United States Environmental Protection Agency

2014 GREEN INFRASTRUCTURE TECHNICAL ASSISTANCE PROGRAM
City of Norfolk
Norfolk, VA

Restoring Knitting Mill Creek through Green Infrastructure

A plan for adapting green infrastructure to a shoreline community subject to sea level rise

December 2015
EPA 832-R-15-012

About the Green Infrastructure Technical Assistance Program

Stormwater runoff is a major cause of water pollution in urban areas. When rain falls in undeveloped areas, soil and plants absorb and filter the water. When rain falls on our roofs, streets, and parking lots, however, the water cannot soak into the ground. In most urban areas, stormwater is drained through engineered collection systems and discharged into nearby water bodies. The stormwater carries trash, bacteria, heavy metals, and other pollutants from the urban landscape, polluting the receiving waters. Higher flows also can cause erosion and flooding in urban streams, damaging habitat, property, and infrastructure.

Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, *green infrastructure* refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water. Green infrastructure can be a cost-effective approach for improving water quality and helping communities stretch their infrastructure investments further by providing multiple environmental, economic, and community benefits. This multi-benefit approach creates sustainable and resilient water infrastructure that supports and revitalizes urban communities.

The U.S. Environmental Protection Agency (EPA) encourages communities to use green infrastructure to help manage stormwater runoff, reduce sewer overflows, and improve water quality. EPA recognizes the value of working collaboratively with communities to support broader adoption of green infrastructure approaches. Technical assistance is a key component to accelerating the implementation of green infrastructure across the nation and aligns with EPA's commitment to provide community focused outreach and support in the President's *Priority Agenda Enhancing the Climate Resilience of America's Natural Resources*. Creating more resilient systems will become increasingly important in the face of climate change. As more intense weather events or dwindling water supplies stress the performance of the nation's water infrastructure, green infrastructure offers an approach to increase resiliency and adaptability.

For more information, visit *http://www.epa.gov/greeninfrastructure*

Acknowledgements

Principal USEPA Team
Jamie Piziali, USEPA
Christopher Kloss, USEPA
Eva Birk, ORISE, USEPA
Ken Hendrickson, USEPA Region 3

Community Team
John Stewart, Lafayette Wetlands Partnership
Lisa Renee Jennings, Friends of Norfolk Environment
Justin Shafer, City of Norfolk

Consultant Team
Jonathan Smith, Tetra Tech
Martina Frey, Tetra Tech
Christy Williams, Tetra Tech
Kelly Meadows, Tetra Tech
Bobby Tucker, Tetra Tech
Alex Porteous, Tetra Tech
Adam Orndorff, Tetra Tech

This report was developed under EPA Contract No. EP-C-11-009 as part of the 2014 EPA Green Infrastructure Technical Assistance Program.

Cover illustration by Tetra Tech.

Contents

Figures

Tables

1 Executive Summary

Green infrastructure design is an adaptable and multi-functional approach to stormwater management that includes an evolving list of practices which can be integrated into any community across the United States. Norfolk, Virginia, -- a highly-developed coastal Chesapeake Bay community with limited opportunity to treat stormwater runoff -- faces challenges to both mitigating stormwater pollution from existing urban areas, as well as long-term geologic subsidence and future sea level rise due to its geographic location. In an effort to address these challenges, a green infrastructure plan was developed for Norfolk's Knitting Mill Creek watershed. The plan incorporates green infrastructure practices into two locations: (1) a green street retrofit of three blocks at the intersection of a residential and commercial corridor and (2) a planned shoreline stabilization project with considerations for sea-level rise. Specific practices included roadside bioretention cells, permeable parking stalls/walkways, and an extensive bioswale system along the Knitting Mill Creek shoreline. Although the concept designs include practices that are typically adopted throughout the Bay region, this project highlights the adaptability of green infrastructure to a community's changing environmental conditions and provides a template for how these practices can be implemented throughout urban areas of the Chesapeake Bay shoreline.

The green street design is proposed for a single long residential block along 35th Street and two commercial blocks along Colley Avenue. Runoff from these areas currently collects in roadside gutters and is routed to a set of curb inlets at the western extent of 35th Street which are connected to the subsurface drainage network. As part of the green street retrofits, seven roadside bioretention planter boxes are proposed for the 35th Street block. Planter box areas for 35th Street will treat between 25% and 30% of a 1" rainfall event from their respective drainage areas. The Colley Avenue green street design includes five roadside planter boxes and four permeable concrete paver parking areas. Planter areas for Colley Avenue will treat between 69% and 85% of the 1" rainfall event. The concrete paver parking spaces will treat 100% of the 1" rainfall event from their respective drainage areas. The proposed green street retrofit for these two street areas will be hydraulically connected via underdrains and surface overflows, providing a "treatment-train" system to any area where centralized stormwater management is unfeasible due to space limitations.

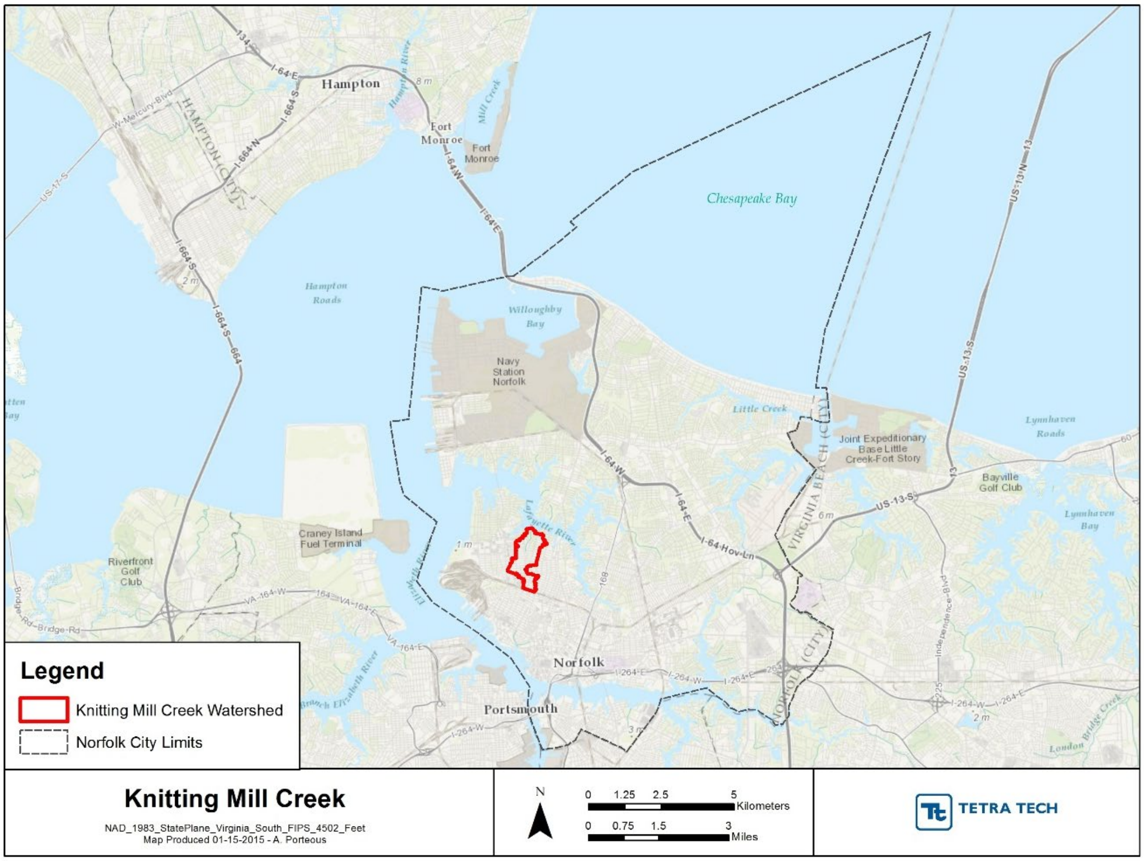
The shoreline stabilization project is located along Mayflower Road and borders Knitting Mill Creek. The concept design presents an approach for improving the long-term function of stormwater infrastructure within shoreline environments that are subject to tidal influences and a rising water table. In this case, a planned succession of an infiltration-based practice (e.g., bioswale) into a best management practice (BMP) type that *requires* a shallow water table (e.g., wetlands and wet ponds) was proposed. This transition can simply occur through manual vegetation replacement, or via a natural succession of plant species over time as subsurface conditions change.

2 Introduction

The City of Norfolk is located in the heart of the Hampton Roads metropolitan area, at the mouth of the Chesapeake Bay in southeast Virginia. Norfolk is home to the world's largest naval base, Naval Station Norfolk, along with the North American Headquarters for the North Atlantic Treaty Organization (NATO). The City is bordered on three sides by water: the Bay to the north and the Elizabeth River to the west and south. In addition, the Lafayette River flows through the City and separates the industrial and downtown southern portions of Norfolk from the Naval Station to the north. Overall, Norfolk contains 144 miles of freshwater and marine shoreline, including seven miles along the Bay. Much of this shoreline is located in residential neighborhoods.

Clearly, water is an important feature of Norfolk and to its estimated 246,139 residents (U.S. Census Bureau 2013) on a number of levels; protecting water resources is a critical task. To that end, the City adopted a general plan to guide decision making regarding physical development and public infrastructure (plaNorfolk2030) on March 26, 2014. One section of the plan focuses solely on promoting environmental sustainability and encourages "a sustainable environment that is not simply protected, but enhanced." The first key issue in this section is to ensure high quality natural resources that will enhance water quality in the City's waterways and reservoirs, including the Chesapeake Bay and its tributaries.

One such tributary, and the focus of this report, is Knitting Mill Creek, a small tidal creek within the City and a tributary to the Lafayette River. (See Figure 2-1.) Land use within the Knitting Mill Creek watershed is dominated by residential neighborhoods, with a commercial corridor along Colley Avenue that bisects the watershed along its north/south axis. Knitting Mill Creek is typical of the many creeks throughout Norfolk in that it is surrounded by a highly developed watershed of mostly residential land uses and it has a history of endemic water quality issues.



Source: Tetra Tech, Inc.

Figure 2-1. Knitting Mill Creek watershed and the surrounding waters

2.1 Water Quality Issues

Like many urban communities located along the Chesapeake Bay shoreline, Norfolk is impacted by water quality contaminants endemic to the Bay watershed. The City also has numerous water quality issues in its many creeks and rivers which originate within or flow through its own borders. For example, due to high levels of fecal coliform, shellfish areas within the entire Lafayette River and its tributaries have been condemned since the 1930's by the Virginia Department of Health (VDH), prohibiting the harvest of shellfish from the area for any purpose (VDH 2014). The Virginia Department of Environmental Quality (VA DEQ) has also listed certain segments of the river as impaired or not meeting the current surface water quality standards of the Commonwealth (VA DEQ 2014). VA DEQ's Final 2012 305(b)/303(d) Integrated Report included the following impairments in the Lafayette River:

- Aquatic life and open water aquatic life uses due to dissolved oxygen;
- Primary contact recreational use due to enterococcus;
- Shellfish condemnation due to fecal coliform bacteria; and
- Fish consumption due to PCBs in fish tissue.

Existing efforts toward improved water quality, however, are making a difference. A recent draft report from the DEQ recommends a partial delisting from the 305(b)/303(d) list, but VDH is awaiting PCB analysis before making a determination and possibly modifying the oyster moratorium.

The mixture of land uses within the Knitting Mill Creek Watershed creates a patchwork of impervious surfaces that limits natural infiltration of stormwater. (See Figure 2-2.) A large portion of stormwater runoff from the watershed is collected in a storm drainage system and discharged into the creek without treatment. Due to the creek's bathymetry and configuration relative to the river, contaminants are often retained in the creek. As a result, it is a source of algal blooms that eventually spread downstream into the Lafayette River. High levels of the bacteria *Escherichia coli* (E. coli) have also been observed throughout the creek, particularly at its head waters.

