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Comparing Costs of Onsite Best Management Practices to Nutrient Credits for Stormwater Management: A Case Study in Virginia

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ABSTRACT: Best Management Practices (BMPs) are widely used to mitigate impacts of increased impervious surfaces on stormwater runoff. However, there is limited detailed and up-to-date information available on the cost of designing, constructing, and maintaining BMPs over their lifetime. The objective of this study is to analyze BMPs recently constructed by the Virginia Department of Transportation (VDOT) to quantify their total cost per pound of phosphorus removed annually. A motivating factor for the study is recent changes to regulatory guidelines in Virginia that allow for full or partial substitution of purchased nutrient credits in lieu of constructing onsite BMPs to achieve compliance with stormwater quality regulations. Results of the analysis of nine BMPs found that their cost ranged from $20,100 to $74,900, in 2014 dollars, per pound ($44,313 to $165,126 per kilogram) of phosphorus removed. Based on these results and assuming current credit prices procured by VDOT, purchasing nutrient credits is a cost effective option for the agency, especially when factoring in the cost of additional right-of-way for the BMP. Based on this finding, we expect compliance with stormwater quality regulations through credit purchases to become more widely used in Virginia. Moving forward, we suggest more direct tracking of BMP costs to support comparisons between BMP costs across a range of types and conditions to credit purchases for meeting stormwater regulations.

KEY TERMS: storm water management, best management practices, nutrients, water resource economics, stormwater control measures costs, nutrient credits, transportation projects

INTRODUCTION

Impervious surfaces including streets and roads increase direct runoff from precipitation events and this increased runoff can have negative effects including flooding, erosion of banks and stream beds, and increased pollutant loading to waterbodies (Arnold and Gibbons, 1996). Regulatory requirements for management of stormwater quality (e.g., removing urban pollutants) and quantity (e.g., reducing pulses and volumes) are established by state and local governments including the Commonwealth of Virginia, the focus area of this study, to mitigate degradation of surface waters due to increased impervious surfaces and general construction activities. These requirements apply both during the construction stage, when using temporary stormwater management measures, and the post-construction stage, when using long-term stormwater management measures (U.S. Environmental Protection Agency (USEPA), 1999; Virginia Department of Conservation and Recreation (VADCR), 2011).

Traditionally, long-term stormwater management measures have focused on Best Management Practices (BMPs), also known as stormwater control measures, that are constructed onsite with the capacity to temporarily hold and treat stormwater runoff (Thurston, 2012). The Virginia Department of Transportation (VDOT) constructed over 1,300 BMPs for long-term management of stormwater for roadway development projects from 1977 to 2014. The majority of these BMPs were extended detention basins (91.9% of the total number of BMPs) but also include manufactured BMPs (3.8%), enhanced extended detention basins (1.8%), retention basins (1.4%), grass swales (0.4%), bioretention filters (0.4%), bioretention basins (0.2%), an infiltration basin (<0.1%), and a sand filter (<0.1%).

These BMPs represent a significant cost to taxpayers, however the exact cost is difficult to quantify. There has been past research on determining the lifetime cost of BMPs, largely looking at the expense for state DOTs. Weiss et al. (2011, 2007) summarized this past research into confidence intervals of BMP costs that include results from a variety of sources (American Society of Civil Engineering (ASCE), 2014; Brown and Schueler, 1997; California Department of Transportation (Caltrans), 2004; Southeastern Wisconsin Regional Planning Commission (SWRPC), 1991). These estimates were generated through a variety of means, but most often they were obtained through surveys rather than actual construction data. Caltrans (2004) is an exception in that the department did include cost data for actual constructed BMPs, but these were for retrofit projects, which are known to be more expensive (Abbasi and Koskelo, 2013).

Our study contributes needed information on actual costs of constructed BMPs obtained through detailed analysis of construction plans and databases maintained by VDOT. For VDOT and other DOTs in the US, BMP costs are typically not tracked separately of other project costs (Abbasi and Koskelo, 2013). For VDOT, we found that cost details are available in project documents, but one must go through a process of separating stormwater management related costs from other project construction costs in order to determine the total cost of stormwater infrastructure for a given project. Furthermore, the required data is spread across different databases maintained by the agency, requiring further work to track and compile actual cost data. We completed this tedious process and compare our cost estimates to the BMP cost confidence intervals reported in Weiss et al. (2011, 2007) in the Results and Discussion section.

One important motivation for accurately quantifying BMP cost is recent regulatory changes in Virginia that allow for compliance with post-construction stormwater quality regulations to be achieved through the purchase of nutrient credits (VADCR, 2011). While past regulatory guidelines required stormwater quality to be managed using onsite measures, there are now options in Virginia for achieving compliance with stormwater quality regulations through substituting nutrient credits. Banks are being established by third party organizations and offer nutrient credits for purchase to organizations like VDOT. For VDOT, purchasing nutrient credits to comply with the required post-construction stormwater quality regulations in lieu of constructing onsite BMPs may offer a more cost-effective means of achieving stormwater compliance. However, with limited data on BMP costs, it is difficult to decide between purchasing credits and constructing onsite BMPs.

To address this research need, we used data from actual BMPs constructed by VDOT to separate out and estimate their total lifetime costs. We determined a lifetime (assumed to be 20 years) cost for the BMPs by taking into account pre-construction costs, purchases of right of way (ROW), construction costs, and routine operations and maintenance (O&M) costs. We limited our study to BMPs that were constructed within 10 years from the start of this study and for stormwater quality regulations only (i.e., the BMP would not have been required if considering only stormwater quantity regulations) so that we could estimate cost effectiveness in terms of the cost to remove a pound of phosphorus annually, the nutrient targeted in stormwater regulations for the region where the BMPs were constructed. These cost effectiveness values allowed us to compare our

BMP costs to current prices procured by VDOT for purchasing nutrient credits from third-party banks.

