Suitability of Stormwater Best Management Practices in the Coastal Plain

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This project was included in the Hampton Roads Planning District Commission FY 2024 Work Program, approved by the Commission on May 18, 2023, and in the Hampton Roads Planning District Commission FY 2025 Work Program, approved by the Commission on May 16, 2024.

Prepared by A. Morton Thomas and Associates, Inc. under contract with the Hampton Roads Planning District Commission.

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ABSTRACT
This report summarizes research of stormwater best management practices to assess their suitability for use in the coastal plain of Virginia, given various environmental constraints and consideration for future impacts from climate change. The report includes both stormwater best management practices and enhancements for best management practices. Findings are summarized in the narrative and in two references tables.

ACKNOWLEDGEMENTS
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DCR

VRA Virginia Resources Authority

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EXECUTIVE SUMMARY

The physiographic conditions of the coastal plain, including a high groundwater table, poorly drained soils, and flat terrain, can present challenges when determining how best to meet stormwater quality and quantity requirements. When stormwater best management practices (BMPs) are evaluated to determine which are most suitable to overcome those conditions, it is also important to consider how resilient they will be to changing climate factors. Doing so improves water quality, reduces flooding, and protects infrastructure investments. This study provides an overview of which BMPs practitioners should consider first when designing stormwater management plans for development sites in the coastal plain. Although performed specifically for the Hampton Roads region of Virginia, the recommendations apply to similarly situated coastal plain areas facing the same challenges.

This effort builds on previous regional and state initiatives. A literature review of academic, regulatory, and other research documents was conducted to identify traditional BMPs, innovative BMPs, and BMP enhancements for further evaluation. Resources such as the Hampton Roads Planning District Commission's (HRPDC) Land and Water Quality Protection in Hampton Roads: Phase II report ("Phase II report"),[1] the Virginia Erosion and Sediment Control Handbook,[2] and the Virginia Stormwater Management Handbook[3] were used to determine which traditional BMPs to assess. Innovative BMPs or BMP enhancements were identified based on a review of additional academic, federal, state, and regional resources, with an emphasis on those BMPs or enhancements most suitable for use in the coastal plain.

These BMPs and BMP enhancements were assessed for resilience when challenged by various climate factors associated with the coastal plain region of the state, as identified by HRPDC. The climate factors considered in this review include long-term weather patterns and events exacerbated by climate change such as tidal flooding, increased precipitation, extended dry weather, high groundwater, increased rainfall concentration, storm surge, and salt exposure. BMPs and BMP enhancements were assigned a vulnerability ranking from low to high for each climate factor. The rankings for each factor were based on the literature review and common engineering practices and standards.

The suitability of the traditional BMPs, innovative BMPs, and BMP enhancements reviewed in this study ranged widely with the considered climate factors and coastal plain conditions. The traditional BMPs, which were previously identified in the Phase II report, are all vulnerable to some if not most of the assessed climate factors. Higher groundwater conditions in particular can limit the performance of those practices that rely on infiltration. More careful siting or additional capacity may address most other potential issues with climate change impacts.

All three BMP enhancements (Floating Treatment Wetlands, Coagulant Enhancement Treatment, and Continuous Monitoring Adaptive Control) are well suited for coastal plain conditions and are approved by the Chesapeake Bay Program (CBP). Regarding climate factors, all three enhancements are resilient to increased precipitation, increased rainfall concentration, and high groundwater. The three enhancements only exhibit low to medium vulnerability to tidal flooding, extended dry weather, storm surge, and salt exposure. Most notably, floating treatment wetlands are vulnerable to salt exposure, but this can be mitigated with salt-tolerant plants.

Each innovative BMP offers unique benefits to stormwater management. Living shorelines, oyster aquaculture and restoration, blue roofs, and submerged gravel wetlands are preferred practices for coastal plain conditions, though they vary in their resilience against climate factors. Incorporating living shorelines, a CBP-approved nature-based practice, aligns with other local, regional, and state resiliency and wetlands protection goals. Blue roofs are applicable in urban areas as they can be retrofitted on existing buildings or implemented during new construction. They should be considered and evaluated by the Virginia Department of Environmental Quality (DEQ). Submerged gravel wetlands should also be considered by DEQ and the CBP as an additional stormwater treatment practice that is well suited in areas where a high-water table or poorly drained soils are present. Submerged gravel wetlands are implemented in neighboring Chesapeake Bay states such as Maryland and Delaware. Design, performance, and application guidance is provided in Maryland's stormwater design manual. Oyster BMPs are one of the most resilient to climate factors. However, their use is geographically limited to coastal areas.

INTRODUCTION

Local governments in Virginia have implemented statewide stormwater management standards since July 1, 2014. The standards protect water quality and manage runoff as impervious cover increases with development. To meet the requirements, developers employ a mix of site design, runoff reduction, and stormwater best management practices (BMPs). The physiographic conditions of the coastal plain, including a high groundwater table, poorly drained soils, and flat terrain, can present challenges when determining how best to meet stormwater quality and quantity requirements. When BMPs are evaluated to determine which are most suitable to overcome those conditions, it is also important to consider how resilient they will be to changing climate conditions. Doing so improves water quality, reduces flooding, and protects infrastructure investments. This study provides an overview of which BMPs practitioners should consider first when designing stormwater management strategies for development sites in the coastal plain.

In 2013, the Hampton Roads Planning District Commission (HRPDC) completed the Land and Water Quality Protection in Hampton Roads: Phase II report ("Phase II report"), a project funded by the Virginia Coastal Zone Management Program that identified which BMPs that had been approved by the Virginia Department of Environmental Quality (DEQ) were suitable for the coastal plain. Several BMPs and BMP enhancements have been developed or approved since the Phase II report was published. The current study was conducted to identify, evaluate, and recommend BMPs and BMP enhancements not included in the previous Phase II report that are best suited for use in Hampton Roads, given the constraints of the coastal plain. Additionally, the study evaluates both previously identified and new BMPs and BMP enhancements for their vulnerability to ongoing and projected impacts from climate change. The HRPDC identified this project in consultation with their regional Coastal Resiliency Committee to build upon previous and ongoing efforts by the committee and staff to support local stormwater and floodplain management programs. The study directly supports the needs of Hampton Roads communities by addressing current and future flood risk and providing a list of recommended stormwater management practices for use in the region.

METHODOLOGY

The identification and evaluation of coastal plain BMPs began with a literature review of existing research and technical documents. Sources were determined by the project team and HRPDC staff and included academic journal articles, stormwater design manuals, state guidance documents, and Chesapeake Bay Program Expert Panel reports.

The literature review focused on functionality for both water quality treatment and water quantity management, with the following goals:

a. Identify newer BMPs not included in the Phase II report.
b. Identify specific design changes or modifications for the BMPs included in the Phase II report and the newer BMPs that could improve their effectiveness in treating and managing stormwater runoff given conditions often found in the coastal plain (high groundwater, flat topography, poorly drained soils, etc.)
c. Identify practices that are well suited to managing stormwater runoff in the coastal plain even if they do not provide much benefit for water quality protection.
d. Evaluate BMPs for their ability to function in response to climate change impacts, including saltwater intrusion, more frequent flooding, increased rainfall, etc.

e. Develop a list of recommended BMPs considering functionality for both climate change impacts and coastal plain conditions.

The literature review was used to identify the best BMPs and BMP enhancements for use in the coastal plain considering their resilience to climate factors and treatment functionality. Each BMP was categorized as either traditional, innovative, or an enhancement. Innovative BMPs are practices developed for stormwater management since the Phase II report was published while traditional BMPs are those previously considered and evaluated in that report. The suitability and resiliency of traditional BMPs were determined based on common engineering practices and the literature review.

The findings of the literature review were compiled into two tables, Table 1 Coastal Plain Suitability, and Table 2 Resilience Vulnerability. Table 1 summarizes the assessment of BMPs and BMP enhancements for their vulnerabilities to: 1) a seasonally high water table, 2) mostly Hydrologic Soil Group (HSG) C or D (poorly drained) soils, and 3) flat terrain. Table 2 includes a suitability ranking for BMPs and BMP enhancements experiencing the following climate factors: 1) tidal flooding, 2) increased precipitation, 3) extended dry weather, 4) increased rainfall concentration, 5) high groundwater, 6) storm surge, and 7) salt exposure.

