Cost-Effectiveness Study of Urban Stormwater BMPs in the James River Basin

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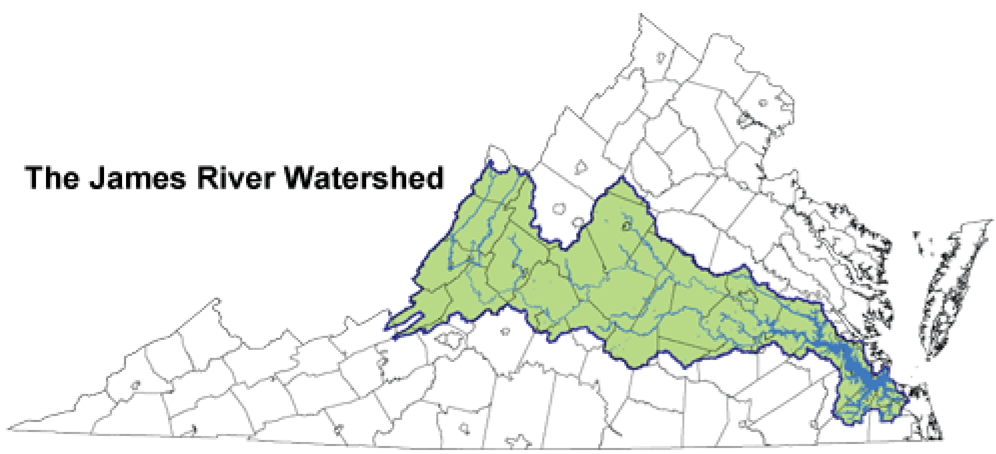

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About This Study

The goal of this study was to evaluate which urban stormwater practices provide the greatest nutrient and sediment reductions for the lowest investment to help localities in the James River watershed more cost-effectively achieve the pollutant load reductions required by the Chesapeake Bay TMDL.

The values presented in this study provide a snapshot of urban BMP cost-effectiveness based on the data available at the time, and are likely to change as new BMPs are approved and/or pollutant removal efficiencies are refined. Localities developing stormwater management strategies are advised to check with the status of the latest CBP panel recommendations, which are available at: http://stat.chesapeakebay.net/?q=node/130&quicktabs_10=3.

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About the Update

This study includes several BMPs that, at the time of data compilation and analysis, were not “credited” by the Chesapeake Bay Program (CBP) and its models, although several BMPs had been proposed for review through the CBP’s *Protocol for Development, Review and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls* (CBP WQGIT, 2010). Subsequent to the derivation of the cost effectiveness values, the CPB convened review panels for stream restoration, urban nutrient management, illicit discharge elimination, stormwater retrofits, and other urban BMPs. The stormwater retrofit panel recommendations were finalized in October 2012, the urban nutrient management panel recommendations were finalized in March 2013, and, as of the first release of this study (March 2013), the stream restoration panel recommendations were finalized in June 2013.

To bring the study up to date with these latest recommendations, the report was revised in June 2013. Although the panel recommendations will not be incorporated into the CBP models until 2017, the panel reports provide values to be used in the interim for planning purposes. The June revision of this report also corrects several errors in the previous version.

Cost-Effectiveness Study of Urban Stormwater BMPs in the James River Basin

Urban stormwater is the fastest growing source of pollution to the James River and if not controlled threatens to undermine the progress that has been made towards restoring the health of the river. Moreover, achieving needed pollution reductions from existing developed areas through improved stormwater management is the most difficult element of the Virginia watershed implementation plan (WIP) to meet the Chesapeake Bay total maximum daily load (TMDL). Local governments have raised significant concerns about being able to meet the pollutant reduction goals for total nitrogen (TN), total phosphorus (TP) and total suspended solids (TSS). For the urban sector, the required reductions were applied to all urban lands, and will be instituted in part through the revision of urban stormwater permits, known as Municipal Separate Stormwater Sewer System (MS4) permits, issued by the Commonwealth and approved by EPA. Currently, the MS4 permits for Virginia's largest 11 municipalities are all expired and up for renewal, and a general permit for most of Virginia's other urban areas must be renewed in 2013.

The James River Association (JRA) would like to support localities in the development of cost-effective plans to meet water quality and permit goals and therefore requested the Center for Watershed Protection (CWP) to complete a study on costs of best management practices (BMPs) for urban stormwater treatment. The purpose of this research was to identify the most cost-effective urban stormwater management strategies that can be used to meet pollutant removal goals of the Chesapeake Bay TMDL, especially those for the James River watershed. CWP's research gathered and reviewed available cost and pollutant removal data for a variety of urban BMPs, and this data was used to analyze the costs and benefits of various BMP scenarios for the City of Richmond. The findings of this research are summarized within this report.

Cost-Effectiveness of Urban Stormwater BMPs

Cost-effectiveness is defined in this paper as an annual unit cost per unit of pollutant removed, and is calculated based on annualized life cycle costs divided by the pounds of pollutants removed per year. This metric is intended to be used by Virginia localities to compare the <u>relative</u> costs and pollutant removal effectiveness of 33 strategies to treat urban stormwater runoff.

The first part of this research involved review and analysis of available cost and pollutant removal data for a variety of urban stormwater BMPs. Table 1 presents the BMPs included in this study. For some BMPs (e.g., bioretention, permeable pavement), multiple cost-effectiveness values are provided because performance data was available for different design variations of these BMPs and/or, cost data was available for both "retrofit" and "new" applications of the practice.

Most of the BMPs in Table 1 are given credit for nutrient and sediment reduction by the Chesapeake Bay Program (CBP) in their watershed models (CBP, 2011). Through its ***<u>Protocol</u>***

for Development, Review and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls (CBP WQGIT, 2010), the Chesapeake Bay Program considers emerging practices and evaluates them for inclusion in the model. Through this same process, long-standing practices are re-evaluated to be sure they are still properly portrayed. Urban nutrient management, urban stream restoration and stormwater retrofits were recently reviewed by CBP expert review panels and the panel recommendations were used in this study. Both the original and recommended interim removal efficiencies for urban stream restoration were used in this study for comparison purposes. Illicit discharge elimination and pet waste programs are not currently credited. The CBP has convened a review panel on illicit discharge elimination but has not yet come to agreement on recommendations. Pollutant reductions associated with illicit discharge elimination and pet waste programs were derived by CWP using assumptions documented in Appendix B.

Table 1. Urban Stormwater BMPs Included in the Study

BMP	Current Status (as of April 2013)	TN Efficiency (%)	TP Efficiency (%)	TSS Efficiency (%)
Bioretention/raingardens (new - suburban), A/B soils, no underdrain	Approved by CBP	80	85	90
Bioretention/raingardens (new - suburban), A/B soils, underdrain	Approved by CBP	70	75	80
Bioretention/raingardens (new - suburban), C/D soils, underdrain	Approved by CBP	25	45	55
Bioretention (retrofit, highly urban, C soils)[1]	CBP panel recommendations approved by Water Quality Goal Implementation Team October 9, 2012	51	59	63
Bioswale (new)	Approved by CBP	70	75	80
Dry Detention Ponds (new)	Approved by CBP	5	10	10
Dry Extended Detention Ponds (new)	Approved by CBP	20	20	60
Filtering Practices (sand, above ground)	Approved by CBP	40	60	80
Filtering Practices (sand, below ground)	Approved by CBP	40	60	80
Forest Buffers	Approved by CBP	25	50	50
Hydrodynamic Structures (new)	Approved by CBP	5	10	10
Illicit discharges- correction of cross-connections[2]	Under review by CBP	100	100	100

[1] Removal efficiencies calculated using retrofit adjustor curves from Schueler and Lane (2012) based on the following assumptions: one acre drainage area, 100% impervious, C soils, facility is 6% of drainage area with one foot of ponding, and treats 0.72 inches per acre of impervious cover (see Appendix B for details)

Table 1. Urban Stormwater BMPs Included in the Study				
BMP	**Current Status (as of April 2013)**	**TN Efficiency (%)**	**TP Efficiency (%)**	**TSS Efficiency (%)**
Illicit discharges- sewer repair[3]	Under review by CBP	100	100	100
Impervious Urban Surface Reduction	Approved by CBP	N/A	N/A	N/A
Infiltration Practices w/ Sand, Veg. (new)	Approved by CBP	85	85	95
Infiltration Practices w/o Sand, Veg. (new)	Approved by CBP	80	85	95
Permeable Pavement w/ Sand, Veg. (new), A/B soils, no underdrain	Approved by CBP	80	80	85
Permeable Pavement w/ Sand, Veg. (new), A/B soils, underdrain	Approved by CBP	50	50	70
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	Approved by CBP	20	20	55
Permeable Pavement w/o Sand, Veg. (new), A/B soils no underdrain	Approved by CBP	75	80	85
Permeable Pavement w/o Sand, Veg. (new), A/B soils, underdrain	Approved by CBP	45	50	70
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	Approved by CBP	10	20	55
Pet waste program[4]	Not currently credited by CBP	Calculated as a load reduction		
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	CBP panel recommendations approved by Water Quality Goal Implementation Team October 9, 2012	20	45	60
Street Sweeping- Mass Loading Method	Approved by CBP	Calculated as a load reduction		
Street Sweeping- Street Lane Method	Approved by CBP	3	3	9
Tree Planting	Approved by CBP	Credited as a land use change		

[2] Assumes 100% of load from cross connections is removed through correction. Loads from cross connections estimated based on average wastewater generation for a typical household and wastewater characteristics (see Appendix B for details)
[3] Assumes 100% of load from sewer leaks is removed through repair. Assumes each sewage discharge requires replacement of 400 feet of pipe to repair the problem (maximum allowable distance between manholes). Loads from sewage discharges estimated based on various assumptions about wastewater characteristics and exfiltration (see Appendix B for details)
[4] Assumes adoption of pet waste ordinance, installation of 56 pet waste stations and educational mailings to residents (see Appendix A for methods to estimate costs and Appendix B for details on estimating pollutant load reductions)

Table 1. Urban Stormwater BMPs Included in the Study				
BMP	**Current Status (as of April 2013)**	**TN Efficiency (%)**	**TP Efficiency (%)**	**TSS Efficiency (%)**
Urban Growth Reduction	Approved by CBP			
Urban nutrient management (recommended efficiencies)[5]	CBP panel recommendations approved by Water Quality Goal Implementation Team March 11, 2013	9	4.5	0
Urban Stream Restoration (original efficiencies)	No longer recommended by CBP	0.02 lbs/ft	0.003 lbs/ft	2 lbs/ft
Urban Stream Restoration (recommended interim efficiencies)	Approved by CBP in January 2012	0.2 lbs/ft	0.068 lbs/ft	52.5 lbs/ft[6]
Vegetated Open Channels, A/B soils, no underdrain	Approved by CBP	45	45	70
Vegetated Open Channels, C/D soils, no underdrain	Approved by CBP	10	10	50
Wet Ponds and Wetlands (new)	Approved by CBP	25	45	60
Wetlands (retrofit)[7]	CBP panel recommendations approved by Water Quality Goal Implementation Team October 9, 2012	25	40	51

Other BMPs have been proposed by states and localities for review by CBP, but the review and research process is not far enough along to derive an initial performance value. Pet waste programs and illicit discharge elimination were considered to be important in Virginia because of their potential to address both the Bay TMDL and the numerous local bacteria TMDLs. Recent findings by CWP have identified illicit discharges as a potentially large contributor to nutrient loads and correcting these discharges may be a very cost-effective way to achieve nutrient reductions (Lilly et al., 2012). Illicit discharges can be caused by a variety of sources, such as

[5] This BMP includes an automatic three-year credit for adoption of statewide P fertilizer legislation, beginning in 2013. Schueler and Lane (2013) recommend this credit be implemented by applying a 26.7% unit area TP load reduction to all pervious acres in the jurisdiction. See Appendix B for details.