Background on Nutrient Credits in Virginia

Nutrient credits, defined as the annual calendar year reduction in nutrients beyond the established regulatory baselines (Va Code Ann., 2015), are generated through BMP enhancements or land conversion. For example, the majority of the currently available nutrient credits were generated from conversion of agricultural land to forested land for perpetuity (VADEQ, 2016). Nutrient credits, as well as stormwater quality regulations (i.e., required nutrient reductions), are expressed in pounds of phosphorus removed annually because the Virginia Department of Environmental Quality (VA DEQ) considers phosphorus a “keystone” pollutant exhibiting some characteristics of both particulate and soluble pollutants, making it an indicator of urban pollutants in general (VADCR, 2011). Nutrient credits are managed through third-party banks and banks are required to document the associated ratio of nitrogen (Va Code Ann., 2015).

Full or partial substitution of nutrient credits may be used to achieve compliance with post-construction stormwater quality regulations provided that the site is in compliance with stormwater quantity regulations and substitution of credits does not violate, if in place, more stringent local stormwater management ordinances to prevent further degradation of localized areas of impaired water quality or water resources. Nutrient credits are perpetual (i.e., credits are purchased once and last a lifetime), substituted at a 1:1 ratio (i.e., one pound of required post-construction stormwater pollutant reduction is equivalent to one pound of nutrient credit), and are available in fractional increments (Va Code Ann., 2015).

Nutrient credits may be substituted to achieve compliance with stormwater quality regulations under the following three scenarios: (1) less than 5 acres (20,234 m^2) of land are disturbed; (2) the post-construction phosphorus removal requirement is less than 10 pounds (4.5 kg) per year; or (3) at least 75% of the required post-construction phosphorus removal can be achieved using onsite BMPs, but full compliance with stormwater quality regulations cannot practicably be met onsite. In order for nutrient credits to be eligible for substitution, credits must be generated within the same or adjacent 8-digit U.S. Geological Survey (USGS) hydrologic unit code (HUC). If no nutrient credits are available in the same or adjacent 8-digit USGS HUC, a credit generated in the same tributary (i.e., river basin) may be considered for eligibility by the VA DEQ, however, credits generated in a tributary outside of the site are ineligible (Va Code Ann., 2015). This study focuses on sites that fall under scenario 2 where 100% of the stormwater quality regulations (i.e., required nutrient reduction) can be substituted with credits. These sites are in compliance with stormwater quantity regulations and, therefore, the constructed BMPs are only used to achieve compliance with stormwater quality regulations.

MATERIALS AND METHODS

Data

A database of over 1,300 stormwater BMPs constructed in Virginia from 1977 to 2014 was provided by VDOT. The database included details for each BMP such as type, date installed, location (coordinates and Virginia Department of Conservation and Recreation 6th order HUCs), and treatment purpose (stormwater quality or quantity). The BMP coordinates were mapped in a geographic information system (GIS) and the location was compared to the VA DCR 6th order HUC listed in the database and 12-digit (6th order) HUC boundaries obtained from the USGS (USGS, 2014) to ensure accuracy of the BMP location. In addition to the BMP database, VDOT also provided construction site plans, a database of construction materials with associated costs (including labor), and ROW parcel sizes with associated land costs pertaining to these projects.

Due to the difficulty in obtaining, analyzing, and deciphering available data to determine BMP costs, we limited our study to include nine BMPs built across three different projects to achieve compliance with stormwater quality regulations (see Figure 1 for project locations and Table 1 for the BMP properties). Project Number (PN) 0095-016-111 C501 was completed in 2008 in Caroline County and focused on relocating Route 652. The project included construction of three extended detention basins (BMP IDs 1- 3 in Table 1). PN 0066-076-113 C501 was completed in 2006 and focused on improving I-66 by widening approximately 3.3 miles of high-occupancy-vehicle lanes in Prince William County. The project included construction of four extended detention basins in 2006 (BMP IDs 4-7 in Table 1). PN 0066-076-113 C506 focused on reconstruction of an interchange for I-66 in Prince William County. The project included construction of an enhanced extended detention basin in 2004 and sand filter in 2005 (BMP IDs 8 and 9 in Table 1).

The selected BMPs were constructed from 2004 to 2006 and include different BMP types and sizes reflective of VDOT's previous stormwater quality management practices. Seven of the nine BMPs (BMPs 1-7) were extended detention basins which are the most dominant BMP used in the past by VDOT for management of stormwater quality (92% [N=1202] of BMPs). The two other BMPs, an enhanced extended detention basin and sand filter (BMPs 8 and 9), were constructed much less frequently (N=24 and N=1, respectively) and selected for comparison based on availability of information in four separate databases maintained by VDOT (i.e., BMP details, construction site plans, construction material costs, and ROW parcel sizes). For eight of the nine BMPs analyzed, credits could have been purchased under scenario 2, that is substitution of nutrient credits to comply with 100% of the stormwater quality regulations. This is because the BMP's post-construction phosphorus reduction requirement was less than 10 pounds (4.5 kg) per year (Va. Code Ann., 2015). One of the BMPs analyzed, BMP 7, would not have qualified for a 100% substitution under current regulations due to the fact its post-construction phosphorus control requirement exceeded 10 pounds (4.5 kg) per year. It would have, however, qualified under scenario 3 for 25% of its required phosphorus reduction to be met offsite provided that 75% reduction could be achieved through onsite controls. To simplify the comparison of BMP costs to nutrient credit prices, we excluded BMP 7 from this portion of the analysis so that only BMPs that qualify for 100% substitution are included in the nutrient credit price comparison.

Cost Estimates

Components of a BMP total cost can include pre-construction, construction, ROW, routine annual O&M, non-routine O&M, and demolition and disposal at the end of the BMP's useful life (Arika et al., 2006; Sample et al., 2003). In this study we limited

BMP cost to include only pre-construction, construction, ROW, and routine annual O&M. Non-routine O&M and end-of-life costs were assumed to be insignificant relative to the other costs.

Pre-Construction Costs

Pre-construction costs include design, permitting, planning, and contingency costs. These costs have been estimated to range between 10% and 40% as the ratio of pre-construction costs to construction costs (King and Hagan, 2011) with two studies suggesting 32% (Arika et al., 2006; Brown and Schueler, 1997) and another study suggesting a ratio of 25% (Wiegand et al., 1986). Based on these prior studies and given that pre-construction costs were not available for the BMPs analyzed in this study, pre-construction costs were assumed to be 32% of construction costs.