In addition, like most creeks within Norfolk, the Knitting Mill shoreline has been structurally modified throughout the City's history and does not represent original or natural conditions. Much of the shoreline has been armored with bulkheads and other hard engineering, a significant portion of which is deteriorating.

Finally, the City faces a relatively unique challenge in addressing water quality issues along shoreline neighborhoods such as Knitting Mill Creek; Norfolk is subject to both rising sea level and land subsidence. Scientists from the Virginia Institute of Marine Science (VIMS) warn that relative sea levels (the combination of rising water and sinking land) could rise by 1.5 feet in the next 20 to 50 years (VIMS 2013). Flooding has become an increasingly common occurrence for residents, businesses, and the naval base. According to FEMA, the City has a total of 12,360 flood insurance policies (FEMA 2012), the second highest in the state of Virginia.

Source: Tetra Tech, Inc.

Figure 2-2. Knitting Mill Creek watershed displaying the stormwater drainage system

2.2 Project Overview

The City of Norfolk has identified green infrastructure approaches to stormwater management as a way to address water quality in highly impervious areas such as the Knitting Mill Creek watershed. To prevent costly damage and a relocation of its residents, the City simultaneously seeks to become more resilient to the impacts of sea level rise and support wise choices in redevelopment efforts. As a result, any green infrastructure retrofits must consider both the short-term conditions (i.e., possible flooding, a high water table) and potential long-term changes in the hydrology (i.e., changes in sea level). To explore the potential for green infrastructure to support city resiliency goals and serve as a template for other waterfront neighborhoods, a green infrastructure plan for Knitting Mill Creek was developed.

This green infrastructure plan identifies, evaluates, and describes conceptual designs for green infrastructure retrofits that will protect and improve the water quality of Knitting Mill Creek. EPA and the community team selected green infrastructure techniques based on pollutant removal effectiveness, as well as the practices' ability to function effectively over time in an area with a high water table that is subject to impacts from sea level rise. Conceptual designs for selected retrofit opportunities have been developed to support the City's efforts to pursue further funding and approval for project implementation. EPA and the community team also educated residents of the Knitting Mill Creek watershed about how these green infrastructure practices can help mitigate water quality issues endemic to the project area and may be designed so that they are resilient to projected sea level rise.

2.3 Project Goals and Benefits

This plan establishes the foundation for a number of green infrastructure retrofit projects that can be further developed by the City and its partners to improve water quality in Knitting Mill Creek and to achieve water quality and community goals. This project also supports Principle Two of the City's *Central Hampton Boulevard Plan (2010)*: "Create safe, walkable and distinctive public realm." The projects described in this green infrastructure plan are also expected to attract business and residential development within the Knitting Mill Creek watershed through benefits which are ancillary to water quality improvements such as improved walkability, improved aesthetics, and pedestrian safety. In other words, restoring the Knitting Mill Creek shoreline and creating a healthy waterway will also improve neighborhood livability. The practices described in this plan are also intended to help make the City more resilient to the long-term challenges it faces with sea level rise and land subsidence.

2.4 Local Challenges

The biggest challenge is uncertainty regarding the extent to which sea level rise and land subsidence will impact the City in coming years. Norfolk has one of the highest frequencies of nuisance flooding in the country (NOAA 2014), which has forced the City to establish a vast array of both simple and complex solutions. The City has also undergone over a century of redevelopment, filling, and potential contamination of soils, which reduces the effectiveness of some practices within these disturbed areas by increasing subsurface compaction and creating unpredictable heterogeneity of soil profiles. Lastly, Knitting Mill Creek is a federally protected navigation channel, which limits the use of living shoreline applications as an alternative to the hardened shoreline that currently exists.

3 Green Infrastructure Opportunity Analysis

In order to begin the green infrastructure project selection and siting process, a desktop screening evaluation of the watershed using GIS data resources was conducted to identify potential green infrastructure retrofit opportunities. The evaluation identified potential retrofit locations (see Figure 3-1) with a specific focus on sites where the absence of buildings, utilities and other infrastructure, coupled with the presence of adjacent runoff-generating impervious surfaces, offered opportunities to capture stormwater using green infrastructure practices. The screening identified 27 locations for potential retrofits, including open space/parkland, residential streets, commercial streets, and storm sewer outfall locations.

On June 26, 2014, the project team conducted an extensive site evaluation of the watershed accompanied by several local stakeholders. The purpose of the visit was to gain insight on the unique features of the watershed, identify green infrastructure practice types suitable for consideration, and visually assess the feasibility of the 27 previously identified green infrastructure retrofit sites. Three additional sites not previously identified during the desktop screening were identified in the field and also assessed. A summary table of site observations and recommendations for these 30 sites is provided in Appendix A.

Source: Tetra Tech, Inc.

Figure 3-1. Potential green infrastructure retrofit locations identified by desktop screening

3.1 General Observations

The Knitting Mill Creek Watershed encompasses 340 acres in south-central Norfolk. The watershed is generally bounded by Old Dominion University to the west, 27th Street and the Norfolk Southern rail line to the south, Newport Avenue to the east, and the Lafayette River to the north. The dominant features of the watershed are the Knitting Mill Creek branch of the Lafayette River and the adjacent Colley Avenue commercial corridor (see Figure 2-2).

Given its location in the Atlantic Coastal Plain, the topography across the project area is quite flat with surface elevations ranging from 13 feet along the watershed headwaters to approximately 1 foot along the shoreline (mean sea level within the watershed is 1.3 ft.). Drainage of stormwater runoff from the watershed is primarily provided via network of storm sewers discharging directly into Knitting Mill Creek. One main system serves the majority of the watershed and discharges into the southern end of Knitting Mill Creek (Figure 3-2), while multiple smaller systems serve the areas adjacent to the creek primarily along the eastern shoreline. Along the western shoreline, where there are few drainage systems, runoff flows directly into the creek via surface flow.

Photo credit: Tetra Tech, Inc.

Figure 3-2. The majority of stormwater enters the southern end of Knitting Mill Creek near the intersection of Mayflower Road and 42nd Street

Historically, no green infrastructure practices (to reduce flooding or improve water quality) were incorporated into the Knitting Mill Creek stormwater drainage system. In recent years, however, the City and local citizen groups have implemented a number of pilot stormwater retrofit projects within the watershed. These have included a shoreline rain garden at 47th Street (see Figure 3-3), an urban stormwater wetland at 46th Street, and a stormwater rain garden at the Knitting Mill Creek Community Garden at Georgia Avenue and Mayflower Road. These pilot projects, although small in scale, have raised awareness with local residents that green infrastructure solutions can address water quality and quantity concerns and be incorporated into urban settings in a way that enhances community aesthetics.

Photo credit: Tetra Tech, Inc.

Figure 3-3. The rain garden at 47th Street enhances the community aesthetic

3.2 Colley Avenue Commercial Corridor

Colley Avenue runs parallel to Hampton Road and helps form the major north/south vehicular corridor that connects the Norfolk Naval Station with the southwest portions of the City. It is flanked along both sides by primarily light commercial uses and residential areas. The commercial businesses and restaurants are frequent destinations for the area residents throughout the watershed, as well as Old Dominion University students, faculty, and staff who walk or drive from the nearby campus. The Colley Avenue right-of-way (ROW) is approximately 60 feet wide and includes two travel lanes (one in each direction), double lanes or turn lanes at some intersections, side-street parking, and paved sidewalks. Vegetation along Colley Avenue is highly variable with sections exhibiting mature trees located in well-managed grass verges and other areas devoid of vegetation and a fully paved ROW (see Figure 3-4 for an example of the latter). This scenario, when coupled with the over-wide roadway cross section, provides an ideal configuration for incorporation of green street elements.

Photo credit: Tetra Tech, Inc.

Figure 3-4. Colley Avenue exhibits extensive paving and limited vegetation

A unique feature of Colley Avenue, relative to other streets within the watershed, is the relative lack of subsurface storm drainage infrastructure to collect and convey excess runoff. Based on observed site conditions, excessive runoff from the roadway and adjacent parcels sheet flows into the roadside gutter system and then is conveyed along surface grade into one of the east/west oriented cross streets before surface discharging to Knitting Mill Creek.

3.3 Mayflower Road and Shoreline

Mayflower Road is a two-lane residential road that parallels the entire eastern shoreline of Knitting Mill Creek. The eastern shoreline runs immediately adjacent to Mayflower Road, in contrast to the western shoreline that adjoins many private residences and businesses and is separated from public infrastructure. Along the northern section of Mayflower Road, the shoreline is well protected by a solid concrete bulkhead of recent construction. Along the southern section, the shoreline exhibits ad-hoc armoring consisting of concrete debris, an aging/failing brick wall, and what appears to be irregularly placed concrete washouts. The southern section of the shoreline is slated to be armored in the coming year with a federally funded shoreline armoring/living shoreline project. The living shoreline component will consist of a shallow offshore stone breakwater, creating a near-shore shallow area for establishment of native shoreline vegetation (see Figure 3-5).

Photo credit: Tetra Tech, Inc.

Figure 3-5. Knitting Mill Creek's shoreline is slated to be armored with a living shoreline; the concrete bulkhead is visible in the background

Vegetation along the shoreline is variable. Several large live oaks are located near the southern terminus of the shoreline, along with intermittent shrubbery. Throughout the length of Mayflower Road, the open area between the roadway and the shoreline is covered in poorly established grass. There are several areas devoid of ground cover, likely due to either foot traffic or soil characteristics insufficient for plant growth. One specific characteristic of this area (noted by local stakeholders) is the regular encroachment by the creek's surface waters during "Nor'easter" storm events. In these storms, wind-driven tides push water along the shore due to its north/south orientation and long fetch north into the Lafayette River. These conditions, though infrequent, create unique challenges for managing stormwater in this area, and will influence the selection of green infrastructure techniques and plant species.

3.4 Residential Neighborhoods

Houses within the residential area date to the early 20th century and consist of single family homes on ¼- to ½-acre lots. Typical of this time period and configuration of construction, there are widespread indicators that residential rooftops historically were directly connected to the street drainage network (see Figure 3-6). However, field observations revealed that most if not all of these rooftop connections had either been disconnected or have clogged with soil and debris, rendering them non-functional. Disconnection of rooftops and other isolated impervious areas is often considered a low-cost, high-return green infrastructure retrofit, as long as the roof runoff can be directed across a well-vegetated area and not endanger structural foundations. Although there were no observed candidates for rooftop disconnection or other widespread green infrastructure practices appropriate for individual lots, local residents should be encouraged to participate in the *River Star Homes* program, a partnership between the Elizabeth River Project and City of Norfolk to encourage residential practices which improve and protect water quality.

Photo credit: Tetra Tech, Inc.

Figure 3-6. Directly connected residential roof drains appear to have been disconnected or are otherwise clogged

The street network throughout the watershed (including residential areas) is laid out in a grid pattern. Within the street rights of way, residential streets are characterized by two-way vehicular travel, side-street parking, a vegetated fringe, and sidewalks on both sides of the road. (See Figure 3-7.) While mature trees or ornamental shrubbery are located within the fringe in most areas, portions of many streets are devoid of any vegetation within the fringe areas except grass or other low-growing ornamentals. These characteristics make the residential streets throughout the Knitting Mill Creek watershed candidates for incorporating green street concepts such as permeable pavement or side street bioretention elements, which are both described in the Stormwater Toolbox (Section 4 below). Additional opportunities for green infrastructure implementation occur at the small outfalls and areas where stormwater sheet flows directly into Knitting Mill Creek.

