalk space.
No Solution	3	Leaves area vulnerable to flooding, but no initial impact.

- ***Criterion SC10–Cost:*** How expensive is the construction and maintenance of this solution relative to others?

Proposed Solution	Score	Reasoning
Permeable Roads	2	High construction and reasonable maintenance

		costs.
Living Seawall	1	High construction and maintenance costs.
Living Shoreline	2	High construction and reasonable maintenance costs.
Floating Wetlands	3	Reasonable construction and maintenance costs.
Gray Infrastructure Improvements	1	High construction and maintenance costs.
Green Roofs	2	High construction costs, reasonable maintenance costs.
Bioswales	5	Relatively inexpensive construction and maintenance costs.
No Solution	5	No construction costs.

4.3 MCDA Criteria Weighting

The highest priority criteria were selected based on the problem statement and project goals. These criteria, “Rainfall Flooding Reduction” and “Storm Surge Flooding Reduction”, were both weighed 25%. The primary objective of this project was to mitigate flood risk in the area and improve the climate resiliency of Fells Point. The next two highest weighted criteria are “Construction Difficulty” and “Lifetime” which were assigned the weight of 10%. These highlight the logistics of bringing a design to fruition. Next, “Sustainability” received a weight of 8%. This decision was made to ensure that any changes made to the existing Fells Point aimed to improve the climate resiliency of the area. The following criteria received a weight of 5%: “Permitting Requirements”, “Historical Preservation”, “Maintenance”, and “Community Acceptance”. This is because all of these criteria were important in selecting the final solution but were all considered in the generation of the potential solutions. The lowest priority criteria was decided to be “Cost”, which received a weight of 2%. One of the key ideas leading this project was that climate resiliency and flood mitigation investments need to be made in communities. While cost is important, it was not of utmost concern when designing flood mitigation solutions, and was designed not to be prohibited for more effective solutions.

4.4 MCDA Chart

The following **Figure 21** shows the completed MCDA chart and the prospective solution final scores.

Criteria	Criteria Weighting	Permeable Roads	Living Seawall	Living Shoreline	Floating Wetlands	Gray Infrastructure Improvements	Green Roofs	Bioswales	No Solution
Rainfall Flooding Reduction	25%	4	1	1	1	5	3	4	1
Storm Surge Flooding Reduction	25%	2	5	3	1	3	1	2	1
Construction Difficulty	10%	3	2	2	3	2	2	4	5
Lifetime	10%	3	4	4	3	5	4	3	1
Sustainability	8%	2	3	5	5	2	4	4	1
Permitting Requirements	5%	4	2	1	4	4	5	5	5
Historical Preservation	5%	2	3	3	4	2	4	3	3
Maintenance	5%	3	3	4	2	3	3	2	1
Community Acceptance	5%	3	3	3	4	2	3	2	3
Cost	2%	2	1	2	3	1	2	5	5
Final Scores		**2.9**	**2.91**	**2.59**	**2.26**	**3.43**	**2.71**	**3.22**	**1.88**

Figure 21: *Multi-Criteria Decision Analysis Chart*. Source: Design Team

5. RECOMMENDATIONS

Based on the conclusions reached in the above alternative analysis, it is recommended that the Thames Street Corridor be safeguarded from pluvial and coastal inundation by a combination of gray infrastructure improvement and renovation, modular bioretention cells, and a concrete seawall. This three-part solution will provide the project site with significant improvements to resiliency from climate hazards and ordinary storm events, and significant mitigation efforts to larger scale coastal storm phenomena.

When designing and constructing a project like this flood resiliency plan, it is vital to consult official engineering codes. These codes provide information about best practices and legal requirements for civil and environmental engineering projects. This could include citing information, schematics of infrastructure units, material type suggestions, and construction details.

Throughout the gray infrastructure design section, Baltimore County public works codes were consulted and followed. This project is located within Baltimore City; however, our engineers and researchers were unable to find its code. We estimate that the engineering codes for public works projects in Baltimore County will be similar to Baltimore City. For final engineering design plans, we recommend consulting the official requirements for the city.

Though the MCDA resulted in “Permeable Roads” scoring high, this was not selected as a part of the solution due to the scope of the design project and the potential damage and altercation of the well known history roads in Fells Point.

5.1 Gray Infrastructure Improvements

Gray stormwater management infrastructure is defined as traditional built infrastructure, including gutters, drains, and pipes. It collects and conveys stormwater, removing it from streets, roofs, and low-lying areas to bring it underground into pipes before it is released into natural waterways (The United States Environmental Protection Agency, 2025). This infrastructure is commonplace around the United States, including Fells Point.

Thames Street, and the larger Thames Street watershed, already contains gray stormwater management infrastructure (Baltimore DPW). This includes regularly placed inlets, typically around intersections, and underground pipes conveying stormwater toward the harbor using gravity. Thames Street's infrastructure is shown in **Figure 22** below.

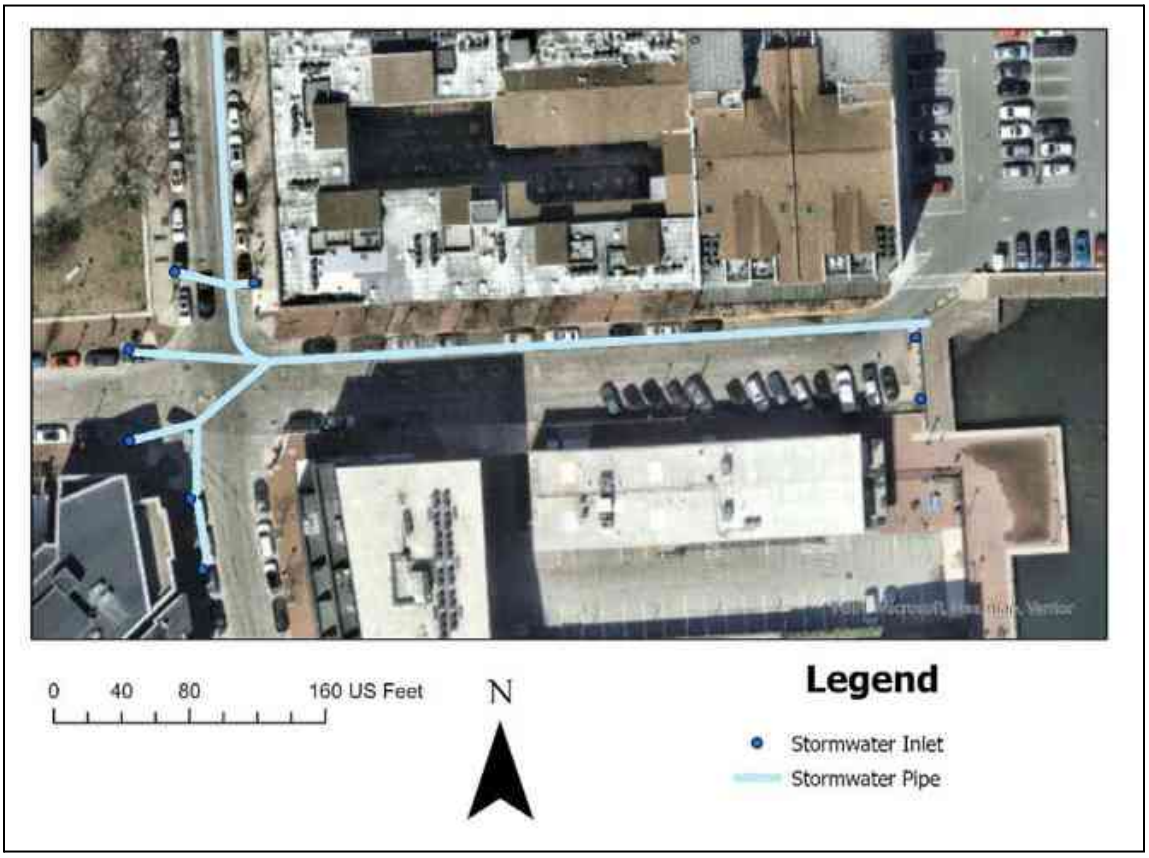


Figure 22: *Thames Street Corridor Stormwater Pipes and Inlets.* Source: Baltimore DPW

As pictured here, a large stormwater pipe is present underneath Thames Street, which conveys water from land into the harbor. It empties into the harbor at the east end of Fells Point. This pipe is 30 inches in diameter and contains no inlets along Thames Street: it's fed only by inlets upstream. These stormwater inlets are present at the intersection of Thames Street and S Wolfe Street and at additional locations north of Thames Street.

While the street doesn't contain inlets that drain into the stormwater management (SWM) pipes, it does contain two drains that directly connect the street's surface to the harbor at the street's east end. These direct drains allow backflow from the harbor onto the street when the sea level is high, and they don't adequately remove water from Thames Street.

This existing infrastructure is failing, as evident by repeated flooding. The gray infrastructure should be improved with additional stormwater inlets, new stormwater pipes connecting these inlets, increased pipe diameters in certain locations, and a pump station with a bypass.

The following gray infrastructure improvements are designed to reduce roadway flooding during modeled 500-year rainfall events in the Thames Street Corridor. Throughout this section, the 10-minute length storm is used because this is similar to the time of concentration (T_C) for the Thames St Watershed. The T_C was calculated to be 7.11 minutes using **Equation 1** in the appendix. T_C is the length of time for stormwater runoff that falls into the farthest part of the watershed to make it to the outlet, so using a storm length similar to the time of concentration will estimate the maximum flow rate that the outlet point could ever possibly experience during a 500-year storm. **Figure 23** below shows the existing SWM infrastructure as well as the delineated catchment area. Any rain that falls inside the red boundary, determined by our engineers by analyzing SWM infrastructure, elevation change, and roof slopes, will exit the catchment area at Thames Street's east end. The total catchment area is 97,700 square feet, or 2.24 acres.

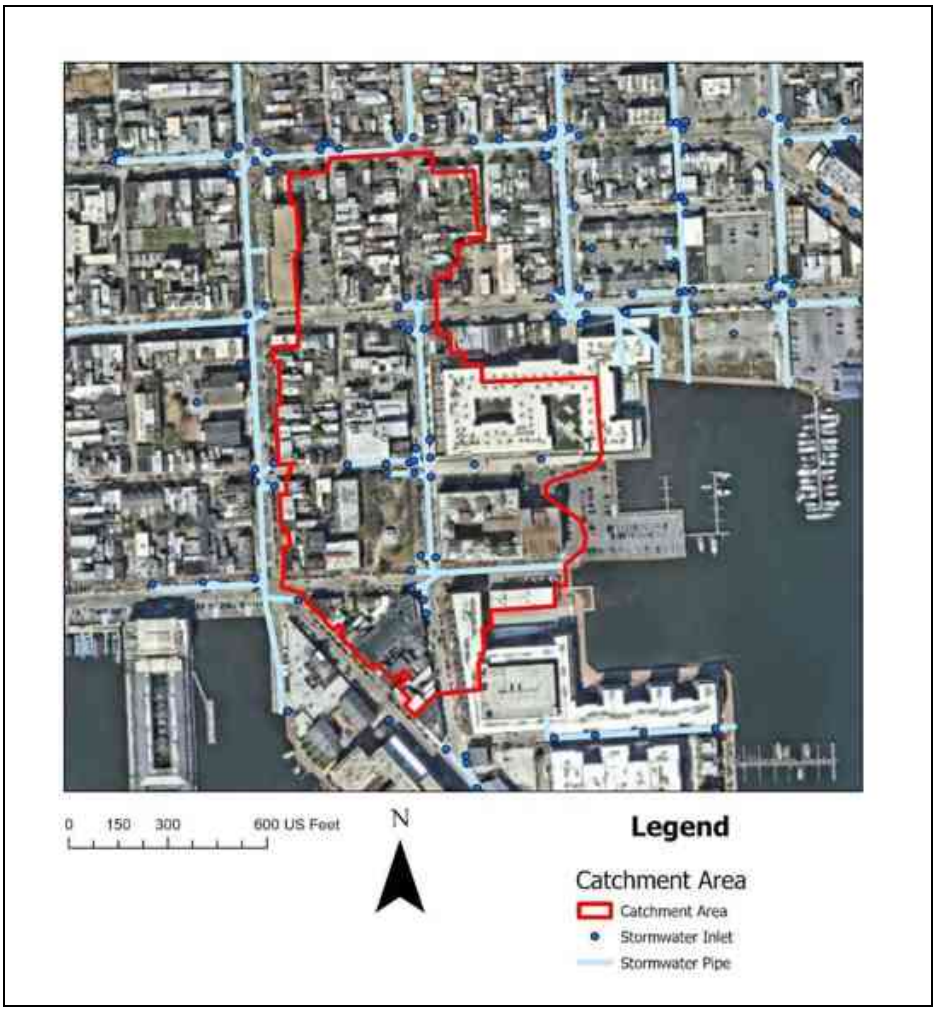


Figure 23: *Thames Street Catchment Area.* Source: ArcGIS Pro

5.1.1 Design: Inlets

Additional stormwater inlets will remove flowing water off the street and drain it into pipes in the subsurface, preventing pooling of water on the surface. **Figure 24** below is an aerial view of our proposed plan for gray stormwater management infrastructure improvements, with each inlet labelled.



Figure 24: *Thames Street Stormwater Inlets, Labelled.* Source: ArcGIS Pro

Key:

Icon	**Meaning**
Green Line	Existing Pipe
Yellow Line	Upgraded Pipe
Blue Line	Proposed Pipe
Orange Circle	Existing Inlet
Blue Circle	Proposed Inlet
Red Circle	Proposed Utility Hole
Purple Rectangle	Proposed Pump Station

Table 1: *Stormwater Inlets.* Source: Design Team

Inlet #	**Status**	**Required Flow Rate During 10-min, 500-yr Storm** (ft^3/sec)
1	Proposed	4.90
2	Proposed	4.90
3	Existing	4.90

4	Existing	4.90
5	Existing	4.90
6	Existing	4.90
7	Existing	4.90
8	Existing	4.90
9	Proposed	4.90
10	Proposed	1.43
11	Proposed	1.43
12	Proposed	1.43

Table 1 above lists every single stormwater inlet present in the Thames Street Corridor, including existing units and units that we propose be constructed. The values for maximum flow rate into an inlet for a 10-min, 500-yr storm in **Table 1** was calculated using the rational method, which is **Equation 2** in the appendix. Inlets nearby to each other are grouped together and given the same value of maximum flow rate because they're designed to handle the full flow rate of runoff entering their drainage area in case nearby inlets are clogged. The two inlet groupings are 1-9 and 10-12.

The positioning of inlets proposed for construction was carefully considered. As seen in **Figure 24**, there are only existing inlets on one side of the intersection of Thames St and S Wolfe St. More are necessary because this intersection floods regularly. Inlets 1, 2, and 9 were positioned at this intersection to fill the gap and reduce flood risk. This matches inlet layouts present at other intersections around Fells Point. By placing inlets 1 and 9 at the highest elevation point on either side of Thames Street, we eliminate any runoff that could enter Thames St from upstream. Inlet 2 was placed to catch any runoff coming from the east side of S Wolfe Street, including off the roof of a portion of the adjacent apartment building. At present, all of this runoff is flowing onto Thames Street; however, SWM infrastructure works best when stormwater isn't flowing along the street for extended lengths.

Proposed inlets 1, 2, and 9 act in conjunction with existing inlets 3-8 and provide redundancy. The total runoff volume that enters into the intersection of Thames Street and S Wolfe Street is 4.90 ft^3/sec (cubic ft per second, cfs) during a 10-minute, 500-year storm event. This runoff comes from multiple directions, primarily the areas west and south of the intersection. This total volume will be split up by the 9 inlets present, so each inlet and connected

pipe won't actually need to be able to handle this flow rate; however, they can in the case of debris causing some inlets to fail. Redundancy around this intersection prevents water from pooling and blocking traffic, even in heavy storms or when multiple inlets are compromised. It's recommended that each inlet not be required to handle more than 5.0 cfs of stormwater, which is consistent with our design even if all but one inlet becomes compromised (Baltimore County, n.d.).

The exact positioning of proposed inlets 1, 2, and 9 require that they're far enough into each street to avoid obstructing the crosswalk area or ramps. Specifically, inlets are to be 5 ft away from where the curb begins to curve for an intersection (Baltimore County, n.d.). Therefore, this is where proposed inlets are placed.

In addition to new inlets at the intersection (1, 2, 9), we've proposed inlets at the east end of Thames Street (10, 11, 12). This is where its lowest elevation is, and where flooding is the worst. Inlets 10, 11, and 12 will be constructed to remove stormwater from either side of the street (10 & 12) and from the lowest elevation point on the street (inlet 11). It's required that an inlet exists at the lowest elevation point and that other inlets exist near the lowest elevation point in case of clogging or failure, which is also why 10 and 12 are vital (Maryland Department of Transportation, 2023).

All proposed inlets for construction follow the same design. They'll be at street level, along a curb, and type "S" combination inlets with both a grate and a curb opening. This type of inlet is appropriate for Thames Street because there is a parking lane on either side of the street. The grate and curb opening allow for the highest volume of stormwater as possible to enter the SWM system. Additionally, this type matches the inlet type throughout Fells Point already. The grate will be made of cast iron, and the bars will be perpendicular to the street direction to protect bicyclists. The design schematics for all proposed inlets is **Figure 25** below (Baltimore County, n.d.). The inlet placement, type, and material is all consistent with Baltimore County public works' requirements.