FINDINGS AND GAP ANALYSIS

The following presents an analysis of the innovative BMPs and BMP enhancements considered in this study. Each discussion includes a definition of the practice, a description of the ideal application, whether it has been approved for use by the DEQ or the Chesapeake Bay Program (CBP), its vulnerability to climate factors, and research needs. For further information on the traditional BMPs, refer to the Phase II report.

Table 1: *Coastal Plain Suitability*

KEY P (Preferred) = Widely feasible A (Accepted) = Functions with design modifications R (Restricted) =	Seasonally High Water Table (≤ 2 ft)			Mostly HSG C or D Soils			Flat Terrain			Recommendations
	P	A	R	P	A	R	P	A	R	As described in the Virginia Stormwater Management Handbook and other resources
Traditional BMPs										
Rooftop Disconnection		💧		💧			💧			Add compost-amended soils to promote pollutant removal, and consider alternative disconnection practices if simple disconnection criteria cannot be met
Sheet Flow to Open Space			💧	💧			💧			Incorporate soil restoration practices in less permeable soils
Grass Channels			💧		💧				💧	Incorporate soil amendments for use with HSG C/D soils and ensure the bottom of the channel does not intercept the water table
Soil Amendments			💧	💧			💧			Most cost-effective for enhancing runoff reduction in grass filter strips, channels, tree clusters, reforested areas, and rooftop disconnections
Vegetated Roofs		💧			💧			💧		Ideal for use in treatment trains, and supplemental irrigation may be needed in hot, dry summers
Rainwater Harvesting		💧			💧			💧		Aboveground cisterns are preferred or underground if above the water table, can be combined with automatic irrigation systems
Permeable Pavement			💧		💧		💧			Impermeable soils in HSG C/D typically need an underdrain
Small Scale Infiltration			💧		💧			💧		Maximize surface area, keep infiltration depth to less than 24 inches
Large Scale Infiltration			💧			💧		💧		Consider constructed wetland practices where large scale infiltration is not feasible
Bioretention			💧		💧		💧			Consider an underdrain with a liner in high water table areas, select plants that tolerate 6-to-12-inch ponding depths
Dry Swales			💧		💧			💧		Choose native plants that can withstand wet/dry periods and high-velocity flows, consider an underdrain in HSG C/D soils
Wet Swales	💧			💧			💧			Incorporate sand/compost into surface soils and plant wet-footed species like sedges or wet meadows for better growth, incorporate a series of on/off-line storage cells
Filtering Practices		💧			💧			💧		Depth to water table can be 18-inches with a large diameter underdrain, and depth can also be reduced if filter is self-contained to prevent untreated stormwater from reaching groundwater
Constructed Wetlands	💧			💧			💧			Incorporate sand/compost into surface soils, use flashboard risers to adjust water levels, can excavate up to 6-inches below the water table for wetland planting zones
Wet Ponds		💧			💧			💧		Install backflow prevention check valves to limit tidal backflow into wet ponds, add landscaping and aeration features to improve pollutant removal
Extended Detention Ponds			💧		💧			💧		Outlet elevation of pond should be above tidal mean high water to limit backflow, consider shallow constructed wetlands as an alternative

Table 1: *Coastal Plain Suitability (continued)*

KEY P (Preferred) = Widely feasible A (Accepted) = Functions with design modifications R (Restricted) = Not well suited	Seasonally High Water Table (≤ 2 ft)			Mostly Group C or D Soils			Flat Terrain			Recommendations
	P	A	R	P	A	R	P	A	R	As described in the Virginia Stormwater Management Handbook and other resources
BMP Enhancements										
Floating Treatment Wetlands (FTW)	💧			💧			💧			Ideal for wet ponds of an average depth of 3.5 to 8 feet
Coagulant Enhanced Treatment (CET)	💧			💧			💧			Best for wet ponds with large drainage areas and a permanent pool volume
Continuous Monitoring Adaptive Control (CMAC)	💧			💧			💧			Use in large wet ponds to be cost effective, avoid salt exposure which can corrode system components
Innovative BMPs										
MTD: Hydrodynamic Devices		💧		💧			💧			Often incorporated as pretreatment for downstream BMPs, well suited for small impervious sites to remove sediments, hydrocarbons, and floatables
MTD: Filtering Devices		💧			💧		💧			Suitable for stand-alone applications and as pre-treatment in a treatment train, primarily treats fine sediment and dissolved pollutants such as phosphorous
Living Shorelines	💧			💧			💧			Choose sites that are not exposed to open wave energy, and select salt tolerant and wet-footed plants
Aquaculture - Oyster BMP	💧			💧			💧			Select culture methods based on siting and wave energy conditions
Restoration – Oyster BMP	💧			💧			💧			Target areas with optimal salinity and temperature for growth
Tree Planting - Urban Tree Canopy Expansion		💧		💧			💧			Plant in low-lying areas for stormwater treatment, choose native species tolerant of standing water and urban environments, and use soil amendments on HSG C/D soils
Tree Planting - Urban Forest Planting		💧		💧			💧			Plant trees in low-lying areas for stormwater treatment, choose native species tolerant of standing water, and use soil amendments on HSG C/D soils
Blue Roofs	💧			💧			💧			Ideal for use in treatment train design and sites with space constraints
Submerged Gravel Wetlands (SGW)	💧			💧			💧			Ideal for areas with a high water table, incorporate a forebay to remove debris and prevent clogging
Stream Restoration		💧			💧				💧	Only suitable for sites with enough grade, consider RSC where stream restoration is not feasible or practical
Regenerative Stormwater Conveyance (RSC)		💧			💧				💧	Shallow ponding areas should have extra storage volume for temporary ponding and water quality volume storage, recommend longitudinal slopes of 5% or less, provide forebays at inflow
Underground Storage			💧		💧				💧	Commonly built under paved surfaces to preserve space for other urban uses, only consider if excavation space available

Resilience Vulnerability Table and Definitions - The following table defines the site-specific considerations (climate factors) utilized in "Table 2", found on this page.

Definition of Site-Specific Considerations	
Tidal Flooding	The frequent, temporary inundation of low-lying areas during high tide events.
Increased Precipitation	The increase in frequency of water released from clouds in the form of rain, freezing rain, sleet, snow, or hail.
Extended Dry Weather	Periods of drought.
Increased Rainfall Concentration	The increase in the amount of rainfall during low frequency storm events.
High Groundwater	The increase in the level of water that exists underground in saturated zones beneath the land surface.
Storm Surge	The abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide.
Salt Exposure	Repeated or in constant contact with salt or saltwater intrusion, either at the surface or through groundwater.

Table 2: *Resilience Vulnerability*

Resilience Vulnerability Table

Level of Vulnerability to Climate Factors

Low or None	Green
Medium	Yellow
High	Red

The resiliency of the BMP depends on several factors. Additional information may be needed to accurately determine the level of vulnerability to selected climate factors. The assumptions are based on common engineering practices and identified sources.