Photo credit: Tetra Tech, Inc.

Figure 3-7. Residential streets in Colonial Place are often characterized by a wide grassed verge between the road curb and sidewalk

3.5 Soil Conditions

Soil classifications within the project area vary between Tomotley-Urban land complex (0 to 2% slopes) and Urban Land based on the USDA Soil Survey (SSURGO). These classifications are considered poorly drained with Hydrologic Soil Group (HSG) values of "D."[1] Tomotley soils have a dark gray, fine sandy loam surface layer. Subsurface layers include a gray fine sandy loam (4–15 inches), and a gray sandy clay loam (15–58 inches), as reported in the most recent soil survey (NRCS 2009). Local stakeholders indicated that observed surface permeability was somewhat variable, possibly due to extensive dredging and fill operations during development of the waterfront. It is believed that much of the shoreline along Knitting Mill Creek resulted from filling of the historic shallow shoreline with material left over from development activities on upland areas.

[1] For guidance on designing GI practices within heavy clay soils, refer to the EPA document "Soil Constraints and Low Impact Development – Careful Planning Helps LID work in Clay Soils" (*http://water.epa.gov/polwaste/green/upload/bbfs8clay.pdf*)

4 Design Approach

4.1 Stormwater Toolbox

Green infrastructure practices and approaches were pioneered in the mid-Atlantic region beginning in the 1990s as a strategy for restoring water quality within the Chesapeake Bay's highly developed watershed. As result, the City of Norfolk has a well-developed toolbox of stormwater best management practices that have been implemented within similar climate, soil, and site conditions, either as retrofit situations or during new construction. Since green street retrofits were identified as part of the Knitting Mill Creek project, this section focuses on urban bioretention practices and permeable pavement.

4.1.1 Bioretention

Bioretention is a practice that employs a depressed vegetated area underlain by a shallow layer of soil media suitable for plant growth and through which accumulated stormwater can filter. The filtering of the stormwater results in removal of pollutant constituents. In areas of restrictive underlying soils, bioretention requires the use of structural underdrains routed to a drainage network to prevent long-term saturation of the bioretention bottom and potential issues with plant growth. Bioretention is already in use in the Knitting Mill Creek watershed; see Figure 4-1.

Photo credit: Tetra Tech, Inc.

Figure 4-1. Bioretention located at the Knitting Mill Creek Community Garden

While bioretention has seen widespread application in parking medians and larger public open spaces, the practice is also being increasingly adapted to urban rights-of-way as a component of green street design (Figure 4-2). Regardless of where in the urban environment bioretention is implemented, the selection of vegetation type and density must consider site-specific conditions. For example, in areas of heavy pedestrian use, the potential for occasional foot traffic may warrant selection of vegetation that serves as a barrier or is hardy to compaction. Likewise, areas near brackish waters may require plants suitable for such conditions.

Photo credit: Tetra Tech, Inc.

Figure 4-2. Example of bioretention integrated within a right of way vegetated fringe in Toledo, OH

4.1.2 Permeable Pavement

Permeable pavement refers to pavement systems that incorporate a permeable paving surface (typically paver block, pervious asphalt, pervious concrete) that allows rainfall to infiltrate into the pavement system, then into an open graded storage/structural layer beneath the pavement, and ultimately into the subgrade. Because of the structural requirements (i.e., being subject to vehicular loading), permeable pavement must be designed to meet both hydrologic and structural criteria. In general, permeable pavement systems are best located on low-traffic surfaces such as sidewalks, parking stalls, and lightly used driveways. See Figure 4-3 for an example of permeable pavement. Selecting the most appropriate permeable pavement surface type depends on aesthetics, structural loading and implementation costs. While each surface type has similar hydrologic characteristics, the performance of each type can vary depending on the storage/structural layer and underlying soils that support it.

Photo credit: Tetra Tech, Inc.

Figure 4-3. Example permeable paver side-street parking in Garden City, ID

4.2 Stormwater Design and Performance Standards

Design guidance for the proposed green infrastructure retrofits in the Knitting Mill Creek watershed was primarily based on guidance from the VA DEQ Stormwater Design Specifications retrieved from the Virginia Stormwater BMP Clearinghouse. For stormwater curb extensions, Appendix 9-A (Urban Bioretention) of the VA DEQ Design Specification No. 9 was used for conceptual design and sizing. VA DEQ Design Specification No. 7 was referenced for permeable pavement sizing. Note that the conceptual-level permeable pavement sizing was only performed relative to hydraulic requirements. A structural analysis for anticipated traffic loads will eventually need to be conducted as part of a more detailed design.

There are a number of Norfolk-specific guidelines and design standards that may be applicable elsewhere. Chapter 6 of the City's *Stormwater Design and Construction Manual* (City of Norfolk 2014) addresses projects implemented to "improve the quality of runoff leaving an existing developed site or from upstream developed areas and not designed to treat stormwater runoff from new land development or redevelopment." The manual encourages designers to use the design standards of the *Virginia Stormwater BMP Clearinghouse* web site (Virginia DCR 2009) to the extent practicable.

The *Norfolk Stormwater Design and Construction Manual* specifies several modifications to the BMPs described in the *Virginia BMP Clearinghouse Manual*. For bioretention (including urban bioretention[2]), these modifications include the following:

> *a. Table 9.3*
>
> > *i. Subsoil Testing – Level 2 Design Criteria shall be utilized*
> >
> > *ii. Underdrain – Level 2 Design shall incorporate an underdrain*
>
> *b. Section 6.2 (pg. 18 of 54) – Notwithstanding the following sentence: "Soil testing is not needed for Level 1 bioretention areas where an underdrain is used." All infiltration and bioretention practices in the City of Norfolk must include site specific infiltration testing at the proposed location of the practice.*
>
> *c. Section 6.7 (pg. 25 of 54)- Notwithstanding the following sentence: "Some Level 2 designs will not use an underdrain (where soil infiltration rates meet minimum standards; see Section 6.2 and Section 6.3 design tables)." all bioretention and infiltration practices proposed in the City of Norfolk must include an appropriately sized underdrain.*

Construction of water quality retrofits is also subject to other standards regarding land-disturbing activities in the City of Norfolk such as those in the *City of Norfolk Design and Specification Manual* (City of Norfolk 2014) and Section 1 of the Hampton Roads Planning District Commission (HRPDC) report *Land and Water Quality in Hampton Roads, Phase II* (HRPDC 2013). The HRPDC report provides design modifications for, and exemptions from, the VA DEQ design specifications that apply to the City of Norfolk for stormwater management practices implemented within Virginia's Coastal Plain. Table 4-1 and Table 4-2 show the Coastal Plain design modifications that apply to bioretention and permeable pavement, respectively.

[2] The City of Norfolk does not specify design modifications for permeable pavement.

Table 4-1. HRPDC design modifications for coastal plain bioretention practices

Design Limitation	Coastal Plain Modifications
Maintain a minimum underdrain slope of .5% and tie into a ditch or conveyance system.	Utilize linear approach of multiple storage cells to conserve hydraulic head.
Minimum depth of filter bed is 18 inches for Level 1 and 24 inches for Level 2.	Underdrains should be connected to the stormwater drainage system.
Obtain media from an approved vendor to ensure nutrient content of the soil and compost is within acceptable limits.	Depth to groundwater can be reduced to 1 foot if a large diameter (6 inches) underdrain is utilized.
Avoid using on-site soils in the coastal plain, unless soil tests show low nutrient concentrations.	Limit surface ponding to 6 to 9 inches.
Select plant species that reflect coastal plain plant communities and are wet-footed and salt-tolerant.	Designers can utilize a turf cover rather than mulch for shallower facilities, but they should follow the design specifications and pollutant removal values for dry swales.

Table 4-2. HRPDC design modifications for coastal plain permeable pavement

Design Limitation	Coastal Plain Modifications
Vertical separation from bottom of system to water table = 2 feet.	Avoid using permeable pavement if the site is near sandy soils to minimize clogging.
Maintain a minimum slope of 0.5% for underdrains to ensure proper drainage.	

The design and sizing objective for all green infrastructure practices was to capture and treat the calculated water quality volume for a 1” rainfall event using the Runoff Reduction Method which is applicable statewide. The central component of the Runoff Reduction Method is treatment volume (Tv), which is calculated by multiplying Virginia’s “water quality” rainfall depth (P = 1”) by the three site cover runoff coefficients (forest, disturbed soils, and impervious cover) present within each site’s drainage area.

Note that with most urban green infrastructure retrofit projects, existing site constraints yield BMPs that often are undersized based on local water quality treatment volume targets. However, even undersized linear treatment systems can provide cost-effective solutions for mitigating runoff volumes and pollutant loads.

4.3 Community Involvement in Green Infrastructure

The restoration of waterways and protection of water quality frequently rely heavily on cooperation among various stakeholders in a community, and these partnerships are strong in the Knitting Mill watershed. For example, in Norfolk, more than 33 wetland restoration projects throughout the City have been completed with assistance from various community partners such as the Lafayette Wetlands Partnership and the Elizabeth River Project. In 2011, the Elizabeth River Project partnered with the Chesapeake Bay Foundation and created *The Plan for Restoring the Lafayette River: Strategies for Community Wide Actio*n. This plan sets out three goals: reduce harmful bacteria to levels that are safe for swimming; achieve healthy, plentiful wildlife in the river; and encourage river stewardship in the community through public awareness and action.

In previous projects throughout the Knitting Mill Creek watershed, public participation has likewise been extensive. Citizens in the Colonial Place and Highland Park neighborhoods have participated in water quality monitoring programs, conducted regular shoreline and inland clean-ups, volunteered to do "Adopt-a-Spot" monitoring of selected shoreline locations, supported City-operated street sweeping programs with education and encouragement for residents, and participated in urban wetland restoration projects along the creek. This project aims to include appropriate approaches suggested by the watershed's residents and seek the support of the public concerning the final design of these practices.

4.3.1 Community Workshop

On June 26, 2014, the project team took advantage of stakeholder resources in the watershed and conducted a green infrastructure workshop and public meeting at the Ernie Morgan Center in Norfolk. The purpose of the workshop and public meeting was to inform stakeholders within the Knitting Mill Creek watershed about the benefits of green infrastructure stormwater practices and obtain valuable initial feedback on preferences for retrofit opportunities and configurations within the community. Attendees included City staff, representatives from various non-profit organizations with an interest in protecting Knitting Mill Creek, and local neighborhood representatives of the Colonial Place, Highland Park, Riverview, and Park Place neighborhoods. The project team presented various benefits that green infrastructure could provide to the community with regard to water quality protection, resilience to sea level rise, and quality of life. The project team presented potential green infrastructure retrofit locations within the Knitting Mill Creek watershed and implications of sea level rise on green infrastructure function and resiliency. Attendees provided valuable feedback, which was utilized during the selection of projects and the development of conceptual designs.

4.4 Project Selection

Following the field investigations and public meeting, the project team discussed opportunities for green infrastructure retrofits for the purpose of development of conceptual designs. Two locations within the Knitting Mill Creek Watershed were selected for green infrastructure retrofits (Figure 4-4).

Source: Tetra Tech, Inc.

Figure 4-4. Watershed area treated by the selected green infrastructure retrofit projects

The project team proposes a green street concept design for the blocks north, south, and west of the 35th Street/Colley Avenue intersection. The BMP retrofits include permeable pavement within the parking lanes on Colley Avenue and bioretention curb extensions sited throughout the project area where allowed by roadway access and utility conflicts within the right of way. The selection of green street practices was informed primarily by the project goals for the site, which include hydrologic and water quality enhancement, improved aesthetics, and improved access for pedestrian and bicycle transportation.

