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

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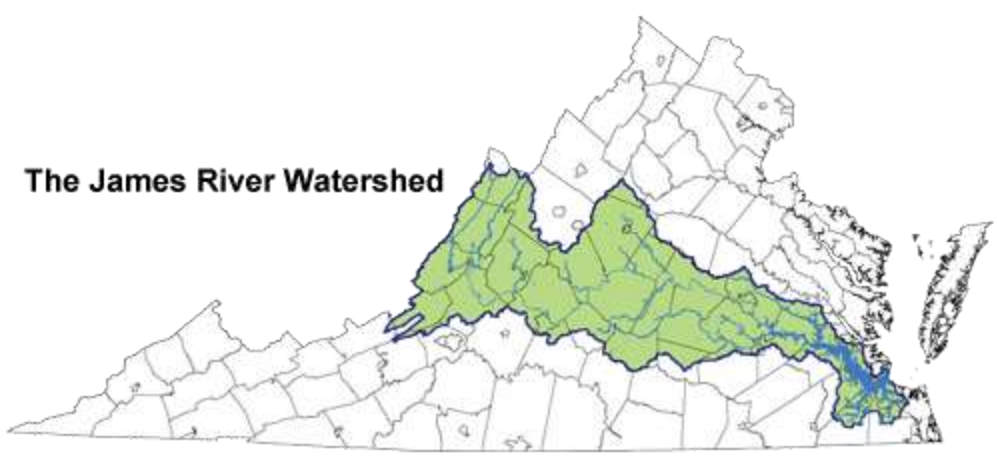

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Urban stormwater is the fastest growing source of pollution to the James River and if not controlled threatens to undermine the progress that has been made towards restoring the health of the river. Moreover, achieving needed pollution reductions from 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. The Center'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 relative costs and pollutant removal effectiveness of 39 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 cost and/or performance data was available for different design variations of these BMPs. 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). The CBP has a process in place for reviewing the current BMP credits and determining whether to add new BMPs or revise the credits for currently included BMPs. Several BMPs are currently under review by the CBP and interim performance values have been proposed by the Chesapeake Stormwater Network (2011). These include revisions to the urban nutrient management and stream restoration credits. Multiple cost-effectiveness values are provided for these BMPs to allow localities to see the potential effects of these revised values, if accepted, on the cost-effectiveness of these practices. Note that the "retrofit" BMPs credited by the CBP involve installation of a new BMP where none previously existed, as opposed to modification of an existing practice.

Table 1. Urban Stormwater BMPs Included in the Study

BMP	Current Status	TN Efficiency (%)	TP Efficiency (%)	TSS Efficiency (%)
Bioretention (new - suburban), A/B soils, no underdrain	Approved by CBP	80	85	90
Bioretention (new - suburban), A/B soils, underdrain	Approved by CBP	70	75	80
Bioretention (new - suburban), C/D soils, underdrain	Approved by CBP	25	45	55
Bioretention (retrofit - highly urban), A/B soils, no underdrain	Approved by CBP	80	85	90
Bioretention (retrofit - highly urban), A/B soils, underdrain	Approved by CBP	70	75	80
Bioretention (retrofit - highly urban), C/D soils, underdrain	Approved by CBP	25	45	55
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
Dry Extended Detention Ponds (retrofit)	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	Not currently credited by CBP	100	100	100
Illicit discharges- sewer repair	Not currently credited 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
Nutrient Management (CBP approved efficiencies)	Approved by CBP	17	22	0

Table 1. Urban Stormwater BMPs Included in the Study				
BMP	**Current Status**	**TN Efficiency (%)**	**TP Efficiency (%)**	**TSS Efficiency (%)**
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	Not currently credited by CBP	N/A	N/A	N/A
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	Not explicitly approved by CBP as a BMP but can be given credit	15	35	50
Street Sweeping	Approved by CBP	3	3	9
Tree Planting	Approved by CBP	N/A	N/A	N/A
Urban Growth Reduction	Approved by CBP	N/A	N/A	N/A
Urban nutrient management program to eliminate fertilizer use on private land	Credit under review by CBP	17	0	0
Urban nutrient management program to reduce fertilizer use on private land	Credit under review by CBP	9	0	0
Urban Stream Restoration (CBP approved efficiencies)	Approved by CBP	0.02 lbs/ft	0.003 lbs/ft	2 lbs/ft
Urban Stream Restoration (proposed revised efficiencies)	Credit under review by CBP	0.068 lbs/ft	0.2 lbs/ft	310 lbs/ft
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
Wet Ponds and Wetlands (retrofit)	Approved by CBP	25	45	60