Site Specific Considerations: Climate Factors

BMP	Tidal Flooding	Increased Precipitation	Extended Dry Weather	Increased Rainfall Concentration	High Groundwater	Storm Surge	Salt Exposure
Traditional BMPs							
Rooftop Disconnection	Low or None	Low or None	Low or None	Medium	Low or None	Low or None	Low or None
Sheet Flow To Open Space	Low or None	Low or None	Low or None	Low or None	Medium	Low or None	Low or None
Grass Channels	Medium	Medium	Low or None	Medium	High	Medium	Medium
Soil Amendments	Low or None	Low or None	Low or None	Low or None	Low or None	Medium	Low or None
Vegetated Roofs	Low or None	Medium	Medium	Medium	Low or None	Low or None	Low or None
Rainwater Harvesting	Low or None	Medium	Low or None	Medium	Low or None	Low or None	Low or None
Permeable Pavement	Medium	Medium	Low or None	Medium	High	Medium	Medium
Small Scale Infiltration	Medium	Medium	Low or None	Medium	High	Medium	Medium
Large Scale Infiltration	Medium	Low or None	Medium	Medium	High	Medium	Medium
Bioretention	Medium	Medium	Medium	Medium	High	Medium	Medium
Dry Swales	Medium	Medium	Medium	Medium	High	Medium	Low or None
Wet Swales	Low or None	Low or None	Low or None	Low or None	Low or None	Medium	Medium
Filtering Practices	Medium	Medium	Low or None	Medium	Medium	Medium	Medium
Constructed Wetlands	Low or None	Low or None	Low or None	Low or None	Low or None	Medium	Medium
Wet Ponds	Low or None	Medium	Low or None	Medium	Low or None	Medium	Medium
Extended Detention Ponds	High	Medium	Medium	Medium	High	Medium	Low or None
BMP Enhancements							
Floating Treatment Wetlands (FTW)	Low or None	Low or None	Low or None	Low or None	Low or None	Low or None	Medium
Coagulant Enhanced Treatment (CET)	Medium	Low or None	Medium	Low or None	Low or None	Medium	Medium
Continuous Monitoring Adaptive Control (CMAC)	Medium	Low or None	Low or None	Low or None	Low or None	Medium	Medium
Innovative BMPs							
MTD: Hydrodynamic Devices	Medium	Medium	Low or None	Medium	Medium	Medium	Low or None
MTD: Filtering Devices	Medium	Medium	Low or None	Medium	Medium	Medium	Low or None
Living Shorelines	Low or None	Low or None	Low or None	Low or None	Medium	Medium	Medium
Aquaculture - Oyster BMP	Low or None	Low or None	Low or None	Low or None	Low or None	Low or None	Low or None
Restoration - Oyster BMP	Low or None	Low or None	Low or None	Low or None	Low or None	Low or None	Low or None
Tree Planting - Urban Tree Canopy Expansion	Low or None	Low or None	Medium	Low or None	Medium	Medium	Medium
Tree Planting - Urban Forest Planting	Low or None	Low or None	Medium	Low or None	Medium	Medium	Medium
Blue Roofs	Low or None	Medium	Low or None	Medium	Low or None	Low or None	Low or None
Submerged Gravel Wetlands (SGW)	Medium	Low or None	Medium	Low or None	Low or None	Medium	Medium
Stream Restoration	Low or None	Low or None	Medium	Low or None	Medium	Low or None	Medium
Regenerative Stormwater Conveyance (RSC)	Low or None	Low or None	Medium	Low or None	Medium	Low or None	Medium
Underground Storage	Medium	Low or None	Low or None	Low or None	High	Low or None	Low or None

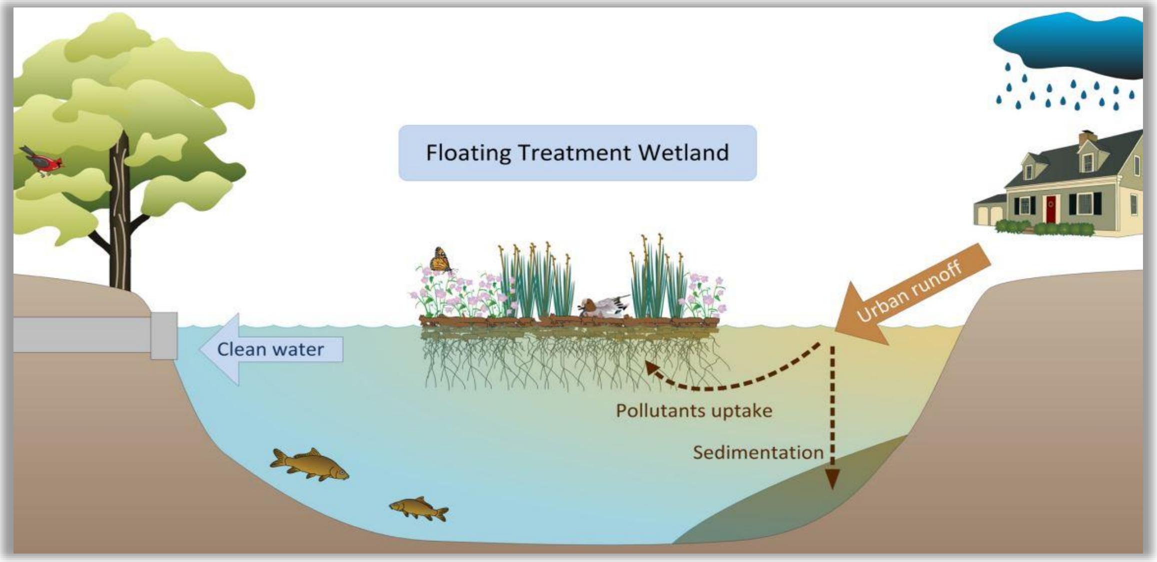
Floating Treatment Wetlands

Floating treatment wetlands (FTWs) are manmade ecosystems that mimic natural wetlands. Floating treatment wetlands are created using floating rafts that support plants grown hydroponically. As shown in Figures 1 and 2, the rafts float on a wet pond water surface and are used to improve water quality by filtering, consuming, or breaking down pollutants (e.g., nutrients, sediment, and metals).

Figure 1: *Floating Treatment Wetlands in a Stormwater Pond*

Note. From "Beemats Floating Treatment Wetlands," by Beemats Floating Treatment Wetlands, 2017 and 2019, http://www.beemats.com/hanover-county-va.html

Figure 2: *Schematic Design of a Floating Treatment Wetland*



Note. From "Innovative Best Management Fact Sheet No.1: Floating Treatment Wetlands," by Virginia Cooperative Extension 2013, https://vtechworks.lib.vt.edu/

The ideal site for an FTW is an existing wet pond used for the treatment of stormwater runoff. Floating treatment wetlands can be a retrofit option that is added to an existing wet pond with an average depth of 3.5 to 8 feet. The FTWs should be anchored at least 3.5 feet above the bottom of the pond and achieve a minimum pond surface coverage of 10%. [4]

Floating treatment wetlands are approved by the CBP, but they are not currently approved by DEQ as a stormwater treatment BMP. (See Endnote 4)

Floating treatment wetlands have low vulnerability to the climate factors listed in Table 2. The FTWs adapt well to water-level fluctuation caused by increased precipitation because they float on the surface of wet ponds. An FTW requires a permanent pond condition and can be implemented as a water quality improvement retrofit to wet ponds with compatible conditions.

The literature review revealed limited information on long-term performance, impacts of climate changes, salt exposure, maintenance cost, and the cost per pound of phosphorus removed. The use of salt tolerant plant species in FTWs enhances the suitability of the practice, especially in coastal Virginia, as saltwater intrudes inland. Native salt marsh plants such as black needle rush, sawgrass, broadleaf cattail, and saltmeadow cordgrass are recommended.

Coagulant Enhanced Treatment

Coagulant enhanced treatment (CET) is a stormwater treatment enhancement that uses a coagulant, usually an aluminum compound, in a wet pond to bind with pollutant particles to form flocs which then settle to the bottom of the pond. Figure 3 shows the effectiveness of CET in removing algae from a large wet pond in Florida.

Figure 3: *Coagulant Enhanced Treatment in Lake Ella in Tallahassee, FL. Before (Left) and After (Right)*

Note. From "Coagulant Enhanced Stormwater Treatment for Use in the Chesapeake Bay Watershed," by Brown and Caldwell 2023, https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/VAB-Coagulant-Enhanced-Treatment-Report_FINAL-w-appendices.pdf

The ideal wet pond for CET is one with a large contributing drainage area, as CET is designed to treat larger volumes of water. The site should have a wet pond with a permanent pool volume that can provide sufficient detention time for the flocculant to settle. Coagulant enhanced treatment can be added as a retrofit option to existing wet ponds or incorporated in the design of new wet ponds. However, CET may not be suitable for smaller wet ponds with smaller drainage areas.

Coagulant enhanced treatment has been approved by the CBP, but it is not currently approved by DEQ as a stormwater treatment BMP.[5]

Coagulant enhanced treatment has a medium to low level of vulnerability to climate factors listed in Table 2. The BMP is resilient to increased precipitation, increased rainfall concentration, and high groundwater. The introduction of salt or brackish water from tidal flooding may impair the performance of the CET.