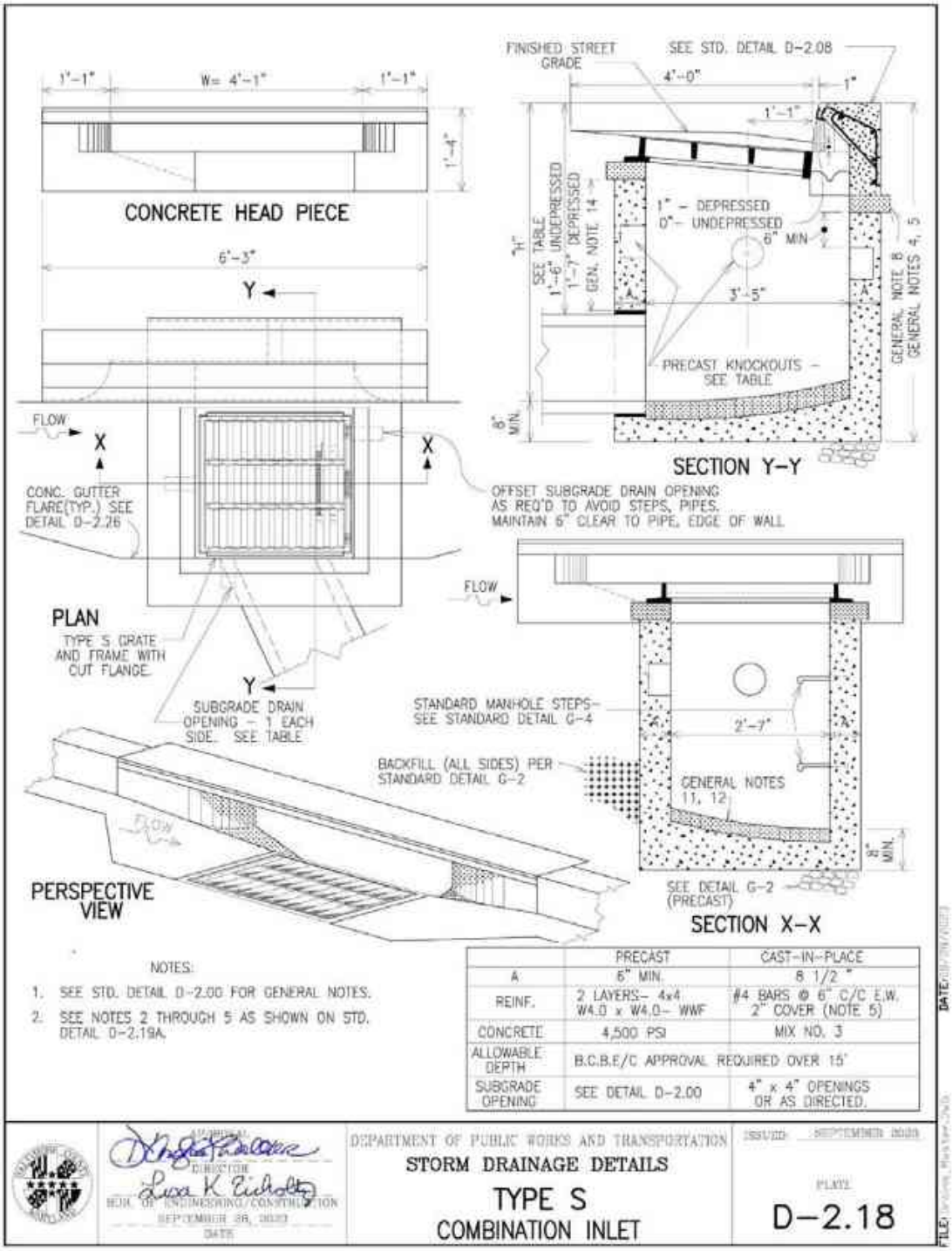


Figure 25: *Stormwater Inlet Schematic*. Source: Baltimore County STORM DRAIN STANDARD DETAIL

5.1.2 Design: Pipes

Certain SWM pipes should be increased in diameter, certain pipes should be constructed, and certain pipes should be rerouted to prevent flooding during a 10-min, 500-year storm event.



Figure 26: *Thames Street Stormwater Pipes, Labelled*

Key:

Icon	**Meaning**
Green Line	Existing Pipe
Yellow Line	Upgraded Pipe
Blue Line	Proposed Pipe
Orange Circle	Existing Inlet
Blue Circle	Proposed Inlet
Red Circle	Proposed Utility Hole
Purple Rectangle	Proposed Pump Station

Table 2: *Stormwater Pipes.* Source: Design Team

Pipe #	**Status**	**Diameter (inches)**	**Slope (ft/ft)**	**Required Flow Rate During 10-min, 500-yr Storm (ft^3/sec)**	**Maximum Flow Rate Possible (ft^3/sec)**

1	Proposed	15	0.005	4.90	4.96
2	Proposed	15	0.005	4.90	4.96
3	Upgraded	15 → 18	(estimated 0.002)	4.90	5.10
4	Upgraded	12 → 18	(estimated 0.002)	4.90	5.10
5	Upgraded	12 → 18	(estimated 0.002)	4.90	5.10
6	Upgraded	12 → 18	(estimated 0.002)	4.90	5.10
7	Upgraded	12 → 18	(estimated 0.002)	4.90	5.10
8	Upgraded	12 → 18	(estimated 0.002)	4.90	5.10
9	Upgraded	(estimated 12) → 18	(estimated 0.002)	4.90	5.10
10	Proposed	15	0.005	4.90	4.96
11	Existing	30	0.002	17.08	18.39
12	Proposed	12	0.005	1.43	2.74
13	Proposed	12	0.005	1.43	2.74
14	Proposed	12	0.005	1.43	2.74
15	Proposed	30	0.002	17.08	18.39
16	Existing	24	0.003	(outside scope)	12.42

Table 2 above contains a comprehensive list of data for all of the pipes present in the Thames Street Corridor's SWM system. For existing pipes, the original diameter and the original slope were taken from the City of Baltimore's Department of Public Works (DPW). Some data was missing, so our designers estimated realistic values based on other pipes we did have data for, and we made conservative estimates so that the actual values are likely more favorable to our

project if they're different than the estimate. For example, pipe 9's diameter was unknown. It was estimated to be 12 inches because that is the diameter of the pipe across from it and most of the others in the intersection area. The slopes of the pipes at the intersection (3-9) are unknown. For calculations of flow, the slope is assumed to be 0.002 because that is the slope of the pipe adjacent to them, pipe 11. The other pipe adjacent to them, pipe 16, has a slope of 0.003. 0.002 is a conservative estimate and likely the lowest possible slope that these pipes would be. In reality, the slope is likely slightly greater, allowing for an even higher flow rate. The slope of a pipe is defined as the vertical change in elevation divided by the horizontal length (WSSC Water, 2008).

The required capacity for each pipe was calculated using the rational method, as mentioned in the above inlet section. This uses **Equation 2** and is detailed in the index. Many of the values in **Figure 26** match **Figure 24** because the same flow rate of water that passes through an inlet must then pass through the connected pipe(s). The maximum possible flow rates will be 4.90 cfs at the intersection, 1.43 cfs at the east end of the street, and 17.08 cfs at the outlet of the entire watershed.

As the first step in the design process, each existing pipe's maximum flow capacity was calculated using Manning's equation, which is **Equation 3** in the index. The pipe's as-is flow capacity was compared to its required flow rate for a 10-min, 500-yr storm event. Pipe 11 was the only one with a flow capacity greater than its required rate. Therefore, we do not recommend any enlargement or design changes to it.

All of the existing SWM pipes at the intersection (3-9) had a flow capacity less than what is required during a 500-yr event. To prevent flooding, we recommend enlarging their diameter to increase their flow rate. To accommodate a maximum runoff rate of 4.90 cfs, their diameter should be 17.7 inches, which is rounded up to 18 to allow for a safety factor and because 18 inch diameter is a standard pipe size available to the City of Baltimore. The original slope of 0.002 is used for calculations both before and after improvement because the slope determined by the initial engineers to account for spacing of inlets, vertical drop to pipes 11 or 16, and other underground utilities is likely what's best. All calculation details are present in the index underneath **Equation 3.**

The material of new, upgraded SWM pipes (pipes 3-9) will be high-density polyethylene (HDPE). These pipes have a manning's n value of 0.012 (Baltimore County, n.d.). HDPE was chosen because it is a standard option in the Baltimore County Storm Drainage Design Manual. The material of pipes 3, 4, 5, 6, 7, 8, and 9 is unknown at present. It is likely cast iron (manning's n of 0.013) because that is the known material of pipes 11 and 16.

The proposed pipes then had to be designed. Most of the proposed pipes (1, 2, 10, 12, 13, and 14) serve to move stormwater from each proposed inlet into the main stormwater pipes (16,

11, and 15). Proposed pipe 15 has a different goal: it's meant to carry the entirety of the stormwater to the pump station, rerouting water from its original path. To design each pipe, multiple criteria had to be determined: material, slope, diameter, and location/angle of cut-in.

The material of proposed pipes 1, 2, 10, 12, 13, and 14 is HDPE, which was discussed previously. The material of proposed pipe 15 is ductile iron. This is the largest pipe we recommend installing. Ductile iron was chosen because it has the same Manning's n value as cast iron of pipe 11 (0.013) (Baltimore County, n.d.). Ductile iron piping is an approved material on Baltimore county's Storm Drainage Design Manual. The goal of pipe 15 was to match pipe 11 as closely as possible, meaning it should have a similar material, the same slope, and the same diameter. This prevents stormwater flow from changing its flow course, like from subcritical to supercritical, and matches pipe 11, which was determined to be adequate for the 500-year storm.

To find the slope of the slope of pipes 12, 13, and 14, we did the following. The minimum grade of constructed stormwater management pipes is 0.5%, or 0.005 (Baltimore County, n.d.). This ensures a high enough flow rate to avoid sediment deposition. Additionally, the minimum velocity of water in pipes is 3 ft/sec (fps) or greater (Baltimore County, n.d.). Using a velocity of 3 fps and a diameter of 12 inches (as a stand-in diameter due to the iterative nature of the equation) in the Manning's Equation, a slope of 0.004 was determined to be the minimum for pipes 12, 13, and 14. Therefore a design slope of 0.005 will be used for pipes 12, 13, and 14. The slope of pipes 12, 13, and 14 was verified to be possible because the length of the pipe was compared to the available drop in height from street level to the level of pipe 11, 15, or the pump station, which was determined to be 1.25 ft or more of vertical drop. The most conservative estimate was used for this, and all, calculations, so that actual conditions will either match our calculations or be more favorable. The originally built pipe's exit elevation is 1.25 ft below sea level. To be safe, the east end of Thames Street was assumed to be at sea level for this calculation; although it is likely a few feet above sea level. The calculations of slope are included with Manning's equation, **Equation 3** in the index.

For pipes 1, 2, and 10, a similar process was used; however, the stand in diameter was 18 inches, not 12, because the intersection has more runoff than the east end of the street. With this, the minimum slope was calculated to be 0.002. Therefore, the design slope is 0.005 to match code requirements.

After the material and slope of each proposed pipe was determined, **Equation 3** was used to find the required diameter. The final results are included in **Table 2** above. The pipes at the intersection (1, 2, 10) needed a diameter of 14.9 inches, so their designed diameter is 15 inches due to pipe size availability. The pipes at the east end of Thames St (12, 13, 14) needed a diameter of 9.4 inches, so their designed diameter became 12 inches due to regular pipe sizing.

The actual flow rates with those slightly larger diameters were calculated and added to **Table 2** as well.

Code requires the angle at which smaller pipes enter larger pipes to be between 30 to 80 degrees (Baltimore County, n.d.), as this maintains proper flow and prevents stormwater from slowing down and depositing sediment. Due to this requirement, the proposed piping's angles were calculated, causing some to be redrawn. Eventually, a plan that has correct angles was designed. Pipe 10 will enter pipe 11 at a 30° angle, pipe 1 will enter 11 at 50°s, pipe 12 will enter 11 at 40°s, and pipe 13 will enter 15 at an 80 degree angle. Pipe 14's flow combines with 15's flow inside the pump station's wet well. Cut-ins will follow the schematic in **Figure 29**.

With new pipe constructions, manholes/utility holes are required to be constructed 10 ft or less away from any cut-in locations, where a smaller pipe connects to a larger pipe. (Baltimore County, n.d.). This means utility holes will be built at the intersection points shown in **Figure 30**. Existing utility holes are not highlighted on the map, as they don't require any analysis by our report. If a utility hole is not proposed at a new cut-in location, it is because a utility hole is already present or is proposed for a location 10 ft or less away. Utility holes will follow the requirements present in Baltimore City code, which likely requires a 2.5 ft diameter manhole for a 30 inch diameter pipe, which is what Baltimore County requires (Baltimore County, n.d.). Utility hole schematics for cut-ins are shown in **Figure 30** below.

Pipe 11's bend, as it turns into pipe 15, is at a 45 degree angle. There will be a utility hole present at this bend, as required by code and as shown in **Figures 27** and **28** (Baltimore County, n.d.).

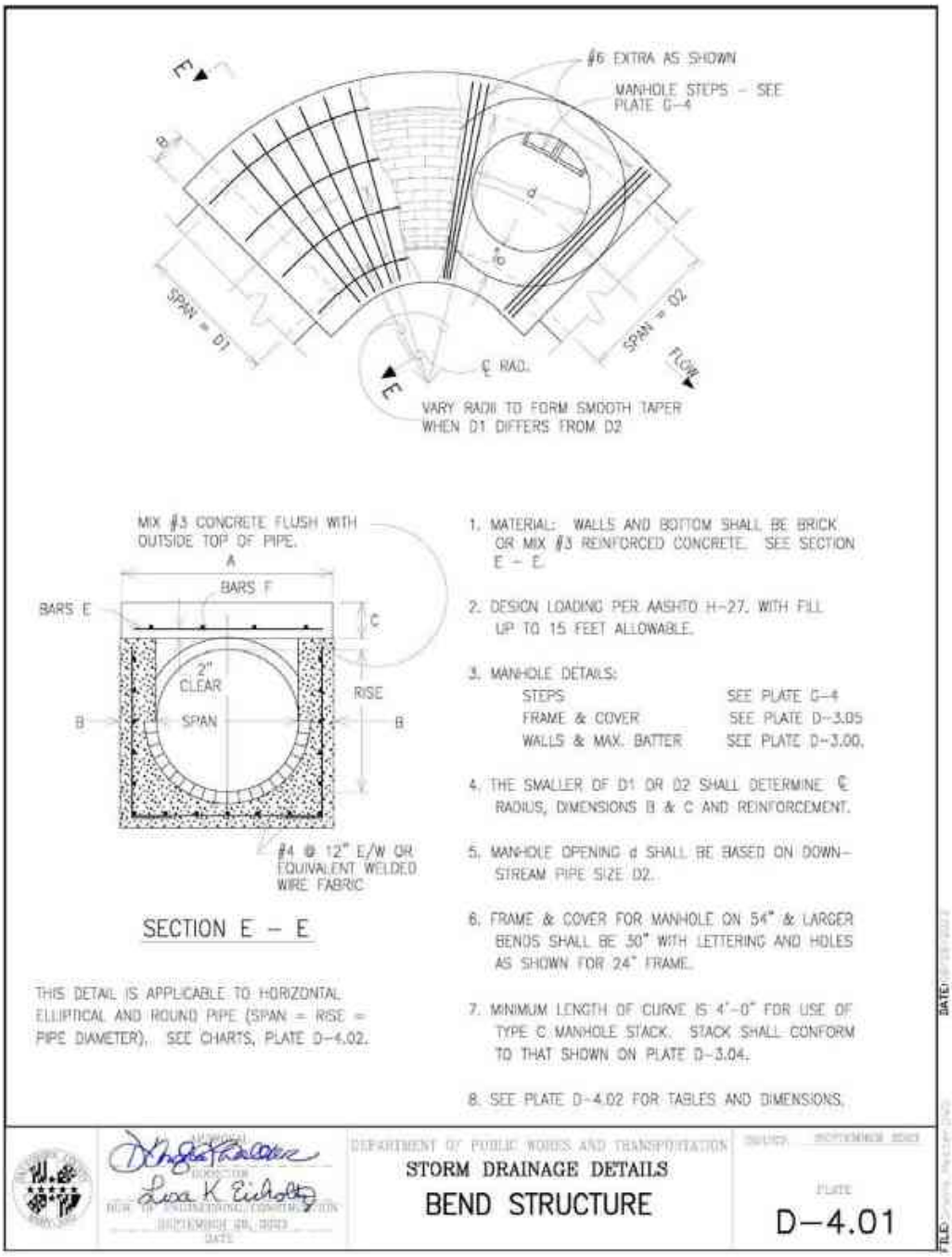
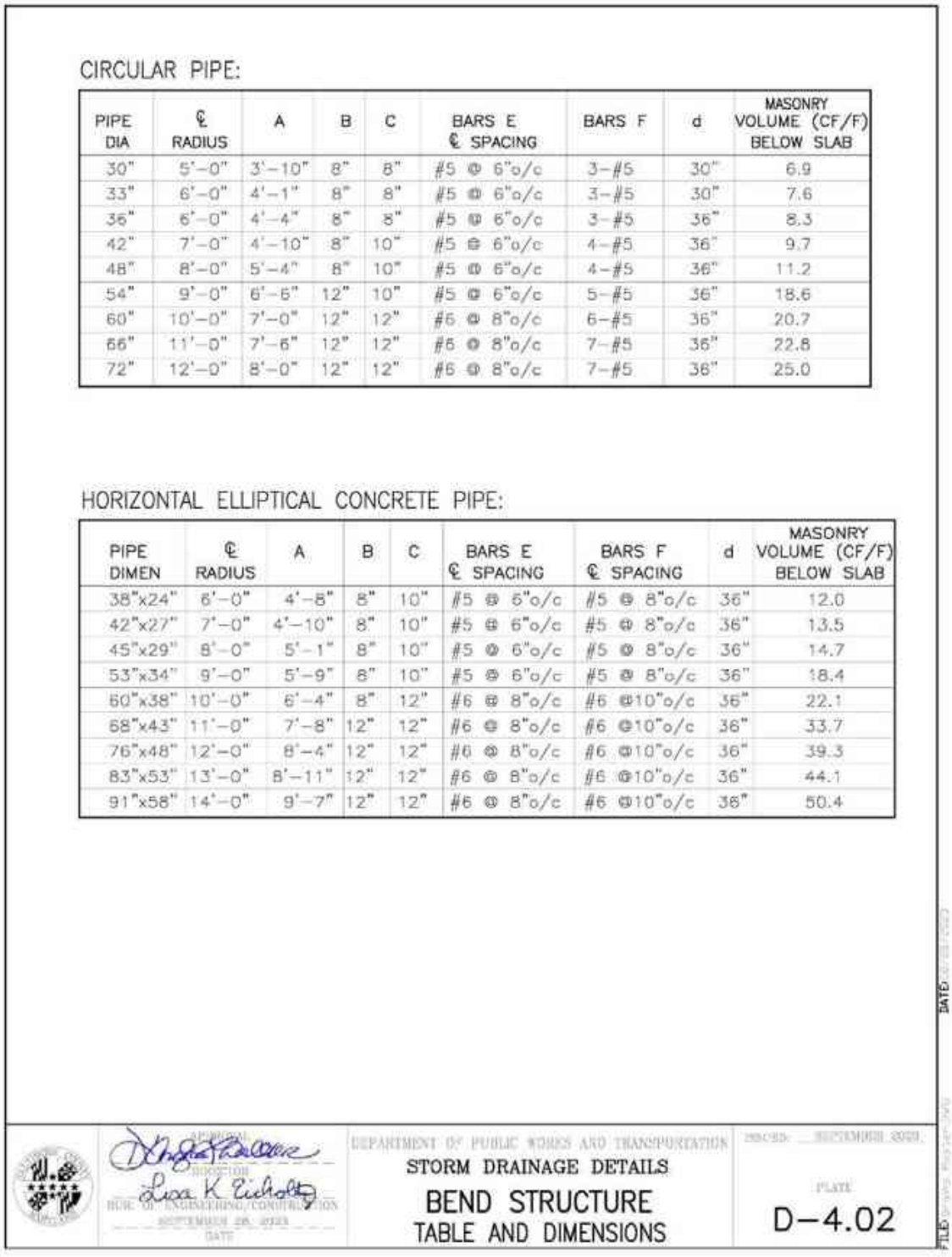


Figure 27: *Bend Schematics & normal pipe schematic (section E - E)*. Source: Baltimore County, n.d.)