Construction Costs

Construction costs for stormwater management are not readily available or tracked on their own by VDOT. It was possible, however, to estimate construction costs by manually reviewing archived construction plans for each of the nine BMPs. VDOT maintains a database that includes past construction plans. Within this database, we identified a stormwater control plan for the three construction projects analyzed in this study. This stormwater control plan listed in detail the materials required for the construction of each BMP for the project. The construction plan database included materials, but did not include cost information. To obtain cost information we used a second database maintained by VDOT with unit cost information. The materials listed in the stormwater control plan were linked via an item number to unit costs (including labor) stored in the other database.

Right of Way (ROW) Costs

ROW costs can be a significant contributor to the cost of a BMP, especially in urbanized areas (King and Hagan, 2011; NCHRP, 2012; Weiss et al., 2011). Because of the variability in the land area requirements for each BMP and the cost of land, ROW costs for BMPs are difficult to estimate (Weiss et al., 2011). In this study, the minimum required ROW for each BMP was determined by measuring the BMP footprint provided by construction site plans. Using the parcel size and associated cost provided by VDOT, the ROW cost for each BMP was determined by multiplying the parcel cost by the percentage of the parcel size that the BMP footprint occupied.

Annual Operations and Maintenance (O&M) Cost

Annual operations and maintenance (O&M) costs were assumed to be 1%, 4.5%, and 12% of the construction cost for extended detention basins, the enhanced extended detention basin, and the sand filter, respectively. These values were based on the average values provided by the USEPA (USEPA, 1999). Annual O&M costs for a 20-year lifetime were discounted at a rate of 3% to determine the present value of O&M at the time of construction. The discount rate was selected based on the U.S. Office of Management and Budget’s reported 10-year real discount rate of 2.5% and 30-year real discount rate of 3.2% as recommended by the Federal Highway Administration (FHWA, 2003). Real discount rates used by states historically have ranged from 3% to 5% (FHWA, 2003).

Total Cost

The four cost components, pre-construction, construction, ROW, and O&M costs, were considered over the 20-year design life and then adjusted to 2014 dollars using the construction cost indexes from the Engineering News Record. These cost components were then summed to determine the total BMP cost. We used the annual inflation rates for each year of the period of analysis (2004 to 2014), which ranged from 4.65% to 2.65%.

Cost Effectiveness

The equations in this section follow English units, following the convention in the Virginia Stormwater Management Handbook (VADCR, 1999). For the equations in SI units, please see the supplementary information document provide online with this paper.

Per Cubic Foot of Water Quality Volume Treated

The BMP costs were divided by the water quality volume (WQV) treated to determine the BMP cost per cubic foot and for comparison to previously published BMP costs. Following standard practices in place when the BMPs were designed and constructed (VADCR, 1999), WQV was estimated as

$$WQV = \left(P \times R \times A \times DV \times 43{,}560 \text{ ft}^2 \text{ acre}^{-1} \div 12 \text{ in ft}^{-1} \right) \qquad (1)$$

where

WQV = water quality volume (ft^3)

P = precipitation depth (in) = 0.5 in,

R = ratio of runoff to rainfall = 0.95,

A = impervious area (acre),

DV = design volume factor (extended detention basins = 2, enhanced extended detention basin = 2, and sand filter = 1) (VADCR, 1999).

This approach for estimating WQV for a BMP using Virginia design codes has since been updated (VADCR, 2011) and projects are just beginning to use the new regulations due to a grandfather period. The potential impact of this change on the results of this study is discussed in the Results and Discussion section.

Per Pound of Phosphorus Removal

For comparison to current prices of nutrient credits, the BMP total costs were divided by the annual phosphorus removal to determine the BMP cost per pound of annual phosphorus removal. Again following standard practices in place when the BMPs were designed and constructed (VADCR, 1999), phosphorus removal was estimated using the following procedure. First, the phosphorus load entering the BMP is estimated as

$$L = P \times P_j \times \left[0.05 + (0.009 \times I)\right] \times C \times A \times 2.72 \div 12 \qquad (2)$$

where

L = annual phosphorus load (lb yr^{-1}),

P = average annual rainfall (in yr^{-1}) = 43 in yr^{-1} for Virginia,

P_j = unitless correction factor for a storm with no runoff = 0.9,

I = percent impervious cover,

C = flow-weighted mean pollutant concentration (mg/L) = 0.26 mg/L,

A = applicable area (acre).

The numbers 2.72 and 12 are unit conversion factors while 0.05 and 0.009 are regression coefficients.

Simplifying Equation 2, the annual phosphorus load entering each BMP per acre of impervious surface is calculated as

$$\begin{aligned} L_{acre} &= \left[0.05 + \left(0.009 \times 100\%\right)\right] \times 1 \text{ acre } \times 2.28 \\ &= 2.17 \text{ lb acre}^{-1} \text{ yr}^{-1} \end{aligned} \quad (3)$$

where

L_{acre} = annual phosphorus load from one impervious acre (lb yr^{-1}).

The impervious acreage treated by each BMP is converted into the annual phosphorus load entering each BMP as

$$L_{BMP} = A_{BMP} \times L_{acre} \quad (4)$$

where

L_{BMP} = phosphorus load entering the BMP (lb yr^{-1}), and

A_{BMP} = impervious area treated by the BMP (acre).

To obtain the annual phosphorus load removed by the BMP, the load entering the BMP was multiplied by the pollutant removal efficiency for that BMP provided in the Virginia Stormwater Management Handbook (VADCR, 1999) as

$$R_{BMP} = L_{BMP} \times Eff_{BMP} \quad (5)$$

where

R_{BMP} = phosphorus removal by a BMP (lb yr^{-1}),

L_{BMP} = phosphorus load entering the BMP (lb yr^{-1}), and

Eff_{BMP} = pollutant removal efficiency of the BMP.