The literature review provided examples of CET applications in Florida implemented to reduce watershed pollutant loads and improve water quality. The CET projects were sited in similar geographic conditions to that of the coastal plain of Virginia with high groundwater and flat terrain. Additional coordination is recommended for the implementation and study of CET use and projects in the Chesapeake Bay watershed. (See Endnote 5)

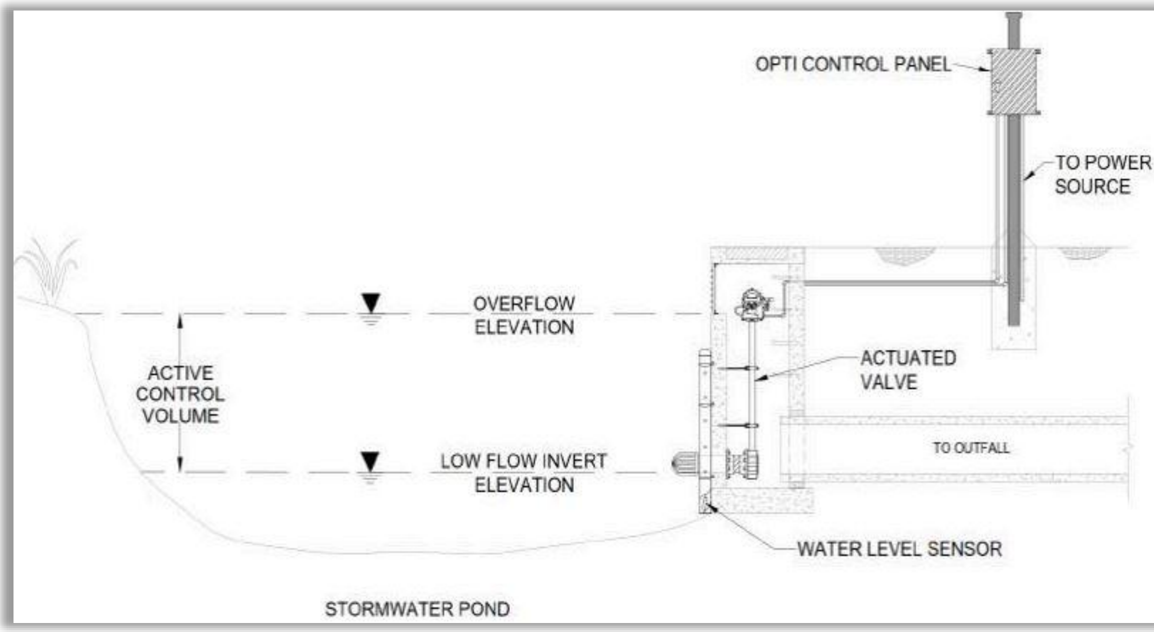
Continuous Monitoring and Adaptive Control

Continuous monitoring and adaptive control (CMAC) is a forecast-based real-time control technology that allows for adaptive management and control of stormwater management facilities using stations like the one shown in Figure 4. The CMAC system can improve the pollutant reduction efficiency and adaptability of stormwater facilities through monitoring performance and controlling storage and flow.

Figure 4: *Continuous Monitoring and Adaptive Control Station Implemented at a Wet Pond*

Note. From "WQ Data Live," by WQ Data Live 2024, https://wqdatalive.com/

Figure 5: *Schematic Design of a Continuous Monitoring and Adaptive Control Station Implemented at a Wet Pond*



Note. From "Opti Design Overview," by OptiTRC, Inc. 2024, https://cdn.prod.website-files.com

The CMAC technology is ideal for sites with existing stormwater facilities such as wet ponds and for sites where new stormwater facilities are proposed. Figure 5 illustrates how one provider of this technology, OptiTRC, designs CMAC systems. The CMAC system provides adaptive control that can enhance the performance and value of existing wet ponds. The forecast-based real-time control technology provided by CMAC systems allows for direct monitoring of performance and active control of storage and flows.[6] The function and performance of a CMAC system can be modified to adapt to climatic and hydrologic conditions. Continuous monitoring allows for proactive and targeted maintenance to detect potential problems before failure occurs.

CMAC has been approved by CBP for use under the BMP retrofit curves. (See Endnote 6)

Continuous monitoring and adaptive control systems have a low level of vulnerability to the climate factors listed in Table 2. Siting and design location should be carefully considered to ensure CMAC systems are not exposed to salt. Salt exposure to system components may cause corrosion and regular maintenance should be performed on the system to ensure functionality.

The literature review provided information on how the CMAC system functions and the benefits of implementing forecast-based real-time controls for stormwater management. Implementation and maintenance costs will vary depending on the scale of the project.

INNOVATIVE BMPs

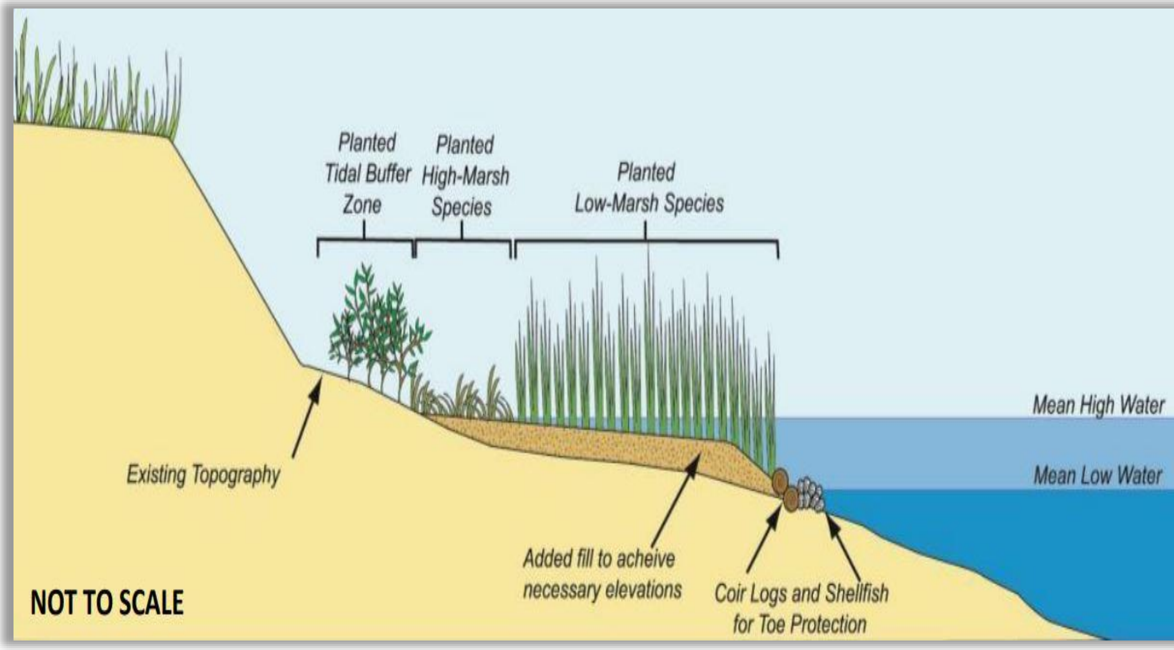
Living Shorelines

Living shorelines, like the example in Figure 6, are erosion control practices that improve water quality and provide habitat using natural and nature-based features. Marsh plants and oyster reefs filter pollutants from stormwater runoff and stabilize sediments.

Figure 6: *An Example of a Living Shoreline*

Note. From "Living Shorelines," by Virginia Association of Soil and Water Conservation Districts 2024, https://vaswcd.org/living-shorelines/

Figure 7: *Schematic Design of a Living Shoreline for Natural Marsh Creation/Enhancement*



Note. From "Living Shorelines in New England: State of the Practice," by Northeast Regional Ocean Council 2017, https://www.northeastoceancouncil.org/

The ideal site for a living shoreline is a sheltered coast, such as a bay or river, that is not exposed to open wave energy. The various adaptive designs for living shorelines make them suitable for a variety of sites and site-specific conditions. Siting considerations should be made to avoid locating these practices in high wave energy areas. Refer to Figure 7 for a schematic of how living shorelines are often designed.

Living shorelines are approved by the CBP as stormwater management practices.[7] They are often used as retrofit projects for treating both single and multiple parcels. Living shorelines have a medium to low level of vulnerability to climate factors, as they are adaptable to low energy fluctuations in water-level and tolerant to extended periods of dry weather.[8] Living shorelines are most resilient on sites where there are no hardened structures, such as bulkheads, that impede their landward migration as sea levels rise.

Living shorelines are a well-established practice utilized in several Chesapeake Bay states including Virginia, Delaware, and Maryland for shoreline stabilization. The cost of a living shoreline can be influenced by the materials chosen, construction techniques, and long-term maintenance. The initial installation cost can range from up to $1,000 to $10,000 per linear foot. Yearly operations and maintenance costs can range from up to $100 to over $500 per linear foot.[9]

Oyster BMPs

Oysters are natural filters, meaning they bioaccumulate nitrogen and phosphorus through their feeding process, which improves water quality. There are two primary types of oyster BMPs, aquaculture and restoration.