CIRCULAR PIPE:

PIPE DIA	℄ RADIUS	A	B	C	BARS E ℄ SPACING	BARS F	d	MASONRY VOLUME (CF/F) BELOW SLAB
30"	5'-0"	3'-10"	8"	8"	#5 @ 6"o/c	3-#5	30"	6.9
33"	6'-0"	4'-1"	8"	8"	#5 @ 6"o/c	3-#5	30"	7.6
36"	6'-0"	4'-4"	8"	8"	#5 @ 6"o/c	3-#5	36"	8.3
42"	7'-0"	4'-10"	8"	10"	#5 @ 6"o/c	4-#5	36"	9.7
48"	8'-0"	5'-4"	8"	10"	#5 @ 6"o/c	4-#5	36"	11.2
54"	9'-0"	6'-6"	12"	10"	#5 @ 6"o/c	5-#5	36"	18.6
60"	10'-0"	7'-0"	12"	12"	#6 @ 8"o/c	6-#5	36"	20.7
66"	11'-0"	7'-6"	12"	12"	#6 @ 8"o/c	7-#5	36"	22.8
72"	12'-0"	8'-0"	12"	12"	#6 @ 8"o/c	7-#5	36"	25.0

HORIZONTAL ELLIPTICAL CONCRETE PIPE:

PIPE DIMEN	℄ RADIUS	A	B	C	BARS E ℄ SPACING	BARS F ℄ SPACING	d	MASONRY VOLUME (CF/F) BELOW SLAB
38"x24"	6'-0"	4'-8"	8"	10"	#5 @ 6"o/c	#5 @ 8"o/c	36"	12.0
42"x27"	7'-0"	4'-10"	8"	10"	#5 @ 6"o/c	#5 @ 8"o/c	36"	13.5
45"x29"	8'-0"	5'-1"	8"	10"	#5 @ 6"o/c	#5 @ 8"o/c	36"	14.7
53"x34"	9'-0"	5'-9"	8"	10"	#5 @ 6"o/c	#5 @ 8"o/c	36"	18.4
60"x38"	10'-0"	6'-4"	8"	12"	#6 @ 8"o/c	#6 @10"o/c	36"	22.1
68"x43"	11'-0"	7'-8"	12"	12"	#6 @ 8"o/c	#6 @10"o/c	36"	33.7
76"x48"	12'-0"	8'-4"	12"	12"	#6 @ 8"o/c	#6 @10"o/c	36"	39.3
83"x53"	13'-0"	8'-11"	12"	12"	#6 @ 8"o/c	#6 @10"o/c	36"	44.1
91"x58"	14'-0"	9'-7"	12"	12"	#6 @ 8"o/c	#6 @10"o/c	36"	50.4

APPROVAL
DIRECTOR
BUR. OF ENGINEERING, CONSTRUCTION
SEPTEMBER 28, 2021
DATE

DEPARTMENT OF PUBLIC WORKS AND TRANSPORTATION
STORM DRAINAGE DETAILS
BEND STRUCTURE
TABLE AND DIMENSIONS

DATED: SEPTEMBER 2021

PLATE
D-4.02

FILED:

Figure 28: *Bend Sizing*. Source: Baltimore County, n.d.

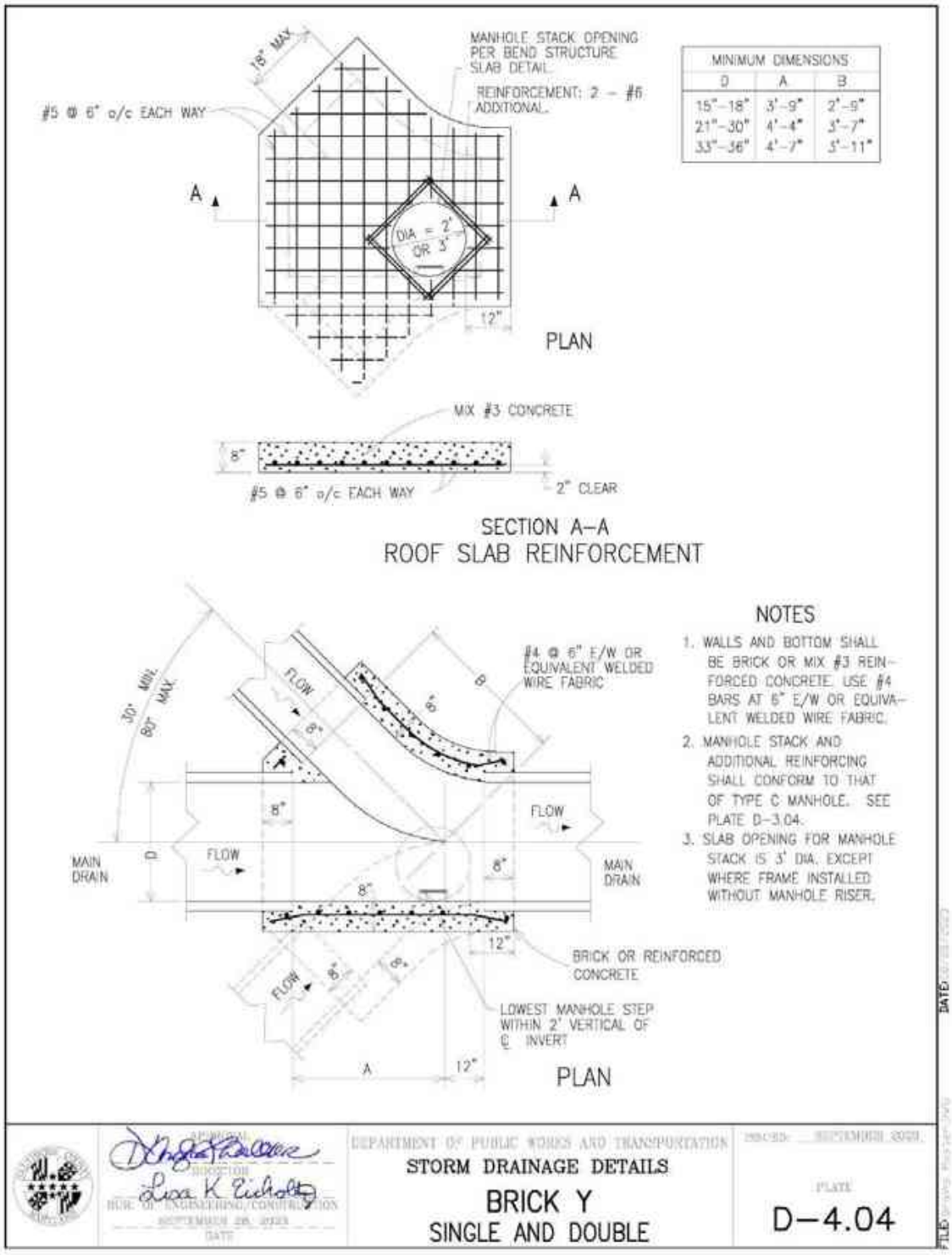


Figure 29: *Cut in Schematics*. Source: Baltimore County, n.d.

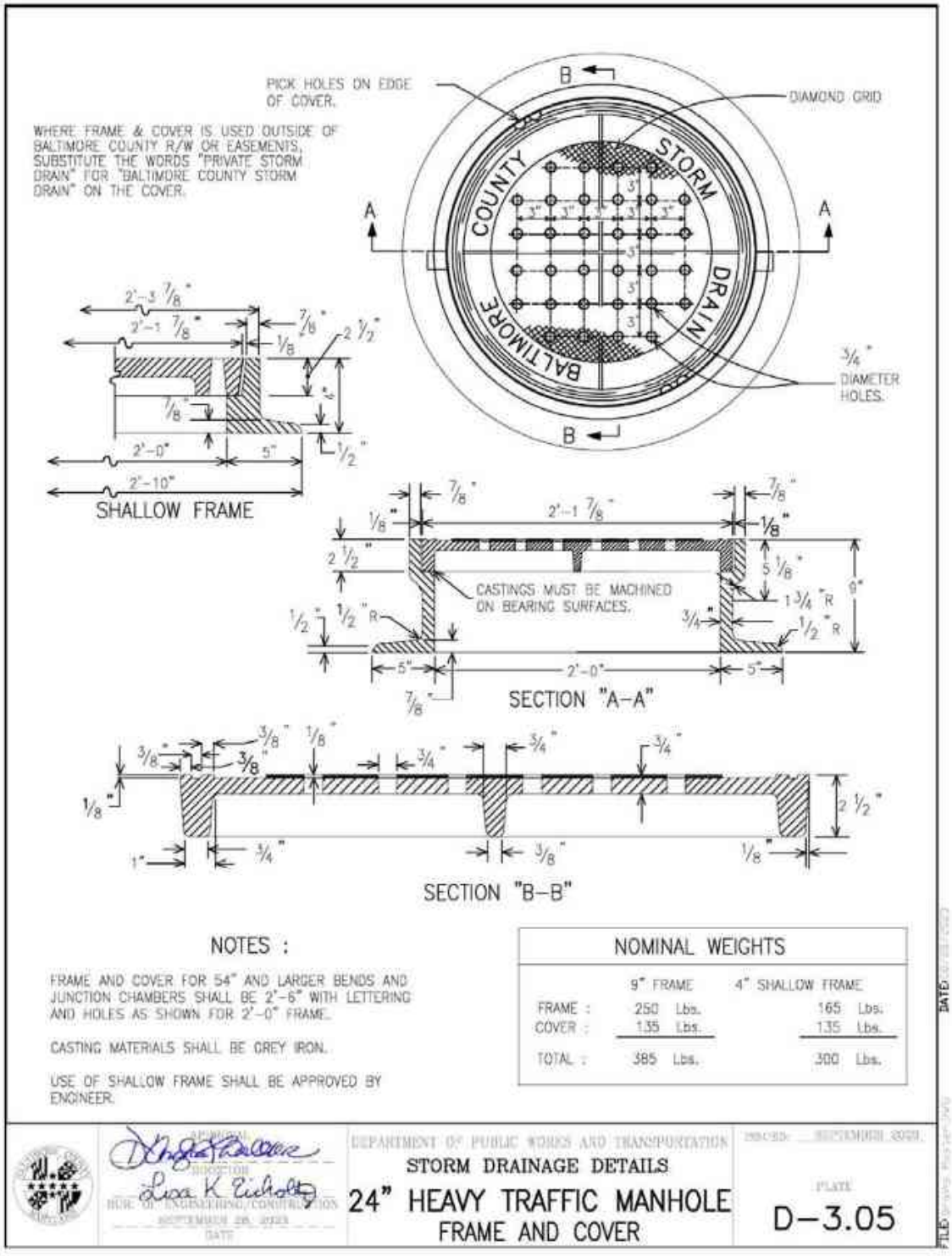


Figure 30: *Utility Hole Schematics*. Source: Baltimore County, n.d.

5.1.3 Design: Pump Station

A pump station is needed right before stormwater is released into the harbor. This will pump stormwater from the end of the stormwater management pipes over the sea wall and into the harbor. It's a vital part of the gray infrastructure upgrades because as sea level rises and heavier rainstorms occur, overland flooding on Thames Street will occur while harbor water levels are higher than the street's elevation. Without a pump, the street will flood until water levels in the harbor recede, which is too great of a risk.



Figure 31: *Thames Street Gray Infrastructure Plan.* Source: ArcGIS Pro

Key:

Icon	**Meaning**
Green Line	Existing Pipe
Yellow Line	Upgraded Pipe
Blue Line	Proposed Pipe
Orange Circle	Existing Inlet
Blue Circle	Proposed Inlet
Red Circle	Proposed Utility Hole
Purple Rectangle	Proposed Pump Station

The pump station will include a bypass pipe so that water can flow by gravity from SWM pipes into the harbor without being pumped whenever water in the harbor is 1.25 ft below sea level or lower, as this is the elevation that the last SWM pipe releases at. This number is used

because it is the exact elevation of the original stormwater outlet pipe present on Thames Street. This bypass will contain a duck bill at its outlet, so that it is automatically closed when harbor water levels rise. This prevents backflow from occurring. A duck bill is chosen as opposed to a traditional flapgate because it avoids possible rusting of hinges or jamming open (Livingston, 2022). Water being bypassed will still flow through the pump station building, but it'll take a different route. This is why the bypass isn't visible in **Figure 31**.

The pump station will be housed in a small building proposed on the southeastern most area of Thames Street, as shown above. This location was chosen because it is at nearly the lowest elevation of the street, it's out of the way of car traffic, and it is on public property. The current use for this space is roughly 2 parking spaces. Taking away these spaces won't have a large impact on the community because Thames Street already has street parking along both sides, and there are also two large parking lots nearby, one for each of the adjacent buildings.

The pumping stations will have the capacity to handle a flow rate slightly higher than the 10-minute, 500-year storm, which is 17.1 cfs. The pump station is fed by a 30 inch diameter pipe (15) and a 12 inch diameter pipe (15), as shown in **Figure 32**.

This pump station will have a standard design. Pipes carrying stormwater will enter into a wet well. The pump station will contain three pumps, each with a capacity of 9 cfs. This ensures that the unit can pump at 18 cfs, which is above the 500-year storm's flow rate of 17.1 cfs, while one pump stays offline. Redundancy in design is important because if one pump fails, the overall pump station is still successful. The pumps move water into a discharge pipe that releases water over the sea wall and into the harbor via an outfall. The wet well gives the pump station storage volume and prevents the pumps from being constantly on, even during events where the harbor water level is high. Its goal is to have enough storage for 120 seconds. While the pump station has capacity for 18 cfs, the wet well doesn't need to be designed for this because it's statistically very unlikely to occur. If it does, the pumps will just run more often to prevent backup. For wet well design, a 24-hour, 1-year return storm is used. This would produce a flow rate of 0.29 cubic ft per second at the pump station according to the rational method equation. The total storage of the wet well for this event will be 34.8 cubic ft.

The total dynamic head (TDH) of the pump station is a unit of length that represents the elevation lift of water and friction losses in the pipe. The static head, or elevation that stormwater needs to be lifted, is 8 ft. This is the sum of the following listed heights, rounded up to the nearest whole number. The sea wall is 3.5 ft taller than the walkway as per our design criteria. The walkway is roughly 3 ft above the road surface. The end of the stormwater pipes, and therefore the wet well elevation of the pumping station, is estimated to be 1.25 ft below ground. Stormwater needs to be lifted by roughly 8 ft.

The Hazen-Williams equation, **Equation 4**, in the appendix, is used to estimate friction loss (The Engineering ToolBox, 2004). For this equation, the variables are estimated to be a pipe length of 100 ft, a diameter of 12 inches, the flow is 18 cfs (8,079 gallons / min), and the pipe is PVC (150 roughness constant) (The Engineering ToolBox, 2004). This gives a friction loss of 9.5 ft. The TDH for the pump station is estimated to be 17.5 ft.

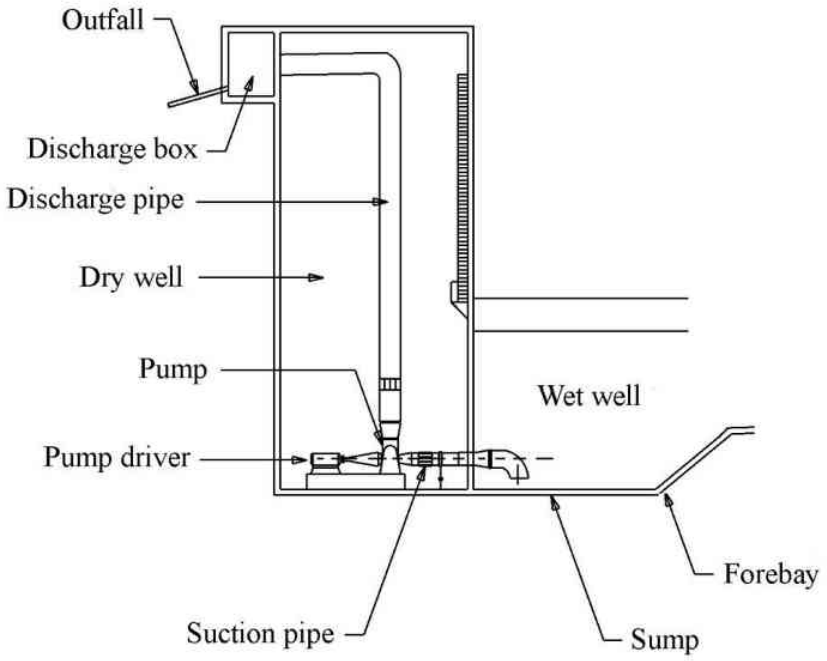


Figure 32: *Sample Pump Station Schematic*. Source: U.S. Department of Transportation Federal Highway Administration (Smith, 2001)

5.1.4 Impact

The design of gray infrastructure improvements are made to accommodate a 10-minute, 500-year storm event. Even with a 1-in-500 year probability of occurring, the 10-minute maximum stormwater flow through Thames Street will not flood with the presented solution. Additionally, the water pump station will allow for proper redirection of excess water back into the harbor or into the wet well. The duck bill will prevent overflow from the harbor from entering into the drainage system and overwhelming it, preventing nuisance flooding that would occur with the harbor levels rising.

The improved inlets will direct waterflow into the drainage pipes as opposed to resting idle on the impermeable street. This nuisance flooding will be limited with the addition of inlets that are larger and strategically placed at the lowest points of the street. Finally, the manholes will allow for easier access in case of clogging, damages to drains, or maintenance repairs. This

will expedite the process of fixing these issues, allowing the drainage system to operate at full capacity.

5.1.5 Constructability, Operations, and Compliance

The general construction process of upgrading the gray infrastructure will begin with digging into the street to replace the pipes that are going to be enlarged. This will require temporary halts on water flow at certain times. This would be done following a schedule that allows for least inconvenience to the residents. After pipe replacements are done, the street will be dug up to add the new pipes to the drainage system. Then, construction will begin on the inlets and manholes. Lastly, the pump will be constructed. All of this will be in compliance with the City of Baltimore's Stormwater Management Requirements, the Code of Maryland Regulations Title 26: Department of Environment, and the FEMA NFIP Floodplain Management Requirements ("Stormwater Management Requirements | Baltimore City"; "Title 26 DEPARTMENT of the ENVIRONMENT | Library of Maryland Regulations"; *National Flood Insurance Program (NFIP) Floodplain Management Requirements a Study Guide and Desk Reference for Local Offi Cials*). This project will have a lifespan of about 50 years (PE100+ Association, n.d.).

5.2 Bioswale Recommendation

The next component to assist in attenuation of rainfall, nuisance flooding, and larger storm events is the modular bioretention cell series located along the length of the north sidewalk of Thames Street Corridor, pictured below in both overhead and street view. This location was chosen due to ease of constructability in rehauling the "rock garden" vegetated structures currently in place, close proximity to peak inundated areas, and relatively low construction-related disturbance compared to other potential solutions (as detailed in **Section 4**). This can be seen in **Figures 33** and **34** below.



Figure 33: *Thames Street Corridor - Plan View.* Source: 1998 Thames St - Google Maps



Figure 34: *Thames Street Corridor - Street View.* Source: 1998 Thames St - Google Maps

The constructed BMP will take up approximately 1,541 ft^2 of previously occupied sidewalk space, spread across 3 modular cells. This square footage was obtained through geospatial measurements and may be subject to distortion, so a sizing discrepancy factor of 25%

is applied to account for distortion-based oversizing, bringing down the effective square footage to about 1,156 ft^2 . In practice, engineers shall verify cell measurements in the field and adjust bioswale sizing accordingly.