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. These BMPs were not included in this analysis with two exceptions: pet waste programs and illicit discharges detection and elimination (IDDE). These two BMPs 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 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 the 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 cost 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.
- For all BMPs that require land it was assumed that: 1) the opportunity cost of developable land is $100,000 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 $50,000 per acre. The values provided by King and Hagan can be replaced with county-specific land costs and percent developable land values since land values can vary widely geographically. 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.
- 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.
- The $100,000 per acre opportunity cost of land used in King and Hagan was replaced with $70,000 to reflect land values in Virginia. The Land Price Index (Davis and Heathcote, 2007) 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, or approximately $70,000/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%. In reality, 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 costs into a fixed cost.
- Costs presented in the King and Hagan report were reported per acre of impervious cover treated so that 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 were applied. A separate report published in 2011 by MDE, *Accounting for Stormwater Wasteload Allocations and Impervious Acres Treated* documents how MDE developed conversion factors for these BMPs. After reviewing these methods, we chose to use the costs from King and Hagan for these BMPs but to leave out the impervious cover

conversion. The conversions appeared to artificially inflate the costs associated with BMPs such as tree planting and urban nutrient management. 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.

- 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). Although numerous (and sometimes conflicting) sources exist for BMP performance, the CBP 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 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.

For BMPs credited by CBP that are credited using a land use change and/or pollutant removal efficiency, the following assumptions were made:

- 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 efficiency was applied to urban pervious
- 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: bioretention, 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: permeable pavement, infiltration and filtering practices.
- 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. The assumptions for pet waste programs, correction of cross connections and removal of illicit discharges, 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, and an average cost effectiveness value in dollar per pound for each BMP. The average cost effectiveness value was calculated by dividing the average annual cost by the average annual pounds of pollutant reduced (TN, TP and TSS combined) for each BMP. BMPs that were not designed to remove a given pollutant, as in the case of TSS and urban nutrient reduction, a pollutant reduction value of zero was used for TSS when calculating the average annual pollutant reduced. Because TSS values are so large, the results are preferential to practices that have high TSS removal rates. An example calculation is shown below for Wet Ponds and Wetlands (retrofit):

Average Pollutant Cost Effectiveness ($/lb) = [Total Cost over 20 Years (annualized construction, design and land costs) + (O&M /20 years)] / Average Annual Pollutant Reduction (lbs/yr)

[$80,650.90 / 20] / [(2.53lbs/yr TN + 0.82 lbs/yr TP + 574.66 lbs/yr TSS) / 3]
= $4032.55 / 192.67
= $20.93