[6] As recommended by Schueler and Stack (2013), a sediment delivery ratio of 0.175 was applied to the edge-of-stream interim approved removal rate of 310 lbs/ft to get to the resulting value of 52.5 lbs/ft

[7] Removal efficiencies calculated using retrofit adjustor curves from Schueler and Lane (2012) based on the following assumptions: 40 acre drainage area, 50% impervious, 50% pervious, C soils, facility is 4% of drainage area with 0.5 foot of ponding, and treats 0.48 inches per acre of impervious cover (see Appendix B for details).

leaks in sewer pipes, cross connections of the sanitary sewer lines to the storm drain system, illegal dumping, discharge of washwater to the storm drain system and sewer overflows. This variety of causes makes it challenging to estimate costs and pollutant reductions associated with removal of illicit discharges; therefore, this BMP was split into two types; 1) correction of cross-connections, which appear to have relatively similar costs across communities/situations; and 2) sewer leaks that require repair or replacement of sewer pipes.

BMP Costs

The goal of the cost analysis was to calculate 20-year life cycle costs associated with BMP implementation, including design, construction, land values, financing and operation and maintenance (O&M). A review of the published literature on BMP costs was conducted to compile the existing data. We limited our search to sources that were published since 2006, based on the assumption that older data may reflect higher initial costs of implementing what were then "new" practices such as bioretention and green roofs. Design and installation costs for these types of practices have presumably decreased in recent years since they are now more commonplace. An initial review of each data source was performed to answer the following questions to ascertain their utility for this research:

- What BMPs are included?
- How old are the data?
- What is the unit of measure (e.g., impervious acre treated, surface area of practice, treatment volume)?
- What types of costs are included (e.g., construction, land acquisition, design, maintenance)?
- What types of development are addressed (redevelopment, new development, retrofit)?
- From what region were the data collected?
- Any potential issues with using the data (e.g., inconsistent definition of storage or treatment volume, limited information on BMP design or site factors)?

Based on this initial assessment, one data source was determined to be most useful for this analysis. The 2011 report *Costs of Stormwater Management Practices in Maryland Counties* by Dennis King and Patrick Hagan was used as the primary source for the BMP cost analysis. This study was commissioned by Maryland Department of the Environment (MDE) to assist Maryland communities with developing cost estimates for their urban BMP scenarios developed to meet the Bay TMDL using the Maryland Assessment and Scenario Tool. This report presents life cycle costs per impervious acre for 24 urban stormwater BMPs in 2011 dollars.

Sources of the costs provided in King and Hagan include national literature review or published articles and reports, previously developed stormwater cost databases and models, Maryland MS4 reports submitted to MDE, interviews with Maryland local stormwater staff, contractors and others who work on stormwater projects in the state, and applications of the WERF stormwater unit cost model using cost adjustment indicators developed for Maryland counties with MEANS 2011 Regional Construction Cost Indicators.

Major assumptions and caveats of the King and Hagan (2011) study are presented below:

- The cost-estimating framework used develops full life cycle cost estimates based on the sum of initial project costs (design, construction and land costs) funded by a 20-year county bond issued at 3%, plus total annual and intermittent maintenance costs over 20 years. Annualized life cycle costs are estimated as the annual bond payment required to finance the initial cost of the BMP (20-year bond at 3%) plus average annual routine and intermittent maintenance costs.
- Design costs include the cost of site discovery, surveying, design, planning, permitting, etc. for which various BMPs tend to range from 10% to 40% of BMP construction costs.
- Construction costs include capital, labor, material and overhead costs, but not land costs, associated with implementation. For street sweeping this includes only the capital cost of the mechanical sweeper and for nutrient management it refers to the cost of an outreach campaign.
- Operational and maintenance (O&M) costs include annual routine annual maintenance, intermittent maintenance and county implementation costs. Intermittent or corrective maintenance tasks are those that accrue very 3-5 years and are averaged over the 20 year period. O&M costs over the 20-year life cycle are assumed to increase by 3%; however, a 3% discount rate is also assumed, thus "washing out" the effect of the increased cost and resulting in a constant present value annual cost throughout the 20-year period.
- Annual county implementation costs are associated with inspecting BMPs and enforcing design, construction and maintenance standards. They are based on the annual cost of Full Time Equivalent staff necessary to perform inspections and deal with enforcement issues plus estimates of the annual number of BMPs a FTE can manage. These costs include staff and overhead, and is averaged out over all BMPs, and assume that staff is not assigned to cover just one BMP.
- Cost estimates for urban nutrient management are not very reliable due to limited data.
- Costs do not include program setup (e.g., stormwater management programs) associated with each BMP. It is assumed that these programs are already in place (with the exception of pet waste programs described in Appendix A).
- It is assumed that the design life of all BMPs (except for street sweeping) is 20 years or greater (e.g., the costs do not reflect replacement over the 20 year time period). For street sweeping, the life cycle was assumed to be 10 years.
- For permeable pavement, it was assumed that the project area would have been paved with traditional asphalt or concrete if permeable pavers were not used; therefore the cost of traditional paving was subtracted from the cost of installing permeable pavers.
- The values presented do not consider potential for cost-sharing associated with a BMP, and instead reflect the total cost associated with BMP implementation, regardless of whether the costs are bourne by counties, homeowners, contractors or other entities.
- Because actual BMP costs are very site-specific and can vary significantly geographically, the costs presented are not suitable for assessing costs in specific

situations. Differences in soils, slope, and utilities can cause significant variation in cost for the same BMP, as can variation in local zoning and permitting conditions, land values, and BMP design features.

Some additional caveats and assumptions related to the use of, and in some cases modifications to, King and Hagan data for this study include:

- The King and Hagan report provided cost adjustment factors for Maryland counties but does not provide Virginia-specific adjustment factors. It was beyond the scope of this study to develop cost adjustment factors for Virginia localities.
- For all BMPs that require land it was assumed that: 1) the opportunity cost of developable land is $70,000 per acre and 2) 50% of projects that require land take place on developable land with the rest taking place on land that is not developable (e.g., stream valleys). This brings the opportunity cost of land for BMPs to $35,000 per acre. It was assumed that county-owned land dedicated to BMPs has opportunity costs that are similar to those associated with private land that may be diverted from development to a BMP, even though the county does not have to buy the land. The sources of the $70,000 was the Land Price Index (Davis and Heathcote, 2007), which accounts for the relative value of land in a time series. The Land Price Index is equal to 1.5801 in Virginia and 2.1875 in Maryland. Applying these values as a ratio, the cost of land in Virginia would be roughly 70% of the value of land in Maryland, which was estimated by King and Hagan as $100,000/acre. It is important to note that these data are statewide and may not reflect land prices in the James River Basin, and in particular, the cost of urban land purchased for BMP implementation. However, the $70,000 figure was considered to be sufficient for this study since the goal was to compare relative cost effectiveness across BMPs, rather than develop a cost estimate for a specific location.
- Design costs presented in King and Hagan are shown as a percent of construction costs, and range from 10-40%. Design costs may be best presented as a fixed cost that does not necessarily increase with the acreage treated (at least for certain BMPs). However, because costs vary so widely with site and BMP characteristics, insufficient data was available from other sources to convert the design cost into a fixed cost.
- Costs presented in the King and Hagan report were reported per acre of impervious cover treated so that Maryland counties with MS4 permits could see the data in terms that align with their permit requirements. For BMPs that do not directly treat impervious cover (e.g., tree planting, stream restoration, urban nutrient management), conversion factors from a report published in 2011 by MDE, *Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated,* were applied. We chose not to convert costs to impervious acres treated for BMPs that do not treat impervious acres, since restoration of a portion of untreated impervious cover is a Maryland-specific permit requirement that is not applicable in Virginia. Therefore, the costs for each BMP are presented in different units, but for each individual BMP these units are consistent with the units in which the pollutant removal performance was calculated to allow for an analysis of BMP cost-effectiveness. We also converted costs from King and Hagan for the following BMPs that were assumed to treat 50% impervious land and 50% pervious land: wet ponds and wetlands, dry detention ponds, hydrodynamic structures, bioretention (suburban),

bioswales and vegetated open channels. The costs for these practices were adjusted so that the costs and pollutant removal values were in the same units (per acre treated), using the calculations described in Appendix A.

- The King and Hagan report did not include cost data for pond retrofits, pet waste programs, urban growth reduction, or removal of illicit discharges. Limited data is available for these BMPs. The assumptions and data sources used in this study to develop cost estimates for these BMPs are summarized in Appendix A.

- The King and Hagan report relies heavily on Maryland-specific data; therefore costs are reflective of Maryland BMPs. Differences in BMP specifications between Maryland and Virginia may affect BMP installation costs but it was beyond the scope of this study to quantify those differences. Determining the implications of the link between design specifications and costs is important for Virginia localities putting together specific cost estimates but could be a challenge since the King and Hagan data are based on a collection of cost data that likely reflect both the current and previous state specifications for stormwater management.