RESULTS AND DISCUSSION

Results from the analysis are presented in this section using English units to be consistent with related studies. Readers can find the same figures, tables, and equations reported in SI units in the supplementary information document provide online with this paper.

BMP Cost Efficiency

Table 1 presents the properties for each BMP including the estimated WQV treatment and annual phosphorus removal while Table 2 presents the present costs for each BMP. The costs are presented both with and without ROW costs, given the variability in ROW costs. Cost efficiency is also reported by dividing the annual phosphorus removal in pounds for each BMP.

The cost estimates for the construction and O&M components of each BMP analyzed in this study were compared to cost estimates for construction and O&M published in the literature using the relationship established by Weiss et al. (2011, 2007). Figure 2 presents the estimated costs compared to the published costs of extended detention basins. Table 3 presents the comparison for enhanced extended detention basins and sand filters. The estimated costs for all BMPs were within or near the 67% confidence intervals of published cost. The enhanced extended detention basin was compared to the combined cost of a constructed wetland (e.g., to incorporate installation of vegetation) and an extended detention basin (e.g. to incorporate excavation and infrastructure) as the closest related BMP type due to the fact that there was no established relationship between WQV treated and the cost of construction and O&M for an enhanced extended detention basin in Weiss et al. (2011, 2007). Overall, this comparison suggests that the cost estimates derived from analyzing historical records on BMPs constructed by VDOT are in line with results from prior studies determining BMP costs.

Figure 2 also highlights the variability in BMP costs with BMPs 1-4 falling near the lower bound of the 67% confidence interval and BMPs 5-7 falling near the upper bound of the confidence interval. Looking specifically at BMPs 3, 5, and 6 illustrates this variability in cost. While each of these BMPs treat approximately the same WQV and all three BMPs fall within the confidence interval reported by Weiss et al. (2011, 2007), BMP 3 is significantly less expensive compared to BMPs 5 and 6. By exploring the construction data for these BMPs, we found that these differences in costs were due to installation of a required clay liner for BMPs 5 and 6 that was not required with BMP 3. In addition, the construction cost for BMP 5 included a temporary sediment basin that was not required for BMPs 3 and 6. Likewise, comparing BMPs 1 and 2, which also both treated the same WQV, shows BMP 2 is about twice as expensive because it required additional excavation and purchase of fill compared to BMP 1. These results are important because it suggests that the lower bound of the Weiss et al. (2011, 2007) confidence interval may be appropriate for VDOT BMPs when no unexpected costs or complications are encountered and the upper bound may represent a price ceiling for BMPs with site constraints or requiring additional features such as clay liners, purchasing of fill, etc..

The two most expensive BMPs were the two non-extended detention basin BMPs: BMP 8, a sand filter, and BMP 9, an enhanced extended detention basin (Table 3). These

BMPs were $6,700 to $14,800 more expensive per pound ($14,771 to $32,628 per kilogram) of annual phosphorus removed compared to the more traditional extended dentation basins. This result is in line with past research that has shown extended detention basins to be among the most cost effective BMPs when sufficient space is available for constructing the BMP (Caltrans, 2004).

Comparison to Nutrient Credit Prices

VDOT has recently procured fixed prices for nutrient credits (expressed in 2014 dollars per a pound of phosphorus removed annually) in the James, Potomac, and York River basins. At the time of this study, the per-pound cost for nutrient credit in the James and Potomac River basins was $10,430 and $18,700 (per-kilogram cost was $22,994 and $41,226), respectively. In the York River basin, costs ranged from $17,000 to $20,000 ($37,479 to $44,092 per kilogram) based on a sliding scale, where the price per pound decreased as more nutrient credits are purchased.

Table 4 and Figures 3 and 4 compare the BMP cost estimates excluding and including ROW to the cost of one pound of nutrient credit. BMP 7 is excluded from this comparison because it would not have qualified for 100% substitution under current regulatory guidelines, as explained earlier. Based on this comparison, if current regulations were in place when these BMPs were constructed, purchasing nutrient credits in lieu of constructing these BMPs could have resulted in a 52% savings on average (ranging from 5% to 75% with a median savings of 62%) when ROW costs are included. For extended detention basins, purchasing nutrient credits in lieu of constructing the basins could have resulted in a 45% savings on average (ranging from 5% to 63% with a median savings of 52%) when ROW costs are included. When ROW costs are excluded, credit prices still offer cost savings for all but two of the BMPs: BMPs 1 and 3. Overall, the average cost savings when excluding ROW costs drops to 32% (ranging from -25% to 65% with a median savings of 47%). For extended detention basins, the average cost savings when excluding ROW costs drops to 21% (ranging from -25% to 53% with a median savings of 29%). The BMP closest to current nutrient credit prices when including ROW costs was BMP 3, an extended detention basin constructed in the York River Basin to treat 8 impervious acres and remove 6 pounds of phosphorus annually. Due to the fact that the BMP treated a large area, and because it had a relatively low pre-construction and construction cost, the BMP was very cost effective. However, compared to current nutrient credit prices obtained by VDOT, the total BMP cost is still 5% higher than purchasing credits when including ROW cost for the BMP footprint.

The least cost effective BMP was an enhanced extended detention basin (BMP ID 9) in the Potomac River Basin. The basin was designed to treat 9.2 impervious acres (39,740 m^2) and remove nearly 10 pounds (4.5 kg) of phosphorus annually, so it was also one of the larger BMPs analyzed. The basin was the most expensive in all four of the cost components. This could be because it was the only enhanced extended detention basin analyzed and because it was significantly more expensive in terms of ROW costs, which were just over $200,000 and $138,000 more expensive than any other BMP analyzed.

At nutrient credit prices available to VDOT at the time of this study, purchasing credits is a cost effective means for achieving compliance with stromwater quality regulations compared to the total cost of BMP construction and maintenance (Table 4). Given that in Virginia nutrient credits are granted in perpetuity, they become even more attractive compared to the total cost of designing, constructing, operating, and maintaining BMPs, which are expected to last 20 years. Assuming current pricing and regulatory frameworks hold, we expect to see nutrient credit purchasing becoming a more widely used practice in Virginia in coming years.