Table 2 presents for each BMP the average cost effectiveness and the cost-effectiveness for TN, TP, and TSS individually. 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 and on average, 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				
BMP	**Cost Effectiveness ($/lb)**			
	Average	**TN**	**TP**	**TSS**
Bioretention (new - suburban), A/B soils, no underdrain	19.96	394.62	3,416.27	6.78
Bioretention (new - suburban), A/B soils, underdrain	22.46	450.99	3,871.77	7.63
Bioretention (new - suburban), C/D soils, underdrain	32.94	1,262.77	6,452.95	11.09
Bioretention (retrofit - highly urban), A/B soils, no underdrain	74.47	1,472.42	12,747.05	25.30
Bioretention (retrofit - highly urban), A/B soils, underdrain	83.80	1,682.77	14,446.65	28.46
Bioretention (retrofit - highly urban), C/D soils, underdrain	122.90	4,711.75	24,077.76	41.40
Bioswale (new)	19.76	396.80	3,406.57	6.71
Dry Detention Ponds (new)	156.75	5,469.95	25,157.05	52.86
Dry Extended Detention Ponds (new)	26.24	1,367.49	12,578.53	8.81
Dry Extended Detention Ponds (retrofit)	43.47	2,265.17	20,835.63	14.59
Filtering Practices (sand, above ground)	13.98	710.97	3,297.05	4.70
Filtering Practices (sand, below ground)	14.94	759.41	3,521.64	5.02
Forest Buffers	14.49	100.31	1,230.76	5.09
Hydrodynamic Structures (new)	161.12	5,622.51	25,858.71	54.34
Illicit discharges- correction of cross-connections	10.41	13.51	54.05	5.11
Illicit discharges- sewer repair	2.33	8.73	34.94	0.87
Impervious Urban Surface Reduction	32.56	2,227.72	6,716.92	10.93
Infiltration Practices w/ Sand, Veg. (new)	14.31	408.65	2,842.61	4.83
Infiltration Practices w/o Sand, Veg. (new)	13.70	415.41	2,719.66	4.62
Nutrient Management (CBP approved efficiencies)	702.07	251.47	3,373.35	N/A
Permeable Pavement w/ Sand, Veg. (new), A/B soils, no underdrain	82.47	2,241.11	15,589.24	27.88
Permeable Pavement w/ Sand, Veg. (new), A/B soils, underdrain	100.48	3,585.77	24,942.78	33.86
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	128.56	8,964.43	62,356.96	43.09
Permeable Pavement w/o Sand, Veg. (new), A/B soils no underdrain	58.95	1,707.53	11,135.27	19.92
Permeable Pavement w/o Sand, Veg. (new), A/B soils, underdrain	71.84	2,845.88	17,816.44	24.18
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	92.05	12,806.44	44,541.09	30.78
Pet waste program	3.61	1.36	10.43	N/A
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	13.89	804.02	3,169.55	4.66

Table 2. Cost-Effectiveness of Urban Stormwater BMPs				
BMP	**Cost Effectiveness ($/lb)**			
	Average	**TN**	**TP**	**TSS**
Street Sweeping	14.86	1,129.97	7,860.12	4.98
Tree Planting	113.58	579.01	8,471.80	40.70
Urban Growth Reduction	7.83	246.65	1,384.16	2.64
Urban nutrient management program to eliminate fertilizer use on private land	754.41	251.47	N/A	N/A
Urban nutrient management program to reduce fertilizer use on private land	1,508.82	502.94	N/A	N/A
Urban Stream Restoration (CBP approved efficiencies)	67.23	2,266.73	15,111.54	22.67
Urban Stream Restoration (proposed revised efficiencies)	0.44	666.69	226.67	0.15
Vegetated Open Channels, A/B soils, no underdrain	13.31	361.93	3,329.11	4.50
Vegetated Open Channels, C/D soils, no underdrain	18.81	1,628.67	14,981.00	6.30
Wet Ponds and Wetlands (new)	15.75	821.53	3,358.51	5.29
Wet Ponds and Wetlands (retrofit)	39.84	2,077.73	8,494.01	13.39

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**
Average	These BMPs cost < $4/lb of pollutant removed: 1. Urban Stream Restoration (proposed revised efficiencies) 2. Illicit discharges- sewer repair 3. Pet waste program	These BMPs cost < $14/lb of pollutant removed: 1. Urban growth reduction 2. Vegetated open channels, A/B soils, no underdrain 3. Infiltration practices w/o sand, veg (new)
TN	These BMPs cost < $15/lb of nitrogen removed: 1. Pet waste program 2. Illicit discharges- sewer repair 3. Illicit discharges- correction of cross-connections	These BMPs cost < $252/lb of nitrogen removed: 1. Forest buffers 2. Urban growth reduction 3. Nutrient management (CBP approved efficiencies)
TP	These BMPs cost < $55/lb of phosphorus removed: 1. Pet waste program 2. Illicit discharges- sewer repair 3. Illicit discharges- correction of cross-connections	These BMPs cost < $2,720/lb of phosphorus removed: 1. Forest buffers 2. Urban growth reduction 3. Infiltration practices, w/o sand, veg (new)

Table 3. BMPs with High Cost-Effectiveness		
Pollutant	**Top 3 of All BMPs**	**Top 3 of CBP-Approved BMPs**
TSS	These BMPs cost < $3/lb of sediment removed: 1. Urban Stream Restoration (proposed revised efficiencies) 2. Illicit discharges- sewer repair 3. Urban growth reduction	These BMPs cost < $5/lb of sediment removed: 1. Vegetated open channels, A/B soils, no underdrain 2. Infiltration practices, w/o sand, veg (new 3. Retrofit of existing dry pond (conversion to wet pond or wetland)

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 one of more of the pollutants. These practices may not be good choices for communities with significant required reductions of these pollutants (TP and TSS).
- The top ranked BMPs, with the exception of urban growth reduction, are not currently approved by the CBP. These include practices to remove illicit discharges as well as pet waste programs and revised efficiencies for urban stream restoration. 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. This finding highlights the importance of the CBP continually reviewing new BMPs for inclusion in the model. Localities would benefit from conducting local monitoring studies to better quantify the cost and impacts of these practices.
- 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.
- 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 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 install certain BMPs.

