A semi-distributed model for locating stormwater best management practices in coastal
environments

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Abstract

New regulations in Virginia and elsewhere require reduction of runoff volume and phosphorus loads after development using approved stormwater best management practices (BMPs) that favor infiltration. The flat terrain, shallow water tables, and impermeable soils present in the Coastal Plain of Virginia limit the use of many BMPs. The BMP Checker facilitates BMP siting; calculating median slope and seasonal high water table depth, soil types, and catchment size from spatial inputs, then compares catchment characteristics to constraints to predict suitable and unsuitable BMPs and phosphorous loads. This process was validated at 11 sites in the City of Virginia Beach, and then applied citywide to assess the spatial applicability of each BMP. Wet ponds that intercept groundwater and constructed wetlands (both at 74%) were the most applicable BMPs. Sheet flow to conservation area and infiltration practices (11% and 24%, respectively) were the least applicable BMPs. Results were consistent with local experience.

Keywords: best management practices (BMPs), Geographic information system (GIS), water table, low impact development (LID), siting, spatial applicability

1.0 Introduction

Urban development creates large amounts of hard surfaces for roads, parking, buildings, and sidewalks. Unlike natural soils, which allow water to infiltrate at varying rates, impervious surfaces created by urban development do not allow any water infiltration. Additionally, pervious portions of urban areas tend to be compacted and are often nearly impervious themselves. As urban development occurs, large increases in runoff volume and discharge rates result from the increase in imperviousness. Further, baseflows are reduced from the loss of infiltration and groundwater recharge to areas directly beneath impervious surfaces (Fletcher et al., 2013; Yang et al., 2011), effectively drying up stream channels. These hydrologic alterations cause a wide variety of downgradient impacts (Kaushal and Belt, 2012) including streambank erosion and channel deepening (Nelson and Booth, 2002); increased sediment, nutrients, and heavy metal loadings (Hatt et al., 2004); and a decline in aquatic health (Alberti et al., 2007). The growing realization that contemporary stormwater management practices may be unable to address impacts from urbanization has made improving the management of runoff volume a key policy recommendation (National Research Council, 2009). In the Mid-Atlantic states, another water quality concern has been the eutrophication of the U.S. Chesapeake Bay estuary, which led to the institution of a Total Maximum Daily Load (TMDL) by the U.S. Environmental Protection Agency (USEPA, 2010). The TMDL is being implemented in the stormwater management sector primarily through modifications of National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer System (MS4) permits. NPDES permits are required for most discharges to water bodies under the U.S. Clean Water Act (U.S. Code, 1972); the permits

contain various programmatic requirements designed to reduce runoff generation and pollutant loads. MS4 refers to jurisdictions and/or entities that operate separate stormwater systems (USEPA, 2016), as opposed to combined systems used in many older urban areas in the U.S. Combined sewers convey stormwater and wastewater in the same conduit, which is problematic for water quality protection (Lucas and Sample, 2015). Combined systems are not regulated via the NPDES MS4 stormwater program.

In Virginia, the Virginia Department of Environmental Quality (VDEQ) responded to the need to protect downstream water quality and manage runoff volume with significant modifications to the Virginia Stormwater Management Program (VSMP) in 2014 (Virginia Administrative Code, 2014). The Runoff Reduction Method (RRM) (Hirschman et al., 2008) was adopted as a compliance tool for evaluation of runoff volume and downstream phosphorus loads. The RRM necessitates use of urban stormwater best management practices (BMPs) to meet regulatory standards. To date, 15 state-approved BMPs exist, ranging from infiltrative practices like bioretention to storage-treatment practices like retention ponds (referred in the Virginia specifications and in this paper as “wet ponds”). The RRM assumes BMPs are constructed to conform with state specifications (Virginia Department of Environmental Quality, 2013). Summary descriptions of each BMP and references to its Virginia specifications are provided in Table A-1 in Appendix A. While the state specifications and the RRM were developed for application to the Piedmont region of Virginia, they are applied statewide (VDEQ, 2013). In addition to the Piedmont, Virginia’s physiography includes the Coastal Plain and karst areas within the Ridge and Valley; each pose different but significant challenges to implementing infiltration-based BMPs. Coastal Virginia, the focus of this paper, is characterized by flat terrain, shallow water tables, and abundance of relatively impermeable soils that limit the application of