Oyster Aquaculture

Aquaculture is the growth and cultivation of aquatic animals or plants for food. Figure 8 shows oysters growing near the surface of the water. The oyster aquaculture BMP is a set of best management practices for oyster cultivation and harvesting that reduce nutrients and suspended sediments in the Chesapeake Bay. While oyster aquaculture provides economic opportunities throughout the Chesapeake Bay watershed, another benefit is nutrient capture and removal from the water column.

Oyster Restoration

Oyster restoration is a collective term for practices designed to restore and protect oysters to increase the wild oyster population. Figure 9 shows an example of an oyster reef in the Elizabeth River. Techniques for restoration include: 1) planting oysters produced from hatcheries and 2) planting oyster shells and/or alternate substrate to attract wild oyster larvae. These techniques are used in areas where removal is not permitted to enhance oyster biomass.

Figure 8: *Oysters Raised in Mesh Bags and Open to Filter Feeding at High Tide*

Note. From “A Look at Oyster Aquaculture,” by NOAA Fisheries 2021, https://www.fisheries.noaa.gov

Figure 9: *Oyster Restoration Practice in the Elizabeth River*

Note. From "Oyster Restoration to Protect Nansemond River Shorelines," by Chesapeake Bay Foundation, Photo by Dr. Lisa Drake, https://www.cbf.org/how-we-save-the-bay/programs-initiatives/virginia/oyster-restoration/oyster-restoration-to-protect-nansemond-river-shorelines.html

The ideal site for oyster BMPs is in tidal waters where oysters can filter feed and assimilate nutrients. Oyster BMPs are suitable in the southern half of the Chesapeake Bay in tributaries where the optimal salinity and temperature for oyster growth is found. In Virginia, the practice is implemented in several rivers, including the Potomac, York, James, Rappahannock, Lynnhaven, and Poquoson Rivers. There are some areas where oyster aquaculture is not feasible or practical due to substrate, depth, or other constraints.

Oyster BMPs are not approved as a stormwater practice by DEQ; however, oyster aquaculture and restoration are approved by the CBP.[10]

Oyster BMPs have a low level of vulnerability to the climate factors listed in Table 2. Oyster reefs are suitable along shorelines and help minimize erosion in addition to filtering pollutants.

The literature review revealed comprehensive knowledge on the benefits and limitations of oyster BMPs as described in the CBP Expert Panel reports. The calculation of pollutant removal rates for oyster aquaculture is based on oyster size and ploidy, and for oyster restoration, the crediting is based on a comparison of the biomass before and after.[11]

Tree Planting

The tree planting BMP refers to actions and/or program elements that result in expanded tree canopy through maintenance of existing tree canopy and/or an increase in trees planted for developed land uses for water quality improvement and other benefits. The tree planting BMP includes two types of practices: 1) urban tree canopy expansion and 2) urban forest planting.

Urban Tree Canopy Expansion

Urban tree canopy expansion refers to tree planting on developed land (impervious or turf) that increases tree canopy but is not intended to result in forest-like conditions. It does not require trees to be planted in a contiguous area. Figure 10 shows urban tree canopy expansion in Downtown Norfolk, VA.

Figure 10: *Urban Tree Canopy Expansion in Norfolk, Virginia*

Note. From "Norfolk Virginia - April 15, 2024: Downtown Norfolk Virginia Granby Street with Trees in Bloom During Spring in the City," by Kyle J Little, https://www.shutterstock.com

Urban Forest Planting

Urban forest planting involves tree planting projects in urban or suburban areas that are not part of a riparian buffer planting, structural BMP, or urban tree canopy expansion BMP with the intent of establishing forest or similar ecosystems. The urban forest in Norfolk, VA is shown in Figure 11.

Figure 11: *Urban Forest Planting in the City of Norfolk, Virginia*

Note. Photo by City of Norfolk

The tree planting BMP can be used in non-contiguous areas, making the BMP flexible for use in various locations. Small areas that accommodate individual or small groups of trees such as sidewalks and parking lots or larger open areas such as athletic fields are ideal. Siting considerations should be followed to ensure the newly planted trees will not interfere with existing infrastructure, utilities, or public safety.

Urban tree canopy expansion has been approved by the CBP and by DEQ.[12] The Virginia Stormwater Management Handbook includes design specifications for tree planting for stormwater treatment credit, including guidance for tree planting locations. Tree species should be selected based on sunlight, soil type, and spacing to allow for growth.

The tree planting BMP has a medium to low level of vulnerability to the climate factors listed in Table 2. Trees may be affected by climate factors like extended dry weather, storm surge, and salt exposure, but selecting stress resistant trees such as sweet gum can reduce these impacts.[13] Additionally, trees can be resilient to tidal flooding, increased precipitation, and increased rainfall concentration, depending on species. Consideration in siting and species selection will help improve the overall resilience.

The literature review revealed limited information on maintenance cost and cost per pound of phosphorus removal, though tree planting is widely considered cost-effective for stormwater management. The additional benefits provided by urban tree canopy, such as public health improvements and temperature reductions, make the tree planting BMPs an attractive solution.

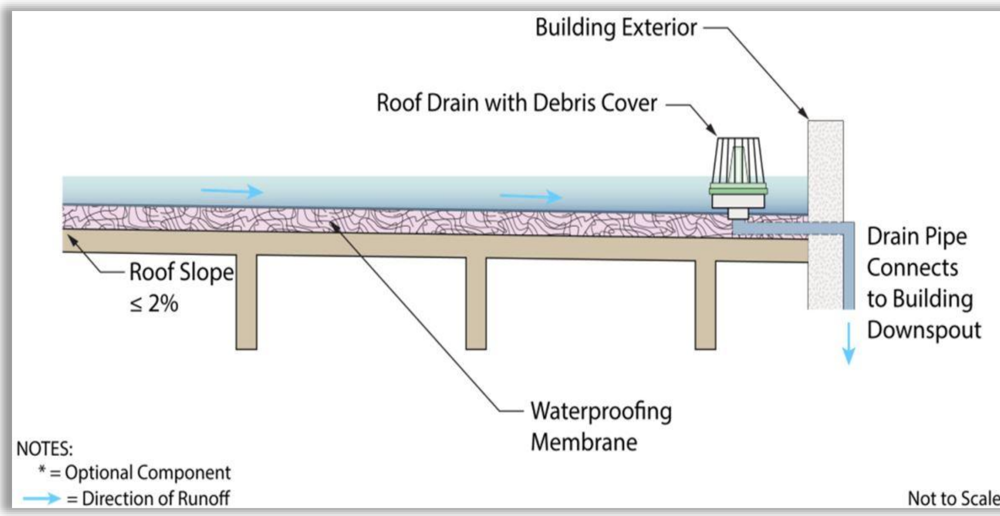
Blue Roofs

A blue roof is primarily a quantity-only BMP that detains runoff on its surface or in engineered trays, as shown in Figures 12 and 13. The water is slowly released through a flow-restriction device around the roof drain.

Figure 12: *An Example of a Blue Roof*

Note. From "Stormwater Management Guidance Manual: Chapter 4.6 Blue Roofs" by Philadelphia Water Department 2023, https://water.phila.gov/development/stormwater-plan-review/manual/

Figure 13: *Schematic Design of a Blue Roof*



Note. From "NJ Stormwater Best Management Practices Manual: Chapter 11.1 Blue Roofs," by New Jersey Department of Environmental Protection 2021, https://dep.nj.gov/stormwater/bmp-manual/

The ideal site for a blue roof BMP is one where roofs constitute most of the impervious surfaces, or in ultra-urban areas with limited space for other BMPs. A blue roof can be implemented on newly constructed buildings or retrofitted onto existing structures. However, its application may be limited by the structural strength of the building roof, particularly for retrofit projects. Placing the

BMP away from debris sources, such as trees, will help prevent outlet clogging and reduce maintenance needs.

The blue roof BMP has not been approved by DEQ; however, it is a suitable candidate for future consideration by DEQ as a quantity-only practice. Since a blue roof BMP is implemented to manage runoff volume rather than to reduce pollutants, CBP approval is likely not warranted.

The blue roof BMP has a low overall vulnerability to the climate factors listed in Table 2. The BMP helps to reduce peak flood and runoff volume through water detention. The BMP may be vulnerable to increased precipitation and rainfall concentration.