Impact of Current Trends in Stormwater Management on Results

This study was based on historical data and regulatory guidelines for designing BMPs in place when those BMPs were constructed. The overwhelming choice for BMPs used by VDOT in the past has been extended detention basins, therefore the majority of the BMPs we analyzed were extended detention basins. Virginia has recently revised its state stormwater regulations (Stephenson et al., 2010; VADCR, 2011). The new regulations focus on updating water quality treatment sizing; updating the efficiencies of select BMPs; and implementing low-impact development approaches such as vegetated filter strips, grass channels, permeable pavement, infiltration practices, bioretention facilities, filtering practices, constructed wetlands, retention basins, and dry/wet swales.

These new regulations will likely alter the way BMPs are designed in the future. Water quality treatment sizing will be based on the first one inch (25.4 mm) of rainfall over the entire development site, rather than the previous treatment size of the first 0.5 inch (12.7 mm) of runoff from only the impervious area of the site (VADCR, 2011). These combined alterations to regulations may result in the need for multiple structural and non-structural BMPs combined into treatment trains to achieve compliance with Virginia stormwater quality regulations for runoff (Stephenson et al., 2010). Because of these changes, construction of BMPs in the future may be more expensive and purchasing nutrient credits may become an even more attractive option in terms of cost savings. However, few projects have been constructed to date under the new regulations due to a grandfathering period, so there is still uncertainty regarding how new regulatory framework will impact actual BMP design, construction, and O&M costs.

Moving forward, it will become increasingly important to track BMP costs separately from other costs within a construction project. Doing so will provide more detailed, accurate, and up-to-date information that will aid in determining break-even points between purchasing nutrient credits and constructing onsite BMPs. This study provides further evidence of the variability in BMPs costs that are a function of the BMP type as well as specific site conditions and constraints. If new regulations result in changes to BMP types preferred by designers, it will be important to collect additional data on these BMP costs and the specific conditions that drive their costs. While this study suggests that the current credit prices procured by VDOT are an attractive option in most circumstances, especially when purchase of additional ROW is required for the BMP, this result was largely based on past construction data and should be periodically updated to reflect future changes in BMP types, construction practices, construction costs, and regulatory guidelines.

Nutrient Credits within a Broader Sustainability Context

Although this study suggests that nutrient credits are a cost effective alternative for BMPs constructed to achieve compliance with stormwater quality regulations, the overall sustainability of a nutrient credit program should be further studied. Environmental challenges of nutrient credits include the uncertainty of the equivalency of pollutant reduction created by a nonpoint source credit generator and potential creation of localized areas of elevated impaired water quality (Fisher-Vanden and Olmstead, 2013; Willamette Partnership, 2012). The uncertainty of pollutant reduction is attributed to the stochastic nature of runoff from nonpoint sources, which can vary greatly spatially and temporally depending on topography, soil characteristics, geology, rainfall, temperature, and vegetative cover. For this reason, substitution of nutrient credits is limited spatially (e.g., in Virginia, trades are limited to within an approximately 700 square mile 8-digit USGS HUC) to reduce environmental risk. Further research could study if this spatial restriction is sufficient. Another inherent challenge to nutrient credits for stormwater quality is non-uniform mixing of a pollutant, which can lead to localized areas of elevated of impaired water quality, unlike air quality trading where one ton emitted from one location is more closely equivalent to one ton emitted elsewhere (Fisher-Vanden and Olmstead, 2013). Trade efficiency issues may arise if impairment of the water quality is non-linearly related to the pollutant concentration (e.g., an endangered species that is sensitive to the pollutant). Monitoring of water quality at a local and watershed levels would enable better assessment of environmental performance for sites eligible for nutrient credit programs (Stavins, 2014; Faeth, 2000).

Social challenges of nutrient credits include the willingness of participation in credit generation and public support. Agricultural farms, a potential source of nonpoint credit generation, may be hesitant to engage in credit generation for a number of reasons including uncertainty of cost effectiveness from the generator's perspective, concern that participation may be a precursor for increased regulation, or the perception to the public that generators are helping purchasers absolve their responsibility for water quality management (Willamette Partnership, 2012). Further research could help quantify the cost effectiveness of credit generation for the agricultural community. With an increasing interest of the general public in water quality, participants of nutrient credit programs could work cooperatively with the general public to address concerns and increase transparency to prevent public opposition (Jarvie and Soloman, 1998).

CONCLUSIONS

Results of the analysis of nine BMPs found that their cost ranged from $20,100 to $74,900 per pound ($44,313 to $165,126 per kilogram) of phosphorus removed. These costs are highly variable both across BMP types and within a given BMP. For example, while this study assumes pre-construction costs to be 32% of the construction costs, pre-construction costs could actually range between 10 to 40% of construction costs. Similar variability exists for other components of the total BMP cost; the values provided in this study should, therefore, be interpreted in light of this variability. Extended detention basins have been the dominant BMP used in the past by VDOT (92% of all BMPs constructed by VDOT from 1997 to 2014 were extended detention basins) and, for this reason, they were the dominant BMP type included in this study. The seven extended detention basins were more cost effective than the two non-extended detention basins (a sand filter and an extended detention enhanced basin) by over $22,000 per pound ($48,502 per kilogram) of phosphorus removed when excluding ROW costs. ROW costs are a major source of variability in the total cost of a BMP, as were the particular site constraints or needs (e.g., additional fill, clay liners, etc.) for construction of the BMP.

Results of this study suggest current prices for nutrient credits available to VDOT present an attractive alternative to constructing onsite BMPs, especially when additional ROW must be purchased for the BMP. With the exception of two of the seven extended detention basins analyzed, nutrient credit prices were less expensive than the total cost of the BMP when excluding the potential cost of purchasing additional ROW for the BMP. After including additional ROW for the BMP footprint, all of the nine BMPs analyzed exceeded the price of nutrient credits on a per pound cost efficiency basis. This result suggests that, at current prices, nutrient credits are a cost effective alternative except perhaps for highly cost effective BMPs like extended detention basins with no unusual site constraints and no need for additional ROW purchase.