the recommended BMPs (Hampton Roads Planning District Commission, 2013; VDEQ, 2013), particularly infiltration-based BMPs that receive the most performance credit. However, the design guidelines include modifications to improve BMP applicability in coastal areas, such as reducing the required seasonal high water table (SHWT) separation or BMP depth. Use of these modifications may reduce the credit given to BMPs in some instances. For example, wet ponds are allowed to intercept groundwater, but do so at a 5% reduction in phosphorous removal credit.

BMP siting is a complex process influenced by objective physical measures, such as depth to SHWT or slope of the contributing drainage area, and by subjective, less concrete measures such as safety. Generally, these constraints should be met for appropriate BMP siting before non-physical objective or subjective measures are considered for final BMP selection. It can be challenging to locate and select BMPs for use on a given site. Iteratively checking suitability of the location's physical parameters against the BMP specifications can be time consuming. Non-physical constraints, such as required maintenance efforts and costs, are not easy to evaluate, yet are of considerable value to designers. A siting, selection, or decision support tool would be helpful to stormwater management professionals during the BMP planning and design process (Jia et al., 2013). As such, many tools have been developed in an attempt to make the selection process more efficient (Elliott and Trowsdale, 2007).

Young et al. (2009a; 2009b; 2010) developed the Virginia Tech BMP Decision Support Software (VT BMP DSS), a BMP selection tool based on the Analytic Hierarchy Process (AHP). AHP is a decision algorithm that utilizes complex matrix manipulation to rank a set of outcomes according to the priorities of the input constraints. The VT BMP DSS uses both physical constraints and performance-based criteria as decision parameters. The user is free to choose as many or as few decision parameters as the user deems to be appropriate. The user also has the

option to rank decision parameters by relative importance, adding or removing weight to or from individual criteria. VT BMP DSS outputs a list of BMPs in ranked order according to their suitability with the decision criteria and weights. The tool was developed to be used statewide across Virginia. Unfortunately, this statewide use hinders the tool's effectiveness in the Coastal Plain. Physical constraints are optional and the user is unable to specify coastal BMP adaptations, such as relaxing the depth to the water table.

The Stormwater BMP Prioritization and Analysis Tool (SPBAT) (Geosyntec, 2012) was designed for use within Orange County, California, and combines spatial information with matrix operations for BMP selection. SPBAT identifies priority catchments that benefit most from BMP implementation and uses a matrix-based algorithm to rank potential BMPs. The user manually checks that ranked BMPs are not physically constrained and removes them from consideration if they are not feasible, placing the burden of appropriate BMP siting on the user.

The System for Urban Stormwater Treatment and Integration (SUSTAIN) BMP Siting Tool (Tetra Tech, 2013) is a spatial tool that focuses on physical constraints to recommend BMP placement. It is an early-stage planning and siting tool that does not take cost, maintenance, or performance-based measures into account. Case study applications of SUSTAIN include Kansas City, U.S. (Lee et al., 2012), Gwangju, South Korea (Baek et al., 2014), and Beijing, China (Jia et al., 2015). The siting constraints are customizable, but are not fully compatible with the RRM constraints and specifications. BMP compatibility is determined on a cell-by-cell basis within ArcGIS. Computational limitations constrain the resolution of spatial inputs, which may negatively impact use in large coastal areas as high resolution is necessary to overcome limitations in flat terrain (U.S. Army Corps of Engineers, 2003). Without significant preconditioning, some native ArcGIS tools manage flat terrain very poorly (Amatya et al., 2013).

Liu et al. (2015) created L-THIA-LID 2.1, a model that identified appropriate BMPs at the hydrologic response unit (HRU) and watershed level. Suitable BMPs for each HRU were based on drainage area, drainage slope (%), imperviousness (%), hydrologic soil group (HSG), and buffers from streams, roads, and buildings. The performance of BMPs was evaluated by a hydrologic rainfall-runoff model and cost-effectiveness was determined. The framework later incorporated an optimization routine based on performance and cost (Liu et al., 2016). Because depth to water table was not a BMP constraint in the L-THIA-LID 2.1 model, it lacks a key feature for use in the Coastal Plain within the RRM framework.