The literature review revealed limited information on water quantity crediting.

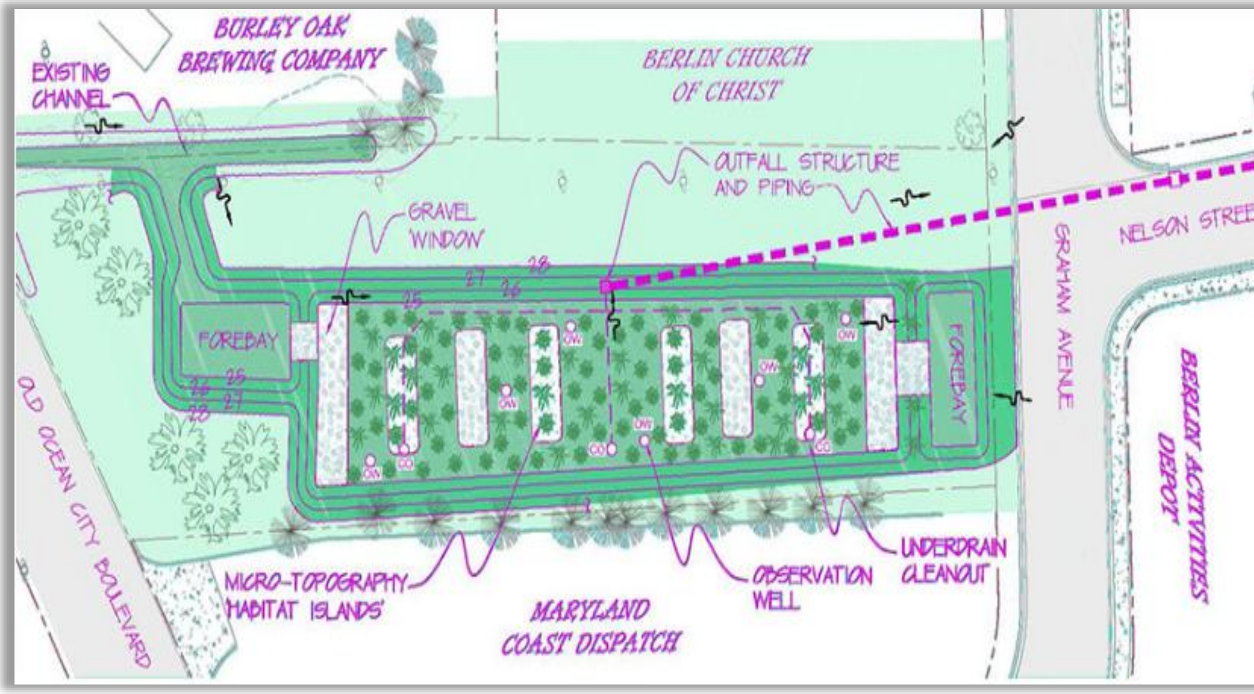
Submerged Gravel Wetland

A submerged gravel wetland (SGW) is a small-scale filtering practice that uses layers of gravel and wetland plants to provide water quality treatment. Figures 14 shows an example of an SGW in Berlin, MD, and the design is included in Figure 15.

Figure 14: *Submerged Gravel Wetland located in the Town of Berlin, Maryland*

Note. From "Graham Avenue Submerged Gravel Wetland," by EA Engineering, Science, and Technology, Inc. PBC 2024, https://eaest.com/projects/graham-avenue-submerged-gravel-wetland/

Figure 15: *Schematic Design of the Submerged Gravel Wetland Shown in Figure 14*



Note. From "Graham Avenue Submerged Gravel Wetland," by EA Engineering, Science, and Technology, Inc. PBC 2024, https://eaest.com/projects/graham-avenue-submerged-gravel-wetland/

The ideal site for an SGW is one that has HSG C or D soils or places with a high groundwater table, as the BMP requires saturated water or hydric soil conditions. An SGW can be used in conjunction with other BMPs, such as wet ponds, bioretention, and rooftop disconnection, or created as a retrofit of an existing dry pond.[14] It is recommended that a forebay or below ground treatment chamber be incorporated in the design of the SGW to trap sediment and debris and avoid clogging the gravel bed.

Submerged gravel wetlands have not been approved by DEQ or the CBP. The practice is a suitable candidate for future consideration by DEQ and the CBP's Urban Stormwater Workgroup to provide an additional stormwater treatment option for sites in Virginia and throughout the Chesapeake Bay watershed.

Submerged gravel wetlands have a medium to low level of vulnerability to the climate factors listed in Table 2. Submerged gravel wetlands may be vulnerable to extended dry weather, tidal flooding, storm surge, and salt exposure. The introduction of salt or brackish water from tidal flooding may impair the performance of an SGW.

Other states in the Chesapeake Bay watershed, including Maryland and Delaware, have approved SGWs.[15] Maryland's stormwater design manual includes design guidance and Delaware's includes SGWs as a variant of constructed wetlands. Submerged gravel wetlands have been shown to remove as much as 58% of total phosphorous, 75% of nitrate, and 95% of total suspended solids.[16]

The literature review revealed limited information on maintenance cost, cost per pound of phosphorus removal, water quality crediting, and water quantity crediting. Addressing these gaps can provide a more comprehensive understanding of the potential benefits and limitations of the BMP.

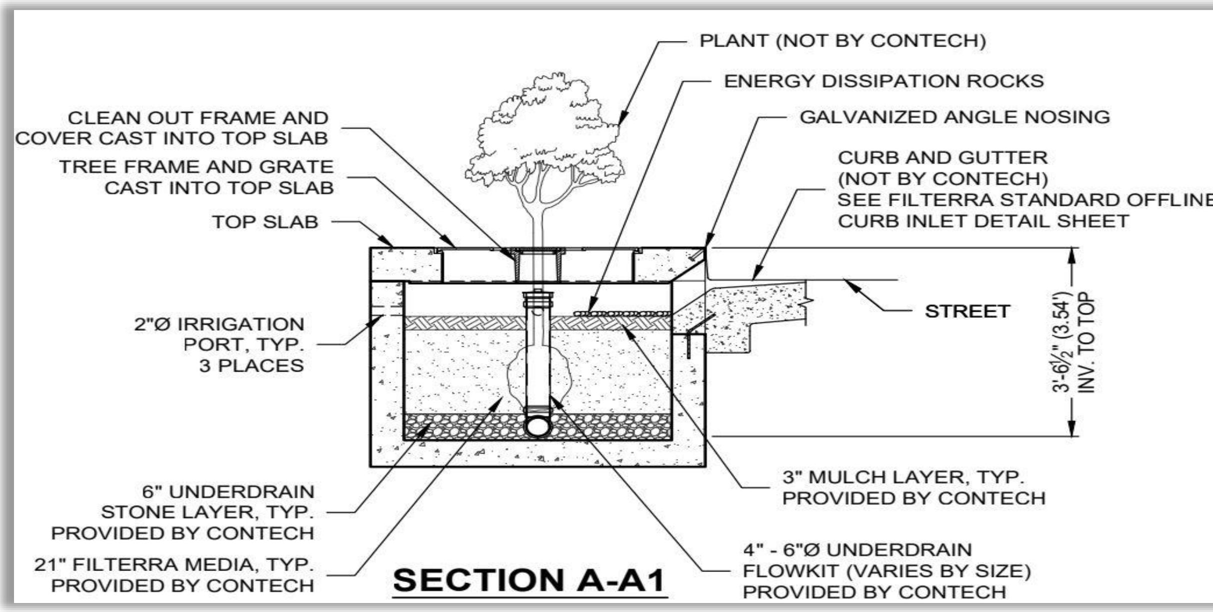
Manufactured Treatment Devices

A manufactured treatment device (MTD) is a proprietary stormwater management BMP designed to remove pollutants from stormwater runoff. Manufactured treatment devices are categorized as hydrodynamic, filtering, or biofilter devices. Hydrodynamic MTDs are underground hydrodynamic separators that remove suspended solids and floatables from stormwater runoff using gravity. Filtering MTDs are structures with one or more chambers of filtration media or cartridges that remove solids and promote microbial breakdown of pollutants. Biofilter MTDs treat runoff with biological processes using soil media and/or vegetation. Filterra systems, such as the one shown in Figure 16, are common biofilter MTDs. Figure 17 illustrates how Filterra systems are designed.