Design includes two trapezoidal basins and a third irregularly shaped cell (to be discussed later in further detail) with 6 inches of ponding depth. To achieve this, current rock gardens will be removed and leveled to street grade height, with the top of the BMP aligned with street level, below the presumed standard 6-inch curb acting as a freeboard. Furthermore, the unlined bioretention cell contains perforated underdrain pipe followed by an internal water storage zone to adequately infiltrate remaining runoff from flooding and rainfall events. Curb cuts will direct water flow into the cell, while the overflow outlet and monitoring well handle excess flow and allow for drainage time and media assessment.

The primary goal of this bioretention cell series is to mitigate the generation of stormwater runoff along the Corridor, allowing water to infiltrate and return to the stormwater system instead of remaining on the surface. This can be accomplished by designing to capture and release a portion of the Water Quality Design Storm, which is assumed to be 1.5 inches of rainfall over the catchment area throughout Eastern Maryland (Maryland Department of the Environment, 2025). The secondary goal is to assist in attenuating larger design storms in tandem with the upgraded stormwater infrastructure, but design and utility constraints, as well as catchment size, limit the extent to which this structure can mitigate larger inundation events.

Using the recommended 1.5-inch water quality design storm depth for Eastern Maryland and the calculated catchment area of approximately 9,075 m^2, the required water quality volume to be treated comes to about 305 m^3 (**Equation 5)**. With the proposed cell parameters and an effective ponding depth of about 1 meter, the bioretention series is capable of capturing and conveying approximately 25% of the water quality storm. Due to the severe undersizing of the retention series from various constraints, the remainder of the water quality storm mitigation will be supported by gray infrastructure improvements including pipe diameter expansion, storm drain additions, and pumping station installation.

5.2.1 Design

The modular bioretention series to be constructed is made up of 3 cells, two of which are rectangular and one being an irregular shape, which is depicted in **Figures 35**, and **36** for a closer look at cells 2 and 3.

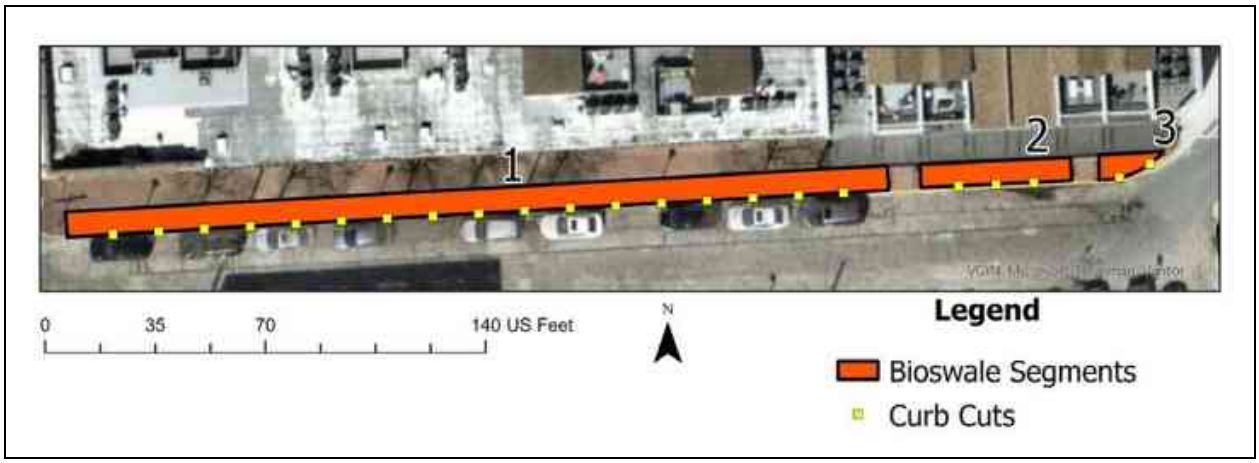


Figure 35: *Thames Street Corridor Bioretention Cells.* Source: ArcGIS Pro

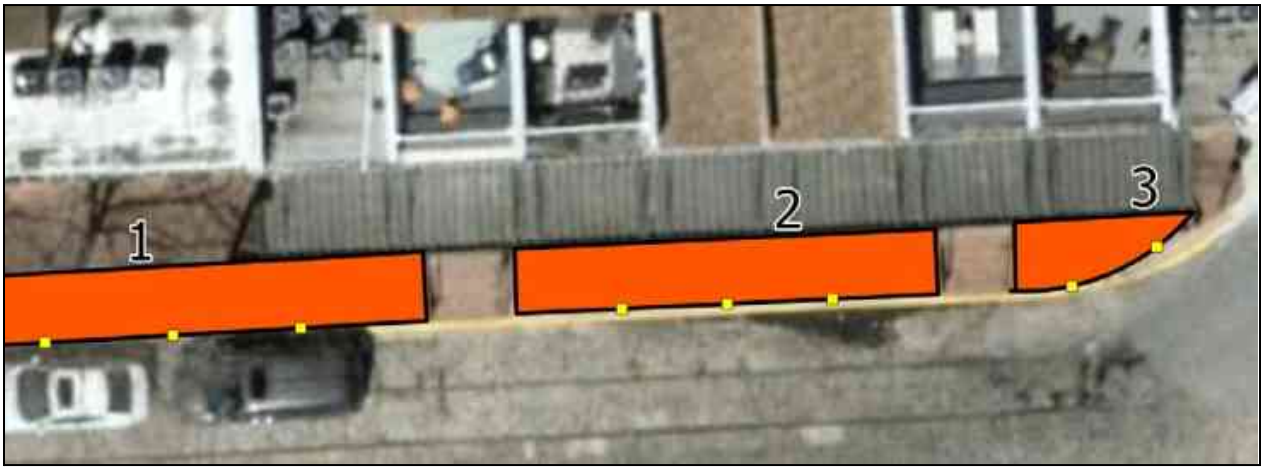


Figure 36: *Zoomed in Bioretention Cells.* Source: ArcGIS Pro

The shaping constraints from this irregular third cell render the trapezoidal cross section difficult to construct without extending curb structures or altering the road. Therefore, this smaller third section will implement a flat retention basin recessed 6 inches to match the bottom height of the trapezoidal trough design and allow for the same effective ponding depth. **Tables 3** and **4** show information on the estimated dimensions for bioswale area, as well as catchment sizing data. For conveyance into the cells, 18-inch curb cuts will be added and spaced evenly approximately every 15 feet of length as recommended by the National Association of City Transportation Officials Urban Street Design Guide, totaling to approximately 17 cuts for cell 1, 3 cuts for cell 2, and 2 cuts for cell 3 (NACTO, 2026). Curb cuts shall be paired with miniature gravel diaphragm structures corresponding to curb cut length to mitigate flow velocity and pretreat coarser particulates (*Gravel Diaphragms*, 2022).

Table 3: *Bioretention Cell Dimensions.* Source: ArcGIS Pro

Cell	Dimensions (L x W,ft)	Area (ft^2, approx)
1	262.5 x 7.5	1246
2	48 x 7.5	217
3	24 x 7.5 (not full rectangle)	78
TOTAL:	-	**1,541** [1]

1. Total before adjustment of 25% sizing discrepancy factor

Table 4: *Upslope Area Statistics.* Source: ArcGIS Pro

Variable	Value	Unit
Catchment Area	97,683	ft^2
Percent Impervious Area	~92.5[1]	%
Catchment Impervious Area	90,387	ft^2
Bioswale Total Area	1,155*	ft^2
Ratio of Catchment impervious area to Practice permeable (footprint) area	78.2[2]	-

1. (EnviroAtlas, 2019)
2. Generally recommended I:P ratio of 5 to 20

One important observation to make about the data above is that the measurements in **Table 3** were calculated using measurement tools in ArcGIS Pro, which, as mentioned above, are subject to distortion. Subsequent calculations that reference bioswale area dimensions are subject to the 25% sizing discrepancy factor. Additionally, the impervious area to practice area ratio was determined to be about 78.2, which is significantly above the recommended range of 5 to 20. Because of the large discrepancy in practice size to catchment area, support of the modular bioretention series by gray infrastructure improvements is critical.

For all swales, based on the design assumptions stated in **Section 3**, the project site likely contains class D hydrologic soil with a very low hydraulic conductivity (K) value of 0.06 $\frac{in}{hr}$ or less, limiting options on natural groundwater infiltration practices (Maryland Government, 2025) (United States Department of Agriculture, 2009). Because the natural soil has a K value of less

than 0.59 $\frac{in}{hr}$, this indicates that a BMP with a perforated pipe underdrain and internal water storage layer is the best option, as opposed to a method relying on infiltration or containment and storage. It is important to note, however, that soil and water table data specific to Fells Point is vague and approximate at best based on geospatial data, and that MDE generally requires proposed BMPs to perform field infiltration tests and a USDA soil textural analysis Maryland Government, n.d.). Therefore, the proposed solution uses the best information currently available, and in practice would perform these measurements as necessary to provide the best possible flood mitigation solution.

For the cross sectional parameters of the bioretention cells, **Table 5** summarizes primary design components, material makeup, and relevant properties. Material specifics will be explained further in the following sections.

Table 5: *Bioretention Cell Layer Components.* Source: *Biorentention: Sizing,* 2024

Layer	**Material and Properties**	**Value (inches)**
Gravel Diaphragm (interspersed throughout vegetated side slope)	Clear Stone Aggregate porosity (n) = 0.4	6
Surface Ponding Depth (including mulch)	For Trapezoidal cells, side slope of 10.3 deg	
Mulch	Double-shredded Hardwood Mulch porosity (n) = 0.7	2
Media	Media blend A porosity (n) = 0.4	30
Choker layer	Clear Stone Aggregate porosity (n) = 0.4	4
8-inch Diameter Perforated Underdrain Pipe	PVC pipe, ⅜ inch circular perforations, every 90 degrees spaced 4 inches apart [1] Surrounded by Clear Stone Aggregate, porosity (n) = 0.4	8
Internal Water Storage Layer	Clear Stone Aggregate porosity (n) = 0.4	12
Total:	—	**60**

1. Maryland Department of the Environment states that perforated underdrain pipes must be wrapped in two layers of ¼ inch stainless steel wire mesh to assist in clogging prevention (*Rain Gardens*, 2013).

As described in **Section 3.2.2**, general utilities are assumed to be located about 4 feet beneath grade level, which is unfortunately surpassed by the internal water storage layer of the reservoir and could potentially cause conflicts in the construction and excavation process. However, similar to the availability of hydrologic and soil data, information on utility locations and depths is generally unavailable for use as a public resource, making it difficult to account for specific constructability conflicts and variations from the proposed BMP. Using the best information currently available, it is assumed that utilities may hinder, but not prevent construction and efficacy of the BMP, and that further construction efforts will account for their presence.

To further detail the material components of the bioretention cell layers, the top layer is composed of two inches of double shredded hardwood mulch to preserve soil moisture and pollutant removal. If mulch proves ineffective in high flow conditions, it shall be replaced with a similarly sized layer of stone or aggregate (*Mulch*, 2020). Next is a 30-inch layer of drainage rate-focused filter media blend, composed of 3 parts sand and 1 part organic components and additives, such as wood chips, biochar, and water treatment residuals (*Bioretention: Filter Media,* 2025). Filter media must follow strict ASTM standards for varying criteria, such as ASTM C33 for the coarse sand fineness modulus index (between 2.8 and 3.1), ASTM D234 for saturated dry conductivity value (75-300 mm/hr) in accordance with ASTM D698 of 85% maximum dry density, plant available or extractable phosphorus concentration of 10-40 ppm, ASTM D6913 for particle size distribution of less than 25% particles smaller than 0.05 nm, ASTM D7928 for 3-12% particles 0.002 mm or smaller, and ASTM F1647 for organic matter content of 3 - 10% filter media by dry weight (*Bioretention: Filter Media*, 2025). Next is the choker layer, which, same as the media surrounding the underdrains and the internal water storage layer, is composed of clear stone aggregate with specifications according to ASTM D2940 maximum wash loss value of 0.5%, a minimum durability index of 35, and a maximum abrasion of 10% of 50% for 100 or 500 revolutions, respectively (*Reservoir aggregate*, 2020).

For the non-media components, the underdrain shall be 8-inch diameter PVC Schedule 40 piping, with ⅜ inch circular drilled perforations spaced 4 inches apart, every 90 degrees around the circumference of the piping (NCSU Bibo Tech Spec, 2015). Only pipe segments within the cells will be perforated; transitionary and downstream conveyance will be solid pipe. Underdrain shall be connected to existing stormwater infrastructure to convey infiltrated water from the BMP. Per MDE guidelines, perforated underdrain pipes must be wrapped in two layers of ¼ inch stainless steel wire mesh to reduce clogging risk (*Rain Gardens,* 2013). MDE also requires both underdrain access through cleanout piping and separate monitoring wells, which

shall be installed in each bioswale segment proportional to length. Cell 1 shall include 3 evenly distributed access pipes and monitoring wells, and cells 2 and 3 shall include 1 access pipe and 1 monitoring well each. Cleanout piping includes 8-inch PVC piping extended to the surface of the bioswale through two 45-degree pipe couplings with a sealed, lockable cap (*Underdrains,* 2022). Monitoring wells shall be 6-inch diameter PVC piping, with 72 inches of length to allow for 6 inches of clearance both above the bottom of the trough and below the internal water storage layer (Maryland Government, n.d.). Inside the piping shall be a water level sensor attached to the lockable cap by a cable. Pipe perforations shall begin at 38 inches of depth (consistent with the centerline depth of underdrain piping) following the same perforation sizing guidance as above, and will continue until 60 inches of depth (bottom of the IWS layer), after which 6 inches of solid pipe will continue downwards followed by a sealed cap stand to provide a small water reservoir for the sensing equipment (*Wells*, 2022). In accordance with MDE, the monitoring well perforated section shall also be wrapped in two layers of ¼ inch stainless steel wire mesh to prevent clogging (*Rain Gardens,* 2013). Representations of these components are shown below in **Figure 37**.

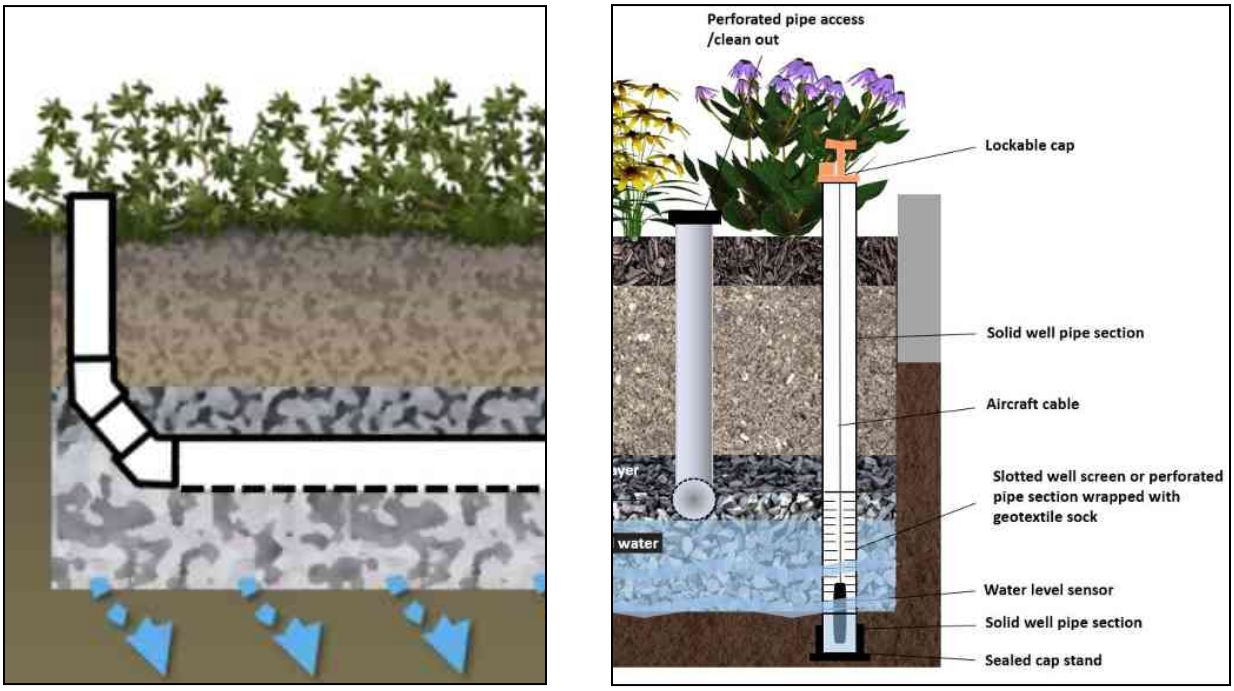


Figure 37: *Underdrain Access and Monitoring Well.* Source: *Underdrains,* 2022; *Wells*, 2022

As referenced above, regularly placed 18-inch curb cut structures shall serve as both conveyance means into the cell and as overflow outlets, controlling inflow velocity and volume. Paired gravel diaphragm structures shall assist in flow mitigation and pretreatment of coarse solids. For materials and parameters, the diaphragm shall extend 12 inches into the sloped retention cell and have a depth of 6 inches, consistent with the vegetated layer above the filter media. The diaphragm trench is lined with geotextile fabric to maintain media separation and

improve water quality (*Gravel Diaphragms*, 2022). Material shall be clear stone aggregate consistent with choker and IWS layers. **Figure 38** shows general diaphragm structure and placement.

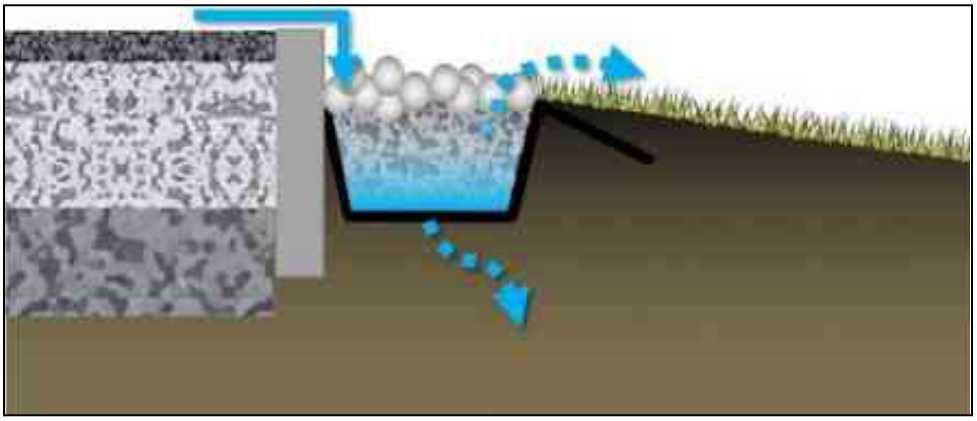


Figure 38: *Gravel Diaphragm.* Source: *Gravel Diaphragms*, 2022

For the vegetative elements of the bioswale, plants shall be selected on the basis of salt and sunlight tolerance, native status, sediment and erosion control, flooding and pollution resistance, and drought tolerance. Per Low Impact Development planting guidance, bioretention features are broken into 3 zones: low, middle, and high, which corresponds to soil moisture levels. These levels are highest in the low zone and are further reduced in the following zones. General recommendations state that low zones should be occupied by salt tolerant and moisture compatible tall grass species, middle zones are occupied by moderately salt resistant plants that thrive in semi-moist conditions, and high zones are usually occupied by shrubs and perennials less adapted to moist or salty conditions (*Plant Lists*, 2026). It is important to note that in practice, engineers must perform soil analyses and chemistry tests to properly determine hydrology, salt exposure, and maintenance requirements for selected plants. One distinction to be made is that due to the flat nature of cell 3, it will exclusively be filled with zone 1 plants.