Table 4. Supplemental Benefits of Urban Stormwater BMPs									
BMP	**Public Health/ Safety**	**Public Education**	**Recreation**	**Neighborhood 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 – Private Land	L	H	L	M	L	L	M	L	L
Nutrient Management – Public Land	L	M	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

Table 4. Supplemental Benefits of Urban Stormwater BMPs									
BMP	**Public Health/ Safety**	**Public Education**	**Recreation**	**Neighborhood 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

"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.

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. 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.

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 feasibility limits 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 developed cost and total pollutant removal associated with the following BMP scenarios:

- Scenario 1: CBP-approved BMPs, with no feasibility limits
- Scenario 2: CBP-approved BMPs, with feasibility limits
- Scenario 3: All BMPs, with feasibility limits

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 to 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, opportunity or local conditions (e.g., urban growth reduction, above ground sand filters, new wetlands/ponds, suburban bioretention), as well as BMPs that they considered infeasible due to cost or limited resources (e.g., street sweeping and urban stream restoration with current CBP credits),
- 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 are presented in Table 5, sorted according to cost-effectiveness for TSS removal (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	**TN Cost Effectiveness (dollars per pound removed)**	**TP Cost Effectiveness (dollars per pound removed)**	**TSS Cost Effectiveness (dollars per pound removed)**
Urban Stream Restoration (proposed revised efficiencies)	$666.69	$226.67	$0.15
Erosion and Sediment Control	$206.76	$584.27	$0.76
Illicit Discharges: sewer repair	$17.01	$68.05	$1.70
Forest Buffers	$134.50	$1,020.24	$3.36
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	$868.31	$2,553.25	$3.97
Infiltration Practices w/o Sand, Veg. (new)	$416.73	$2,152.08	$3.98
Infiltration Practices w/ Sand, Veg. (new)	$409.95	$2,249.37	$4.16
Street Sweeping	$1,133.55	$6,219.74	$4.29
Filtering Practices (sand, below ground)	$761.81	$2,786.69	$4.32
Vegetated Open Channels, C/D soils, no underdrain	$1,758.90	$12,068.03	$5.36
Illicit Discharges: correction of cross-connections	$14.24	$56.94	$5.38
Bioswale (new)	$428.53	$2,744.18	$5.72
Bioretention (new - suburban), C/D soils, underdrain	$1,363.74	$5,198.21	$9.45
Impervious Urban Surface Reduction	$1,617.94	$5,154.84	$9.54
Urban Stream Restoration (CBP approved efficiencies)	$2,266.73	$15,111.54	$22.67
Tree Planting	$808.87	$6,849.54	$23.13
Bioretention (retrofit - highly urban), C/D soils, underdrain	$5,088.50	$19,395.97	$35.26
Hydrodynamic Structures (new)	$6,072.09	$20,830.63	$46.29
Permeable Pavement w/o Sand, Veg. (new), C/D soils underdrain	$38,540.28	$105,734.42	$79.49
Permeable Pavement w/ Sand, Veg. (new), C/D soils, underdrain	$26,978.11	$148,027.74	$111.28
Pet waste program	$1.36	$10.43	N/A
Nutrient Management (CBP approved efficiencies)	$305.71	$2,908.06	N/A
Urban nutrient management program to eliminate fertilizer use on private land	$305.71	N/A	N/A
Urban nutrient management program to reduce fertilizer use on private land	$611.42	N/A	N/A

*shaded BMPs are approved by the CBP

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 certain (less cost-effective) BMPs was not necessary to achieve the load reductions.