Figure 16: *An Example of a Filterra System*

Note. Photo Provided by the City of Norfolk

Figure 17: *Schematic Design of a Filterra System*



Note. From "Contech Technical Guides," by Contech Engineered Solutions LLC 2024, https://www.conteches.com/technical-guides/search

The ideal site for an MTD is a small impervious site. These devices can be installed in locations with space constraints, flat terrain, or limited soil infiltration. Manufactured treatment devices function best in areas that are well established with no on-going land disturbance. Maintenance of some underground MTDs may require confined-space entry and specialized equipment.

A list of DEQ-approved MTDs is included in the Virginia Stormwater Handbook.

Manufactured treatment devices have a low to medium level of vulnerability to the climate factors listed in Table 2. Selecting the appropriate type of MTD for the location and proper siting of the device should be considered to ensure performance goals are met.

The literature reviewed revealed information on MTD design, function, and performance. The manufacturer's specifications and performance data are provided in the Virginia Stormwater Management Handbook.

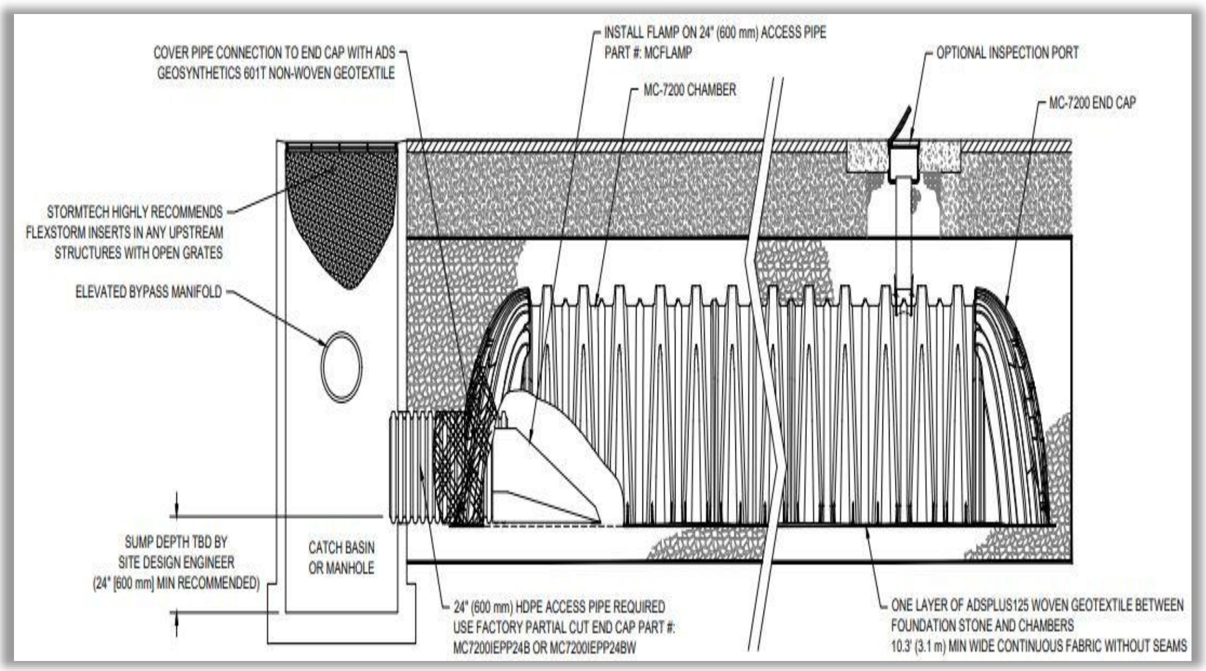
Underground Storage

Underground storage BMPs are systems of underground pipes and/or chambers designed to store stormwater runoff and then slowly release it over time. These systems reduce peak flow to minimize impacts on stormwater systems and to reduce downstream flooding. Figure 18 shows an example of an underground storage BMP in the City of Newport News, and Figure 19 provides a schematic to illustrate how the systems are designed.

Figure 18: *An Example of an Underground Storage BMP*

Note. Photo Provided by the City of Newport News

Figure 19*: Schematic Design for an Underground Storage BMP*



Note. From "StormTech MC-7200 Standard Details and Drawings," by Advanced Drainage Systems 2024, https://www.adspipe.com/water-management-solutions/detention-infiltration/stormtech-mc-7200

The ideal application for underground storage is within a new development project. Underground storage BMPs are commonly built under parking lots, other paved surfaces, and in urbanized areas where space is limited. While these systems are generally more difficult to maintain and clean compared to traditional BMPs, they are a good option in urban areas to preserve space for other uses. Siting consideration for high groundwater and allowable excavation space is needed.

Underground storage BMPs have not been approved by DEQ; however, it is a suitable candidate for future consideration by DEQ as a quantity-only practice. Since underground storage BMPs are primarily implemented to manage runoff volume rather than pollutant reduction, CBP approval may not be warranted. However, by retaining runoff and allowing time for solids to settle, the underground storage BMP also provides some water quality benefits.

Underground storage systems have a medium level of vulnerability to the climate factors listed in Table 2. High groundwater and poor draining soils impact the feasibility and constructability of the BMP. Although, there are sites within the coastal plain with a large enough depth to the water table to accommodate an underground storage facility.

The literature review revealed information on design considerations for construction material and siting constraints. Limited information was available on underground storage systems implemented in the coastal plain.

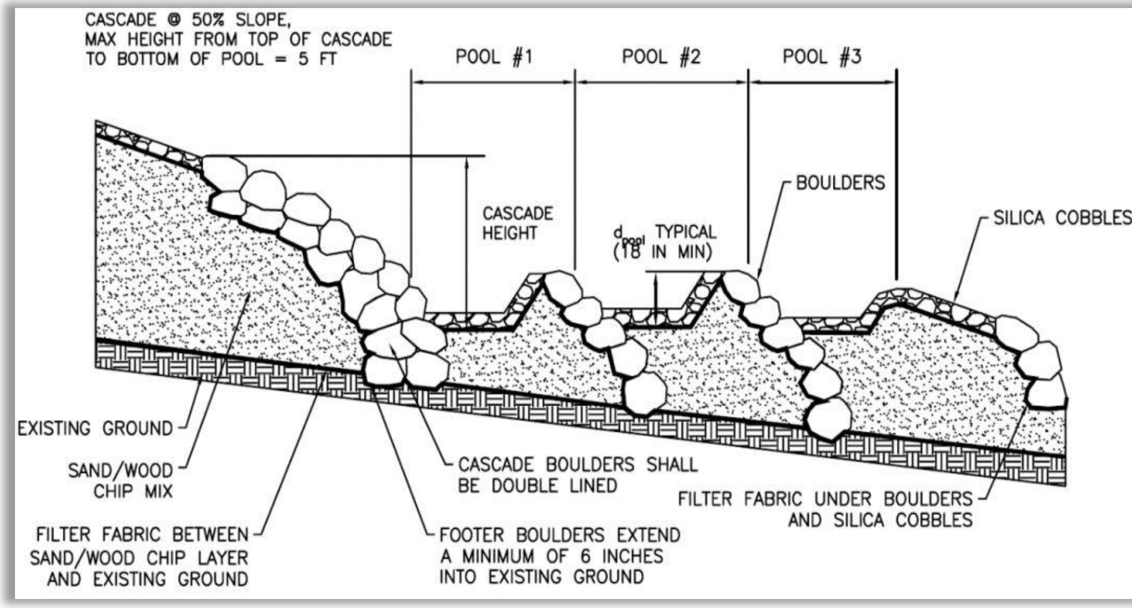
Regenerative Stormwater Conveyance

Regenerative stormwater conveyance (RSC) is used to convey runoff from developed areas to streams, reducing erosion, improving stormwater quality, and recharging shallow groundwater. Regenerative stormwater conveyance is a modified channel consisting of pools alternating with steps or cascades designed to mimic the rocks and logs found in naturally occurring step-pool channels. An RSC directs runoff into a series of pools with beds composed of permeable, sand-based filter media similar to bioretention media. Figure 20 shows an example of an RSC, and Figure 21 shows a schematic of a typical design.