Based on this guidance, **Table 6** summarizes plant choices, planting zones, and notes indicating important characteristics.

Table 6: *Bioretention Cell Plant Selection.* Source: *Plants List,* 2026; Natural Resources Conservation Service, 2013; Natural Resources Conservation, 2014; Natural Resources Conservation, 2015; Uchytil, 2018

Plant Name	Planting Zone	Characteristics
Smooth Cordgrass	1	Tolerates brackish-to-saline water, helps stabilize the cell bottom.

Switchgrass	1	Good for erosion control, tolerates wide range of salinity conditions
Saltmeadow Hay	1 and 2	Soil stabilization and salt tolerance
Black Rush	2	Suited for transition zones, tolerates periodic inundation
Seaside goldenrod	3	Tolerates saline soils, good for pollinator value

5.2.2 Impact

To analyze the effectiveness of the modular bioretention series, hydrologic performance must be determined using the water quality design storm, which was previously established as 1.5 inches of rainfall throughout Eastern Maryland (Maryland Department of the Environment, 2025). From this, the design water quality volume was obtained through **Equation 5**, utilizing catchment area, impervious area cover, and the given rainfall depth. This was determined to be about **10,776** cubic feet, or **2.24** acres. When comparing this number with the bioswale storage volume and accounting for sizing discrepancy factor (**Equation 7**), total bioswale storage volume (considering ponding depth, layer volume and porosity) came to approximately **2,740** cubic feet, or **25.4%** of the storage capacity necessary to contain the water quality storm. Once again, this undersizing will be supported by local gray infrastructure improvements to effectively mitigate the water quality storm and beyond.

In determining filter drawdown time, there are several methods to calculate how long the infiltration BMP will take to drain down. Two methods include calculating peak flow rate through underdrain piping and through filter media (Equations **5.2-3** and **5.2-4**). Using head of bioretention components, filter media hydraulic conductivity, and the ratio of pipe perforation area per unit length, peak flow rates through underdrain and media were determined to be **27.5** and between **0.11** and **0.42** cubic feet per second, respectively. Because media infiltration is the limiting factor, it may be used to calculate the theoretical maximum drawdown time. Combining the water quality volume of **10,776** cubic feet with between **0.11** and **0.42** cubic feet per second, theoretical time to drain the infiltration cells of the water quality volume is between **7.10** and **28.42** hours, well below the maximum recommended drawdown time of 48 hours (**Equation 12**)(*Bioretention: Sizing*, 2024).

Next, in accordance with the design storm for the other solutions, bioswale sizing calculations were additionally performed for the 100-year, 24-hour storm, which will be taken from the Maryland Stormwater Design Manual 2025 Draft as opposed to other sources because

of the projections reflective of climate change, as detailed in **Section 3.1.2** and **Figure 10**. Per the 2025 draft report, the climate-adjusted rainfall depth is 10.03 inches, 16% higher than the NOAA Atlas 14 value of 8.65 (*Biorentention: Sizing*, 2024). Using the adjusted rainfall depth along with the catchment impervious area, effective ponding depth, native and design infiltration rates, and an infiltration safety factor, the required surface ponding area to handle the 100-year storm is about 11,796.9 ft^2, or a little over 10 times the size of the current BMP footprint (**Equation 5.2-6**). It is worth noting, however, that bioretention cells are not traditionally sized to handle storms of this caliber, and because the current stormwater piping is capable of conveying the 100-year 24-hour storm, the bioretention BMP can serve as a supportive structure that provides more benefits than solely stormwater management.

Overall, the proposed modular bioretention series is expected to benefit the Thames Street Corridor through increased management of nuisance flooding and low-impact storm events, as well as assisting gray infrastructure measures during larger scale inundation scenarios. Additionally, water infiltrated through the BMP will have increased quality with effective total suspended solids, nutrient, and metal removal in accordance with general performance standards of the 2025 draft manual (Maryland Department of the Environment, 2009).

5.2.3 Constructability, Operations, and Compliance

For construction of the modular bioretention series, currently in-place trees, shrubbery, and established rock gardens shall be removed to make way for infiltration cell excavation. Upon reaching the excavation depth of 4 ft below grade level, contractors shall evaluate specific utility constraints and coordinate with engineers, utility owners, and city agencies to determine if further excavation through or around piping is possible to establish the internal water storage layer.

In addition, once the current rock gardens are removed to accommodate for the new at-grade and sub-grade BMP (seen in **Figure 34**), a 1-2 foot drop from the elevated brick sidewalk will pose a new safety hazard to pedestrians. Therefore, a 1-2 foot barrier shall be built along the elevated sidewalk sections adjacent to the swales to provide a necessary safety buffer to the new retention cells.

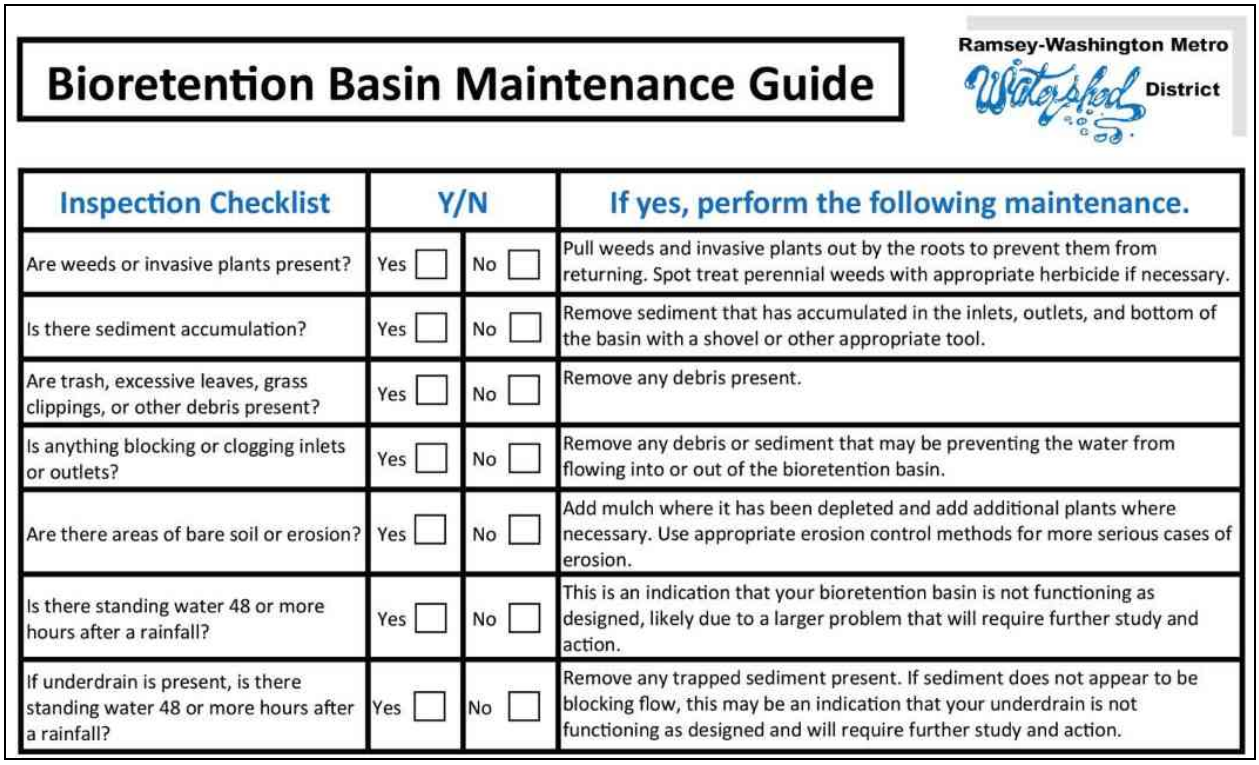
During the underdrain and media installation process it is critical to avoid any and all compaction of media and underlying soil layers through heavy machinery or equipment use in the BMP area. Once media and vegetation layers are established, curb cuts shall be installed to bring the system online, and vegetation planting density shall exceed 80% of allotted cell area (*Bioretention*, 2016)). It is important to delay installing the curb cuts until the BMP is completely constructed because keeping a system offline can lead to “(i) less risk of erosion, clogging, and

compaction, (ii) greater opportunity for establishment of seeded/planted areas, and (iii) easier access for construction, repairs or maintenance of the area" (*Bioretention,* 2016).

After the completion of the construction process, there are several elements of maintenance that must be performed continuously throughout the BMP life cycle. To encourage plant establishment and reduced future maintenance, plants must be routinely watered throughout the first two-year period, with more intense watering schedules within the preliminary establishment period and the first two weeks (*Bioretention,* 2016). This task may be added to current scheduling for Baltimore City Forestry & Tree Services or Department of Public Works, or can be taken over by non-profit organizations such as Blue Water Baltimore, assisting in the community trust and buy-in of this project. The following **Table 7** and **Figure 39** states recommended maintenance scheduling and recommended maintenance tasks.

Table 7: *Bioretention Maintenance and Frequency*. Source: *Bioretention*, 2016, Titov, n.d.

Maintenance Measure	**Frequency**
Watering and Debris Removal	Weekly to Monthly for the first 2 years
Routine Inspection	2-4 times annually (including spring and late fall), after storm events
Mulch Replacement	Every 1-3 Years
Monitoring Well and Clearout Piping Inspection; flushing and cleaning of underdrains if necessary	2-4 times annually (including spring and late fall), after storm events
Drawdown Report Completion (with a rainfall event equal to or greater than the design capture depth)	Every 1 Year
Camera Inspection of Pipes	Every 5 Years



Bioretention Basin Maintenance Guide

Ramsey-Washington Metro Watershed District

Inspection Checklist	Y/N		If yes, perform the following maintenance.
Are weeds or invasive plants present?	Yes ☐	No ☐	Pull weeds and invasive plants out by the roots to prevent them from returning. Spot treat perennial weeds with appropriate herbicide if necessary.
Is there sediment accumulation?	Yes ☐	No ☐	Remove sediment that has accumulated in the inlets, outlets, and bottom of the basin with a shovel or other appropriate tool.
Are trash, excessive leaves, grass clippings, or other debris present?	Yes ☐	No ☐	Remove any debris present.
Is anything blocking or clogging inlets or outlets?	Yes ☐	No ☐	Remove any debris or sediment that may be preventing the water from flowing into or out of the bioretention basin.
Are there areas of bare soil or erosion?	Yes ☐	No ☐	Add mulch where it has been depleted and add additional plants where necessary. Use appropriate erosion control methods for more serious cases of erosion.
Is there standing water 48 or more hours after a rainfall?	Yes ☐	No ☐	This is an indication that your bioretention basin is not functioning as designed, likely due to a larger problem that will require further study and action.
If underdrain is present, is there standing water 48 or more hours after a rainfall?	Yes ☐	No ☐	Remove any trapped sediment present. If sediment does not appear to be blocking flow, this may be an indication that your underdrain is not functioning as designed and will require further study and action.

Figure 39: *Bioretention Cell Routine Inspection Checklist.* Source: Great Lakes Restoration Initiative, 2016

Lastly, for compliance and permitting, the primary requirements to be addressed for the modular bioretention series are erosion and sediment control (ES&C) plan approval, and Stormwater Management (SWM) plan approval. Because the bioretention cell excavation and installation process disturbs slightly more than 100 cubic yards of earth, it is subject to both COMAR 26.17.01 and the Baltimore City Code Article 7, § 32-7 (City of Baltimore, n.d.)(*Code of Maryland Regulations,* n.d.). For stormwater management, relevant codification is included in COMAR 26.17.02 and the 2009 Revised Maryland Stormwater Design Manual, on which this design is based (*Bioretention: Sizing,* 2024) (Maryland Department of the Environment, 2009). This means that prior to the construction phase of this project, both ES&C and SWM plans must be approved by the city in order to continue with development.

5.3 Seawall Recommendations

The last part of our design recommendations is a seawall around the Waterfront Promenade to mitigate the hazards and associated damages from storm surges. The design must take into account the growing impacts of climate change, hydraulic conditions, and the historic urban setting. This section will outline the design process for a living seawall. The proposed seawall will span the length of the Promenade around the Thames Street Corridor, as shown in **Figure 40**. The Promenade in this location is approximately 1 foot above the still water level, indicating that it's a low-elevation area susceptible to storm surge flooding. A seawall could help significantly reduce flooding and damage costs in this area.

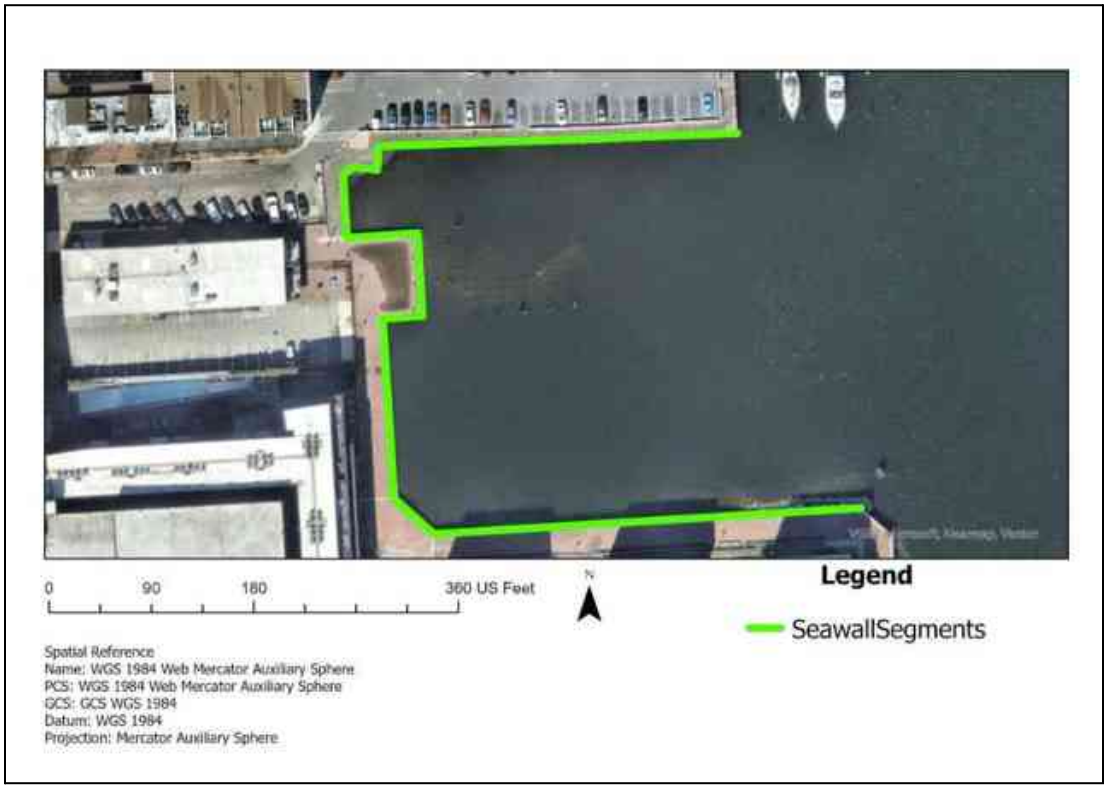


Figure 40: *Waterfront Promenade around the Thames Street Corridor*. Source: ArcGIS Pro

The seawall will run along the Waterfront Promenade, spanning 905 ft. The design will include two main parts: a stepped seawall that will run from the toe of the wall up to the preexisting sidewalk and a vertical wall above the sidewalk. Additionally, the toe of the wall will be lined with rocks and shellfish reefs to prevent scouring and help improve water quality. The seawall will also be lined with modular living seawall panels to promote ecological development and biodiversity.

The overall goal of this proposed seawall is to reduce wave energy from storm surges and reduce the volume of floodwater from wave overtopping. This was designed with a 1-in-3,000-year storm in mind to prove its effectiveness (First Street Technology, Inc., n.d.).

5.3.1 Design

Fells Point is subjected to tidal fluctuations, storm surges, and wind-driven wave action. The area is low-lying, and existing walkways and bulkheads along the water are aging and barely above the still water level (approximately 1 foot above). The current conditions at the site can be found in **Figure 41** below. The 1-in-3,000-year storm was used to establish a baseline for hydraulic conditions to better understand the climate mitigation of the proposed solution. The significant wave height – the average height of the highest one-third of waves in a wave spectrum – associated with the design storm was used for the design of the seawall. These wave conditions were estimated using fetch-limited wave growth equations consistent with the Coastal Manual from the United States Army Corps of Engineers. For Fells Point, limited fetch within the harbor reduces the overall wave heights compared to open water conditions; however, the strong winds from the design storm can still generate significant wave action.

The seawall type that was selected for the proposed design will be an extension of the current walkway and is a combination between a steep stepped wall and a typical vertical wall – all made from concrete. A cross-sectional diagram of the proposed seawall can be found below in **Figure 42**. The stepped seawall is designed to dissipate wave energy and is effective for reducing the amount of wave runup from storm surges and tides. It will extend from the toe of the wall, which is at a depth of approximately 3 feet below the still water level, and up to the existing sidewalk, which is 1 foot above the still water level. The vertical wall portion will be 3.5 feet tall above the current walkway and will primarily help with reducing the overtopping volume rate, which is the rate that water floods over the top of a seawall. The slope of the entire wall is approximately 1:3. This decision reflects the space constraints, existing urban infrastructure, the need to dissipate wave energy, and the overall aesthetic of the waterfront.



Figure 41: *Waterfront Promenade at Thames Street Corridor - Street View.* Source: Google Maps

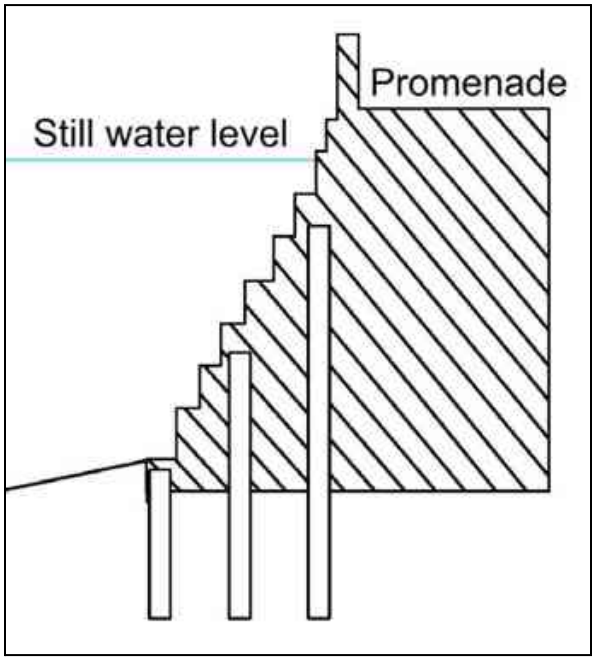


Figure 42: *Cross-sectional Diagram of Proposed Seawall.* Source: Design Team

Additionally, the seawall will utilize shellfish reefs and armor stones to prevent scouring at the toe of the seawall. The shellfish reefs will also help improve water quality within the area and create important habitats for various fish, invertebrates, and other shellfish. These reefs are able to serve as effective barriers against storm surges and tides, preventing erosion at the base of the seawall by reducing wave energy and stabilizing the bottom of the harbor (NOAA, 2026).