BMP Performance

BMP performance was measured in terms of annual reduction of TN, TP, and TSS, in pounds. The primary source of BMP performance data was the CBP's February 9, 2011 version of the BMP efficiencies used in their Scenario Builder Model (CBP, 2011). For BMPs recently reviewed by the CBP, performance was determined based on Schueler and Lane (2013), Schueler and Stack (2013), and Schueler and Lane (2012). Although numerous (and sometimes conflicting) sources exist for BMP performance, the CBP-derived values were used because they determine the credit Virginia localities will receive for measures included in the WIPs. For example, the pollutant removal efficiencies associated with BMPs on the Virginia Stormwater BMP Clearinghouse may differ from those approved by the CBP and could certainly influence local decisions regarding selection of a suite of practices to achieve TMDL goals. However, most of the urban BMPs are expected to be installed by localities as retrofits; therefore, local stormwater requirements will not be as relevant. Also, the goal of this study was to compare BMP cost effectiveness given the credits provided by the CBP.

The following assumptions were made to estimate BMP performance:

- Impervious surface reduction: assumed land use change from urban impervious to urban pervious
- Forest buffers: assumed land use change from urban pervious to forest, plus an efficiency applied to adjacent urban pervious acreage treated by the buffer
- Urban tree planting: assumed land use change from urban pervious to forest
- Urban nutrient management: pollutant removal efficiencies for TN and TP were applied to urban pervious to reflect urban nutrient management practices applied to urban lawns; in addition to this credit, a credit of 0.134 lbs of TP per pervious acre was calculated to reflect the automatic credit of 26.7% recommended by Schueler and Lane (2013) for adoption of statewide P fertilizer legislation (see Appendix B)
- Urban growth reduction: assumed land use change from urban impervious to forest (applies to future forecasted conditions)

- The following structural stormwater BMPs were assumed to have 50% urban impervious land and 50% urban pervious land within their drainage area: new bioretention (suburban), bioswales, wet ponds, wetlands, dry ponds, hydrodynamic structures, vegetated open channels and extended detention ponds.
- The following structural stormwater BMPs were assumed to treat 100% impervious drainage areas: new bioretention retrofits, permeable pavement, infiltration and filtering practices.
- For the mass loading method of determining street sweeping credits, it was assumed that the average mass of street dirt removed annually was 246.93 pounds per impervious acre swept. This estimate was based on street sweeping reports from the City of Baltimore, as described in Appendix B.
- It is assumed that due to maintenance of BMPs that they maintain constant removal rates every year over the 20 year timeframe.

Pollutant loading rates for each land use type were derived from the Virginia Assessment and Scenario Tool (VAST), using an average for the state of Virginia (derived from VAST in March 2012). The assumptions for pet waste programs and illicit discharge elimination, which are not currently credited by the CBP, are documented in Appendix B.

Results

The cost data developed for this study was combined with data on BMP performance to develop a cost-effectiveness metric. The cost-effectiveness for each BMP was calculated based on the average annual cost (over 20 years) and the annual pollutant reduction in pounds. The following values were calculated: cost effectiveness in dollars per pound for TN, TP and TSS for each BMP. An example calculation is provided below for TN.

$$\textit{Cost effectiveness for TN (\$/lb)} = \frac{\textit{Average annual cost over 20 years (\$)}}{\textit{Annual TN reduction (lbs)}}$$

Where:

- *Average annual cost over 20 years = (annual maintenance cost + average annual intermittent maintenance cost + average annual County implementation cost) + annualized initial cost*

- *Annualized initial cost = annual bond payment required to finance the initial cost (construction costs + design costs + cost of land) of the BMP at 3% interest over 20 years*

Table 2 presents the cost-effectiveness for TN, TP, and TSS for each BMP. Gray shaded BMPs in Table 2 are approved by the CBP. These values were used to group each BMP into categories of High, Moderate and Low cost-effectiveness for each of the three pollutants, as depicted by the green (High), yellow (Moderate), and orange (Low) shading in Table 2. Cutoff values between groups were based on natural breaks in the data.

Table 2. Cost-Effectiveness of Urban Stormwater BMPs[8]			
	Cost Effectiveness ($/lb)		
BMP	**TN**	**TP**	**TSS**
Bioretention (new - suburban), A/B soils, no underdrain	339.00	2,934.83	5.82
Bioretention (new - suburban), A/B soils, underdrain	387.43	3,326.14	6.55
Bioretention (new - suburban), C/D soils, underdrain	1,084.81	5,543.56	9.53
Bioretention (retrofit, highly urban C soils)	2,078.97	12,500.51	22.25
Bioswale (new)	309.13	2,653.91	5.23
Dry Detention Ponds (new)	4,597.20	21,143.16	44.43
Dry Extended Detention Ponds (new)	1,149.30	10,571.58	7.41
Filtering Practices (sand, above ground)	979.43	4,541.97	6.47
Filtering Practices (sand, below ground)	1,065.38	4,940.56	7.04
Forest Buffers	150.86	1,851.00	7.66
Hydrodynamic Structures (new)	7,146.10	32,865.88	69.06
Illicit discharges- correction of cross-connections	17.70	70.79	6.69
Illicit discharges- sewer repair	8.86	35.43	0.89
Impervious Urban Surface Reduction	2,439.05	7,354.09	11.96
Infiltration Practices w/ Sand, Veg. (new)	488.64	3,398.98	5.78
Infiltration Practices w/o Sand, Veg. (new)	496.65	3,251.47	5.53
Permeable Pavement w/ Sand, Veg. (new), A/B soils, no underdrain	2,528.09	17,585.50	31.45
Permeable Pavement w/ Sand, Veg. (new), A/B soils, underdrain	4,044.94	28,136.81	38.19
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	10,112.36	70,342.02	48.61
Permeable Pavement w/o Sand, Veg. (new), A/B soils no underdrain	1,926.47	12,563.10	22.47
Permeable Pavement w/o Sand, Veg. (new), A/B soils, underdrain	3,210.79	20,100.97	27.28
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	14,448.56	50,242.42	34.72
Pet waste program	0.44	3.36	N/A
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	565.52	2,311.92	3.64
Street Sweeping – Mass Loading Method	1,389.99	3,474.98	11.58
Street Sweeping – Street Lane Method	2,259.29	15,715.71	9.95
Tree Planting	657.58	9,621.48	46.23
Urban Growth Reduction	246.60	1,383.85	2.64

[8] Cost-effectiveness values were used to group each BMP into categories of High, Moderate and Low cost-effectiveness for each of the three pollutants, as depicted by the green (High), yellow (Moderate), and orange (Low) shading in Table 2. Cutoff values between groups were based on natural breaks in the data.

Table 2. Cost-Effectiveness of Urban Stormwater BMPs[8]			
	Cost Effectiveness ($/lb)		
BMP	**TN**	**TP**	**TSS**
Urban nutrient management (recommended efficiencies)	476.59	2,378.97	N/A
Urban Stream Restoration (original efficiencies)	2,613.21	17,421.41	26.13
Urban Stream Restoration (recommended interim efficiencies)	261.32	768.59	0.96
Vegetated Open Channels, A/B soils, no underdrain	289.61	2,663.93	3.60
Vegetated Open Channels, C/D soils, no underdrain	1,303.25	11,987.68	5.04
Wet Ponds and Wetlands (new)	696.63	2,847.91	4.49
Wetlands (retrofit)	1,160.28	6,670.36	10.99

Table 3 lists the top three most cost-effective BMPs for each pollutant (based on the values in Table 2), in decreasing order of cost-effectiveness.

Table 3. BMPs with High Cost-Effectiveness		
Pollutant	**Top 3 of All BMPs**	**Top 3 of CBP-Approved BMPs**
TN	These BMPs cost < $18/lb of nitrogen removed: 1. Pet waste program 2. Illicit discharges- sewer repair 3. Illicit discharges- correction of cross-connections	These BMPs cost < $265/lb of nitrogen removed: 1. Forest buffers 2. Urban growth reduction 3. Urban stream restoration (recommended interim efficiencies)
TP	These BMPs cost < $72/lb of phosphorus removed: 1. Pet waste program 2. Illicit discharges- sewer repair 3. Illicit discharges- correction of cross-connections	These BMPs cost < $1,860/lb of phosphorus removed: 1. Urban Stream Restoration (recommended interim efficiencies) 2. Urban growth reduction 3. Forest buffers
TSS	These BMPs cost < $3/lb of sediment removed: 1. Illicit discharges- sewer repair 2. Urban Stream Restoration (recommended interim efficiencies) 3. Urban growth reduction	These BMPs cost < $4/lb of sediment removed: 1. Urban Stream Restoration (recommended interim efficiencies) 2. Urban growth reduction 3. Vegetated open channels, A/B soils, no underdrain

Key observations and discussion of these results are presented below:

- In general, phosphorus is most expensive to remove and sediment is the cheapest.
- In general, cost effectiveness decreases when practices are installed as retrofits (compared to new), have underdrains (compared to none), or have poorly drained soils (compared to A/B soils).
- Some practices, including urban nutrient management and pet waste programs, are not effective for sediment removal. Although these BMPs do not help localities meet sediment reduction targets, their moderate to high cost-effectiveness for nutrient reduction make them a priority for meeting nutrient reduction targets and achieving other local benefits (e.g., cleaner streets and parks, bacteria reduction).
- Of the two methods available for calculating street sweeping credits, the mass loading approach results in greater nutrient and sediment reductions.
- Permeable pavement, dry detention ponds and hydrodynamic structures consistently rank in the least cost-effective category, due to their low water quality benefit (dry detention ponds and hydrodynamic structures) or high cost (permeable pavement).
- Two of the top ranked BMPs for nutrient reduction, pet waste programs and illicit discharge elimination, are not currently approved by the CBP but may be in the near future. While the cost and performance estimates for these practices are preliminary and based on limited data they show enormous potential to play a significant role in local urban stormwater strategies. The recently approved interim pollutant removal efficiencies for urban stream restoration make this practice the second most cost-effective for sediment removal. Using the new efficiencies results in stream restoration being 27 times more cost-effective than it was using the previously accepted efficiencies. This highlights the importance of the CBP continually reviewing new BMPs for inclusion in the model. Localities would benefit from conducting local monitoring and cost studies to help quantify the cost and impacts of these practices.
- The performance estimates for these BMPs assume that regular inspection and maintenance is occurring to keep them functioning properly. Given the relatively low cost of inspection (which is included in the Annual County Implementation Cost category) and maintenance and their importance for maintaining pollutant reduction, these activities are a very cost-effective use of public dollars.
- Cost-effectiveness is just one factor to consider when developing local water quality strategies. The feasibility of each BMP type in a given locality must also be considered. Site conditions, available land, local goals and conditions will affect the extent to which each BMP can be implemented. In addition, certain BMPs are opportunistic. For example, a locality can only use removal of illicit discharges to meet load reduction targets if illicit discharges exist and can be identified. Similarly, urban growth reduction may not be an option in some localities that are already built out, and the number of dog or lawn owners will limit the pollutant reductions that can potentially be achieved through outreach programs to change behaviors.