Table 6. Assumptions and Data Used to Determine Feasibility Limits of BMP Implementation in Richmond

BMP	Assumptions and Data Used to Determine Feasibility Limits	
	Scenario 1	**Scenarios 2 and 3**
Stream restoration	• 617,275 linear feet of stream are present within the City limits • 10% of total stream length is feasible for restoration (123,454 linear feet of stream, or 61,727 linear feet on both sides of the stream)	• 4,000 linear feet of stream restoration (2,000 feet on both sides of stream) already planned as a demonstration project by the City
Urban nutrient management	• Non-forest vegetation is proxy for turf • Urban nutrient management can be applied on 30% of turf located on single family residential, institutional and vacant land (1,324 acres) • Urban nutrient management can be applied on 50% of public turf (445 acres); the remaining 50% will be needed for tree planting and stormwater retrofits	
Tree planting	• 25% of non-forest vegetation on public land can be planted with trees (222 acres) • 10% of non-forest vegetation on single family residential, institutional and vacant land can be planted with trees (441 acres)	• 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 • 25% of privately owned unforested buffer (255 acres) has a willing landowner	• 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 • 50% of ponds are feasible for retrofitting • This BMP is only relevant for 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**	
	Scenario 1	**Scenarios 2 and 3**
Impervious surface reduction	• 1% of all parking lots can be replaced with pervious surface (30 acres)	• 1% of public parking lots can be replaced with pervious surface (3 acres)
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	
Erosion and sediment control	• Assume this practice is applied as 0.5% of the City's total land area is redeveloped each year (192 acres)	• Assume 23 acres per year (based on City's estimate from WIP submission)
Street Sweeping	• Assume sweeping is expanded so that 50% of parking lots are swept (1,511 acres)	• Expansion of street sweeping not desired by the City

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				
		Units Treated by Scenario		
BMP	**Units**	**CBP BMPs- no limits**	**CBP BMPs - w/ limits**	**All BMPs- w/ limits**
Bioretention (retrofit - highly urban), C/D soils, underdrain	Acres treated (50% impervious, 50% pervious)	0	0	0
Bioswale (new)	Acres treated (50% impervious, 50% pervious)	200	100	50
Erosion and Sediment Control	Acres of active construction treated	192	23	23
Filtering Practices (sand, below ground)	Acres of impervious land treated	63	100	40
Forest Buffers	Acres of pervious land planted	340	85	85
Illicit discharges- correction of cross-connections	Number of cross-connection corrected	0	0	30
Illicit discharges- sewer repair	Number of illicit discharges repaired	0	0	6
Impervious Urban Surface Reduction	Acres of impervious cover removed	30	3	3

Table 7. Urban BMPs Implemented in Three Scenarios for the City of Richmond				
BMP	**Units**	**Units Treated by Scenario**		
		CBP BMPs- no limits	**CBP BMPs - w/ limits**	**All BMPs- w/ limits**
Infiltration Practices w/ Sand, Veg. (new)	Acres of impervious land	400	200	0
Infiltration Practices w/o Sand, Veg. (new)	Acres of impervious land	0	263	200
Nutrient Management (CBP approved efficiencies)	Acres of pervious land treated	1,769	1,769	1,769
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	1
Retrofit of Existing Dry Pond (conversion to wet pond or wetland)	Acres treated (50% impervious, 50% pervious)	0	0	29
Street Sweeping	Acres of impervious cover treated	1,511	0	0
Tree Planting	Acres of pervious land planted	663	200	200
Urban Stream Restoration (CBP approved efficiencies)	Linear feet of stream restored	72,000	4,000	0
Urban Stream Restoration (proposed revised efficiencies)	Linear feet of stream restored	0	0	4,000
Vegetated Open Channels, C/D soils, no underdrain	Acres treated (50% impervious, 50% pervious)	200	0	0

*shaded BMPs are approved by the CBP

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 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.