Stormwater regulations in Virginia have recently changed and it is likely that these changes will result in new BMP implementation strategies to meet regulatory guidelines in the future. These changes in stormwater regulations follow national trends and emphasize reducing the runoff volume from developed sites in addition to limiting the post-construction peak discharge to pre-development conditions. It remains to be seen exactly how these changes will impact BMP selection, design, and costs in the future because few projects have been constructed under these new conditions. Based on this and related research, it is clear that BMP costs are time dependent for a variety of reasons and so it is important to periodically update BMP cost estimates.

While this study focused on cost, there are other important factors to consider tor projects that meet the regulatory criteria to allow for nutrient credit substitution. The ultimate decision of whether to construct onsite BMPs or purchase credits should extend beyond a simple cost analysis to also take into consideration environmental and social aspects of the project. Within this broader sustainability context, it is important for future research to improve understanding of the environmental equivalency of onsite pollutant reduction compared to pollutant reduction through credit purchase. While this relationship is uncertainty and can vary greatly across sites, new tools and approaches for establishing environmental equivalency that take these factors into account will benefit the overall sustainability of nutrient credit use.

Obtaining detailed, place-specific, and up to date information on the lifetime costs of BMPs that include design, construction, and maintenance remains a very challenging task. Our approach for obtaining construction cost data required careful consideration and interpretation of overall site plans for construction projects to piece-out the stormwater specific costs. If procedures were put in place to track costs specific for stormwater management separately within a larger construction project in the future, then it would greatly simplify the process that we used, and potentially result in more accurate cost data. With this detailed BMP cost data more readily available in the future, decision makers would be better able to produce accurate break-even points early in the stormwater planning process for deciding between purchasing credits in lieu of constructing onsite BMPs.

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SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: a version of the Cost Effectiveness section written using SI units along with figures and tables also in SI units.

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Table 1: BMP properties. (See Table S.1 in the supplemental document for the equivalent information in SI units.)

ID	BMP Type	4-digit HUC	Impervious Area Treated (acres)	WQV Treated (ft^3)	Annual Phosphorus Removal (lb)	Removal Efficiency
1	Extended detention basin[a]	York	2.44	8414.34	1.85	35%
2	Extended detention basin[a]	York	2.56	8828.16	1.94	35%
3	Extended detention basin[a]	York	8.01	27622.49	6.08	35%
4	Extended detention basin[b]	Potomac	4.27	14725.10	3.24	35%
5	Extended detention basin[b]	Potomac	7.33	25277.51	5.57	35%
6	Extended detention basin[b]	Potomac	7.42	25587.87	5.64	35%
7	Extended detention basin[b]	Potomac	15.15	52244.78	11.51	35%
8	Sand filter[c]	Potomac	4.40	7586.70	6.21	65%
9	Extended detention enhanced basin[c]	Potomac	9.20	31726.20	9.98	50%

BMP = best management practice; HUC = hydrologic unit code; WQV = water quality volume.

[a] Functional class: rural collector rolling undivided.

[b] Functional class: rural principal arterial.

[c] Functional class: urban minor arterial.

Table 2: BMP component costs, total costs, and cost effectiveness. (See Table S.2 in the supplemental document for the equivalent information in SI units.)

					Total		Per Pound of Annual Phosphorus Removal	
BMP ID	Pre-Construction	Construction	Lifetime O&M	ROW	Excluding ROW	Including ROW	Excluding ROW	Including ROW
1	$7,487.90	$23,399.69	$3,481.28	$24,081.55	$34,368.87	$58,450.43	$18,545.89	$31,540.61
2	$15,049.60	$47,030.01	$6,996.88	$35,691.84	$69,076.49	$104,768.33	$35,527.32	$53,884.30
3	$20,083.53	$62,761.02	$9,337.26	$30,077.16	$92,181.80	$122,258.96	$15,152.52	$20,096.50
4	$15,265.14	$47,703.55	$7,097.08	$35,327.13	$70,065.77	$105,392.89	$21,604.80	$32,497.93
5	$48,580.29	$151,813.40	$22,586.00	$57,992.14	$222,979.68	$280,971.82	$40,052.86	$50,469.73
6	$46,085.87	$144,018.34	$21,426.29	$62,088.79	$211,530.50	$273,619.28	$37,535.42	$48,552.88
7	$79,023.29	$246,947.78	$36,739.59	$53,814.44	$362,710.66	$416,525.10	$31,522.45	$36,199.35
8	$29,889.55	$93,404.84	$166,755.37	$49,801.21	$290,049.76	$339,850.97	$46,735.48	$54,759.91
9	$88,069.13	$275,216.03	$184,253.38	$200,549.55	$547,538.54	$748,088.08	$54,852.59	$74,943.71

BMP = best management practice; O&M = operation and maintenance; ROW = right-of-way

Note: Costs are presented in 2014 U.S. dollars.

Table 3: Comparison of estimated and published costs for construction and O&M of the sand filter and enhanced extended detention basin.

		Construction + O&M Cost			
ID	BMP Type	Cost Estimate	Average	Upper 67% CI	Lower 67% CI
8	Sand filter	$260,160.21	$196,720.33	$440,089.49	$110,547.15
9	Enhanced extended detention basin	$459,469.41	$218,790.39	$128,836.32	$437,005.44

BMP = best management practice; O&M = operation and maintenance; CI = confidence interval, Average = average published cost; Upper and Lower 67% CI = 67% confidence interval for published cost.

Note: Costs are presented in 2014 U.S. dollars.

Table 4: Potential cost savings of purchasing nutrient credit in lieu of constructing onsite BMPs. BMP 7 was excluded from the table because it would not have qualified for 100% off-site nutrient credits due to its disturbed area being greater than 10 acres (40,469 square meters) and post-construction phosphorus reduction requirement being greater than 10 pounds (4.5 kilograms) per year. (See Table S.3 in the supplemental document for the equivalent information in SI units.)