- Localities may want to consider the additional community benefits provided by certain BMPs when developing stormwater strategies. For example, BMPs that conserve or increase tree cover provide air quality benefits, recreation, shade, and aesthetic value. Removal of illicit discharges and cross connections addresses the public health concern of raw sewage entering waterways. The matrix provided in Table 4 summarizes how the BMPs in this study may provide the following benefits in addition to reducing stormwater nutrient loads:
    - **Public Health/ Safety:** BMPs improve public health and safety primarily by reducing bacteria and toxic chemicals in streams, or by cleaning streets or neighborhoods.
    - **Public Education:** Some BMPs have the direct purpose of educating the public, such as Nutrient Management Education, while others may contribute to public education by their placement, particularly if paired with signage or other information.
    - **Recreation:** Recreation, such as walking paths, can be directly incorporated into some BMPs, and others can enhance recreation by improving the quality of recreation areas.
    - **Neighborhood Beautification:** BMPs can improve the appearance of a neighborhood by their presence, or by contributing to the cleanliness of the neighborhood as a whole.
    - **Urban Heat Island:** This column refers to BMPs that reduce air temperature, typically by incorporating vegetation or reducing pavement.
    - **Carbon Footprint**: BMPs may reduce carbon in the atmosphere either directly by incorporating more vegetation or indirectly by contributing to more compact forms of development.
    - **Wildlife Habitat:** BMPs that offer habitat provide this benefit.
    - **Stream Habitat:** BMPs can improve stream habitat directly (such as in stream restoration), or more indirectly by controlling hydrology in the contributing watershed.
    - **Flood Control:** BMPs that detain or reduce the volume of stormwater, or protect the flood plain offer this benefit.
- BMP cost-effectiveness could greatly increase if some of the costs are shifted from the local government to a private homeowner or other party. It was beyond the scope of this analysis to tailor the cost and performance data to account for all possible situations; therefore it was assumed that all costs would be bourne by the municipality. As localities develop their water quality strategies, they should consider how to shift some of these costs by, for example, undertaking an outreach or incentive program to encourage private landowners to plant trees or install rain gardens.

Table 4. Supplemental Benefits of Urban Stormwater BMPs[9]									
BMP	**Public Health/ Safety**	**Public Education**	**Recreation**	**Neighbor-hood Beautification**	**Urban Heat Island**	**Wildlife Habitat**	**Carbon Footprint**	**Stream Habitat**	**Flood Control**
Bioretention	M	H	L	H	M	M	L	M	M
Bioswale	L	L	L	M	M	L	L	L	M
Dry Detention Ponds and ED Ponds	L	L	L	L	L	L	L	M	H
Above Ground Filtering Practices	M	M	L	L	L	L	L	L	L
Below Ground Filtering Practices	M	L	L	L	L	L	L	L	L
Forest Buffers	M	H	H	H	H	H	H	H	H
Hydro-dynamic Structures	L	L	L	L	L	L	L	L	L
Illicit Discharges	H	L	M	L	L	L	L	L	L
Urban Impervious Surface Reduction	L	L	M	H	H	M	M	M	H
Infiltration Practices	M	M	L	L	L	L	L	M	M
Nutrient Management	L	H	L	M	L	L	M	L	L
Permeable Pavement	M	M	L	M	M	L	L	M	H
Pet Waste Program	H	H	M	M	L	L	L	L	L

[9] "High" means that the BMP directly and often provides this benefit, while "Medium" means that the BMP may indirectly contribute to this benefit, or that the benefit is provided sometimes depending on the design. "Low" means that the practice provides little or no benefit.

Table 4. Supplemental Benefits of Urban Stormwater BMPs[9]									
BMP	**Public Health/ Safety**	**Public Education**	**Recreation**	**Neighbor-hood Beautification**	**Urban Heat Island**	**Wildlife Habitat**	**Carbon Footprint**	**Stream Habitat**	**Flood Control**
Retrofit of Existing Dry Pond	L	H	L	H	L	M	L	M	L
Street Sweeping	M	L	L	H	L	L	L	L	L
Tree Planting	M	M	M	H	H	H	H	M	M
Urban Growth Reduction	M	L	H	L	H	H	H	H	H

How to Use the Data

The cost and performance data compiled through this study can be used to develop planning-level cost and pollutant reduction estimates for Virginia Chesapeake Bay localities to compare results for different BMP scenarios. Localities should consider which pollutant requires the greatest percent load reduction (based on current loads and load allocations), and prioritize BMPs based on their cost-effectiveness for removing that pollutant. Other factors that localities will need to consider when developing their BMP scenarios (in addition to BMP cost-effectiveness) include feasibility of implementation and whether BMPs can achieve other local goals (e.g., local TMDL goals, community greening). Cost data can also be modified based on local data and the potential for cost-sharing associated with each BMP should also be considered. Given the numerous caveats and limitations described above, the data should not be used to develop detailed cost estimates for budgeting purposes or to develop cost estimates for specific projects/sites.

The values presented in this study provide a snapshot of urban BMP cost-effectiveness based on the data available at the time, and are likely to change as new BMPs are approved and/or pollutant removal efficiencies are refined. As of May 2013, panels are reviewing the following urban BMPs: urban tree planting, forest buffers, enhanced erosion and sediment control, illicit discharge elimination, urban shoreline erosion control, and urban filter strip/stream buffer upgrades. Other urban BMPs that will be scheduled for review include impervious disconnection, floating wetlands, street sweeping and MS4 minimum management measures. Localities developing stormwater management strategies are advised to check with the status of the latest CBP panel recommendations, which are available at: http://stat.chesapeakebay.net/?q=node/130&quicktabs_10=3.

Case Study Analysis

The BMP cost-effectiveness data compiled through this study provides a starting point for determining the most cost-effective range of options for localities to meet their urban nutrient load reduction goals for the Bay TMDL. The City of Richmond was selected for a case study analysis. The Center defined the implementation constraints for applying urban BMPs within the City (e.g., how much land is available for tree planting, miles of stream that could be restored) and determined cost and pollutant removal associated with the following BMP scenarios:

- Scenario 1: Old (pre-2012) CBP-approved BMPs (uses old rates for stream restoration and urban nutrient management, does not include stormwater retrofits) with no constraints on BMP implementation
- Scenario 2: Currently approved CBP BMPs (based on latest CBP panel recommendations) with implementation constraints
- Scenario 3: All BMPs (includes pet waste programs and illicit discharge correction) with implementation constraints

Originally, a fourth scenario was considered-- the existing WIP BMP scenario submitted to the state as part of the Phase II WIP. However, it was determined with the City that calculating load reductions and costs associated with this scenario would not be useful as the BMPs were selected to achieve a given load reduction that has since changed, and many of the assumptions used in developing the scenario are already outdated.

Methods

The Center had a telephone discussion with City staff to discuss the project goals, review the cost-effectiveness spreadsheet, identify data needs and discuss the applicability of the urban BMPs included in the study for Richmond. Following the meeting, City staff:

- provided GIS data so that Center staff could calculate metrics to help determine the feasibility of implementing the range of BMPs within the City;
- reviewed the list of BMPs and identified practices they considered to have limited applicability in Richmond due to lack of space (e.g., new wetlands/ponds, suburban bioretention), the built-out nature of the City (e.g., urban growth reduction), soil conditions (e.g., above ground sand filters, any practices on A/B soils), or other logistical factors (e.g., expansion of street sweeping would require coordination on private land);
- identified BMPs not included in the spreadsheet that the City wanted to include in their strategy (e.g., erosion and sediment control); and
- reviewed the spreadsheet to identify costs to be replaced with locally-derived values (permeable pavement was estimated at $15/square foot in Richmond, and replacement of sewer pipes was estimated at $450/linear foot).

Center staff modified the cost-effectiveness spreadsheet to replace Virginia average pollutant loading rates with Richmond-specific ones (derived from VAST), replace the above mentioned costs and modify the BMP list as described above. GIS was used to make estimates of the extent to which certain BMPs could reasonably be implemented within the City. BMPs were sorted according to cost-effectiveness and the maximum feasible implementation was entered for each BMP starting with the most cost-effective practice and going down the list, until the load reduction target or feasibility limits were met (depending on the scenario). BMPs that were determined to be infeasible for Richmond were skipped. The final set of BMPs considered in the Richmond scenarios is presented in Table 5, sorted according to cost-effectiveness for TSS removal, as the City indicated that sediment would be the most challenging pollutant reduction goal to reach.

Table 5. Urban BMPs Applicable in City of Richmond, Sorted by Cost-Effectiveness for TSS Removal

Urban BMP[10]	TN Cost Effectiveness (dollars per pound removed)	TP Cost Effectiveness (dollars per pound removed)	TSS Cost Effectiveness (dollars per pound removed)
Erosion and Sediment Control	83.17	235.02	0.30
Urban Stream Restoration (recommended interim efficiencies)	261.32	768.59	0.96
Illicit Discharge Elimination: sewer repair	17.14	68.54	1.71
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	610.74	1,862.38	3.10
Vegetated Open Channels, C/D soils, no underdrain	1,407.46	9,656.75	4.29
Bioswale (new)	333.85	2,137.87	4.45
Infiltration Practices w/o Sand, Veg. (new)	498.22	2,572.90	4.76
Infiltration Practices w/ Sand, Veg. (new)	490.19	2,689.63	4.98
Forest Buffers	202.28	1,534.39	5.05
Filtering Practices (sand, below ground)	1,068.76	3,909.49	6.06
Illicit Discharge Elimination: correction of cross-connections	17.70	70.79	6.69
Bioretention (new - suburban), C/D soils, underdrain	1,171.55	4,465.65	8.12
Impervious Urban Surface Reduction	1,771.42	5,643.84	10.45
Bioretention (retrofit, highly urban, C soils)	2,085.56	9,891.71	19.15
Urban Stream Restoration (original efficiencies)	2,613.21	17,421.41	26.13
Tree Planting	918.63	7,779.07	26.27
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	20,288.82	55,661.95	41.84
Hydrodynamic Structures (new)	7,717.49	26,475.29	58.83
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	14,490.26	79,507.43	59.77

[10] Shaded BMPs are approved by the CBP

Table 5. Urban BMPs Applicable in City of Richmond, Sorted by Cost-Effectiveness for TSS Removal			
Urban BMP[10]	**TN Cost Effectiveness (dollars per pound removed)**	**TP Cost Effectiveness (dollars per pound removed)**	**TSS Cost Effectiveness (dollars per pound removed)**
Pet waste program	0.44	3.36	N/A
Nutrient Management (old efficiencies)	306.73	641.91	N/A
Nutrient Management (recommended efficiencies)	579.38	2,055.82	N/A

The assumptions used to determine the likely extent of BMP implementation feasibility in the City of Richmond are described in Table 6. Note that, in some scenarios, the maximum possible implementation for each BMP was not necessary to achieve the load reductions (e.g., pet waste programs in Scenario 3).