Armor stones will serve as normal toe protection in conjunction with the shellfish reefs. Since most cases of seawall failures are due to scouring of the toe, it is important to add rock toe protection to prevent undercutting and to reduce the energy of waves (O'Neill, 1986).

The seawall will also utilize three sets of foundation piles made from high-performance concrete (HPC) driven into the ground to create durable, corrosion-resistant protection. It will limit the amount of erosion at the base of the seawall and prevent failure by providing vertical stability, supporting structural loads, and resisting any lateral forces from oncoming waves. The piles help keep the wall stable in softer soils by transferring loads to deeper layers of the ground (O'Neill, 1986).

The stepped portion of the seawall will be lined with modular living seawall panels to promote ecological development and biodiversity. The living seawall panels are based on the work done by the Stone Living Lab located in Boston and the Reef Design Lab located in Australia. This nature-based solution utilized 3D printing technology to bring habitat panels to seawalls that mimic the natural features that help promote ecological development (Stone Living Lab, 2026; Reef Design Lab, 2025). Generally, urban structures along the coast, such as seawalls, are incredibly flat and featureless, providing little to no space for marine life to thrive. With the expansion of urban development especially in regards to marine environments, it has become increasingly important to develop solutions that combine the need for improved infrastructure while also minimizing any negative footprints on the environment. The utilization of a nature-based solution will not only help combat flood risks but also ensure that natural habitats in the Baltimore Harbor are not being destroyed. The modular seawalls panels are adaptable, scalable, and can accommodate a wide variety of marine organisms. According to Living Seawalls, a program of the Sydney Institute of Marine Science, these panels have already been installed along many of the existing seawalls in Sydney Harbour, Australia, noting a 36% increase in the number of fish, seaweeds, and invertebrates as a result (Living Seawalls, 2025).

5.3.2 Impact

One of the most important considerations for the seawall's performance is its ability to reduce flooding from storm surges, as this is a major source for property damage in Fells Point. The flooding, as previously stated, is based on the one-minute sustained wind speed from a 1-in-3,000 year storm, with wind speeds of 74 mph (33.073 m/s). Following the Coastal Manual from the United States Army Corps of Engineers (USACE), wave conditions were estimated using fetch-limited wave growth equations (**Equations 14-21**), utilizing fetch length (unobstructed distance that wind blows over water), wind speed, wind duration, and coefficient of drag. The maximum wind fetch for the Thames Street Corridor is 757.817 feet (2485.64 meters). From these calculations, the significant wave height was found to be 3.390 feet (1.0331 meters).

The significant wave height allows for the calculation for the wave overtopping volume, which is the rate that water floods over the top of the seawall. The R&D Technical Report W178 on Wave Overtopping of Seawalls was used as a guide for the calculations of the overtopping volumetric rate for the proposed seawall design. Using **Equation 24**, the overtopping rate across the entire length of the 905 foot seawall is 2,977.634 gal/s. To put this into perspective, current conditions at the Thames Street Corridor without the proposed seawall design would result in an overtopping rate of 22,559.372 gal/s along the entire section of the walkway. These calculations can be found in the Appendix. This shows that the implementation of the seawall can potentially reduce storm surge flooding for the design storm by up to 86.801%, which is a significant reduction in volume and damage for the area. Any water that does overtop the wall can be removed or captured via the modular bioswales, additional storm drainage inlets, and pump station.

5.3.3 Constructability, Operations, and Compliance

For construction, the existing promenade will be used as a basis for the adapted seawall. Due to the area being within a constrained urban waterfront with active pedestrian use, construction will more likely need to be sequenced into phases to maintain partial public accessibility and to minimize disruption to the community. Initial steps will include site analysis and site preparation. The edge of the water needs to be cleared of debris and old wall materials. Soil must be tested for stability, and any unstable soil needs to be removed to create a stable foundation. Piling will be installed deep into the ground to allow for stable construction of the seawall, and the stepped seawall portion can be precasted to allow for easier installation. The living seawall panels can be installed after the primary structural elements are all set in place. The armor stone toe protection should be placed soon after the installation of the stepped seawall to immediately provide scour protection. The shellfish reefs should be installed after all major in-water construction is complete to avoid any sedimentation or disturbances of the reefs. Construction will need to be coordinated with tidal cycles to optimize construction feasibility.

The living seawall will require regular maintenance to ensure proper function. Yearly inspections should be done on the structural components of the seawall such as the stepped and vertical elements, the armor stones, etc. for any cracking, displacement, degradation, or any other damages. For the living seawall panels, water quality and sediment accumulation should be monitored to assess ecological performance. Maintenance might involve selective cleaning or repairs/replacement of damaged panels. Due to the nature of the stepped seawall, floating debris might get trapped, which will require routine cleaning to ensure proper ecological function as well as waterfront aesthetics.

The construction of a seawall in Fells Point will require a range of regulatory work and permits to construct in navigable water and coastal zones. According to the USACE, the construction of the seawall will require regulatory compliance under Section 10 Permit of the Rivers and Harbors Act (which is required for any work in navigable waters), Section 404 Permit of the Clean Water Act (which is required for placement of fill material such as armor stones and concrete), and the Maryland State Programmatic General Permit (MDSPGP, used to authorize all types of work in all waters). Additionally, the Maryland Department of the Environment requires compliance with Section 401 of the Water Quality Certification (a project will not impact Maryland water quality standards, required if altering a floodplain or waterway), Tidal Wetlands License/Permit (required for any work that may change a tidal wetland), and a Waterway Construction Permit.

6. COST ESTIMATE AND BENEFIT ANALYSIS

6.1 Cost Estimate

In order to evaluate the feasibility of this project for real-world implementation, it is important to calculate the estimated costs for material components, construction, operations and maintenance, as well as any other incidental costs. Then, a damage mitigation analysis will be conducted, quantifying reduced risk level in dollar values, allowing for comparison between cost, benefits, and an estimation of when this project's benefits will outweigh its original costs.

6.1.1 Cost Estimate - Gray Infrastructure Improvements

The table below shows costs for pipe construction, pipe enlargements, inlet construction, and manhole construction.

Table 8: *Gray Infrastructure Cost Estimates*

Necessary Infrastructure	Length or Number	Cost Materials per Unit ft	Cost of Installation per Unit ft	Total Cost ($)
Proposed Pipe (15 inch diameter) - HDPE	77.6 ft	15 per ft (Tractor Supply Co, 2026)	60 (Musial, 2026)	5820
Proposed Pipe (12 inch diameter) - HDPE	50.7 ft	14.36 per ft (Tractor Supply Co, 2026)	60	3770
Proposed Pipe (30 inch diameter) - ductile iron	32.1 ft	50 /ft (Tractor Supply Co, 2026)	60	3531
Enlarged Pipe (12 to 18 inch diameter) - HDPE	212.7 ft	22.5 (Tractor Supply Co, 2026)	60	17,547.75
Enlarged Pipe (15 to 18 inch diameter) - HDPE	34.5 ft	22.5 (Tractor Supply Co, 2026)	60	2,846.25
Proposed Inlets -	6	(included in 2,000)	2,000	12,000

cast iron			(Young, 2026)	
Manholes - cast iron	3	(included in 7500)	7500 (Appendix O: Project Profiles and Cost Estimates, 2017)	22,500

These estimates account for both the cost of labor, permits, equipment of installation and the cost of the item itself.

The pump station is also a large expense (*Silver Spring Intermediate Neighborhood Park - Park Renovation Project,* 2019). The pump station will have a maximum capacity of 18 cubic ft per second, which is equivalent to 8,078 gallons per minute (GPM). Comparable pump stations, like one constructed in King County Washington, has 17,500 GPM (Johnston, 2009). This particular pump station had a total project cost of $587,000 in 2009. Adjusting for inflation, that's equal to $918,000 in 2026 (*CPI Inflation Calculator*, 2025). The pump station designed in this report has less than half the capacity, so we're estimating that the cost of our pump station will be a little over half the cost of the King County project. This accounts for any unforeseen or additional costs. We estimate the pump station part of our project will be $500,000.

The totals for gray infrastructure are listed below.

The total cost of gray (not including pump station): **$68,015**

Pump station: **$500,000**

TOTAL construction cost: **$568,015**

The maintenance cost of gray infrastructure is estimated as $1.00/ft/yr (*Appendix B -Basis of Cost Opinions Costs for Combined Sewer Overflow Control Technologies and Alternatives Table of Contents*, n.d.) The new gray infrastructure pipe lengths total 160 ft. This means the cost is $160/yr for piping. The cost of additional stormwater inlets is roughly $25/inlet/yr, which totals $150. The pumping station's annual maintenance is estimated to be $20,000/yr, or 4% of its base cost, which is $20,000/yr (Bertowski, 2025; *DC Water Stormwater Services - Cost of Service and Recovery Methodology Study FINAL MEMO REPORT / Febru Ary 2 024*, n.d.).

The total maintenance cost of gray infrastructure is estimated to be **$20,310/year,** with most of the cost being due to the pumping station.

6.1.2 Cost Estimate - Bioswale

For determining the costs of bioswale construction, operations, and maintenance, online green infrastructure life cycle cost calculators were utilized with assumed construction, maintenance costs, and BMP life cycle as shown in **Figure 43**.

Construction Costs		
Range	**Cost**	**Source**
Low	$3.38/ft^2	EPA, 2016
Medium	$17.58/ft^2	U.S. Army Corps of Engineers, 2014
High	$169.51/ft^2	Missouri Dept. of Natural Resources, 2012
Annual Maintenance Costs		
Range	**Cost**	**Source**
Low	$0.04/ft^2	EPA, 2016
Medium	$0.26/ft^2	City of Lancaster, PA, 2011
High	$8.27/ft^2	City of Portland Environmental Services, 2006
Component Lifespan		
Range	**Lifespan**	**Source**
Short	5 years	Belanger. City of Toronto, 2008
Medium	20 years	Belanger. City of Toronto, 2008
Long	50 years	University of Toronto, 2013

Figure 43: *Bioswale Life Cycle Cost Components.* Source: *Compare the performance, costs, and benefits of Green Infrastructure to conventional stormwater practices*, n.d.

Sources for average construction, maintenance costs, and BMP life cycle were found in the U.S. Army Corps of Engineers 2014 Cost-Estimation Tool, A 2013 Assessment of Life Cycle Costs for Low Impact Development Stormwater Management Practices by the University of Toronto, and a green infrastructure operations and maintenance manual from Lancaster, Pennsylvania (*Green Infrastructure*, 2019; Seters, 2013; US Army Corps of Engineers, 2014).

Plugging in site-specific BMP values to this calculator and utilizing an average discount rate of 3% for total life cycle cost, upfront construction costs for the full 1,541 ft^2 came to approximately $27,091, and with an estimated annual maintenance cost of $401 (*Compare the performance, costs, and benefits of Green Infrastructure to conventional stormwater practices*, n.d.). For this calculation, the full bioswale area not including the sizing discrepancy factor was used to apply a more conservative cost estimate and better reflect real world conditions.

Comparing this value to other calculated bioretention estimates is a useful method of verifying cost estimation accuracy. In the aforementioned 2013 University of Toronto Stormwater BMP report, life cycle cost estimations were reported for three infiltration BMPs sized similarly to the bioretention series in this project. In **Figure 44**, the partial infiltration

practice most closely emulates the practice described in **Section 5.2**. In comparison, the calculated value of $27,091 is in the correct ballpark with respect to the partial infiltration life cycle cost of $58,831, especially considering that the net present value is calculated for 5 more years of maintenance than this project's BMP, proving that the previously calculated cost is a reasonable estimate (Seters, 2013).

Table 3.2: Bioretention life cycle costs (130 m^2)

	Full Infiltration	Partial Infiltration	No Infiltration
Input Parameters			
Life span	25 years	25 years	25 years
Capital cost	$31,973	$41,476	$39,028
Rehabilitation cost at 25 years	$7,504	$7,504	$7,504
Annual maintenance	$945	$952	$952
Present Value including capital, maintenance and rehabilitation costs			
NPV at 50 years			
if i = 0 %	$86,716	$96,604	$94,156
if i = 3 %	$60,471	$70,146	$67,698
if i = 5 %	$52,183	$61,798	$59,350
NPV at 25 years			
if i = 0 %	$56,266	$65,923	$63,475
if i = 3 %	$49,228	$58,831	$56,383
if i = 5 %	$46,129	$55,709	$53,261

Note: i = discount rate

Figure 44: *Bioswale Life Cycle Cost Estimate.* Source: Seters, 2013

6.1.3 Cost Estimate - Seawall

The cost estimate for the seawall was determined using existing rates from various construction companies. The overall construction costs and costs of maintenance of a seawall is priced per linear foot of seawall. The rates were based on Pearce Marine Construction. For a high-end commercial-grade project, the cost per linear foot is around $1,500 per linear foot. For the proposed 905 foot seawall, that results in a base construction cost of $1,357,500 for the entire wall.

Annual routine inspections of the seawall must be conducted by a professional marine engineer or a licensed contractor, which can cost up to $800 (Team Renick, 2025). Seawall repairs can cost $100 - $250 per linear foot depending on the severity of the issue, which can include minor cracks or surface damages. Seawall replacement is much more expensive, ranging from $150 - $800 per linear foot, and is necessary for major issues such as structural failure, widespread cracks, and toe failure. If repairs cost around 50% of the cost of a new wall or the seawall is close to the end of its lifespan (~60 years), a replacement is recommended (Pearce Marine Construction, 2025).

The cost of the shellfish reefs was determined using cost estimates from NOAA and active shellfish reef restoration projects. A 358 acre shellfish reef project (Little Choptank River project) cost around $28.89 million, averaging $80,698 per acre (NOAA Fisheries, 2026). The area that the seawall will cover is approximately 1.5 acres.

A general price breakdown for the construction, inspection, and maintenance of the seawall is provided in **Table 9** below.

Table 9: *Seawall Price Breakdown.* Source: Pearce Marine Team, 2025

Description	Unit cost	Length/Frequency	Total Cost
Base construction	$1,500/linear foot	905 feet	$1,357,500
Annual inspection	$800	Once per year Lifespan: ~60 years	$48,000
Minor repairs	$100 - $250/linear foot	905 feet	$90,500 - $226,250
Major repairs	$150 - $800/linear foot	905 feet	$135,750 - $724,000
Shellfish reef	$80,698/acre	1.5 acres	$121,047

6.1.4 Cost Estimate - Total

The total cost of this project includes design, engineering, materials, permitting, and construction. First, the total upfront costs per solution are listed below:

Gray Infrastructure: **$568,015**
Bioswale: **$27,091**
Seawall: **$1,478,547**
Shellfish reef: **$121,047**

TOTAL: **$2,073,653**

Next, maintenance costs will be summarized for each of the above solutions:

Gray Infrastructure: **$20,310**
Bioswale: **$401**
Seawall: **$48,000**

TOTAL: **$68,711**

Then, life cycle costs, or total project, maintenance, and incidental costs over the project lifespan converted to present value, are calculated in **Equation 25** and shown below (Bragg 2018). For calculations, an estimated solution lifespan of 50, 20, and 50 years is used, as well as a conservative infrastructure interest rate of 3%.

Gray Infrastructure, over 50 years: **$33,057**
Bioswale, over 20 years: **$1,090,587**
Seawall, over 50 years: **$2,713,576**

TOTAL: **$3,837,220**

Lastly, because engineering projects often run over budget, an additional 20% contingency cost was added for unexpected expenses, including minor or major repairs, inflation, and any other unexpected costs. This brings the total, contingency-adjusted project cost to **$4,604,664**.

6.2 Monetary Benefits

4.6 million dollars for an infrastructure project on one street and intersection is undoubtedly a large price tag. However, it is important to put this price in perspective with how much this project is expected to save in the long term. In determining these savings, provided benefits must be properly defined as well. This section will estimate the monetary value of damage mitigated by project solutions over the lifetime of the solution and on an annual basis. This analysis follows the standard, FEMA/USACE-recommended expected annual damage (EAD) approach, which combines flood probabilities, flood depth-damage curves, and building use statistics to compute expected losses (USACE Hydrologic Engineering Center, n.d.).

It is important to note, however, that because this design report is based on preliminary assumptions with a healthy amount of uncertainty, the calculated monetary benefit value is subject to large uncertainty as well. Therefore, this expected range of yearly savings and return on investment will be presented with a large uncertainty value as necessary.

Currently, the design project is set to protect approximately 97,683 square feet of area spread across approximately 5-6 large blocks of primarily mixed, pedestrian-oriented land use and high density housing, the exact percentage of which is unknown due to data constraints and poor analysis tools on Baltimore Cityview (*Baltimore CityView,* n.d.). Based on visual estimates, the working assumption of land use for calculation purposes is about 40% commercial mixed use area and about 60% high density residential use. For damage mitigation estimation in relevant storm events, the 10-, 25-, and 100-year coastal flood events are used, based on the assumption

of average, region-typical damage levels pre-solution implementation, and for post implementation, it is assumed that flooding damage is effectively mitigated in the catchment area, resulting in negligible damages from storms that the BMP is sized for.

Based on available estimates for medium-scenario avoided damage for the above levels of storm events, approximate damage avoided values due to the proposed solution are listed below in **Table 10**.

Table 10: *Approximate Damage Avoided Estimations Per Block Group*. Source: Jacobs, 2025

Storm Occurrence	**Avoided Damages (Residential, $)**	**Avoided Damages (Commercial, $)**
10-year	150,000	280,000
25-year	350,000	650,000
100-year	900,000	1,800,000

Utilizing **Equation 26** to determine EAD and **Equation 27**, to determine the Net Annual Benefit (gross annual benefit minus annual maintenance costs), the final calculation for annual benefits of the proposed practices yields a mean value of $189,289 per year in damages mitigated, with an expected range of $141,966 - $236,611 (using a 25% margin of error).

Now, using **Equation 28** to determine the expected return-on-investment period, this comes to a mean return period of 24.3 years, with an expected range of 19.5 - 32.4 years (using a 25% margin of error) to recoup construction, operations, and maintenance costs.

7. PRELIMINARY SCHEDULE

7.1 Preliminary Schedule

Each phase below has a rough outline of the various tasks that should begin within each phase. This preliminary schedule is subject to change based on the availability of resources and the results from each proposed study. Each phase of the proposed schedule is expected to be completed with the approval and with full transparency towards the City of Baltimore and affected agencies.