A second project area consists of the Mayflower Road shoreline from the southern extent of Knitting Mill Creek north to the mouth of Knitting Mill Creek near the intersection of Mayflower Road and New Hampshire Avenue. The southern portion of this concept is proposed to be implemented in conjunction with the proposed shoreline restoration. This green infrastructure concept includes a stormwater treatment system that can be installed between the existing edge of curb and the proposed shoreline armoring/living shoreline. Due to the shallow water table, soil conditions, and projected sea level rise, a modified wet swale/bioretention practice was configured to allow for functions and geometries that can be adapted as sea levels rise over the next few decades. (Note that adapting stormwater management practices and design standards to account for impacts from climate change over the next decades is a new but growing practice, especially in coastal communities.) Furthermore, a permeable pavement sidewalk is proposed to parallel the shoreline to alleviate pedestrian compaction, which was observed as one cause of poor vegetative cover. The northern portion of the concept design will extend the permeable sidewalk and associated shoreline buffer north of the shoreline armoring/living shoreline project to the mouth of Knitting Mill Creek. In addition to improved water quality, the selection of the Mayflower Road project also strives to improve an important and highly visible public amenity and serve as a demonstration for how green infrastructure can be designed to be resilient to sea level rise.

5 Conceptual Design

Conceptual designs were developed for the two selected green infrastructure retrofit locations using appropriate local or regional design methodologies adapted to local site conditions.

5.1 35th Street and Colley Avenue Green Street

Existing ROW widths and roadway configurations strongly influence the specific design geometries for green street retrofit practices. The ROW width for the 35th Street block is approximately 64–65’ with a curb-to-curb width of 50’. Existing sidewalks are approximately 4–5’ wide with a 2’ landscape strip adjacent to the curb. Currently, both sides of the road are used for parallel parking, leaving two excessively wide travel lanes.

A 7-foot wide bioretention cell is proposed for each curb extension on the 35th Street block. The curb extensions, which are designed to help calm traffic and ease transitions into the parking stalls and driveway accesses, also include a 6”-wide roadside curb, a 6” concrete edge along the sidewalk, a 40 sq. ft. cobble energy dissipation pad on the up-gradient end, a raised landscape strip on the down-gradient end, and two curb cuts (one inlet and one overflow outlet). The bioretention component contains a 3” top layer of triple-shredded hardwood mulch, 2 feet of soil media, a 2” choker layer of ASTM C33 washed sand, and a 12” drainage layer of washed #57 stone surrounding a perforated PVC underdrain. The curb extensions vary in length from 26’ to 46’ (measured from the end of each curb transition location).

Since part of the bioretention cell will be constructed within the existing landscape strip to minimize impacts to parking and travel lanes, the green street retrofit for 35th Street would yield a minimum curb-to-curb width of 40’. As a result, future roadway modifications could accommodate dual bicycle lanes (each 5’-wide) and either (2) 10’-wide travel lanes with a center turn lane, or two 15’+ travel lanes. Of the estimated 32 available parking spaces currently located along 35th Street block, implementation of the proposed curb extensions would reduce the existing roadside parking by approximately 14 spaces.

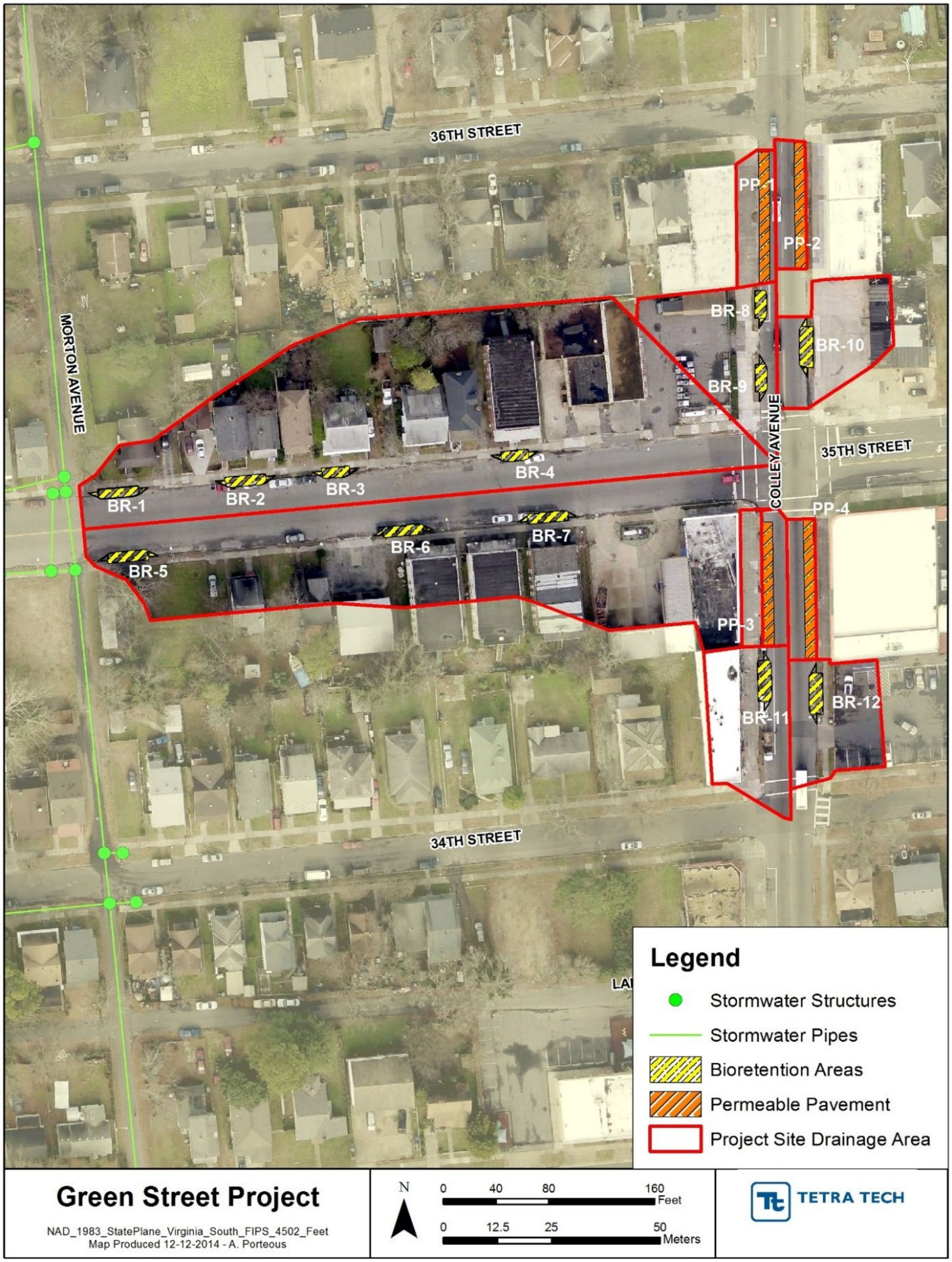
The existing ROW width along the Colley Avenue corridor varies, but is typically 58’ wide between 34th and 36th Streets. For the block north of 35th Street, curb-to-curb width is typically 36’ while the block south of the 35th Street is 40’ wide. Other variations along the corridor include the extent and width of landscape strips, building frontage setbacks, and sidewalk widths. Based on the Commercial Street template from the Downtown Norfolk Street Plan (City of Norfolk 2009), 10’-wide travel lanes and 8’-wide parking stalls are appropriate dimensions for both sides of Colley Avenue. These general dimensions are reasonable for the north Colley Avenue block and allow for two 12’-wide travel lanes along the south block.

The proposed Colley Avenue green street design includes four separate permeable interlocking concrete paver parking lanes installed along the north side of each block wherever there are no access driveways. Interlocking concrete pavers were selected as the preferred pavement surface during field investigations. Each 8’- wide concrete paver section will be approximately 100’ long and contain both a washed stone bedding and a reservoir layer below the concrete paver course. The concrete paver system will also contain an underdrain within the reservoir layer and a raised concrete curb edge on the sidewalk to prevent non-roadway runoff from draining onto the parking lane. Several bioretention curb extensions were also sited around the roadway entrances along the southern half of each Colley Avenue block. The curb extensions are similar in geometry and configuration to the ones proposed on 35th Street, except the bioretention cell widths are increased up to 9.5’ to maximize footprint area due to the wider sidewalk and landscape strip dimension on Colley Avenue. Before and after representations of Colley Avenue are shown in Figure 5-1 and a detailed concept design is provided in Appendix B.

Source: Tetra Tech, Inc.

Figure 5-1. Before and after images of Colley Avenue green street design

Figure 5-2 shows the drainage areas for the proposed green retrofits in the 35th Street/Colley Avenue project area. For the 35th Street block, drainage areas were delineated for the entire block using the roadway centerline for subdivision. The bioretention cells, which were maximized based on available area, will treat runoff from each drainage area by allowing untreated overflow bypass from the highest curb extension to drain to the next down-gradient cell, and so on. An underdrain will connect all the curb extensions on each side of the road before connecting to the existing catch basins at Morton Avenue. Drainage areas for the Colley Avenue corridor were delineated for each separate BMP practice. Raised curb edges along the permeable concrete paver parking lanes will limit the drainage area ratios to 2:1 or below, per VA BMP specifications.



Source: Tetra Tech, Inc.

Figure 5-2. Drainage areas for proposed Colley Avenue/35th Street retrofits

Table 5-1 provides the drainage area properties and the water quality treatment volume (Tv) calculated for each catchment.

Table 5-1. Drainage area and runoff volumes for Colley Avenue/35th Street green street retrofits

Attribute	BR #1-4	BR# 5-7	BR# 8-9	BR# 10	BR# 11	BR# 12	PP# 1	PP# 2	PP# 3	PP# 4
DA (ac)	1.25	0.99	0.19	0.15	0.16	0.14	0.07	0.05	0.05	0.05
Imperv. (%)	85	80	100	100	100	98	100	100	100	100
Tv (cf)	3843	2900	650	509	557	468	231	176	156	179

a. Estimate from aerial photography
b. Treatment volume calculated using Runoff Reduction Method

Table 5-2 displays the design parameters for the proposed bioretention curb extensions on 35th Street. The total storage depth includes both the 6" surface ponding and the instantaneous void storage within the soil media underdrain layer. BMP footprint areas represent the cumulative surface areas of all the curb extensions within each drainage area. As shown, the undersized retrofits provide a range of treatable volumes between 25% and 85% of the calculated 1" water quality volume from their respective drainage areas.

Table 5-2. Design parameters for 35th Street bioretention curb extensions

Parameter	BR #1-4	BR# 5-7	BR# 8-9	BR# 10	BR #11	BR #12
Total storage depth[1] (ft)	1.4	1.4	1.4	1.4	1.4	1.4
Required footprint (s.f.)	2745	2071	464	363	557	466
Design footprint (s.f.)	700	630	320	284	284	284
Percent of T_v treated (%)	25	30	69	78	71	85

[1] Includes surface ponding and storage in media voids; V_r-soil = 0.25; V_r-gravel = 0.4

Given the adherence to the permeable pavement's drainage area/surface area maximum design ratio, the permeable concrete paver parking lanes were adequately sized to capture their targeted treatment volume. As previously mentioned, the concrete paver system was only designed based on hydraulic loading. Although advanced design will need to account for traffic loading per the guidance provided in VA DEQ Design Specification No. 7, the gravel reservoir depths proposed for the Colley Avenue design will certainly help provide additional structural integrity along this commercial corridor.