Table 6. Assumptions and Data Used to Determine Feasibility Limits of BMP Implementation in Richmond	
BMP	**Assumptions and Data Used to Determine Feasibility Limits for Scenarios 2 and 3**
Stream restoration	• 97.2 stream miles are present within the City limits, 25 of which are on City property • Up to 5% of stream length within the City is feasible for restoration (6,600 linear feet of stream including both banks)
Urban nutrient management	• Non-forest vegetation is proxy for turf • Urban nutrient management practices can be applied on 30% of turf located on single family residential, institutional and vacant land (1,324 acres) • Urban nutrient management practices can be applied on 50% of public turf (445 acres); the remaining 50% will be needed for tree planting and stormwater retrofits • 100% of non-forest vegetation (8,917 acres) qualifies for an automatic credit for adoption of P fertilizer legislation (a reduction of 0.155 lbs TP/acre)
Tree planting	• 25% of non-forest vegetation on public land can be planted with trees (222 acres)
Forest buffers	• 1,100 acres of non-forest vegetation within 100-foot stream buffer • 100% of publicly owned unforested buffer (85 acres) can be reforested
Retrofit of existing dry pond	• Area treated by existing detention basins is 58.67 acres • These ponds provide no effective water quality treatment • 50% of ponds are feasible for conversion to a wet pond or wetland
Impervious surface reduction	• 1% of public parking lots can be replaced with pervious surface (3 acres)

Table 6. Assumptions and Data Used to Determine Feasibility Limits of BMP Implementation in Richmond	
BMP	**Assumptions and Data Used to Determine Feasibility Limits for Scenarios 2 and 3**
Structural stormwater BMPs	• 15% of impervious cover on public and institutional land is feasible for retrofitting (163 acres) • 15% of impervious cover on private land is feasible for retrofitting, but only 25% of this land has a willing landowner (500 acres) • Site constraints will limit the applicability of specific BMPs; therefore, a mix of BMPs will need to be included in each strategy. It was assumed the maximum acreage that could be treated by any one type of BMP was 200 acres, with the exception of infiltration practices which had a limit of 50 acres since they are so limited by soil type.
Erosion and sediment control	• Assume 23 acres per year for redevelopment sites (based on City's estimate from WIP submission)
Illicit discharge elimination	• Assumed that up to 50 cross connections and up to 25 sewer leaks could be found and fixed. Assumptions are conservative based on comparison to data from the City of Baltimore, where the City's Water Quality Management Section initiated 67-92 pollution source investigations per year from 2004-2008 (Scenario 3)
Pet waste programs	• Assumed 1 pet waste program could be implemented. Assumptions about number of pet waste stations and bag refills and mailings to residents taken from the Bacterial Implementation Plan for the James River and Tributaries in the City of Richmond (Maptech, 2011) (Scenario 3)

Table 7 presents the number of units implemented in the three BMP scenarios.

Table 7. Urban BMPs Implemented in Three Scenarios for the City of Richmond

BMP[11]	**Units**	**Units Treated by Scenario**		
		Old CBP BMPs	**Current CBP BMPs**	**All BMPs**
Bioretention (retrofit, highly urban, C soils)	Acres treated (100% impervious)	0	13	9
Bioswale (new)	Acres treated (50% impervious, 50% pervious)	1,200	200	200
Erosion and Sediment Control	Acres of active construction treated	23	23	23
Filtering Practices (sand, below ground)	Acres of impervious land treated	0	200	200

[11] shaded BMPs are approved by the CBP

Table 7. Urban BMPs Implemented in Three Scenarios for the City of Richmond				
BMP[11]	Units	Units Treated by Scenario		
		Old CBP BMPs	Current CBP BMPs	All BMPs
Forest Buffers	Acres of pervious land planted	450	85	85
Illicit discharges- correction of cross-connections	Number of cross-connection corrected	0	0	50
Illicit discharges- sewer repair	Number of illicit discharges repaired	0	0	25
Impervious Urban Surface Reduction	Acres of impervious cover removed	0	3	3
Infiltration Practices w/ Sand, Veg. (new)	Acres of impervious land	0	0	0
Infiltration Practices w/o Sand, Veg. (new)	Acres of impervious land	0	50	50
Nutrient Management (old efficiencies)	Acres of pervious land treated	2,500	0	0
Nutrient Management (recommended efficiencies)[12]	Acres of pervious land treated	0	10,686	8,917
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	Acres of impervious land	0	0	0
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	Acres of impervious land	0	0	0
Pet waste program	Number of programs implemented	0	0	0
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	Acres treated (50% impervious, 50% pervious)	0	29	29
Tree Planting	Acres of pervious land planted	0	222	220
Urban Stream Restoration (original efficiencies)	Linear feet of stream restored	0	0	0
Urban Stream Restoration (recommended interim efficiencies)	Linear feet of stream restored	0	6,600	6,600
Vegetated Open Channels, C/D soils, no underdrain	Acres treated (50% impervious, 50% pervious)	1,000	200	200

Results and Discussion

The total pollutant reduction and cost for each scenario is summarized in Table 8. The estimated target load reductions for the City of Richmond reflect the latest calculations from the state on

[12] * In Scenarios 2 and 3, an automatic credit was given for adoption of statewide phosphorus fertilizer legislation, which applies a 26.7% reduction to all pervious land in the jurisdiction, in this case an estimated 8,917 acres. There is no cost associated with this reduction. In Scenario 2, urban nutrient management practices were applied to an additional 1,769 pervious acres and this part of the credit does have a cost associated with it.

required reductions from municipal separate storm sewer systems. These targets are continually being refined and it is expected that they will change from what is presented here.

Only Scenarios 1 and 3 achieve the required load reductions, but Scenario 3 does so at a cost savings of more than $27 million due to the inclusion of some highly cost effective BMPs that are not yet approved by the CBP (e.g., illicit discharge removal, pet waste programs). Because limited data is available on how many illicit discharges are present in the City, the estimates used in Scenario 3 were conservative. It may be possible for the City to realize significantly greater pollutant reductions from illicit discharge removal but field surveys are needed to make this evaluation. Also, it is improbable that Scenario 1 could actually be implemented, since it is not based on real-world constraints to BMP implementation (for example, it would be difficult to find enough appropriate sites to treat 1200 acres with bioswales or enough willing landowners to reforest 450 acres of buffers). In Scenario 2, the assumed limits of BMP implementation were reached before the target pollutant load reductions for TN and TSS were met. Therefore, the true cost will be upwards of the $67 million shown in Table 8 to make up the difference.

Table 8. Pollutant Reduction and Costs Associated with Three BMP Scenarios in the City of Richmond

Scenario	TN Load Reduction (lbs/yr)	TP Load Reduction (lbs/yr)	TSS Load Reduction (lbs/yr)	Total Cost (over 16 years)
1. Old CBP BMPs with no constraints	15,119	3,301	1,089,336	$89.2 million
2. Current CBP BMPs with constraints	13,007	3,282	885,949	$67.8 million++
3. All BMPs with constraints	32,544	8,132	1,081,485	$62.0 million
Estimated Target Load Reduction for City of Richmond	15,100	2,730	1,080,518	N/A

++ Because this scenario does not meet the required reductions for TS or TSS, the total cost will be greater than $67.8 million

At present, only the suite of BMPs included in Scenario 2 are considered acceptable by the CBP. Some suggested next steps for the City to further refine a BMP scenario that achieves the required reductions, is cost-effective, and is realistic from an implementation standpoint include:

- Evaluate the potential to use the most cost effective practices for TSS reduction, including erosion and sediment control, stream restoration and sewer repairs.
- If the City considers erosion and sediment control a realistic option, they may want to invest resources in programs and incentives to encourage redevelopment of City land in order to achieve the estimated load reductions from applying erosion and sediment control practices on redevelopment sites. They will also want to keep abreast of the

expert panel for enhanced erosion and sediment control, whose recommendations are expected to be finalized in Summer 2013.

- Conduct stream assessments to identify stream reaches in need of restoration, collect data to develop concepts for stream restoration projects, and prioritize sites for restoration in coordination with upstream retrofit projects and riparian plantings. As the second most cost-effective BMP for sediment, it could greatly benefit the City to determine how much stream restoration is possible and invest in pursuing restoration projects. These stream surveys could be combined with the outfall surveys described below.
- The City will need to conduct outfall surveys and monitoring using the latest IDDE protocols if they wish to rely on illicit discharge removal for nutrient reduction credits, both to establish baseline conditions and to verify corrections of discharges. The City should stay informed of the expert panel recommendations on this topic, which are expected in Summer 2013. Any new Richmond-specific data that is collected can be used to further refine the costs and pollutant reductions associated with this practice.
- Consider expansion of the municipal street sweeping program to help achieve the sediment reduction goal. Although the City has indicated that this will require coordination on private land, the relative cost-effectiveness of this practice for reducing sediment could offset the additional resources needed to expand the program. In particular, the mass loading approach results in greater credit than the street lane approach, and this requires tracking of the debris removed by sweepers each year.
- Inventory public lands, open space, institutional land, rights-of-way and vacant lands to identify opportunities for practices such as tree planting, urban nutrient management and stormwater retrofits and refine the targets for implementation of these BMPs accordingly. The cost and pollutant removal associated with stormwater retrofits can also be refined using more detailed information from specific candidate sites.
- Consider aggressive pursuit of implementation on private land to achieve pollutant reductions at a lower cost, especially for non-structural BMPs such as forest buffers, tree planting and urban nutrient management. This will likely require financial incentives or direct assistance as well as outreach.

Some additional options for the City to refine their plan to meet the Bay TMDL goals and help to fund its implementation are to:

- Explore whether additional credit can be given for BMPs already in the ground. It is unclear to what extent existing BMPs have been taken into account in the 2009 progress loading rates from VAST. There may be opportunity to locate and report practices that were not previously accounted for in the model.
- Explore nutrient credit trading as an option for the City to more cost-effectively achieve its water quality goals. The mechanisms for doing so have not been fully fleshed out by the state, but should be further investigated. This can include a scenario where the City purchases credits as well as the possibility of the City generating credits. For example, in Scenario 3, in order to meet the TSS target, the resulting TN and TP reductions exceeded the targets by more than 2.1 times. It may be possible for the City to sell these credits to another entity.
- Implement the more cost effective CBP-accepted BMPs in the short term, and save the more costly structural retrofits for the longer term, to provide more time for CBP adoption of newer and more cost effective BMPs, such as pet waste programs and

removal of illicit discharges. The illicit discharge removal credit is currently under discussion and recommendations are expected to be presented to the Urban Stormwater Workgroup this summer.