7.1.1 Phase 1

1. Conduct a thorough analysis and review of plans to determine the location of public and private utilities along Thames and Wolfe Street.
    a. Rigorously conduct and record findings of test pitting along the site location.
    b. Commence bathymetric and wave energy studies.
    c. Begin formal study on the expected lifespan and serviceability needs of the living seawalls, bioswales, pumping station construction and improvements, as well as
2. Begin consulting with structural engineers on the stability of the soil currently at the base of the harbor.
3. Conduct thorough hydraulic analysis in soil subsurface to ensure stability of proposed and existing structures.
4. Confirm cost estimates and create dynamic cost analysis for components of each solution for the duration of the project.

7.1.2 Phase 2

1. In tandem with the City of Baltimore:
    a. Begin garnering community feedback and address concerns regarding safety features, proposed implementation timeline, and expected infrastructure hardening benefits. Begin this process with city council representatives and slowly work your way to the general public.
    b. Continue applying study results to design parameters.
    c. Begin amendments to harbor soil for increased structural stability.

7.1.3 Phase 3

1. Complete construction and design plans for each component of the hardened ecosystem of Fells Point.

7.1.4 Phase 4

1. Begin construction of each hardening solution. Begin construction in the following order:
    a. Storm water management system (pipes and inlets),
    b. Living seawall construction,
    c. Pumping station construction and system merge,
    d. Bioswale construction.

7.1.5 Phase 5

1. Conduct the following studies to determine and define factors on the efficacy, maintenance costs, and proposed maintenance schedule for the following components.
    a. Storm water management system (pipes and inlets),
    b. Living seawall construction,
    c. Pumping station construction and system merge,
    d. Bioswale construction.

8. CONCLUSIONS

Fells Point will not be able to withstand the predicted intensity and frequency of rainfall and sea events given its current infrastructure. Though the neighborhood was originally founded in the 18th century, The City of Baltimore and the United States as a whole, risk losing a historically significant site unless hardening infrastructure is implemented. To harden Fells Point, we suggest that adjustments to the current storm water systems be made in addition to the construction of three bioswales and a living seawall. Focusing initial resources on the intersection of Wolfe and Thames streets will allow for a dynamic and adaptable multi-modal solution to the challenges impacting Fells to be implemented in an area at severe risk. Having addressed the most at risk area of Fells Point, we expect that solution to be adaptable to the needs of other communities and cities.

The proposed solution is designed to address both rainfall and storm surge flood hazards through an integrated system of green and gray infrastructure. During heavy rainfall events, the addition of bioswales, upgraded inlets, expanded drainage pipes, and the pump station will work together to redirect excess stormwater. The bioswale is sized to convey 25% of the water quality storm in the area, while the new piping infrastructure is sized for the 500-year storm. The addition of new storm drains and bioswales will assist with localized, nuisance flooding and show a marked reduction of nuisance flooding,

During storm surge events, the addition of the seawall, duck bill backflow prevention, and pump station will manage the rise in water levels, with the seawall being sized for a 87% volumetric reduction of overtopping water flow from the 3000 year storm. During severe storm events consisting of both intense rainfall and storm surge, these systems are designed to work together to provide comprehensive flood protection, improving the overall resiliency of Fells Point.

9. APPENDIX

9.1 References

2B-4 Design Manual Chapter 2 -Stormwater 2B -Urban Hydrology and Runoff Runoff and Peak Flow. (n.d.). https://www.iowasudas.org/wp-content/uploads/sites/15/2020/03/2B-4.pdf

Appendix B -Basis of Cost Opinions Costs for Combined Sewer Overflow Control Technologies and Alternatives Table of Contents. (n.d.). https://capitalregionwater.com/wp-content/uploads/2018/04/15-Appendix-B-Basis-of-Cost-Opinions.pdf

Appendix O: Project Profiles and Cost Estimates. (2017). Clark Regional Wastewater District. https://www.crwwd.com/wp-content/uploads/bsk-pdf-manager/2019/12/GSP-Appendix-O.pdf.

Baltimore CityView. (n.d.). City of Baltimore. https://experience.arcgis.com/experience/065cf51484e045a09647a05299e4eb20/page/CityView?org=baltimore#widget_1=active_datasource_id:dataSource_4,level:10.456269669093361.

Baltimore County. (n.d.). *Public Works Design Manual-Storm Drainage Design.* https://www.baltimorecountymd.gov/files/Documents/Public_Works/standardsandspecs/ept2010/07stormdrain2010.pdf.

Bertowski, N. (2025, July). Estimating O&M Costs | National Stormwater Trust. https://nationalstormwater.com/estimating-om-costs/

Bioretention. (2016). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/images/5/5a/LID_poster_-_bioretention_-_vfinal2.pdf.

Bioretention: Filter Media. (2025). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Bioretention:_Filter_media.

Bioretention: Sizing. (2024). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Bioretention:_Sizing.

Bragg, S. (2018, April 7). AccountingTools. AccountingTools. https://www.accountingtools.com/articles/life-cycle-costing.html

Building with Nature Science based Design. (2026). Living Seawalls. https://www.livingseawalls.com.au/.

Chapter 6 Storm Sewer. (n.d.). https://wsdot.wa.gov/publications/manuals/fulltext/M23-03/Chapter6.pdf

Chow. (1959). *Manning's n Values*. Www.fsl.orst.edu. https://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm

City of Baltimore. (n.d.) *Baltimore City Code, Article 7, 23-4.1,* City of Baltimore Law Library. https://codes.baltimorecity.gov/us/md/cities/baltimore/code/7/23-4.1#(c).

Coastal Flood Exposure Mapper. (2026). Noaa.gov. https://coast.noaa.gov/floodexposure/#-8526416

Code of Maryland Regulations. (n.d.). Library of Maryland Regulations. Doi.26.17.01.09. https://regs.maryland.gov/us/md/exec/comar/26.17.01.09#I(4).

Compare the performance, costs, and benefits of Green Infrastructure to conventional stormwater practices. (n.d.) CNT, Green Values, Stormwater Management Calculator. https://greenvalues.cnt.org/#tabtop.

CPI Inflation Calculator. (2025). U.S. Bureau of Labor Statistics. https://www.bls.gov/data/inflation_calculator.htm.

DC Water Stormwater Services - Cost of Service and Recovery Methodology Study FINAL MEMO REPORT / February 2 024. (n.d.). https://www.dcwater.com/sites/default/files/finance/budgets/2024/DC%20Water%20Stormwater%20Costs_FinalReport.pdf?

Design of Coastal Revetments, Seawalls, and Bulkheads. (1995). US Army Corps of Engineers. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1614.pdf.

The Engineering ToolBox. (2004). *Hazen-Williams Water Flow Formula: Head Loss, Data, Charts & Calculator*. https://www.engineeringtoolbox.com/hazen-williams-water-d_797.html

EnviroAtlas. (2019). *ArcGIS Web Application*. Epa.gov. https://enviroatlas.epa.gov/enviroatlas/interactivemap/

Escamilla, C., Scaroni, A. E., & White, S. A. (2024). *An introduction to floating wetlands for stormwater ponds*. Land-Grant Press by Clemson Extension. https://lgpress.clemson.edu/publication/an-introduction-to-floating-wetlands-for-stormwater-ponds/

Fells Point, MD Hurricane Map and Climate Risk Report. (2026). First Street. https://firststreet.org/neighborhood/fells-point-md/5591_fsid/wind.

Gallagher, M. (2025, August 5). *Benefits Of Floating Wetlands Explained*. GreenPacks. https://greenpacks.org/what-are-the-benefits-of-floating-wetlands/

Gravel Diaphragms. (2022). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Gravel_diaphragms.

Great Lakes Restoration Initiative. (2016). *Operation and Maintenance of Green Infrastructure*

Receiving Runoff from Roads and Parking Lots. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2016-11/documents/final_gi_maintenance_508.pdf.

Green Infrastructure: Operations & Maintenance Plan. (2019). City of Lancaster. https://www.cityoflancasterpa.gov/wp-content/uploads/2014/03/Lancaster-GI-O-M-Plan_FINAL_reduced.pdf.

Hazen-Williams Equation - calculating Head Loss in Water Pipes. (2019). Engineeringtoolbox.com. https://www.engineeringtoolbox.com/hazen-williams-water-d_797.html

HR Wallingford LTD. (1999). *Wave Overtopping of Seawalls: Design and Assessment Manual.* Environment Agency. https://www.overtopping-manual.com/assets/downloads/EA_Overtopping_Manual_w178.pdf.

Jacobs. (2025, February 14). *Damage calculations*. Flood Modeller. https://help.floodmodeller.com/docs/damage-calculations

Johnston, Bruce. (2009). *King County Tabula: Task 1- Revise/Update Existing Wastewater Capital Construction Cost Estimates.* Brown and Caldwell. https://your.kingcounty.gov/dnrp/library/wastewater/csi/tabula/docs/Task1_Memo01-08-09.pdf?utm_source=chatgpt.com.

Living Seawalls. (2026). Reef Design Lab, Sydney Institute of Marine Science. https://www.reefdesignlab.com/living-seawalls

Living Seawalls. (2026). Stone Living Lab, North American Pilot. https://stonelivinglab.org/living-seawalls/.

Living Shorelines. (n.d.). Texas General Land Office.

https://www.glo.texas.gov/coastal/living-shorelines/what-living-shoreline

Livingston, Katie. (2022). *Why use a duckbill valve?. UTILITY.* https://utilitymagazine.com .au/why-use-a-duckbill-valve/.

Manning's Equation. (n.d.). Www.fsl.orst.edu. https://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Manning_s_Equation.htm

Maryland Department of Agriculture. (n.d.). *MDE/Federal Permits*. https://mda.maryland.gov/plants-pests/Pages/mde_federal_permit.aspx.

Maryland Department of the Environment. (2025). *Draft Maryland Stormwater Design Manual: Advanced Notice of Proposed Rulemaking.* https://www.naiopmd.org/wp-content/uploads/2025/10/Stormwater-Design-Manual-Draft-9-19-2025.pdf.

Maryland Department of the Environment. (2009). *Maryland's Stormwater Design Manual, Volumes I and II.* Maryland Government. https://mde.maryland.gov/programs/water/stormwatermanagementprogram/pages/stormwater_design.aspx.

Maryland Department of the Environment. (n.d.). *Nontidal Wetland and Waterway Permits, Approvals and Certifications.* https://mde.maryland.gov/programs/Water/WetlandsandWaterways/PermitsandApplications/Pages/nontidal_permits.aspx.

Maryland Department of Transportation. (2023). *Highway Drainage Manual. https://roads.maryland.gov/ohd2/MDOT%20SHA%20Drainage%20Manual%20-%20September%2023.pdf.*

Maryland Government. (n.d.). *Construction Specifications for Infiltration Practices, appendix B.2.* https://mde.maryland.gov/programs/water/StormwaterManagementProgram/Documents/www.mde.state.md.us/assets/document/appendixb2.pdf.

Maryland Government. (2025). *Maryland SSURGO Soils - SSURGO Soils. MD iMAP Data Catalog.*https://data.imap.maryland.gov/datasets/maryland::maryland-ssurgo-soils-ssurgo-soils/about.

Maryland State Programmatic General Permit (MDSPGP). (n.d.) https://mde.maryland.gov/programs/water/wetlandsandwaterways/regulations/documents/www.mde.state.md.us/assets/document/wetlandswaterways/mdspgp.pdf.

Maryland Permitting. (2022). US Army Corps of Engineers. Maryland Department of the Environment. https://www.nab.usace.army.mil/Missions/Regulatory/Permits-MD/.

Mulch. (2020). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Mulch.

Musial, Dave. (2026). *Sewer Line repair Cost 2026 Guide.* Four Seasons. https://www.fourseasonsheatingcooling.com/blog/sewer-line-repair-cost/.

NACTO. (2026). *Design Guide: Bioswales.* https://nacto.org/publication/urban-street-design-guide/street-design-elements/stormwater-management/bioswales/.

National Flood Insurance Program (NFIP) Floodplain Management Requirements a Study Guide and Desk Reference for Local OffiCials. 2005. https://www.fema.gov/sites/default/files/documents/fema-480_floodplain-management-study-guide_local-officials.pdf

Natural Resources Conservation Service. (2013). *Saltmeadow Cordgrass: Plant Guide.* United States Department of Agriculture. https://www.nrcs.usda.gov/plantmaterials/njpmcpg14233.pdf.

Natural Resources Conservation Service. (2014). *Seaside Goldenrod: Plant Guide.* United States Department of Agriculture. https://plants.sc.egov.usda.gov/DocumentLibrary/plantguide

/pdf/pg_sose.pdf.

Natural Resources Conservation Service. (2015). *Spartina alterniflora*. *Plants Database*, United States Department of Agriculture. https://en.wikipedia.org/wiki/Sporobolus_alterniflorus#cite_note-1.

NCSU Bibo Tech Spec. (2015). *Bio-Infiltration Bump Outs (BIBO), sec 1.* https://stormwater.bae.ncsu.edu/wp-content/uploads/sites/11/2016/03/Bioretention.pdf.

Office of Habitat Conservation. (2026). *The Value of Oyster Reef Habitat*. NOAA Fisheries. https://www.fisheries.noaa.gov/national/habitat-conservation/oyster-reef-habitat.

O'Neill, Jr., Charles R. (1986). *Structural Methods for Controlling Coastal Erosion. Cornell Cooperative Extension Publication*. https://seagrant.sunysb.edu/glcoastal/pdfs/StructuralMethodstoControlErosion.pdf.

PE100+ Association. (n.d.). *PE-Pipe Lifetime*. PE100+ Association. https://www.pe100plus.com/PE-Pipes/Technical-guidance/model/Design/Lifetime/r1024.html

Pearce Marine Team. (2025). *Don't Get Washed Away: Your Guide to Seawall Pricing*. Pearce. https://www.pearcemarine.com/blog/cost-of-a-seawall.

Plant Lists. (2026). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Plant_lists.

Rain Gardens. (2013). Watershed Stewards Academy Rainscaping Manual. https://extension.umd.edu/sites/extension.umd.edu/files/2021-03/FC-MGPub%20Rain%20Gardens%20RaInscaping.pdf.

Renick, Michael. (2025). *What Do Seawall Maintenance Costs Look Like in Sarasota?*. Team Renick. https://blog.teamrenick.com/understanding-seawall-maintenance-costs/.

Reservoir aggregate. (2020). Sustainable Technologies Evaluation Program. https://wiki.sustainabletechnologies.ca/wiki/Reservoir_aggregate.

Section 11: Time of Concentration. (2019). Txdot.gov. https://www.txdot.gov/manuals/des/hyd/chapter-4--hydrology/section-11--time-of-concentration.html

Silver Spring Intermediate Neighborhood Park - Park Renovation Project. (2019). Montgomery Planning Board. https://montgomeryplanningboard.org/wp-content/uploads/2019/08/7-Detailed-Cost-Estimate_8x11.pdf.

Smith, P. N. (2001). *Highway stormwater pump station design*. US Department of Transportation, Federal Highway Administration, National Highway Institute.

"Stormwater Management Requirements | Baltimore City." *Baltimorecity.gov*, 2026, www.baltimorecity.gov/publicworks/water-system-in-the-city/stormwater/stormwater-management-requirements.

"Title 26 DEPARTMENT of the ENVIRONMENT | Library of Maryland Regulations." *Maryland.gov*, 2026, regs.maryland.gov/us/md/exec/comar/26.

Titov, Roman. (n.d.). *Bioretention Design: Performance, Longevity, and Sustainability.* CED Engineering. https://www.cedengineering.com/userfiles/C10-008%20-%20Bioretention%20Design%20Performance,%20Longevity,%20and%20Sustainability%20-%20US.pdf.

Tractor Supply Co. (2026). *NuFlo 12 in. x 9.75 ft. Corrugated HDPE Drainage Pipe. https://www.tractorsupply.com/tsc/product/neat-distributing-hdpe-%28plastic%29-culvert-12-in-x-975-ft-hdpe-12975.*

Tractor Supply Co. (2026). *NuFlo 15 in. x 20 ft. Corrugated HDPE Drainage Pipe*.

https://www.tractorsupply.com/tsc/product/culvert-hdpe-15-in-x-20-ft-hdpe-1520.

Tractor Supply Co. (2026). *NuFlo 18 in. x 20 ft. Corrugated HDPE Drainage Pipe*. https://www.tractorsupply.com/tsc/product/culvert-hdpe-15-in-x-20-ft-hdpe-1520.

Tractor Supply Co. (2026). *NuFlow 30 in. x 20 ft. HDPE Double Wall Corrugated Pipe 4 in Dia., AASHTO. https://www.tractorsupply.com/tsc/product/neat-distributing -30-in-x-20-ft-hdpe-double-wall-corrugated-pipe-4-in-dia-aashto.*

Uchytil, Ronald J. (2018). *Juncus roemerianus.* Fire Effects Information System (FEIS). US Department of Agriculture. https://en.wikipedia.org/wiki/Juncus_roemerianus #cite_note-feis-3.

Underdrains. (2022). Sustainable Technologies Evaluation Program. https://wiki.sustain abletechnologies.ca/wiki/Underdrains.

United States Department of Agriculture. (2009). *Hydrologic Soil Groups, ch. 7. Natural Resources Conservation Service.* https://directives.nrcs.usda.gov/sites/default/files 2/1712930597/11905.pdf.

United States Environmental Protection Agency (2025). *Green and Gray Infrastructure Research.* https://www.epa.gov/water-research/green-and-gray -infrastructure-research.

Urban Drainage Design Fourth Edition. (2024). https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif24006.pdf

USACE Hydrologic Engineering Center. (n.d.). *Expected Annual Damage*. HEC-FDA Technical Reference. https://www.hec.usace.army.mil/confluence/fdadocs/techref/expected-annual-damage-167248971.html

US Army Corps of Engineers. (2002). *Coastal Engineering Manual.* USACE Publications.

https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u4354
4q/636F617374616C20656E67696E656572696E67206D616E75616C/.

Wells. (2022). Sustainable Technologies Evaluation Program. https://wiki.sustain
abletechnologies.ca/wiki/Wells.

WSSC Water. (2008). *Sewer Design Guidelines.* pt. 2, sec. 15. https://www.wsscwater.com/
sites/default/files/sites/wssc/files/Design%20Manuals/S-15-2008_61609.pdf.