Hydraulic design is performed to ensure adequate storage of the water quality treatment volume within the reservoir layer. The depth of the reservoir layer (d_p) is calculated using the following equation, which assumes outflow through the underdrain (and not through the underlying soil):

$$d_p = \frac{\left\{(d_c \times R) + P - \left(\frac{i}{2} \times t_f\right) - \left(q_u \times t_f\right)\right\}}{V_r}$$

The assumed input parameters for the permeable concrete paver design are shown in Table 5-3.

Table 5-3. Design assumptions for permeable concrete paver reservoir depth calculation

Parameter	Design Value	Unit
Depth of runoff (d_c)	1.0	inch
Infiltration rate (i)	1	ft/day
Void ratio (V_r)	0.4	n/a
Fill time (T_f)	0.083	day
Drain time (T_d)	1.5	day
Reservoir hydr. conductivity (k)	100	ft/day
Underdrain slope (m)	0.005	ft/ft
Underdrain flow (q_u)	0.5	ft/day

The maximum allowable depth of the reservoir layer ($d_{p\text{-}max}$) is constrained by the maximum allowable Drain time, and is calculated by the following:

$$d_{p-max} = \frac{\left\{\left(\frac{i}{2} \times t_f\right) - (q_u \times t_d)\right\}}{V_r}$$

The final design parameters for the Colley Avenue permeable parking lanes are shown in Table 5-4.

Table 5-4. Design parameters for permeable concrete parking lanes

Parameter	PP #1	PP #2	PP #3	PP #4
Direct drainage area (DA) (sf)	2127	1458	1218	1438
Concrete paver footprint area (PA) (sf)	790	761	750	827
DA/PA Ratio	1.7	0.9	0.6	1.7
Reservoir depth, d_p (ft)	2.6	2.5	2.4	2.6
Max depth, $d_{p\text{-}max}$ (ft)	3.8	3.8	3.8	3.8

Through the incorporation of streetside bioretention and permeable pavement parking lanes within the Colley Avenue and 35th Street ROW corridors, the City of Norfolk can reduce the volume of stormwater discharged to Knitting Mill Creek from the project area by encouraging infiltration into subsurface soils. Additional pollutant removal will be accomplished for that portion of runoff which exceeds the capacity of underlying soils and is discharged through underdrains connected to the existing sewer system. Other benefits of the green street conceptual design include a reduction of impervious surface, modest reduction of peak flow rates, improved street aesthetics, and a more inviting pedestrian connection between residential neighborhoods and commercial areas. The green street concept design detailed above can also serve as a template for the integration of roadway green infrastructure practices both within the Colley Avenue commercial corridor and elsewhere in the Knitting Mill Creek watershed.

5.2 Mayflower Road and Shoreline

The Mayflower Road project area highlights today's challenges with implementing green infrastructure within coastal plain and shoreline environments. The area comprising the 4200-4600 blocks of Mayflower Road was designated for retrofit with a series of bioswales installed between the roadway and the planned bulkhead/shoreline protection revetment on Knitting Mill Creek. In addition, a riparian buffer and pervious walkway will be installed along the shoreline throughout the entire 2400 ft. eastern shore of Knitting Mill Creek, including areas north of the section proposed for bioswale retrofit, which are not suitable for incorporation of bioswales due to the presence of a recently constructed concrete bulkhead and less suitable topographic conditions. Although the section of Mayflower Road suitable for bioswale implementation extends for 1,250 feet, only 500 linear feet of bioswale is required to treat the contributing roadway in accordance with the selected design criteria. As a result, final configuration of the bioswales and the alignment of the pervious walkway can be adjusted to accommodate existing and future landscape and infrastructure elements such as the live oak trees at the southern end of the project. Curb cuts installed directly upslope of the existing catch basins will allow runoff from the western half of Mayflower Road to enter the bioswale system, which will treat an 80% impervious drainage area that is approximately 28,000 sq. ft. A small embankment with buffer planting will be constructed between the bioswale and the shoreline to ensure that peak flood volumes overflow onto Mayflower Road and discharge through the existing catch basins. Pedestrian access paths, sited at all the existing culvert crossings, will hydraulically separate each bioswale and provide convenient locations for the underdrains to connect into the drainage network.

Hydraulic restrictions due to shallow gradients between the roadway and the mean high water elevation limit the depth of the bioswales and their media layer. As specified in the design guidance provided by the HRPDC for bioretention systems installed in the Coastal Plain, the depth to ground water can be reduced to 1 foot if a 6" diameter underdrain is utilized. Therefore, the minimum elevation of the bioswale underdrain is approximately 2.3' Mean Sea Level (MSL) along the project reach. Existing catch basin rim elevations along the west side of Mayflower Road vary between 4.4' and 5.9' MSL. Assuming a 6" ponding depth and an 8" gravel underdrain layer, the bioretention media depths will range from 1.0' to 2.4', depending on adjacent curb elevation. Due to the shallow media depths, a sodded turf grass is proposed for the internal side slopes to limit rooting depth and potential underdrain clogging. Several varieties of turf grass perform well in bioretention cells (provided they adequately drain between storm events), including bermuda varieties. Before and after representations of the Mayflower Road project area are shown in Figure 5-3 and a detailed concept design is provided in Appendix C.

Source: Tetra Tech, Inc.

Figure 5-3. Before and after representations of Mayflower Road green infrastructure design

Table 5-5 shows the conceptual design parameters for the bioswale system. The footprint area required to treat the water quality runoff volume is based on a minimum media depth of 1.0’, although actual footprint areas could be decreased to account for additional storage volume provided in the deeper bioswale sections. Note that the required bioswale area also accounts for ponding volume within the 3:1 side slopes.

Table 5-5. Drainage area and design parameters for Mayflower Road bioswales

Attribute	Value
Drainage area (ac)	0.65
Imperv. (%)	80
Tv (cf)	1898
Req'd bioswale footprint area (s.f.)[1]	1502
Design width (ft)	3.0
Minimum design length (ft)	500

[1] Includes 6" surface ponding and void storage in 1' of media (Vr = 0.25) and 8" gravel (Vr = 0.4)

Extra consideration was given to account for forecasted sea level rise. Under this future conditions scenario, the bioswale system will eventually function as a seasonal, subsurface wetland since drainage through the underdrain will be hindered during parts of the year. Although these anaerobic conditions may provide additional nitrogen removal through de-nitrification processes, the raised water table may continually decrease infiltration rates, limiting the initial plant selection to those unaffected by shallow water tables (including shallow-rooted turf grass). Regardless, observation and feedback in plant response will be necessary to manage the continuum in bioswale function and supported plant species as conditions evolve (e.g., raised water table, higher salinity levels, more frequent surface ponding, lower infiltration rates, etc.). In the case that deleterious conditions hinder the survival of turf grass, the internal bioswale zones can be replanted (or even over-seeded) with an advanced succession of native herbaceous species that are better adapted to the altered in-situ conditions.

Table 5-6 provides a brief list of suggested plant species for the bioswale that are native to eastern Virginia. These species were selected for their medium (M) or high (H) tolerance to salinity, and their adaptability to a wide range of moisture requirements (Dry, Moist, or Wet). The plant selections were limited to grasses, lower-growing perennials, and shrubs due to the limited bioswale dimensions and potential water table rise. In addition to changing environmental factors, the flexibility in plant species and ground cover type within the bioswale provide options depending on the community's desired aesthetics and maintenance needs.

Table 5-6 Suggested Bioswale plant species

Species	Salinity	Moisture	Comments
Red fescue (*Festuca rubra*)	M	D/M/W	Cool-season turf grass
Big Bluestem (*Andropogon girardii*)	M	D/M/W	Warm-season bunchgrass; H 36"- 72"
Switch grass (*Panicum virgatum*)	M	D/M/W	Warm-season clump grass; H 36"- 60"
Indian grass (*Sorghastrum nutans*)	M	D/M	Tall clump grass; H 30"- 72"
Talus slope penstemon (*Penstemon digitalis*)	M	D/M	Clumping, drought-tolerant; H 24"- 48"
Inkberry holly (*Illex glabra*)	M	M	Tolerates occasional flooding; H 6'- 8'
High-tide bark (*Iva frutescens*)	H	M/D	Grows in brackish/salt marshes; H 4'– 10'
Highbush blueberry (*Vaccinium corymbosum*)	H	D/M/W	Edible, shallow-rooted; H 6'- 12'

The Mayflower Road green infrastructure concept design incorporates an adapted bioswale in a setting that falls outside of the standard design criteria (due to a shallow water table). By modifying the bioswale geometries to both fit the existing condition and retain functionality in projected future conditions, the concept design serves to ensure that this infrastructure improvement is resilient to potential sea level rise. The use of a permeable pavement walkway[3] serves to protect vegetative fringe around the bioswale and along the shoreline, as well as provide an inviting recreational trail for residents. The integration of both of these practices with a planned living shoreline project provides an example of how green infrastructure practices can be implemented in communities subject to sea level rise in a manner that is both resilient and adaptive.

5.3 Cost Estimate

Planning-level cost estimates were prepared for each the proposed Knitting Mill Creek green infrastructure retrofits. Unit costs were developed using RSMeans Construction Cost Data (2014) specific to Norfolk, supplemented with engineer's estimates (based on comparable bid summaries) where available. A summary of implementation costs for the three green infrastructure projects is provided in Table 5-7 and detailed planning-level costs for each scenario are provided in Appendix D.

Table 5-7. Summary of planning-level implementation costs

Scenario	Implementation Costs
35th Street	$92,215
Colley Avenue	$182,255
Mayflower Road Shoreline	$90,674

[3] Note that the use of permeable pavement for the walkway surface is optional, and may be replaced with bituminous asphalt or conventional concrete as a cost saving measure with limited impact on stormwater management function.

6 Conclusion

Norfolk, like many communities along the Chesapeake Bay shoreline, faces a significant challenge in addressing stormwater pollutant contributions to the Bay from existing urban areas. In the extensive residential neighborhoods that border the City's shores, stormwater runoff often discharges directly into the Bay system without treatment. The extensive development along the shoreline limits opportunities to implement stormwater treatment systems at the outfall. Given its coastal setting and location in an area of long-term geologic subsidence, the City is further challenged with high rates of future sea level rise which could endanger existing and new infrastructure.

In recent years, green infrastructure practices have been identified as part of a suite of solutions that can address long-term pollutant issues within the Chesapeake Bay. These practices, including those proposed in the conceptual designs for Knitting Mill Creek, have been successfully implemented throughout the Bay watershed. Design criteria for these practices, however, typically recommend deep groundwater levels that may not exist in certain coastal settings. Furthermore, in areas where significant sea level rise is projected, stormwater infrastructure along the shoreline may experience a shorter functional lifespan or provide reduced level of service due to encroaching waters. One possible solution to this challenge, as presented in the Mayflower Road concept design, is to account for the planned succession of infiltration-based practices into BMP types that *require* shallow water tables (i.e., wetlands and wet ponds). In most cases, this transition simply occurs through manual vegetation replacement or via a natural succession of plant species over time as subsurface conditions change.

The green infrastructure concept designs developed for the Knitting Mill Creek watershed are typical of practices being adopted throughout the Bay. The Colley Avenue/35th Street green street concept design provides a template for implementing green infrastructure in the rights of way throughout Knitting Mill Creek, as well as in other streets elsewhere in Norfolk and in other shoreline communities in the region. The Mayflower Road concept design serves as an example of how standard green infrastructure practice criteria, in this case for bioswales and permeable pavement, can be adapted to the shoreline environment in a way that is resilient to future sea level rise.

7 References

City of Norfolk. 2009. Downtown Norfolk Pattern Book: Architectural Guidelines for Place Making. Accessed November 11, 2014. *http://www.norfolk.gov/DocumentCenter/View/1634.*

City of Norfolk. 2014. Norfolk Stormwater Design and Construction Manual. July 2014. Department of Public Works – Operations Division.