References

Amick, R.S., and E. H. Burgess. 2000. *Exfiltration in Sewer Systems.* National Risk Management Research Laboratory, Edison, New Jersey 08837 National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268

Brown, E., D. Caraco and R. Pitt. 2004. *Illicit Discharge Detection and Elimination: a guidance manual for program development and technical assessments*. Center for Watershed Protection and University of Alabama. EPA X-82907801-0.U.S. EPA Office of Wastewater Management, Washington, D.C.

Burks, B.D. and M.M. Minnis. 1994. *Onsite Wastewater Treatment Systems.* Madison, WI: Hogarth House, Ltd.

Caraco, D. 2001. *The Watershed Treatment Model: Version 3.1*. U.S. Environmental Protection Agency, Region V. Center for Watershed Protection. Ellicott City, MD.

Chesapeake Stormwater Network. 2011. *Nutrient Accounting Methods to Document Local Stormwater Load Reductions in the Chesapeake Bay Watershed*. Technical Bulletin No. 9. Chesapeake Stormwater Network. Ellicott City, MD.

Chesapeake Bay Program. 2011. *Nonpoint Source Best Management Practices and Efficiencies currently used in Scenario builder.* Last updated February 9, 2011. Available at: http://www.chesapeakebay.net/about/programs/watershed_implementation_plan_tools/#2

Chesapeake Bay Program Water Quality Goal Implementation Team (CBP WQGIT). 2010. *Protocol for the Development, Review and Approval of Loading and Effectiveness Estimates for Nutrient and Sediment Controls in the Chesapeake Bay Watershed Model*. http://www.chesapeakebay.net/documents/merged_Nutrient-Sediment_Control_Review_Protocol.pdf

City of Richmond. 2010. *Sanitary Sewer System Design Standards and Standard Specifications and Details.* Department of Public Utilities. Richmond, VA.

Davis, Morris A. and Jonathan Heathcote, 2007, "The Price and Quantity of Residential Land in the United States," Journal of Monetary Economics, vol. 54 (8), p. 2595-2620; data located at Land and Property Values in the U.S., Lincoln Institute of Land Policy http://www.lincolninst.edu/resources/

Hashemi, S.B. 2008. *Construction Cost of Underground Infrastructure Renewal: A Comparison of Traditional Open-Cut and Pipe Bursting Technology*. M.S. Thesis, University of Texas at Arlington. 142 pp.

King, D., and P. Hagen. 2011. *Costs of Stormwater Management Practices in Maryland Counties*. Prepared for Maryland Department of the Environment by the University of Maryland Center for Environmental Services. Technical Report Series No. TS-626-11 of the University of Maryland Center for Environmental Science.

Lilly, L. A., Stack, B. P., and D. S. Caraco. 2012. Pollution Loading from Illicit Sewage Discharges in Two Mid-Atlantic Subwatersheds and Implications for Nutrient and Bacterial Total Maximum Daily Loads. *Watershed Science Bulletin* 3(1): 7-17.

Maptech, Inc. 2011. *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond Technical Report*. Prepared for Virginia Department of Environmental Quality.

Maryland Department of the Environment (MDE). 2011. *Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated.* Guidance for National Pollutant Discharge Elimination System Stormwater Permits. Maryland Department of the Environment. Baltimore, MD.

Metcalf and Eddy. 1991. *Wastewater Engineering: Treatment, Disposal, and Reuse*. McGraw-Hill, Inc. New York, NY.

Narayanan, A. and R. Pitt. 2006. *Costs of Urban Stormwater Control Practices*. University of Alabama. Department of Civil, Construction, and Environmental Engineering. Tuscaloosa, AL.

Reese, A. 2000. NPDES Phase II Cost Estimates. In: *National Conference on Tools for Urban Water Resource Management and Protection*. Chicago, IL.

Schueler, T. and C. Lane. 2013. *Recommendations of the Expert Panel to Define Removal Rates for Urban Nutrient Management*. Prepared by the Chesapeake Stormwater Network. Final Approval by the Water Quality Goal Implementation Team on March 11, 2013.

Schueler, T. and C. Lane. 2012. *Recommendations of the Expert Panel to Define Removal Rates for Urban Stormwater Retrofit Projects*. Prepared by the Chesapeake Stormwater Network. Final Approval by the Water Quality Goal Implementation Team on October 9, 2012.

Schueler, T. and B. Stack. 2013. *Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects.* Prepared by the Chesapeake Stormwater Network. Final Approval by the Water Quality Goal Implementation Team on May 13, 2013.

Schueler, T., Hirschman, D., Novotney, M., and J. Zielinski. 2007. *Urban Stormwater Retrofit Practices Version 1.0*. Center for Watershed Protection. Ellicott City, MD.

Swann, C. 1999. *A Survey of Residential Nutrient Behaviors in the Chesapeake Bay*. Widener-Burrows, Inc. Chesapeake Research Consortium. Center for Watershed Protection. Ellicott City, MD.

Tribo, J. 2011. *Implementation Plan for Fecal Coliform TMDL for Mill Creek and Powhatan Creek*. Hampton Roads Planning District Commission.

Appendix A: Development of Cost Estimates

To develop costs for BMPs not included in the King and Hagan (2011) study, the Center used the methods and assumptions outlined below. For consistency with King and Hagan, the costs included design, installation, land values and maintenance costs.

The costs in King and Hagan are reported in dollars per impervious acre treated. Our study assumed that the following BMPs treat 50% impervious land and 50% pervious land: wet ponds and wetlands, dry detention ponds, hydrodynamic structures, bioretention (suburban), bioswales and vegetated open channels. Therefore, the costs for these practices were adjusted so that the costs and pollutant removal values were in the same units. This conversion was made based on the following assumptions. The surface runoff coefficient for turf is approximately 0.20 inches per inch of rainfall, while the runoff coefficient for impervious cover is 0.95 (from the Virginia Stormwater Management Spreadsheet, assumes B soils). Consequently, an acre of turf is equivalent to 0.2 acres of impervious cover in terms of the runoff produced. To convert the construction cost from dollars per impervious acre to dollars per acre treated for a BMP that treats 0.5 acre of impervious cover and 0.5 acre of pervious cover, we used the following calculation:

Cost per acre treated (assumes drainage area is 50% impervious, 50% pervious) =
*Cost/impervious acre * [0.5 pervious * 0.2 (impervious/pervious) + 0.5 impervious], or*
*Cost/impervious acre * 0.6*

Urban growth reduction
Costs for urban growth reduction (e.g., restricting development on undeveloped parcels through purchase of easements or zoning changes) were derived using best professional judgment. It was assumed that the only up-front costs associated with this practice would involve the cost of land. Using the assumptions from King and Hagan, it was assumed that the entire acreage is required for this practice but only 50% is actually developable so the opportunity costs are 50% of the cost of land. It was also assumed that there would be no annual maintenance costs, annual intermittent maintenance costs, or county implementation costs associated with this practice.

Pond retrofits
Costs for pond retrofits (e.g., conversion of dry ponds to a wet pond or wetland) were derived from Appendix E of the manual *Urban Stormwater Retrofit Practices* (Schueler et al., 2007). The median value for construction cost per impervious acre treated was used and was brought up to 2011 dollars using an online inflation calculator. [13] This cost was converted to a cost per acre treated as described above. It was assumed that design costs for pond retrofits would be similar to the design cost associated with installing a new wet pond or wetland as a retrofit, so the value of 50% from King and Hagan was used. The operation and maintenance and county implementation cost assumptions provided by King and Hagan for wet ponds and wetlands were assumed to be applicable to pond retrofits. Land values were set at zero since the BMP involves modification to an already-constructed practice for which land has already been acquired.

[13] http://data.bls.gov/cgi-bin/cpicalc.pl.

Pet waste programs

Very limited data was available to estimate the cost of programs to reduce pollution from pet waste. This is due in part to the limited number of these programs across the county and the fact that these programs can be variable in terms of their components. In some cases, municipalities conduct outreach programs that focus on various topics including pet waste but the costs for pet waste reduction are not tracked as separate from other program costs. For this analysis, we assumed that a community was setting up a program for the sole purpose of reducing pollution from pet waste. It was assumed that pet waste programs include the following components: adoption of a pet waste ordinance, installation of pet waste stations complete with signs, basket and bags for picking up pet waste in parks and public places, and an educational component where mailings are used to inform residents of the pet waste pickup law and encourage/teach them how to properly dispose of pet waste.

In order to determine the total annual cost of the program, assumptions were made about the number of pet waste stations installed and the number of bag refills needed per year. Most of these assumptions were taken from the *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond* (Maptech, 2011) for a typical program in Virginia. For example, it was assumed that 10 bags per day would be used at each pet waste station location. These same assumptions were used when estimating the pollutant reduction associated with pet waste programs so that program costs and reductions were estimated for the same number of mailings and pet waste bags. Localities who wish to use the cost data to estimate program costs can change the assumptions about these units to be more reflective of their population and program goals.

The program components included in the "construction" cost are: adopting a pet waste ordinance, installation of 56 pet waste stations with a sign and basket, purchase of 204,400 bags to fill pet waste stations for the first year, and the cost of 161,024 mailings for the educational campaign (printing and postage). The cost to adopt a pet waste ordinance is from Narayanan and Pitt (2006) and was converted to 2011 dollars using the online inflation calculator. The *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond* (Maptech, 2011) provided unit costs for installation of pet waste stations with sign and basket and bag refills. The current price of a stamp was used as the basis for the cost of mailings and printing costs were assumed to be $0.25/color copy. Design costs included development of educational materials, which were taken from Tribo (2011).

Annual maintenance costs included bag refills (204,400 per year), the labor to replace bags and empty trashcans (1 day per week of staff time * $25/hr), and trash disposal fees. For trash disposal, we assumed 10 bags a day collected per station * 0.1 lbs of waste per bag * 56 stations * 365/year = 20,440 lbs of waste collected per year. We then applied some discounts to account for bags that were taken but not disposed of in the trashcan (75%) and people who would have properly disposed of the dog waste anyway (40%) = 6,132 pounds per year. At a typical cost of $0.05 per pound for trash disposal, the total annual cost for trash disposal is $307. Intermittent maintenance included replacement of two pet waste stations (due to vandalism or other damage) and additional mailings for the educational campaign (printing and postage). Each household would receive five mailings over the course of the program based on the notion that multiple exposures are needed to promote and maintain behavior change. Annual county implementation costs were extrapolated from the county implementation costs estimated by King and Hagan (2011) for urban nutrient management, which is expected to have similar requirements.