BMP ID	BMP Type	Total BMP Cost Per Pound of Annual Phosphorus Removal		Credit Cost Per Pound of Credit Removal[1]	Potential Cost Savings from Purchasing Credits in lieu of onsite BMP	
		Excluding ROW	Including ROW		Excluding ROW	Including ROW
1	Extended detention basin	$18,545.89	$31,540.61	$20,000	-7.84%	36.59%
2	Extended detention basin	$35,527.32	$53,884.30	$20,000	43.71%	62.88%
3	Extended detention basin	$15,152.52	$20,096.50	$19,000	-25.39%	5.46%
4	Extended detention basin	$21,604.80	$32,497.93	$18,700	13.45%	42.46%
5	Extended detention basin	$40,052.86	$50,469.73	$18,700	53.31%	62.95%
6	Extended detention basin	$37,535.42	$48,552.88	$18,700	50.18%	61.49%
Median	Extended detention basin	$28,566.06	$40,525.41	$18,850	28.58%	51.98%
Average	Extended detention basin	$28,069.80	$39,506.99	$19,183	21.24%	45.31%
8	Sand filter	$46,735.48	$54,759.91	$18,700	59.99%	65.85%
9	Enhanced extended detention basin	$54,852.59	$74,943.71	$18,700	65.91%	75.05%
Median	Overall	$36,531.37	$49,511.31	$18,700	46.95%	62.19%
Average	Overall	$33,750.86	$45,843.20	$19,063	31.67%	51.59%

[1] Current credit prices for the watershed in which the BMP is located.

BMP = best management practice; ROW = right of way.

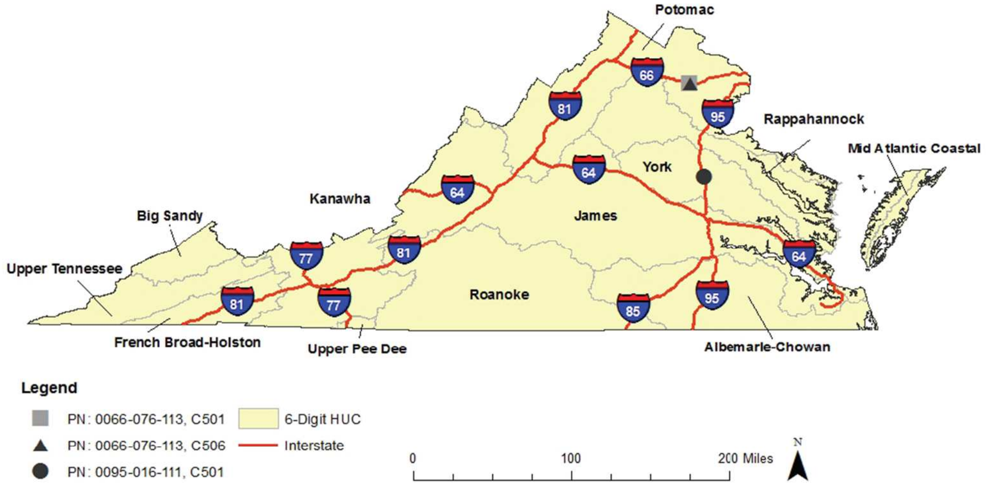
Note: Costs are presented in 2014 U.S. dollars.

Figure 1: Map showing Virginia's 6-digit hydrologic unit code (HUC) basins and the locations of the three construction projects used in the cost comparison. PN = project number.

Figure 2: Comparison of estimated and average published costs for construction and O&M of extended detention basins. The data points represent the cost estimates, the dashed line represents the average published cost, and the solid lines represent the 67% confidence interval for the average published cost (Weiss et al., 2011, 2007). Circled numbers represent BMP IDs. Costs are presented in 2014 U.S. dollars. (See Figure S.1 in the supplemental document for the equivalent information in SI units.)

Figure 3: Comparison of total BMP cost (excluding right of way, ROW) and nutrient credit cost. Costs are presented in 2014 U.S. dollars. (See Figure S.2 in the supplemental document for the equivalent information in SI units.)

Figure 4: Comparison of total BMP cost (including right of way, ROW) and nutrient credit cost. Costs are presented in 2014 U.S. dollars. (See Figure S.3 in the supplemental document for the equivalent information in SI units.)



Map showing Virginia’s 6-digit hydrologic unit code (HUC) basins and the locations of the three construction projects used in the cost comparison. PN = project number.

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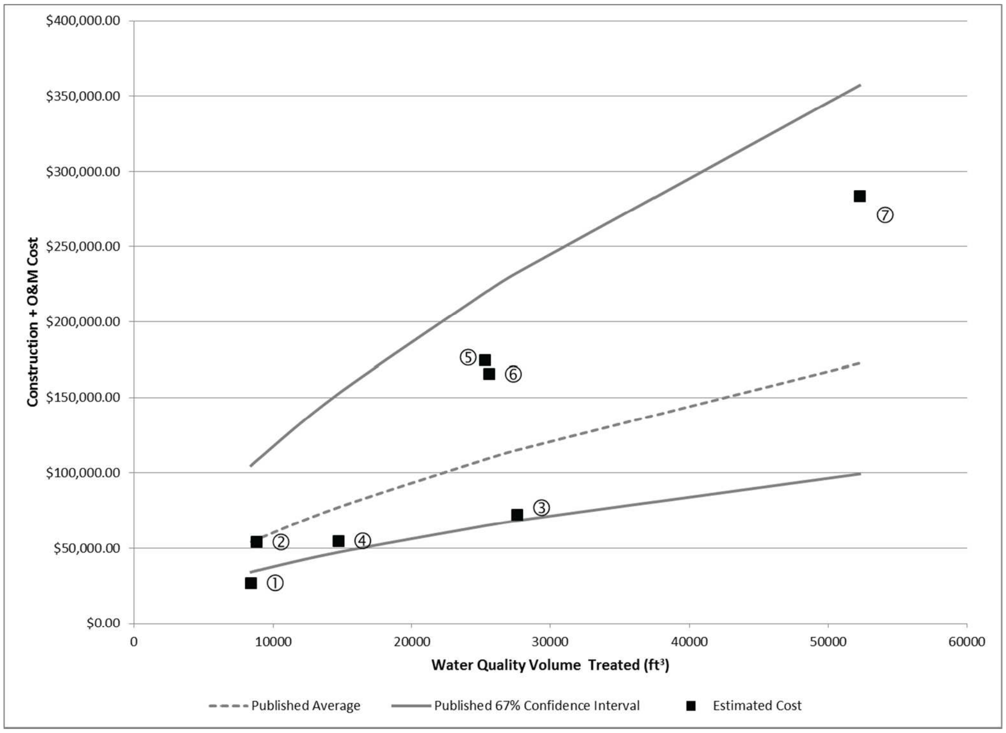