City of Norfolk Department of Public Works. 2014. *Norfolk City Design Standards*. NCDS2014.06

Federal Emergency Management Agency (FEMA). 2012. Flood Insurance Policies and Community Rating System Participation: State of Virginia. May 2012.

Hampton Roads Planning District Commission (HRPDC). 2013. *Land and Water Quality in Hampton Roads, Phase II*. November 2013.

National Oceanic and Atmospheric Administration (NOAA). 2014. Sea Level Rise and Nuisance Flood Frequency Changes around the United States. NOAA Technical Report NOS CO-OPS 073. June 2014. *http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf*.

Natural Resources Conservation Service (NRCS). 2009. Soil Survey of Tidewater Cities Area, Virginia. USDA.

RSMeans. 2014. Version 5.1.1. Accessed December 23, 2014. *http://rsmeansonline.com/.*

United States Census Bureau. 2013. State and County QuickFacts: Norfolk city, Virginia. Accessed January 16, 2015. *http://quickfacts.census.gov/qfd/states/51/51710.html*.

United States Department of Agriculture (USDA). 2014. Web Soil Survey. Accessed December 18, 2014. *http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm*.

Virginia Department of Conservation and Recreation (DCR). 2009. Various stormwater management BMP specifications. Virginia Stormwater BMP Clearinghouse web site: *http://www.vwrrc.vt.edu/swc/*. Richmond, VA.

Virginia Department of Environmental Quality. 2011. *Virginia DEQ Stormwater Design Specification No. 9. – Bioretention*. Version 1.9. March 1, 2011

Virginia Department of Environmental Quality. 2011. *Virginia DEQ Stormwater Design Specification No. 7. – Permeable Pavement*. Version 1.8. March 1, 2011

Virginia Department of Environmental Quality (VA DEQ). 2014. *Final 2012 305(b)/303(d) Water Quality Assessment Integrated Report*. January 2014. *http://www.deq.virginia.gov/Programs/Water/WaterQualityInformationTMDLs/WaterQualityAssessments/2012305(b)303(d)IntegratedReport.aspx*.

Virginia Department of Health (VDH). 2014. Notice and Description of Shellfish Area Condemnation Number 056-007, Hampton Roads. January 2014. *http://www.vdh.virginia.gov/EnvironmentalHealth/shellfish/closure/cond056-007.pdf*.

Virginia Institute of Marine Science (VIMS). 2013. Recurrent Flooding Study for Tidewater Virginia. Report submitted to the Virginia General Assembly. January 2013. *http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf*.

Appendix A: Site Investigations Summary

Site number	Location	Observation	Recommendation
1	Carolina Circle at intersection of Carolina and Newport Avenues	Circular park within intersection, slightly elevated relative to adjacent roadways surface drainage away from sites.	None
2	Delaware Circle at intersection of Delaware and Gosnold Avenues	Circular park within intersection, slightly elevated relative to adjacent roadways surface drainage away from sites.	None
3	Rhode Island Circle at intersection of Rhode Island and Newport Avenues	Circular park within intersection, slightly elevated relative to adjacent roadways surface drainage away from sites.	None
4	Munson Park at W 27th and Munson Place	Large block scale open park, slightly elevated relative to adjacent streets surface drainage away from site.	None
5	Intersection of New York and Newport Avenues	Relatively wide streets (particularly Newport Avenue), curb inlets at all corners, narrow verge with some utility conflicts and mature vegetation.	Curb bump out planter boxes.
6	Intersection of W 28th St. and Gosnold Ave.	Moderate street width, curb inlets at every corner and some utility and mature trees in ROW.	Curb bump out planter boxes.
7	East of Post Office Parking Lot	Very small landscaped area.	None
8	W 46th Street west of Colley Ave	Narrow street with curb inlets on both sides. Multiple driveway entrances.	None
9	Eastern extent of W 46th Street at Knitting Mill Creek	Existing wetland restoration project.	None
10	Outfall at Mayflower Road and Delaware Avenue	Site of proposed shoreline armoring incorporating a section of living shoreline. Outfall serves adjacent Delaware Avenue and some portion of Mayflower Road.	Implement shoreline bioswale, using curb cuts to divert western half of Mayflower Road drainage.
11	Upstream (southernmost) extent of Knitting Mill Creek	Large RCP outfall with adjacent (failing) retaining wall surrounded by Mayflower Road, a small grassed area, and an adjacent parking lot.	Implement bioretention area in grassed space serving adjacent parking lot.
12	Western extent of W 43rd Street. at Knitting Mill Creek	Gravel parking lot serving marina with corrugated metal pipe outfall into creek.	Convert parking area to permeable pavement or install bioretention.
13	Western extent of W 50th Street at Knitting Mill Creek	Surface flows from street discharge across narrow gently sloped shoreline with native shrub vegetation.	None
14	Intersection of Mayflower Road and W 41st Street	15-20 ft wide grassed area with moderate slope situated between Mayflower Road and Parking area behind Pancho & Luigi's.	Small bioswale to treat parking area.
15	Open area along Mayflower Road north of Carolina Avenue	Gently sloping grassed area, potions of adjacent parking drain to site.	Consider bioswale or roadside bioretention area, Possible daylighting of creek in this area.
16	Western shoreline of Knitting Mill Creek south of W 45th Street	Narrow grassed area between gravel parking lot and shoreline. Runoff sheet flows across grassed area.	Convert parking area to permeable pavement or install bioretention.
17	Shoreline at Tidewater Boat Club	Impervious road/lot along shoreline.	None, insufficient space for retrofitting.
18	Commercial at Colley Avenue and W 45th Street	One story building with impervious road street frontage surrounded by very small amount of pervious area.	Consider incorporating planter box or other landscape elements into street frontage.
19	Industrial building at Newport Avenue and W 23rd Street	Industrial building currently in use as self-storage facility. Surrounded by narrow grassed building setback. Two roads without curb and gutter.	Investigate green roof for building and consider bioswale along Newport Avenue and W 23rd Street.

Site number	Location	Observation	Recommendation
20	Industrial building at Newport Avenue and W 23rd Street	Building has been demolished.	Explore GI elements as part of redevelopment.
21	Gosnold Avenue between W. 25th Street and W 24th Street	Relatively wide street with inset parallel parking and wide grassed verge.	Convert northernmost parking spaces to permeable pavement (adjacent catch basins allow use of underdrains).
22	W 41st Street Between Colley and Killam Avenues	Wide street with very wide vegetated fringe. No evidence of subsurface drains.	Reduce street width and/or consider roadside bioswale (dependent on infiltration or connection to drainage network).
23	W 42st Street Between Colley and Killam Avenues	Wide street with very wide vegetated fringe. No evidence of subsurface drains.	Reduce street width and/or consider roadside bioswale (dependent on infiltration or connection to drainage network).
24	38th Street playground	Park area between 37th and 38th Streets set in area of low elevation. Main storm drain runs underneath. Park appears to be heavily used.	Implement bioretention areas along 37th and 38th streets to treat street runoff before it enters drainage network.
25	Alley between W 37th Street and W 36th Street west of Colley Avenue	Narrow alley between streets lined with narrow grass verge without curb	Implement roadside swales to encourage infiltration.
26	Undeveloped lots at 1020 W 36th Street.	Three undeveloped lots with managed grass vegetation roadway drainage surface flows along curb to the east.	None
27	Large gravel lot at 831 W 39th Street	Large gravel lot which appears to serve adjacent ASCO facility	None
28	Mayflower Road at New Jersey Avenue	Small outfall along shoreline serving New Jersey Avenue and small portion of Mayflower Road.	Consider roadside bioswale serving western half of Mayflower Road.
29	Knitting Mill Creek Community Garden	Majority of adjacent restaurant building rooftop discharges nearest the garden.	Install rainwater cistern to capture rooftop runoff and provide irrigation water for garden.
30	Western end of W 48th Street at Knitting Mill Creek	Small wooded area in shoreline buffer where street runoff discharges into creek.	None

Appendix B: 35th Street and Colley Avenue Green Street Conceptual Design

KNITTING MILL CREEK, NORFOLK, VIRGINIA
GREEN INFRASTRUCTURE CONCEPTUAL PLAN
SITE: COLLEY AVENUE AND 35TH STREET

Site Location			
Date of Field Visit	6/26/2014	Latitude	36° 52' 40" N
Field Visit Personnel	J. Smith	Longitude	76° 17' 41" W
Major Watershed	Lafayette River	Landowner	City of Norfolk
Street Address	Blocks north, south, and west of 35th St./Colley Ave. intersection		

Existing Site Description: The proposed project site includes the blocks immediately north, south, and west of the Colley Avenue/35th Street intersection. Colley Avenue is a commercial corridor through Norfolk that is primarily a 2-lane roadway with parking lanes and sidewalk on both sides of the street. 35th Street has a similar configuration, but is a residential corridor with significantly wider travel lanes. Sanitary sewer and water supply lines are located throughout the project area, although no stormwater drains currently exist directly within the three blocks.

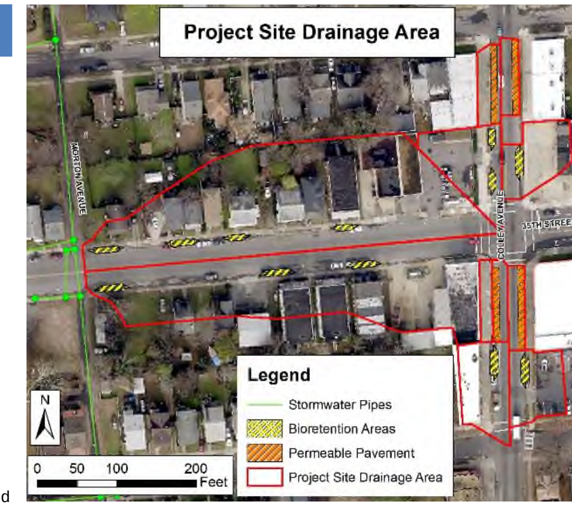
Drainage Area Characteristics	
Drainage Area, acres	3.1
Hydrologic Soil Group	D, Urban
Total Impervious, %	86
Design Storm Event, in	1.0

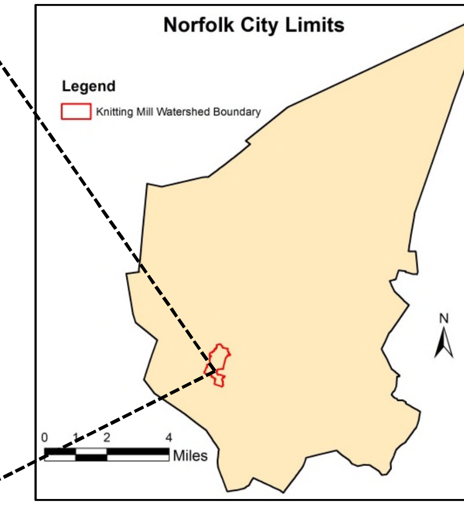
Proposed Characteristics*	
Proposed BMPs	BR, PP
Total Detention Vol., ft^3	3,500
Bioretention Area, ft^2	2,500
Perm. Pavement Area, ft^2	3,130