We recognize that there are many other approaches a community may wish to employ to encourage adoption of this BMP; therefore, these estimates should be treated with caution.

Illicit discharges- correction of cross connections
The cost to correct cross connections of the sanitary sewer system to the storm sewer do not vary as widely as the costs to fix other types of illicit discharges and are typically relatively inexpensive fixes. Cost data was collected for 8 cross connections in 6 communities: Cambridge, MA; Boston, MA; Knoxville, TN; Raleigh, NC; Springfield, MO; and Monroe County, NY. The source of data for the first 5 communities was a survey conducted to develop the *Illicit Discharge Detection and Elimination Manual* (Brown et al., 2004), brought up to 2011 dollars using an online inflation calculator: http://data.bls.gov/cgi-bin/cpicalc.pl. The correction cost per connection for each data source was used to develop an average "construction cost" for this BMP. In some cases, the cost of correction required dye testing and televising.

Design costs for this BMP included the estimated cost of identifying sewage discharges through outfall surveys and the cost to isolate the source of the discharge. The assumptions used to develop this per-connection design cost were derived from CWP data collected in the Sligo Creek Watershed in MD and include the following: the average number of stormwater outfalls per mile of stream is 22.5; the percent of assessed outfalls that have dry weather flow is 27%; and the percent of flowing outfalls having indicators for sewage is 60%. These assumptions allowed us to estimate the number of outfalls (and therefore stream miles) a team would need to assess in order to identify one sewage discharge, as well as the number of outfalls that actually require water quality sampling. An average cost to conduct the outfall survey per mile of stream was taken from Brown et al (2004) and brought up to 2011 dollars. The average cost of sample analysis was derived using CWP data from past IDDE projects and assumes field or in-house analysis of ammonia, fluoride, potassium, detergents and bacteria as well as contract lab analysis for TN and TP. The sample analysis cost assumes 1 hour of staff time (at $25/hour) per sample.

Annual maintenance costs associated with this practice include the cost to conduct annual monitoring to verify that discharges have been eliminated. We assumed this would require annual sampling at the outfall as well as the point of discharge. Costs include 1 hour of staff time per site to collect samples (at $25/hr). Sample analysis costs include $40/sample for in-house or field analysis of ammonia, flouride, potassium, detergents and bacteria, plus 1 hour of staff time (at $25/hr) plus $20 per sample for contract lab analysis of TN and TP. It was assumed that monitoring to verify the discharge has been corrected would be required for 5 years, so the maintenance costs associated with 5 years of monitoring were spread over 20 years.

Illicit discharges- sewer repair
It is difficult to determine costs for illicit discharges caused by factors other than cross connections due to the limited available data and wide variability in the costs of correction, depending on the source of the problem. In most cases, particularly in older sewerage systems that are known to have leaks, replacement of a section of pipe is required to fix the discharge. A simplified cost estimate for correction of illicit discharges was derived for this study by assuming

a given length of pipe would need to be replaced. A pipe length of 400 feet was assumed, based on the maximum allowable distance between manholes cited in the City of Richmond's sanitary sewer system design standards (City of Richmond, 2010). The average cost of pipe replacement using pipe burst and open cut technologies was taken from *Construction Cost of Underground Infrastructure Renewal: A Comparison of Traditional Open-Cut and Pipe Bursting Technology* (Hashemi, 2008) and costs were brought up to 2011 dollars. Other methods of pipe replacement (e.g., cured in place, trenchless technologies) exist but limited cost data was available for these methods.

Design costs for repair of illicit discharges were assumed to be very low relative to the construction cost. Therefore, the low end of the range of design costs from King and Hagan (10%) was used to estimate the design costs associated with this BMP. Annual maintenance costs associated with this practice include the cost to conduct annual monitoring to verify that discharges have been eliminated. We assumed this would require annual sampling at the outfall as well as the point of discharge. Costs include 1 hour of staff time per site to collect samples (at $25/hr). Sample analysis costs include $40/sample for in-house or field analysis of ammonia, flouride, potassium, detergents and bacteria, plus 1 hour of staff time (at $25/hr) plus $20 per sample for contract lab analysis of TN and TP. It was assumed that monitoring to verify the discharge has been corrected would be required for 5 years, so the maintenance costs associated with 5 years of monitoring were spread over 20 years. Overall, the cost estimates for this BMP are based on limited data and assumptions and should be treated with caution.

Erosion and sediment control (Richmond case study)
The costs in King and Hagan are reported in dollars per impervious acre treated. The King and Hagan study assumed a "typical" project being a new residential subdivision at a 14-acre medium density development site with 30% impervious acreage coverage and BMPs including silt fences, sediment ponds, and related practices. To convert the King and Hagan costs to dollars per acre of cleared land (the units used to estimate performance) we assumed that on a typical site, 75% of the site is cleared. Therefore, to convert the cost per impervious acre to a cost per cleared acre, we divided the costs by 2.5.

Urban nutrient management
This practice includes the application of qualifying urban nutrient management practices on urban lawns as a result of outreach campaigns, as well as an automatic credit for statewide adoption of P fertilizer legislation. We assumed that the latter part of the credit had no cost associated with it. Costs for urban nutrient management outreach campaigns were taken from King and Hagan (2011) and the assumptions are described below:

Best available data indicate that "retail" (i.e., direct mail) public outreach campaigns cost about $15 per household contacted. For an illustrative county, we assumed that each household has 5,941 square feet of turf and 2,406 square feet of impervious cover (medium density development). This means that 7.33 households need to adopt this BMP to potentially result in an acre of turf being treated, at a cost $109.98 per turf acre. Based on a review of direct mail response rates, we assumed that 2% of households contacted will respond positively to this outreach effort aimed at reducing nutrient runoff which brings the cost per turf acre treated to $5,497.50/acre. Our estimate does not include any additional costs for soil tests to determine the appropriate amount of fertilizer required. We recognize that there are other approaches a community may wish to employ to encourage adoption of this BMP. For the reasons described above, our estimate should be treated with caution.

Appendix B: Development of Pollutant Reduction Estimates

Stormwater retrofits

Pollutant removal effectiveness of stormwater retrofits was determined based on recommendations by a CBP review panel. The final draft report (Schueler and Lane, 2012) was approved by the Water Quality Goal Implementation Team on October 9, 2012. The panel classified retrofits into two broad project categories -- new retrofit facilities and retrofits of existing BMPs. These two categories encompass a broad range of potential retrofit application, including new constructed wetlands, green streets or rain gardens, as well as conversion, enhancement or restoration of older BMPs to boost their performance. Given the diversity of possible retrofit applications, the panel decided that assigning a single universal removal rate was not practical or scientifically defensible. Every retrofit is unique, depending on the drainage area it treats, the treatment mechanism employed, its volume or size and the antecedent degree of stormwater treatment, if any. Instead, the panel elected to develop a protocol whereby the removal rate for each individual retrofit project is determined based on the amount of runoff it treats and the degree of runoff reduction it provides.

The panel conducted an extensive review of recent BMP performance research and developed a series of retrofit removal adjustor curves to define sediment, nitrogen and phosphorus removal rates. Removal rates for new retrofits are derived from the adjuster curves based on the runoff depth captured by the practice and whether the BMP is defined as a "runoff reduction" or "stormwater treatment" practice. Removal rates for retrofits that involve conversion of an existing BMP to another BMP type can be done in one of two ways. For older BMPs that provide no water quality treatment, the removal rate for the converted practice is derived from the CBP modeling efficiencies associated with that practice (CBP, 2011), or from the retrofit removal adjustor curves if the conversion involves multiple treatment mechanisms. The second method defines the removal rate for BMP conversions as the incremental difference between the removal rate for the converted BMP and the removal rate for the original BMP, which are derived using the retrofit removal adjustor curves.

The site-specific nature of stormwater retrofit performance made it a challenge to include them in the present cost-effectiveness study in a meaningful way. We chose to incorporate the recommendations by including three common examples of stormwater retrofits so they could be compared to other BMPs in terms of their cost-effectiveness. The methods outlined in the panel report should be used by localities to refine their projected pollutant load reductions once they have identified specific and feasible locations for retrofits within the community, and drainage area characteristics and runoff volume treated by the practice are known. The major benefit of the panel recommendations is that communities now have a mechanism by which to get credit for retrofit practices that do not capture the full treatment volume dictated by state stormwater standard, due to the limitations of installing BMPs in the developed landscape.

For the current study we included three representative stormwater retrofits. First was conversion of a dry detention pond to a wet pond or wetland, which is one of the most likely scenarios. We assumed for this example that the detention pond was designed solely for flood control purposes and provided no water quality benefit. Based on the recommendations in Schueler and Lane (2012), it was assumed that the removal rate associated with the existing BMP was zero and the removal rates associated with the converted BMP were 20% for TN, 45% for TP and 60% for

TSS. The second retrofit type included in the study was a new bioretention retrofit in a highly urban area. We assumed the facility drained one acre of 100% impervious cover with C soils, the facility made up 6% of the drainage area, with one foot of ponding and provided 0.72 inches of treatment per impervious acre. Using the methods described in Schueler and Lane (2012), we determined the removal rates for this practice to be 51% for TN, 59% for TP, and 63% for TSS. The third retrofit type included in the study was a new constructed wetland. We assumed the facility drained 40 acres, with 50% impervious cover and 50% pervious cover and C soils, the facility comprised 4% of the drainage area, with 0.5 feet of ponding and provided 0.48 inches of treatment per impervious acre. Using the methods described in Schueler and Lane (2012), we determined the removal rates for this practice to be 25% for TN, 40% for TP, and 51% for TSS. The examples included in this study provide a snapshot of cost-effectiveness for specific retrofit site examples that represent a BMP conversion, a "runoff reduction" practice and a "stormwater treatment" practice.

Pet waste programs

Pollutant reductions resulting from educational programs, such as pet waste programs, are not readily available and are difficult to measure. Therefore, a number of assumptions were used to develop an initial estimate of performance for pet waste programs. This estimate should be treated with caution. The same assumptions regarding specific program components that were used to develop the costs of a pet waste program were used to estimate performance.

The two major components of a pet waste program for which specific pollutant reductions were calculated included installation of pet waste stations complete with signs, basket and bags for picking up pet waste in parks and public places, and an educational component where mailings are used to inform residents of the pet waste pickup law and encourage/teach them how to properly dispose of pet waste. In order to determine the pollutant reduction associated with these activities, assumptions were made about the number of pet waste stations installed (56), number of residents targeted through the educational program (161,024), and the number of bag refills needed (204,400 per year). These assumptions were based on the *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond* (Maptech, 2011). Localities who wish to use this data to estimate program performance can change the assumptions about these units to be more reflective of their population and program goals.