Young, Lewis. (2026). *Municipalities - Open Drainage Inlets - Required Grating Systems
(Mason's Law).* Department of Legislative Services. https://mgaleg.maryland.gov
/2026RS/fnotes/bil_0009/sb0189.pdf

9.2 Equations and Extended Calculations

9.2.1 Gray Infrastructure Calcs

Time of Concentration: ((*Section 11: Time of Concentration*, 2019)

$$T_C = T_{gutter\ sheet\ flow} + T_{storm\ pipe\ flow} \quad \textbf{Equation 1}$$

The values plugged into this equation are below:

Variable	Length (ft)	Speed of Travel (ft / s)
$T_{gutter\ sheet\ flow}$	480	2 (*Chapter 6 Storm Sewer*, n.d.)
$T_{storm\ pipe\ flow}$	933	5 (*Urban Drainage Design Fourth Edition*, 2024)

$$T_C = 4\ min + 3.11\ min = 7.11 \text{ min} \quad \textbf{Equation 1}$$

Rational Method: (*2B-4 Design Manual Chapter 2 -Stormwater 2B -Urban Hydrology and Runoff Runoff and Peak Flow*, n.d.)

$$Q = C * i * A \quad \textbf{Equation 2}$$

The variables in the equation are listed below:

Variable	Meaning
Q (cfs)	Flow Rate at Outlet Point
C (unitless)	Runoff Coefficient
i (in/hr)	Rainfall Intensity
A (acres)	Catchment Area

Rainfall intensity varied depending on the storm intensity. The values for rainfall intensity are taken from this source: *NOAA Atlas 14 Point Precipitation Frequency Estimates for Baltimore, MD*

Runoff coefficient was calculated based on the percent of the catchment area with a certain infiltration coefficient. For us, 92.5% of the area is impervious, with a runoff coefficient C of 0.98 (EnviroAtlas, 2019). 7.5% of the area is pervious with soil class D, with a C of 0.75 (USDA, 2009). We used the weighted average of these numbers.

The values for area were calculated by outlining the catchment area of interest in ArcGIS Pro.

The following is what was plugged in and calculated. Bolded lines mean the resulting runoff rate was mentioned in the text above.

Desired Result	C	i (in/hr)	A (acres)	Q (cfs)
Total Catchment 10-min, 100-yr storm	0.963	6.9	2.24	14.88
Total Catchment 10-min, 500-yr storm	**0.963**	**7.92**	**2.24**	**17.08**
Total Catchment 10-min, 100-yr storm	0.963	0.42	2.24	0.90
Total Catchment 24-hr, 100-yr storm	0.963	6.9	2.24	14.9
Thames St & S Wolfe Intersection 10-min, 500-yr storm	**0.963**	**7.92**	**0.643**	**4.90**
East End of Thames St 10-min, 500-yr storm	**0.963**	**7.92`**	**0.188**	**1.43**

Manning's Equation: (*Manning's Equation*, n.d.)

$$Q = V * A = \frac{1.49}{n} * A * R^{2/3} * S^{1/2} \qquad \textbf{Equation 3}$$

The variables in the equation are listed below:

Variable	Meaning
Q (cfs)	Flow Rate at Outlet Point
n (unitless)	Manning's Roughness Coefficient
A (ft^2)	Flow Area, $\frac{\pi}{4} * D^2$, where D is diameter in ft
R (ft)	Hydraulic Radius, $\frac{D}{4}$ for pipes
S (ft/ft)	Channel Slope

Values for Manning's n are found here (Chow, 1959).

The following is what was plugged in and calculated.

Desired Result	n	D (ft)	S (ft/ft)	Q (cfs)
Pipe 11, as-is, find Q	0.013	2.5	0.002	18.39
Proposed Pipe 12, 13, 14, find min S	0.012	1	0.004 (result)	Q = VA, A cancelled, V = 3 ft/sec
Proposed Pipe 12, 13, 14, find D	0.012	0.78 (result)	0.005	1.43
Proposed Pipe 12, 13, 14, find Q	0.012	1	0.005	2.74
Proposed Pipe 1, 2, 10, find min S	0.012	1.5	0.002 (result)	Q = VA, A cancelled, V = 3 ft/sec
Proposed Pipe 1, 2, 10, find D	0.012	1.24 (result)	0.005	4.90
Proposed Pipe 1, 2, 10, find Q	0.012	1.25	0.005	4.96

Upgraded Pipes 3-9, find D	0.012	1.48 (result)	0.002	4.90
Upgraded Pipes 3-9, find Q	0.012	1.5	0.002	5.10
Pipe 16, find Q	0.013	2	0.003	12.42

Hazen-Williams Equation: (*Hazen-Williams Equation - Calculating Head Loss in Water Pipes*, 2019)

$$h_{100\,ft} = 0.2083 * \left(\frac{100}{c}\right)^{1.852} * q^{1.852} / d^{4.8655} \qquad \textbf{Equation 4}$$

The variables in the equation are listed below:

Variable	Meaning	Value for Pump Station
$h_{100\,ft}$ (ft)	Friction head loss in 100 ft of pipe	9.51 (calculated)
C (unitless)	Hazen-Williams roughness constant	150
q (gal/min)	Volume of Flow	8079
d (inches)	Pipe Diameter	12

9.2.2 Bioswale Calculations

Parameters	Notation	Value
Calculated upslope area (ft^2)	A_c	97,683
Impervious surface ratio in catchment Area (%)	I	92.5
Water quality rainfall depth (in)	P	1.5
Sizing discrepancy factor (%)	F_S	25

To find the water quality volume of the 1.5-inch design storm for eastern Maryland, **Equation 5** must be utilized

$$WQV = \frac{P \bullet Rv \bullet A_c}{12} \qquad \textbf{Equation 5}$$

where WQV is water quality volume in acre-feet, P is water quality rainfall depth in inches, A_c is the catchment area in square feet, and Rv is the volumetric runoff coefficient, which is calculated as

$$R_v = 0.05 + 0.009I \qquad \textbf{Equation 6}$$

where I is the percentage of impervious surfaces in the catchment area. Through these, R_v is determined to be 0.8825, and the water quality volume for the design storm is 0.247 acre-feet, or 10,775 cubic feet.

Parameters	Notation	Value
Bioswale surface area (ft^2)	A_B	1,541
Bioretention Cells 1 and 2 Ponding Volume (ft^3)	$V_{p1,2}$	737.43
Bioretention Cell 3 Ponding Area (ft^3)	V_{p3}	39
Media Layer Void Storage (ft^3)	V_m	1155.75
Choker Layer Void Storage (ft^3)	V_c	154.1
Underdrain Layer Void Storage (ft^3)	V_u	191.44

IWS Layer storage (ft^3)	V_{IWS}	462.3
Sizing discrepancy factor (%)	F_S	25

To calculate the bioswale storage volume and compare it to the required water quality volume, **Equation 7** must be used

$$V_B = V_{p1,2} + V_{p3} + V_m C_m + V_c C_c + V_u C_u + V_{IWS} C_{IWS} \quad \textbf{Equation 7}$$

where V_B is the bioswale storage volume in square feet, $V_{p1,2}$ is the ponding volume of bioretention cells 1 and 2 in square feet, V_{p3} is the ponding volume of bioretention cell 3 in square feet, $V_m C_m$ is the media layer volume multiplied by its porosity, $V_c C_c$ is the choker layer volume multiplied by its porosity, $V_u C_u$ is the media surrounding the underdrain piping volume multiplied by its porosity, and $V_{IWS} C_{IWS}$ is the internal water storage layer volume multiplied by its porosity. Porosities for the media layer, choker layer, media surrounding the underdrain piping, and internal water storage layer are 0.7, 0.4, 0.4, and 0.4, respectively. To calculate the volume of the media around the underdrain piping, **Equation 8** is used

$$V_u = A_B \bullet (1 - F_s) \bullet \frac{8}{12} feet - (\pi r^2 \bullet l) \quad \textbf{Equation 8}$$

where $A_B \bullet F_s$ is the adjusted bioswale storage volume in square feet and $\pi r^2 \bullet l$ is pipe volume in cubic feet with a radius of 4 inches. Computing all of this results in an effective bioswale storage volume of $V_B = 2{,}740$ cubic feet, and when divided by the water quality volume, results in a capturing of 25.4% of the water quality volume.

Parameters	**Notation**	**Value**
Pipe Length (ft)	L	334.5
Clogging Factor	B	1
Coefficient of Discharge	C_d	0.61
Gravitational acceleration (ft^2/s)	g	32.174
Total head above the underdrain (ft)	h	3.33

Perforation area (ft^2)	A_{perf}	0.00077
Number of perforations per section	S	4
Horizontal spacing between perforations (ft)	R	0.33

To calculate the peak flow rate through the underdrain piping, **Equation 9** must be used

$$Q_{max,u} = L \bullet B \bullet C_d \bullet A_o \bullet \sqrt{2gh} \qquad \textbf{Equation 9}$$

where L is pipe length in feet, B is a clogging factor, which is 1 for a new BMP, C_d is a discharge coefficient, A_o is the total open area per unit pipe length in square feet per unit length, and h is the total head above the underdrain. To find A_o, the following equation is used

$$A_o = \frac{A_{perf} \bullet S}{R} \qquad \textbf{Equation 10}$$

where A_{perf} the circular perforation area, S is the number of sides the perforation is on, and R is the horizontal spacing between perforations. After computation, this comes to be $Q_{max,u} =$ 27.5 cubic feet per second.

Parameters	**Notation**	**Value**
Hydraulic Conductivity of filter media (in/hr)	K	2.95-11.81
Bioswale surface area (ft^2)	A_B	1,541
Sizing discrepancy factor (%)	F_S	25
Total head above the underdrain (ft)	h	3.33
Depth of filter media (ft)	h_m	2.5

To calculate the peak flow rate through the filter media, **Equation 11** must be used

$$Q_{max,m} = \frac{K \bullet (A_b \bullet F_s) \bullet (\frac{h}{h_m})}{3.6 \bullet 10^6} \qquad \textbf{Equation 11}$$

where $A_B \bullet F_s$ is the adjusted bioswale storage volume in square feet, h is the total head above the underdrain in feet, and h_m is the depth of filter media in feet. This calculation comes out to $Q_{max,m}$ = 0.11 to 0.42 cubic feet per second, depending on the selected hydraulic conductivity value.

Parameters	**Notation**	**Value**
Water Quality Volume (ft^3)	WQV	10,775.72
Peak flow rate through the filter media (cfs)	$Q_{max,m}$	0.11 - 0.42

For calculating the theoretical drawdown time, **Equation 12** is used

$$t_d = \frac{WQV}{Q_{max,m}} \bullet \frac{hours}{3600\ seconds} \qquad \textbf{Equation 12}$$

where WQV is water quality volume in cubic feet, $Q_{max,m}$ is Peak flow rate through the filter media in cubic feet per second, and t_d is converted to hours. This comes out to t_d = between 7.10 and 28.42 hours.

Parameters	**Notation**	**Value**
Impervious catchment area (ft^2)	A_i	90,356.78
Design storm length (hr)	D	24
Design storm intensity (in/hr)	i	0.42
Effective depth of surface ponding (in)	d_p'	6
Minimum saturated hydraulic conductivity of filter media (in/hr)	K_f	2.95

To calculate the theoretical surface ponding area to contain the 100-year, 24-hour storm, **Equation 13** is used

$$A_p = (i \bullet D \bullet A_i) \div [d_p' + (K_f \bullet D)] \qquad \textbf{Equation 13}$$

where i is the design storm intensity in inches per hour, D is the design storm length in hours, A_i is the impervious catchment area in square feet, d_p' is the Effective depth of surface ponding in inches, and K_f is the minimum saturated hydraulic conductivity of filter media in inches per hour. This comes to $A_p =$ 11,790.42 square feet, or about 10.2 times the size of the current BMP.

9.2.3 Seawall Calculations

Parameters	Notation	Value
Freeboard of the sea wall (ft)	R_c	4.5
Wall length (ft)	length	905
Width (ft)	width	3
Water depth (ft)	depth	3.5
Toe to crest height (ft)	height	8
Mean wave period at the toe of the wall (sec)	T_m	5
Fetch length (m)	x	2485.64
Wind speed (mph)	u_{10}	74
Wind speed (m/s)	u_{10}	33.0739
Wind duration (sec)	duration	60

To find the significant wave height (H_s) and spectral peak wave period, the design assumed conditions for a 1-in-3,000-year storm event with a 1-minute sustained wind speed of 74 mph (33.07 m/s). To check if this situation is fetch-limited or duration-limited, the required wind duration ($t_{x,u}$) was calculated using **Equation 14**:

$$t_{x,u} = 77.23 \frac{x^{0.67}}{u_{10}^{0.34} g^{0.33}} \qquad \textbf{Equation 14}$$

where x is the fetch, u_{10} is the wind speed, and g is the acceleration due to gravity.

$$t_{x,u} = 77.23 \frac{2485.64^{0.67}}{33.0739^{0.34} 9.81^{0.33}} = 2083.79\ sec$$

If the wind duration is equal to or greater than the required wind duration, then a fetch-limited situation exists.

Next, the coefficient of drag (C_D) was estimated using **Equation 15**.

$$C_D \approx 0.001\left(1.1 + 0.035 u_{10}\right) \qquad \textbf{Equation 15}$$

$$C_D \approx 0.001(1.1 + 0.035 \cdot 33.0739) = 0.00226$$

Using the coefficient of drag, the friction velocity (u_*) was estimated using **Equation 16**.

$$u_* = \sqrt{0.00215} u_{10} \quad \textbf{Equation 16}$$

$$u_* = \sqrt{0.00215} \cdot 33.0739 = 1.571\ m/s$$

Nondimensional fetch ($\hat{x}$) was calculated using **Equation 17**.

$$\hat{x} = \frac{gx}{u_*^2} \quad \textbf{Equation 17}$$

$$\hat{x} = \frac{9.81 \cdot 2485.64}{1.571^2} = 9873.98$$

From here, the nondimensional wave height ($\hat{H}_s$) was calculated using **Equation 18** below:

$$\hat{H}_s = \lambda_1 \hat{x}^{m_1} \quad \textbf{Equation 18}$$

where

$$\lambda_1 = 0.0413$$

$$m_1 = \frac{1}{2}$$

$$\hat{H}_S = 0.0413 \cdot (9873.98)^{\frac{1}{2}} = 4.104$$

and the significant wave height (H_s) was calculated using **Equation 19**.

$$H_s = \hat{H}_s \cdot \frac{u_*^2}{g} \quad \textbf{Equation 19}$$

$$H_s = 4.104 \cdot \frac{1.571^2}{9.81} = 1.033\ m\ or\ 3.390\ ft$$

To calculate the spectral peak wave period, the nondimensional spectral peak period ($\hat{T}$) was estimated first using **Equation 20**:

$$\hat{T_P} = \lambda_2 \hat{x}^{m_2} \quad \textbf{Equation 20}$$

where

$$\lambda_2 = 0.751$$

$$m_2 = \frac{1}{3}$$

$$\hat{T_P} = 0.751 \cdot 9873.98^{\frac{1}{3}} = 16.112$$

The spectral peak wave period (T_P) was determined with **Equation 21**.

$$T_P = \hat{T_P}\frac{u_*}{g} \quad \textbf{Equation 21}$$

$$T_P = 16.112\frac{1.571}{9.81} = 2.581$$

To calculate the mean overtopping discharge, the dimensionless freeboard (R_*) was calculated using **Equation 22**:

$$R_* = \frac{R_c}{T_m(gH_s)^{0.5}} \quad \textbf{Equation 22}$$

where R_c is the freeboard of the sea wall and T_m is the mean wave period at the toe of the seawall.

$$R_* = \frac{4.5}{5(32.174 \cdot 3.390)^{0.5}} = 0.0862$$

The dimensionless discharge (Q_*) was calculated using **Equation 23**:

$$Q_* = A \cdot exp\left(\frac{-BR_*}{r}\right) \quad \textbf{Equation 23}$$

where r is the roughness coefficient and A, B are empirical coefficients based on the cross-section of the seawall.

$$Q_* = 1.09 \cdot 10^{-2} \cdot exp\left(\frac{-28.7 \cdot 0.0862}{0.95}\right) = 8.07 \cdot 10^{-4}$$

Finally, the mean overtopping discharge rate (Q) can be calculated using **Equation 24** below.

$$Q = Q_* T_m g H_s \quad \textbf{Equation 24}$$

$$Q = 8.07 \cdot 10^{-4} \cdot 5 \cdot 32.174 \cdot 3.390 = 0.440\ ft^3/s/ft$$

Using this mean overtopping discharge rate and the overall length of the sea wall, the total overtopping volume rate for the sea wall was calculated.

$$905\ ft \cdot 0.440\ ft^3/s/ft = 398.0794\ \frac{ft^3}{s}\ or\ 2977.634\ \frac{gal}{s}$$

Using the current conditions at our site location in Fells Point (R_c = 1 ft), the 1-in-3,000-year storm event previously mentioned, and the above equations, the total overtopping volume rate for the current area is 3015.959 ft^3/s or 22559.372 gal/s. Compared to the conditions with the proposed sea wall, the percent reduction in overtopping volume is

$$Percent\ reduction = \frac{No\ sea\ wall - With\ sea\ wall}{No\ sea\ wall} * 100$$

$$Percent\ reduction = \frac{22559.372 - 2977.634}{22559.372} * 100 = 86.801\%$$

9.2.4 Benefit Calculations

Parameters	Notation	Value
Gray Infrastructure Lifespan	n_g	50
Bioretention Lifespan	n_b	20
Seawall Lifespan	n_s	50
Interest Rate (%)	i	3

For determining the life cycle cost of proposed solutions, **Equation 25** is used for each solution

$$LCC = CC + \frac{(1+i)^n - 1}{i\,(1+i)^n} \qquad \textbf{Equation 25}$$

Where CC is capital costs per solution and i is the interest rate.

To calculate the theoretical expected annual damage costs mitigated by the proposed solutions **Equation 26** is used

$$EAD = \sum_{a_1}^{a_3} (2C_a + 3R_a) \text{, where } a = \{10, 25, 100\} \qquad \textbf{Equation 26}$$

where C_a is the expected damage mitigated by design storms in high density residential areas (see **Table 10**) and R_a is the expected damage mitigated by design storms in mixed commercial areas.

Parameters	Notation	Value
Expected Annual Benefit for 10-year Storm ($)	EAD_{10}	1,010,000
Expected Annual Benefit for 25-year Storm ($)	EAD_{25}	2,350,000

Parameters	Notation	Value
Expected Annual Benefit for 100-year Storm ($)	EAD_{100}	6,300,000
Chance of Storm Occuring (%)	p_i	{0.1, 0.04, 0.01}

For determining the Net Annual Benefit from the expected annual damages avoided, **Equation 27** is used

$$NAB = \sum_{a_1}^{a_3}(EAD_a \bullet p_i) - M \text{, where } a = \{10,\ 25,\ 100\} \qquad \textbf{Equation 27}$$

where EAD_a is the overall expected annual damage and M is annual maintenance cost, which was determined in section 6.1.4 to be about $68,711. This means that $NAB \approx$ $189,289.

Lastly, **Equation 28** is used to estimate the return-of-investment period

$$ROI = \frac{C_T}{NAB} \qquad \textbf{Equation 28}$$

where NAB is the net annual benefit of about $189,289 $\frac{\$}{yr}$, C_T is the total solution cost of about $4,604,664. This means that the estimated return-of-investment period is approximately $ROI =$ 24.3 years.

9.3 ArcGIS Maps

The City of Baltimore , & Department of Public Works. (2026). *Open Baltimore.* Retrieved February, 2026, from https://data.baltimorecity.gov/
United States Census Bureau. *Census bureau data and maps.*https://www.census.gov/data.html

9.4 CADD Modeling

Autodesk. *Fusion 360*
Trimble. *SketchUP*