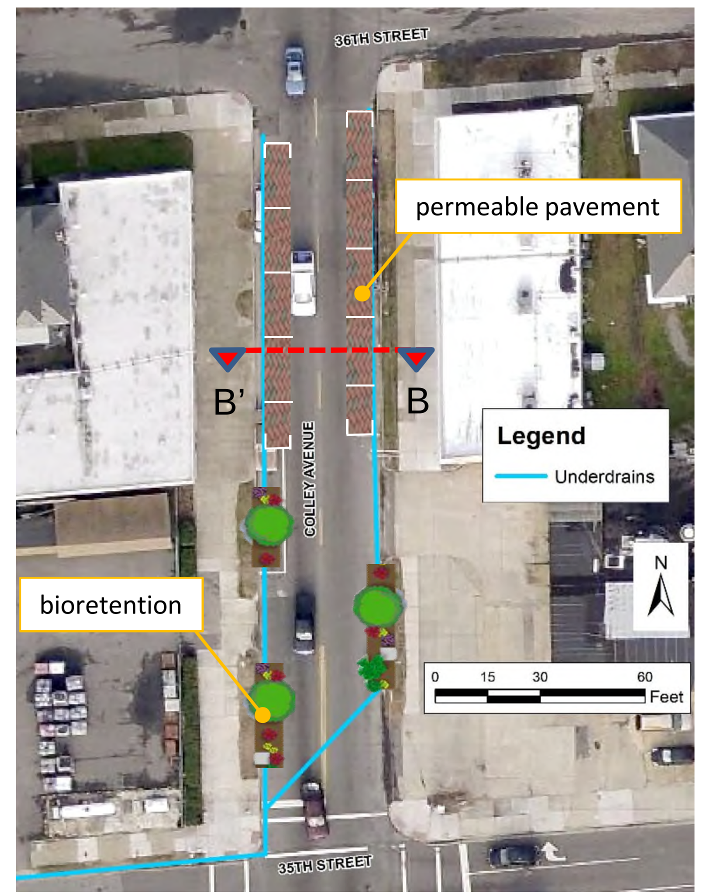
Proposed Green Infrastructure Description: Proposed BMPs within the right-of-way (ROW) include bioretention curb extensions on 35th St., and both porous asphalt parking lanes and bioretention curb extensions along Colley Avenue. These BMPs are designed to capture and treat runoff from the entire ROW while still allowing pedestrian, vehicle, and transit access.

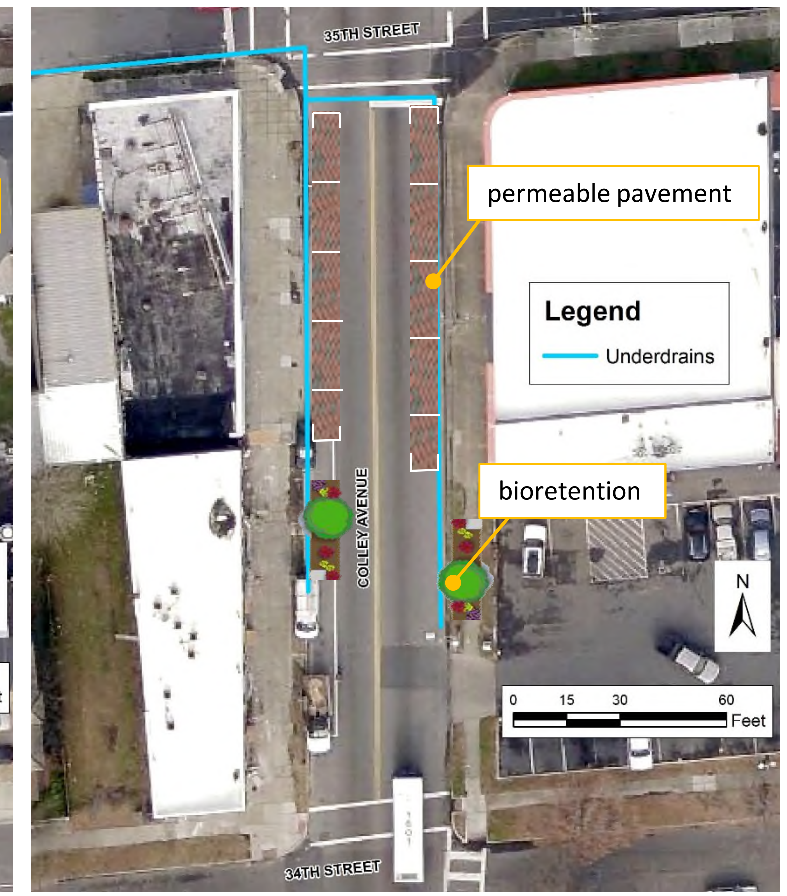
BR = Bioretention, PP = Permeable Pavement

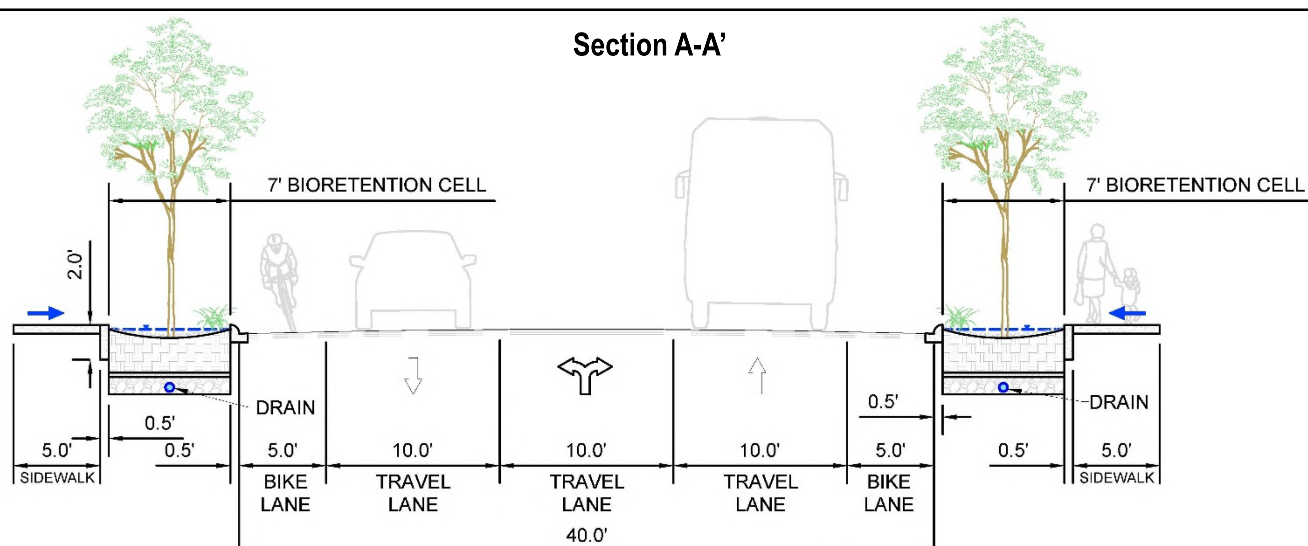
*Green Infrastructure characteristics are based on field observations and GIS data resources available at the time of conceptual design analysis. Note that final design characteristics will be dependent on a detailed site survey and could vary slightly from conceptual design characteristics.

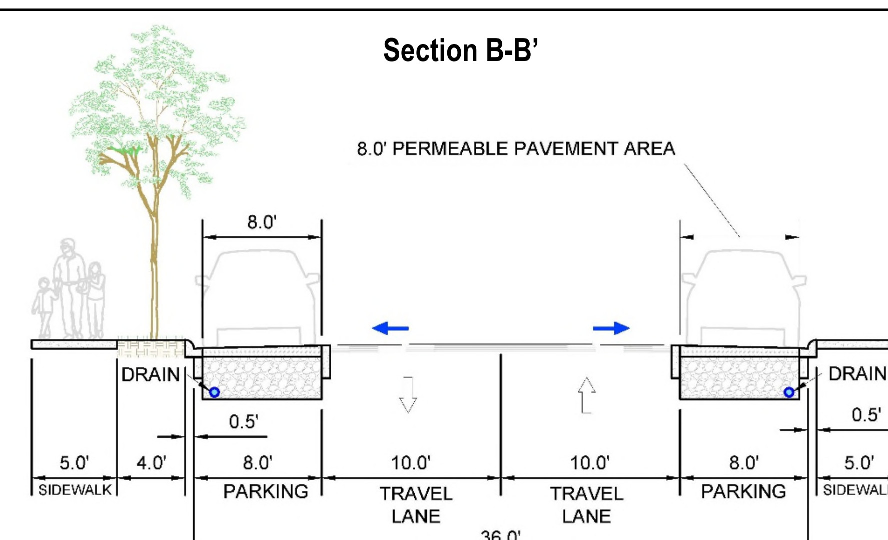












Appendix C: Mayflower Road Shoreline Conceptual Design

KNITTING MILL CREEK, NORFOLK, VIRGINIA
GREEN INFRASTRUCTURE CONCEPTUAL PLAN
SITE:MAYFLOWER ROAD SHORELINE

Site Location

Date of Field Visit	6/26/2014	Latitude	36° 53' 7" N
Field Visit Personnel	J. Smith	Longitude	76° 17' 36" W
Major Watershed	Lafayette River	Landowner	City of Norfolk
Street Address	4200-5000 blocks of Mayflower Rd		

Existing Site Conditions: Mayflower Road borders the eastern shore of Knitting Mill Creek. The northern section of shore consists of a new concrete bulkhead and the southern section of shore consists of a badly eroding shoreline which is planned to be protected by a living shoreline/shoreline armoring project in the coming years. Throughout this entire extent there is a 10-15 ft wide grass verge between the road edge and the shoreline exhibiting signs of heavy foot traffic and poor plant health. Stormwater runoff from Mayflower Road directly discharges into Knitting Mill Creek via curb and gutter directed to subsurface drainage system.

Drainage Area Characteristics

Drainage Area, acres	0.65
Hydrologic Soil Group	n/a (fill)
Total Impervious, %	80
Design Storm Event, in	1.0

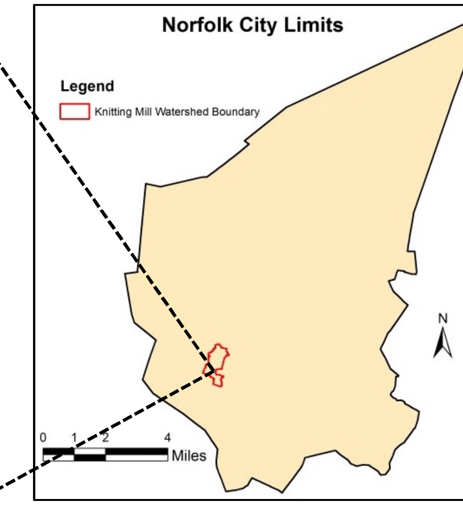
Proposed Characteristics*

Proposed BMPs	BR, PP
Total Detention Vol., ft^3	1,900
Bioretention Area, ft^2	1,500
Perm. Pavement Area, ft^2	7,200

Proposed Green Infrastructure Description: Approximately 500 feet of bioswale will be installed directly adjacent to the existing curb to capture , via curb cuts, and treat runoff along the southern section of roadway. A pervious walkway is proposed between the bioswale and shoreline to provide pedestrian access and necessary freeboard and will also extend along the northern section of roadway.