For pollutant reduction associated with pet waste stations, it was assumed that a certain nutrient load was captured and properly disposed of on an annual basis in pet waste bags located in public places such as parks. The following formula was used:

*# of bags/yr * waste production (lbs/dog/day) * concentration of pollutant in dog waste (lb/lb) * fraction of daily waste captured per bag * fraction of pollutant delivered to stream * fraction of bags used to properly dispose of pet waste * 365 days/yr * fraction of dog walkers who rarely clean up after their dogs*

The values for waste production, concentration of pollutant in dog waste, and fraction of pollutant delivered to the stream were derived from the Watershed Treatment Model (Caraco, 2001), which calculates pollutant loads and reductions at the watershed scale. We assumed that only some portion of bags taken from the pet waste stations would actually be used to properly dispose of pet waste, while some (25%) were either not used or were not properly disposed of. We also assumed that each bag would be taken by a dog owner and would capture approximately 1/3 of their dog's daily waste. Finally, we assumed that some portion of the bag users would have brought their own bag and properly disposed of the waste anyway, so the pollutant load reduction estimate was discounted based on data from Swann (1999) regarding the proportion of dog owners who typically do not clean up after their dogs. The resulting value is considered to be somewhat conservative.

For the educational component of the pet waste program, we first estimated the maximum potential annual nutrient load reduction using the following formula, assuming that all dog owners targeted by the outreach change their pet waste disposal behavior:

*# households reached * waste production (lbs/dog/day) * concentration of pollutant in dog waste (lb/lb) * fraction of households with a dog * fraction of pollutant delivered to stream * 365 days/yr*

Then, we discounted the maximum potential nutrient load reduction to account for the fact that not all households targeted by the outreach actually walk their dog, some already properly dispose of pet waste, some will never look at the flyer and others will be unwilling to change their behavior. We used the following formula:

*Potential pollutant load reduction per year (if everyone that has a dog changes behavior) * of households with dogs, fraction who walk them (0.50) * of dog walkers, fraction that rarely clean up after their dog (0.40) * of those, fraction who are willing to change behavior (0.60)* awareness factor (0.08)*

The above values were taken from a variety of sources including Caraco (2001), Swann (1999), NSR (1998) and Pellegrin Research Group (1998). We assumed that each household would receive five mailings over the implementation time period, and that the resulting pollutant load reduction would occur annually.

Illicit discharges- correction of cross connections

Pollutant removal performance associated with correction of cross connections was estimated based on the assumption that 100% of the pollutant load would be removed for each correction, and the pollutant load per connection was estimated based on the wastewater generation and characteristics for a typical household. It also assumed that the cross connection was present for the entire year before being corrected. The following formula was used to estimate the pollutant load from a typical cross connection:

*[Wastewater generation per dwelling unit (gallons per capita per day) * individuals per dwelling unit * 365 days/yr * 3.78 liters per gallon * pollutant concentration in wastewater (mg/L)] / 454000 mg/lb*

The values for wastewater generation per dwelling unit and concentration of TSS and TP in wastewater were derived from Metcalf and Eddy (1991). The lower end of the range for phosphorus was used to account for programs to reduce phosphorus in wastewater. The TN concentration in wastewater was derived from Burks and Minnis (1994) and the number of individuals per dwelling unit was taken from Reese (2000). The resulting values are based on limited data and should be used with caution.

Illicit discharges- sewer repair
Pollutant removal performance associated with correction of illicit discharges was estimated based on the assumption that 100% of the pollutant load would be removed for each corrected discharge, and the pollutant load per discharge was estimated based on the following assumptions:

- Assumes that 400 feet of pipe must be replaced to correct each individual discharge
- This method applies to older sewerage systems that are known to have leaks as indicated by elevated baseflow concentrations of bacteria or ammonia
- The method applies to sections of the sewerage system that are within the groundwater matrix
- A conservative assumption was used regarding delivery to the stream, i.e., when sewage enters the groundwater matrix, not all of it reaches surface water but instead, some processing occurs. Therefore, a delivery ratio was applied.

The following formula was used to estimate the annual pollutant load from a typical illicit discharge:

*[Pipe length (miles) * pipe diameter (inches) * ex-filtration rate (gallons/day/inch diameter/mile of pipe) * pollutant concentration in wastewater (mg/L) * 365 days/yr * 3.785 liters/gallon * 2.2046 lbs/kg * delivery ratio] / 1000000 mg/kg*

Ex-filtration refers to the leakage of wastewater from sanitary sewer pipes. The values for concentration of TSS and TP in wastewater were derived from Metcalf and Eddy (1991). The lower end of the range for phosphorus was used to account for programs to reduce phosphorus in wastewater. The TN concentration in wastewater was derived from Burks and Minnis (1994). The pipe length of 400 feet was determined based on the maximum allowable distance between manholes in the City of Richmond's Sanitary Sewer System Design Standards. An average pipe diameter of 10 inches was assumed. The sewer exfiltration rate was taken from Amick and Burgess (2000). The resulting values are based on very limited data and should be used with caution.

Urban nutrient management
Pollutant removal effectiveness of urban nutrient management was determined based on recommendations by a CBP review panel. The final report (Schueler and Lane, 2013) was approved by the Water Quality Goal Implementation Team on March 11, 2013. The panel recommended three types of credits. The first credit is based on statewide phosphorus fertilizer legislation where an automatic credit is given for states that have adopted statewide P fertilizer legislation, such as Virginia. States that have not adopted this legislation also receive a lower credit based on the gradual industry phase-out of phosphorus fertilizer. The credit begins in 2013 and reflects declines in P fertilizer application rates due to this legislation and to the gradual industry phase out of P in fertilizer products. The automatic credit expires in three years and will be replaced by a more verifiable and variable credit based on declines in unit area P application

rates derived from improved non-farm fertilizer sales statistics. States may also be eligible for a state-wide N reduction credit in 2014 if they can document declines in unit N fertilizer applications relative to the current application rate benchmark employed in the Watershed Model. States that implement N fertilizer regulations that satisfy certain verification requirements may also quality for an automatic credit, although Virginia has yet to do so.

The third part of the credit is a reduction in TN and TP applied to the acreage of pervious land covered by qualifying urban nutrient management practices, based on the site risk for N and P export. This credit is calculated as an efficiency that is applied to acres of pervious land. For this study, a blended rate of 4.5% TP reduction and 9% TN reduction was used given that site risk will vary within individual jurisdictions.

Schueler and Lane (2013) recommend a TP reduction credit of 26.7% for Virginia, which has adopted P fertilizer legislation, and it is implemented by applying a unit area load reduction to all pervious acres within the state. For this study, the average TP loading rate in Virginia is 0.5 lbs/acre of urban pervious land (from VAST). Therefore a 26.7% in this rate is equivalent to a reduction of 0.134 lbs TP per acre of pervious land. This value was added to the total per-acre TP reduction calculated using the blended rates for qualifying urban nutrient management described above. The load reduction from pervious areas is assumed to be additive as statewide guidance of how to implement this credit has not yet been developed[14]. A statewide reduction in nitrogen is not available at this time in Virginia.

To use the resulting cost-effectiveness value to estimate the total cost and pollutant reduction associated with urban nutrient management for an individual jurisdiction will require entering both the total number of acres of pervious land in the jurisdiction and the acres of pervious land on which qualifying urban nutrient management practices will be applied. However, there should be no cost associated with the automatic credit, which is applied to all pervious acres in the jurisdiction. This approach was chosen because the credit is temporary and is essentially a credit against the required load reduction as opposed to a permanent adjustment to pervious land loading rates in the Watershed Model. Note that in 2016, the automatic credit will be replaced with improved state reported estimates of P fertilizer application to pervious land using procedures outlined in Schueler and Lane (2013).

Urban stream restoration

Pollutant removal effectiveness of urban stream restoration was determined based on recommendations by a CBP review panel. The final draft report (Schueler and Stack, 2013) was approved by the Water Quality Goal Implementation Team on May 13, 2013. The panel crafted four general protocols to define the pollutant load reductions associated with individual stream restoration projects, However, the panel acknowledged that the new protocols may not be easily integrated into existing CBP modeling tools to evaluate BMP scenarios, and recommended that in the short term the interim pollutant removal rates for stream restoration (approved by the CBP in January 2012) be used for watershed planning purposes. These values are 0.20 lb/ft/yr for TN, 0.068 lb/ft/yr for TP, and 310 lb/ft/yr for TSS. The removal rate for TSS is representative of edge-of-field rates and is subject to a sediment delivery ratio in the Watershed Model to

[14] For example, the credit for urban nutrient management practices may be applied as a reduced loading rate for all pervious areas (i.e., 0.367 lbs TP/acre urban pervious multiplied by 4.5%)

determine the edge-of-stream removal rate. A sediment delivery factor of 0.175 was applied. This means the adjusted rate for TSS is 52.5 lb/ft/year.

Street sweeping
The CBP currently approves two methods for crediting street sweeping:

Mass Loading Approach: For the mass loading approach, the street dirt collected is measured in tons at the landfill or ultimate point of disposal and converted to pounds. The TSS load is then estimated by multiplying the total particulate dry mass collected by 30%, or the fraction of material reflecting the particle size that dominates TSS (Law et al., 2008). The pounds of TN and TP can be calculated by multiplying the TSS load by 0.0025 and 0.001, respectively. For this study, the City of Baltimore provided an estimate of the lane miles swept and tons of debris removed per year for the period 1999-2008. We converted the lane miles swept to impervious acres swept, assuming a lane width of 10 feet. We converted tons of debris to pounds and converted the mass of solids to dry weight using a factor of 0.7. These values were used to determine the average pounds of debris removed per year from an acre of impervious cover. We increased the amount of debris removed/impervious acre by 1.5 times because the City sweeps once per month, but the credit assumes a twice/month sweeping frequency. This estimate is considered conservative.

Street Lane Approach: For the street lane approach, a jurisdiction reports the number of lane miles they have swept during the course of the year. The following formula is used to convert lane miles swept into acres:

$$\frac{\text{(miles swept) x (5,280 ft/mile) x (lane width ft)}}{\text{43,560 ft/acre.}}$$

The total acres swept is multiplied by the annual nutrient and sediment load for impervious surfaces, to arrive at a baseline load, which is multiplied by pollutant removal efficiencies to determine the load reduction associated with street sweeping. For this study, we used the average nutrient and sediment loading for Virginia (from VAST), and the removal efficiencies provided by CBP, which reflect the lower end of the pickup efficiencies documented in Law et al (2008).