Comparison of estimated and average published costs for construction and O&M of extended detention basins. The data points represent the cost estimates, the dashed line represents the average published cost, and the solid lines represent the 67% confidence interval for the average published cost (Weiss et al., 2011, 2007). Circled numbers represent BMP IDs. Costsare presented in 2014 U.S. dollars. (See Figure S.1 in the supplemental document for the equivalent information in SI units.)

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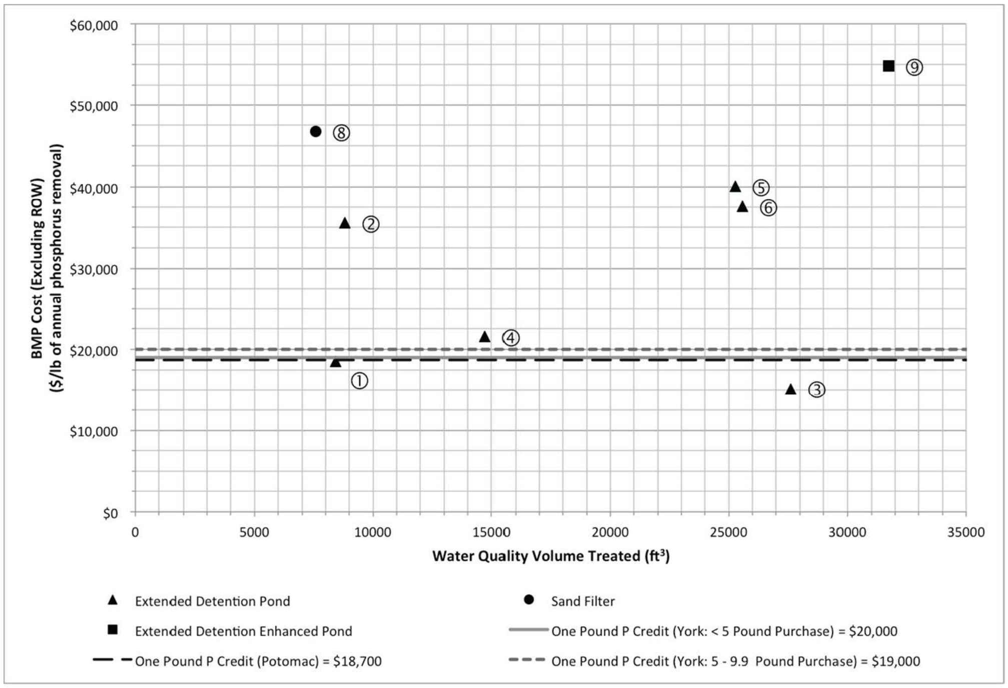

Comparison of total BMP cost (excluding right of way, ROW) and nutrient credit cost. Costs are presented in 2014 U.S. dollars. (See Figure S.2 in the supplemental document for the equivalent information in SI units.)

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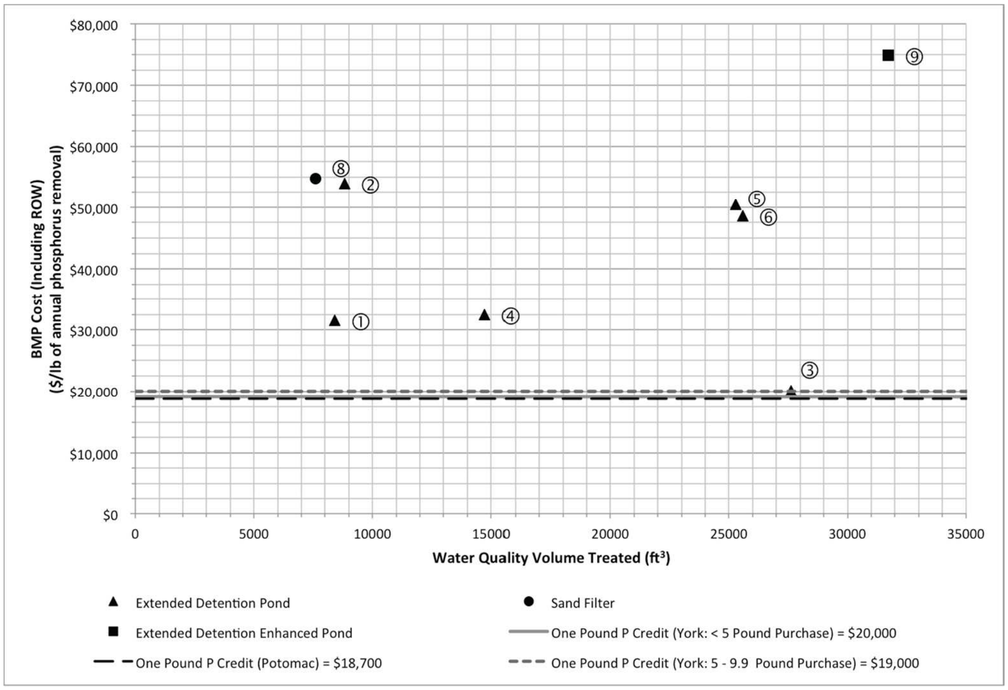

Comparison of total BMP cost (including right of way, ROW) and nutrient credit cost. Costs are presented in 2014 U.S. dollars. (See Figure S.3 in the supplemental document for the equivalent information in SI units.)

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