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. CBP BMPs- no feasibility limits	15,109	2,827	1,520,711	$162,602,352
2. CBP BMPs- w/ feasibility limits	9,721	1,621	741,659	$68,500,647
3. All BMPs- w/ feasibility limits	15,154	3,542	1,674,527	$46,227,268
Estimated Target Load Reduction for City of Richmond	15,100	2,730	1,080,518	N/A

Only Scenarios 1 and 3 achieve the required load reductions, but at significantly different costs due to the inclusion of some highly cost effective BMPs in Scenario 3 that are not yet approved by the CBP. In Scenario 2, the assumed limits of feasibility were reached before the target pollutant load reductions were met. At present, Scenario 1 is the only one that would be considered acceptable in terms of the CBP Watershed Model, yet the cost and level of effort will require significant resources. In order to meet the targets for BMP implementation proposed in scenario 1, the City would need to invest resources in the following:

- Expansion of municipal street sweeping program
- 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 (which also provide potential to implement stormwater retrofits)
- A stormwater retrofit inventory of public lands, open space, institutional land, and rights-of-way to identify feasible projects and refine the targets for implementation of structural BMPs accordingly
- Outreach and/or provide incentives to encourage tree planting on private lands
- Inventory public lands, open space, institutional land, rights-of-way and vacant lands to identify opportunities for tree planting and urban nutrient management
- Work directly with riparian landowners to encourage buffer reforestation- this will likely require financial incentives or assistance
- Conduct stream assessments to identify stream reaches in need of restoration, and prioritize sites for restoration in coordination with upstream retrofit projects and riparian plantings
- Outreach and/or provide incentives to encourage urban nutrient management on private lands

In addition to the above, the City may want to consider enhancing programs that outreach to landowners and provide cost-sharing or other incentives to encourage installation of BMPs on private land. Aggressive pursuit of implementation on private land could be a more cost effective method to achieve pollutant reductions, especially for highly cost-effective BMPs like forest buffers and urban nutrient management. Nutrient credit trading may also be 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 explored.

Two additional options for the City to refine their plan to meet the Bay TMDL goals 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.
- Implement the more cost effective CBP-accepted BMPs in the short term, and save stormwater retrofits for the longer term, to provide more time for CBP adoption of newer and more cost effective BMPs, such as pet waste programs, removal of illicit discharges and revised efficiencies for urban stream restoration. The urban stream restoration credit and illicit discharge removal credit are currently under discussion and will be complete by the end of 2013.

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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. Best professional judgment was used to estimate the average annual county implementation cost based on the anticipated level of inspection and enforcement associated with the BMP.

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 or annual intermittent maintenance 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. [1] 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 values provided by King and Hagan for wet ponds and wetlands were assumed to be applicable to pond retrofits and these values were used. Land values were set at zero since the BMP involves modification to an already-constructed practice for which land has already been acquired.

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.

The program components included in the "construction" cost are: adopting a pet waste ordinance, installation of pet waste stations with a sign and basket, purchase of bags to fill pet waste stations for the first year, and the cost of educational mailings for the first year of the

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

program. Design costs included development of educational materials, and annual maintenance costs included bag refills and additional mailings to local residents.

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. Some of the remaining costs and assumptions for this BMP came from local TMDLs developed for bacteria in Virginia. The *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond* (Maptech, 2011) provided cost estimates 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. In order to determine the total annual cost of the program, assumptions were made about the number of pet waste stations installed, number of residents targeted through the educational program, and the number of bag refills needed per year. Costs for development of educational material were taken from Tribo (2011). Required units for a typical program in Virginia were taken from the *Bacterial Implementation Plan for the James River and Tributaries- City of Richmond* (Maptech, 2011). These same assumptions were used when estimating the pollutant reduction associated with pet waste programs. 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.

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. It was assumed that there would be no annual maintenance costs associated with this practice.

Illicit discharges- sewer repair

Illicit discharges caused by factors other than cross connections are difficult to determine costs for 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. It was assumed that there would be no annual maintenance costs associated with this practice. Overall, the cost estimates for this BMP are based on limited data and assumptions and should be treated with caution.

Appendix B: Development of Pollutant Reduction Estimates

Pond retrofits

The CBP does not currently have an explicit credit for pond retrofits as a BMP. However, credit can be calculated based on the difference in pollutant removal efficiencies between the BMP type being retrofitted and the BMP type to which the practice is converted. For this analysis, we assumed the most common type of retrofit conversion: dry pond to a wet pond or wetland, although cost effectiveness values for different types of BMPs could be calculated.

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 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, number of residents targeted through the educational program, and the number of bag refills needed per year. Required units for a typical program in Virginia were taken from 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 * 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.

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 sewage use 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 newer techniques 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] / 100000 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 newer techniques 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.