Figure 20: *An Example of a Regenerative Stormwater Conveyance System*

Note. From "Not Your Everyday Stormwater Conveyance System,"
by raSmith 2020, https://www.rasmith.com/blog/not-your-everyday-stormwater-system/

Figure 21: *Schematic Design for a Regenerative Stormwater Conveyance System*



Note. From "Greenville County Technical Specification for: WQ-15 Regenerative Stormwater Conveyance," by Greenville County, SC, 2018 https://www.greenvillecounty.org/LandDevelopment/pdf/designmanual/WQ-15_Regenerative_SW_Conveyance_Spec_2018.pdf

The ideal sites for RSC are eroded outfalls and channels, first-order streams that have longitudinal slopes between 2% and 10%, or areas where grades make traditional stormwater practices difficult to implement.[17] The BMP can be used as an ecosystem restoration practice and is designed to convey flows associated with extreme floods in a non-erosive manner. The typical contributing drainage area for RSC is around 10 to 30 acres and tends to be highly impervious.[18] Regenerative stormwater conveyance is designed to promote infiltration and the slow release of runoff. For sites where water quality benefits are the goal, a sand-woodchip filtration mixture should be used to promote infiltration.

Regenerative stormwater conveyance as a BMP is approved by DEQ and the CBP.[19]

Regenerative stormwater conveyance has a low level of vulnerability to the climate factors listed in Table 2. High groundwater may reduce the available storage and infiltration abilities. Extended periods of dry weather may stress certain plant species and reduce soil moisture, which can affect the ecological function of the BMP.

Regenerative stormwater conveyance is a relatively new BMP and the literature reviewed revealed limited information on its expected performance. Regenerative stormwater conveyance installed on steep slopes or in areas with high water tables may have limited runoff reduction and/or quality benefits. The estimated construction cost for RSC is typically $500 to $750 per linear foot; however, this amount is likely to vary based on site conditions and other outside factors. (See Endnote 17)

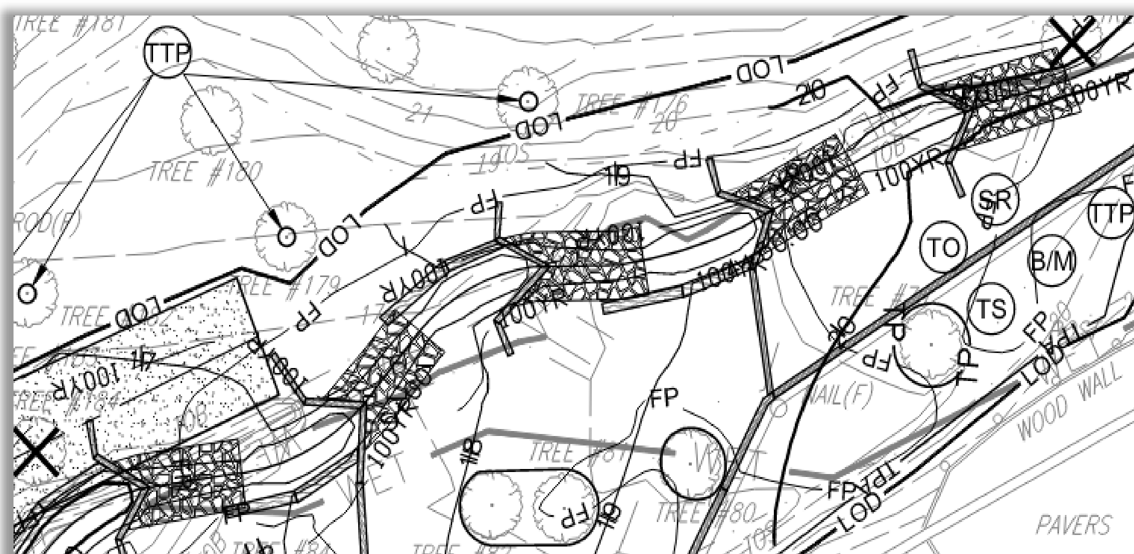
Stream Restoration

Stream restoration is the re-establishment of the general structure, function, and self-sustaining behavior of a stream system that existed before disturbance. Stream restoration projects include a broad range of practices, including the removal of watershed disturbances causing instability, installation of structures and planting of vegetation to protect streambanks, and reshaping or replacement of unstable stream reaches. Figure 22 shows an example stream restoration project, and Figure 23 shows a site plan for a stream restoration project.

Figure 22: *An Example of a Stream Restoration Project and In-Stream Features*

Note. From "Pine Camp Stream Restoration Project" Photo Courtesy of A. Morton Thomas & Associates, Inc.

Figure 23: *Schematic Design of a Stream Restoration Project and In-Stream Structures*



Note. From "Port Anne Outfall Stream Restoration Plan," by A. Morton Thomas & Associates, Inc.

The ideal site for stream restoration is within a watershed with little or no expected future development or changes in land use. Current and future zoning information can be important in site selection. The availability of construction access is an important constraint to consider in urban watersheds. A cost-effective way to move equipment in, out, and around the site should be available. Additionally, significant clearing of riparian vegetation may be required to provide access, which could outweigh the potential benefits of the proposed project.

Stream restoration as a BMP has been approved by the CBP.

Stream restoration has a low level of vulnerability to the climate factors listed in Table 2. Extended periods of dry weather may stress certain plant species required for establishment of the restored area. Limited grade and low-lying land conditions in coastal plain conditions may limit construction feasibility in certain areas.

Stream restoration is known to be a cost-effective practice for total phosphorous and sediment reductions. While most of eastern Hampton Roads is too flat for stream restoration projects, they are a popular stormwater management practice in the western part of the region, such as James City County, York County, and the City of Newport News.

CONCLUSION

Practitioners use a suite of techniques when designing stormwater management plans for development sites. They incorporate low impact design principles, looking to preserve vegetated areas and reduce imperviousness while maintaining space for the needs of the project. They also evaluate several potential BMP types to meet stormwater quality and quantity requirements in a cost-effective and resilient manner. The purpose of this study was to serve as a resource for which BMPs should be considered first when looking to implement practices that are most suitable in the coastal plain and most resistant to changing climate conditions.

The suitability of the traditional BMPs, innovative BMPs, and BMP enhancements reviewed in this study ranged widely with the considered climate factors and coastal plain conditions. The traditional BMPs, which were previously identified in the Phase II report, are all vulnerable to some if not most of the assessed climate factors. Higher groundwater conditions in particular may degrade the performance of those practices that rely on infiltration. More careful siting or additional capacity may address most other potential issues with climate change impacts.

All three BMP enhancements (Floating Treatment Wetlands, Coagulant Enhancement Treatment, and Continuous Monitoring Adaptive Control) are well suited for coastal plain conditions and are approved by the CBP. Regarding climate factors, all three enhancements are resilient to increased precipitation, increased rainfall concentration, and high groundwater. The three enhancements only exhibit low to medium vulnerability to tidal flooding, extended dry weather, storm surge, and salt exposure. Most notably, floating treatment wetlands are only vulnerable to salt exposure, but this may be mitigated with salt-tolerant plants.

Each innovative BMP offers unique benefits to stormwater management. Living shorelines, oyster aquaculture and restoration, blue roofs, and submerged gravel wetlands are preferred practices for coastal plain conditions, though they vary in their resilience against climate factors. Incorporating living shorelines, a CBP approved nature-based practice, aligns with other local, regional, and state resiliency and wetlands protection goals. Blue roofs are applicable in urban areas as they can be retrofitted on existing buildings or implemented during new construction. They should be considered and evaluated by DEQ. Submerged gravel wetlands should also be considered by DEQ and the CBP as an additional stormwater practice that is well suited in areas where a high-water table or poorly drained soils are present. Submerged gravel wetlands are implemented in neighboring Chesapeake Bay states such as Maryland and Delaware. Design, performance, and application guidance is provided in Maryland's stormwater design manual. Oyster BMPs are one of the most resilient to climate factors. However, their use is geographically limited to coastal areas.

The selection of appropriate BMPs should be based on site-specific factors and desired stormwater management outcomes. Continued collaboration and support among the Chesapeake Bay states, regional programs and partnerships, and state and federal agencies will be necessary to identify and evaluate innovative BMPs and BMP enhancements, addressing gaps in available research and literature. Promoting the implementation of innovative BMPs and BMP enhancements used in other Chesapeake Bay states and similar geographic regions will improve the effectiveness of treating and managing stormwater runoff in the conditions often found in the coastal plain of Virginia, especially as climate impacts intensify.

ENDNOTES

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