BR = Bioretention, PP = Permeable Pavement

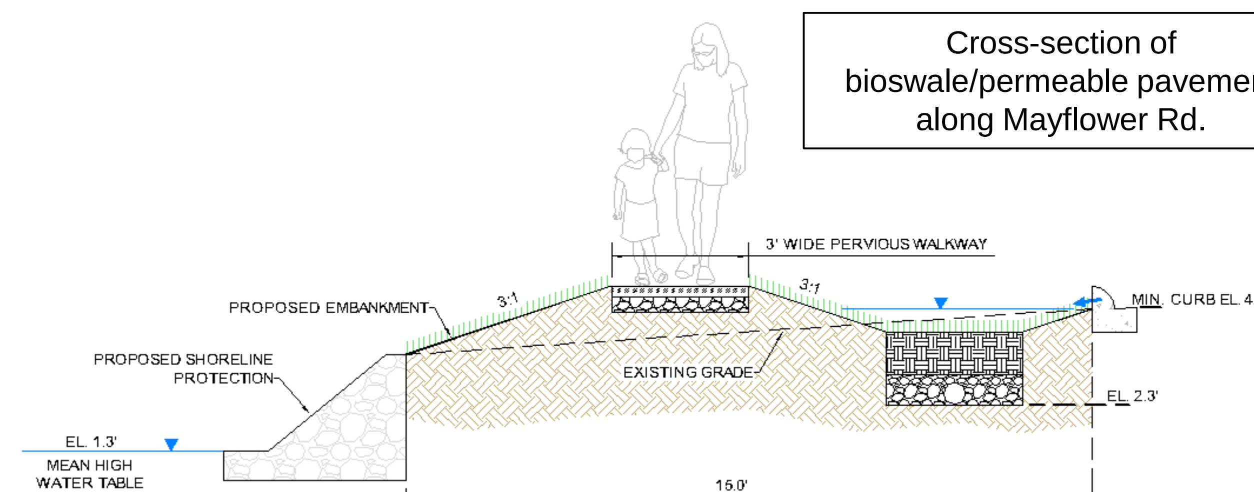
*Green Infrastructure characteristics are based on field observations and GIS data resources available at the time of conceptual design analysis. Note that final design characteristics will be dependent on a detailed site survey and could vary slightly from conceptual design characteristics.



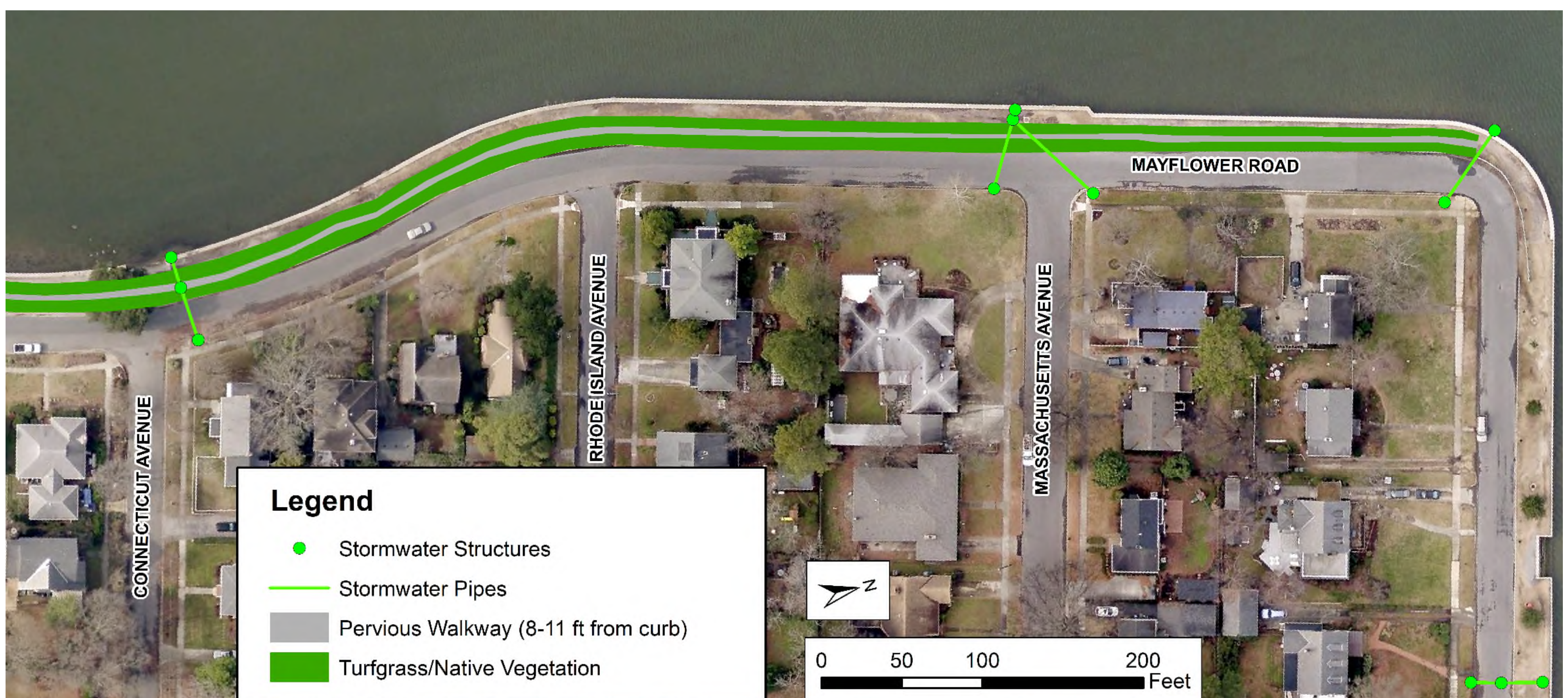
Existing conditions along Mayflower Rd., view looking north

Artist's rendering of proposed future conditions

Cross-section of bioswale/permeable pavement along Mayflower Rd.



KNITTING MILL CREEK, NORFOLK, VIRGINIA
GREEN INFRASTRUCTURE CONCEPTUAL PLAN
SITE:MAYFLOWER ROAD SHORELINE



Appendix D. Green Infrastructure Conceptual Design Detailed Cost Estimates

Table D-1. Cost estimate for 35th Street bioretention

Item No.	Description	Reference	Quantity	Unit	Unit Cost	Total
Preparation						
1	Traffic Control		21	day	$1,000.00	$21,000
Site Preparation/Earthwork						
2	Saw-cut asphalt	RSMeans	1407	LF	$2.31	$3,250
3	Asphalt Removal, BMP	RSMeans	239	SY	$4.18	$999
4	Excavation, BMP	RSMeans	199	CY	$16.24	$3,233
5	Excavation, underdrain trench	RSMeans	540	LF	$1.13	$610
6	Curb removal	RSMeans	302	LF	$4.30	$1,299
7	Haul and disposal		199	CY	$8.55	$1,702
Bioretention Curb Extension						
8	Bioretention Media - 2' Depth	RSMeans	99	CY	$31.31	$3,085
9	Filter Layer (washed concrete sand)	RSMeans	8	CY	$60.82	$499
10	Drainage stone (washed #57 stone)	RSMeans	49	CY	$47.91	$2,360
11	Grouted River Rock	Engineer's estimate	6	CY	$150.00	$933
12	Curb Cuts	Engineer's estimate	14	EA	$125.00	$1,750
13	Hardwood mulch (triple shredded)	Engineer's estimate	12	CY	$55.00	$674
14	Concrete Curb (6" vertical, straight)	RSMeans	262	LF	$11.73	$3,069
15	Concrete Curb (6" vertical, radius)	RSMeans	65	LF	$19.03	$1,245
16	4" SCH 40 perforated PVC cleanout	Engineer's estimate	7	EA	$100.00	$700
17	Vegetation	Engineer's estimate	1330	SF	$1.00	$1,330
Underdrain						
18	6" PVC Underdrain, perforated	RSMeans	190	LF	$10.80	$2,052
19	6" PVC Underdrain, solid	RSMeans	540	LF	$5.94	$3,208
Construction Subtotal						$52,997
20	Planning (20% of subtotal)					$10,599
21	Mobilization (10% of subtotal)					$5,300
22	Bond (5% of subtotal)					$2,650
23	Construction contingency (10% of subtotal)					$5,300
Construction Total						$76,846
24	Design (20% of Construction Total)					$15,369
Total Cost						**$92,215**

Table D-2. Cost estimate for Colley Avenue green street

Item No.	Description	Reference	Quantity	Unit	Unit Cost	Total
Preparation						
1	Traffic Control		21	day	$1,000.00	$21,000
Site Preparation/Earthwork						
2	Saw-cut asphalt	RSMeans	1779	LF	$2.31	$4,109
3	Asphalt Removal, BMP	RSMeans	564	SY	$4.18	$2,359
4	Excavation, BMP	RSMeans	585	CY	$16.24	$9,496
5	Excavation, underdrain trench	RSMeans	580	LF	$1.13	$655
6	Curb removal	RSMeans	591	LF	$4.30	$2,541
7	Haul and disposal		585	CY	$8.55	$5,000
Bioretention Curb Extension						
8	Bioretention Media - 2' Depth	RSMeans	87	CY	$31.31	$2,718
9	Filter Layer (washed concrete sand)	RSMeans	7	CY	$60.82	$440
10	Drainage stone (washed #57 stone)	RSMeans	43	CY	$47.91	$2,080
11	Grouted River Rock	Engineer's estimate	4	CY	$150.00	$667
12	Curb Cuts	Engineer's estimate	10	EA	$125.00	$1,250
13	Hardwood mulch (triple-shredded)	Engineer's estimate	11	CY	$55.00	$595
14	Concrete Curb (6" vertical, straight)	RSMeans	182	LF	$11.73	$2,140
15	Concrete Curb (6" vertical, radius)	RSMeans	46	LF	$19.03	$868
16	4" SCH 40 perforated PVC cleanout	Engineer's estimate	5	EA	$100.00	$500
17	Vegetation	Engineer's estimate	1172	SF	$1.00	$1,172
PICP Pavers						
18	Porous concrete	Engineer's estimate	3128	SF	$8.00	$25,024
19	Bedding layer (No. 8 stone)	RSMeans	58	CY	$40.00	$2,317
20	Reservoir layer (No. 57 stone)	RSMeans	437	TN	$24.57	$10,745
Underdrain						
21	6" PVC Underdrain, perforated	RSMeans	521	LF	$10.80	$5,623
22	6" PVC Underdrain, solid	RSMeans	580	LF	5.94	$3,445
Construction Subtotal						$107,744
23	Planning (20% of subtotal)					$20,949
24	Mobilization (10% of subtotal)					$10,474
25	Bond (5% of subtotal)					$5,237
26	Construction contingency (10% of subtotal)					$10,474
Construction Total						$151,879
27	Design (20% of Construction Total)					$30,376
Total Cost						$182,255

Table D-3. Mayflower Road shoreline project

Item No.	Description	Reference	Quantity	Unit	Unit Cost	Total
Preparation						
1	Traffic Control		14	day	$1,000.00	$14,000
Site Preparation/Earthwork						
2	Excavation, BMP		341	CY	$16.24	$5,539
3	Curb removal		14	LF	$4.30	$60
4	Haul and disposal		341	CY	$8.55	$2,916
5	Finish Grade		2083	SY	$1.10	$2,292
Bioswale						
6	Bioretention Media - 2' Depth		94	CY	$31.31	$2,957
7	Filter Layer (washed concrete sand)		9	CY	$60.82	$563
8	Drainage stone (washed #57 stone)		37	CY	$47.91	$1,783
9	Grouted River Rock		3	CY	$150.00	$467
10	Curb Cuts		7	EA	$125.00	$875
11	4" SCH 40 perforated PVC cleanout		7	EA	$100.00	$700
12	Turf sod		4	MSF	$640.00	$2,560
13	Native planting for riparian buffer		12	MSF	$1,000.00	$12,000
Underdrain						
14	6" PVC Underdrain, perforated		500	LF	$10.80	$5,400
Porous Walkway						
15	Porous concrete		7200	SF	$4.00	$28,800
16	Reservoir layer (No. 57 stone)		132	TN	$24.57	$3,243
Construction Subtotal						$52,112
17	Planning (20% of subtotal)					$10,422
18	Mobilization (10% of subtotal)					$5,211
19	Bond (5% of subtotal)					$2,606
20	Construction contingency (10% of subtotal)					$5,211
Construction Total						$75,562
21	Design (20% of Construction Total)					$15,112
Total Cost						$90,674