Other BMP decision support, siting, or selection tools are available (Tetra Tech, 2010; Viavattene et al., 2008; WERF, 2009), but are not suitable for early-stage BMP siting and planning. Available tools fail to adequately account for coastal siting conditions and place the burden of appropriate siting on the user. Local experience with implementation of the RRM in a coastal Virginia city has indicated that the impact of the state specifications has significantly restricted the ability to site particular BMPs on any given site (Johnson, 2016a). To address these challenges, there is a need to develop a tool that reduces the complexity of BMP siting in the Coastal Plain that considers spatial variability, coastal conditions, and coastal design modifications. Such a tool would save resources, reduce uncertainty of water quality and runoff reduction credits, and reduce the overall complexity of BMP selection in coastal Virginia.

The objective of this paper is to develop an easy-to-use BMP siting and planning tool, which we have called “BMP Checker” that works well with coastal physiography and the RRM compliance framework and to investigate its application in the study area, the City of Virginia Beach. By applying the tool citywide, the feasible extent of each BMP will then be assessed,

saving time in the initial planning stages of a development. By identifying feasible regions for each BMP, resources will not be wasted attempting to site ill-suited BMPs in those areas.

The BMP Checker tool is freely available on an “as is” basis (see software availability section at the end of this paper). While the tool was developed for siting BMPs in coastal Virginia, its use is not strictly limited to this region. The main inputs of the tool are soil and drainage boundary shapefiles, and elevation and water table raster files. In the U.S., soil data are readily available from the Natural Resources Conservation Service (NRCS), Soil Survey Staff et al. (2015). Watershed boundaries are specifically developed by the user for a particular site. Digital elevation model (DEM) raster files are typically available from local or national geographic information system (GIS) datasets (e.g., www.usgs.gov); however, water table raster information is not. A water table raster can be developed from interpolation of boring logs, monitoring wells, and geological maps; a constant raster can even be created and used as input. The authors developed a methodology reliant on surface water elevations and available monitoring data (Johnson, 2016b). Other inputs, such as the types of BMPs and their physical constraints are contained within a provided spreadsheet. While these are suitable for Virginia, they can be customized by the user to match their local requirements and the site. Finally, since the tool is designed to be used by practitioners in the U.S., U.S. customary units are used for input and output, so appropriate conversions are needed before using SI units. In this paper, SI units are provided, with U.S. customary units in parenthesis where needed for clarity.

2.0 Methods

2.1 Study Area

The application was developed using data from the City of Virginia Beach, a coastal city adjacent to the Atlantic Ocean and Chesapeake Bay in southeastern Virginia, encompassing 808 km² of coastal lowlands and wetlands (Figure 1). Topographic relief of Virginia Beach is relatively low and flat, with an average altitude of 3.7 m above sea level. A majority of the land has less than 3% slope and is presumed to have a SHWT less than 0.3 m below the surface (Hampton Roads Planning District Commission, 2013). From investigations of spatial data obtained from the United States Department of Agriculture (USDA) Web Soil Survey, no soils in Virginia Beach are classified as having a D-type HSG outright, but over 70% of Virginia Beach soils have a dual-type HSG (Figure 1a). Dual-type HSGs have an A, B, or C classification when the soil is drained and a D classification when the soil is undrained, where undrained is defined as having the water table within 0.6 m of the land surface (USDA, 2009). Accounting for the predicted SHWT of less than 0.3 m, Virginia Beach dual-type soils are a D classification a majority of the time. Land use in Virginia Beach is predominately urban, and including office, commercial, residential, and several military bases; the southern portion of the City is predominately agricultural (Figure 1b). Significant areas are inundated by water. The flat terrain, shallow water tables, and poor soil permeability of Virginia Beach provide the necessary inputs to develop a BMP siting tool that performs well in coastal conditions.

2.2 Development of the BMP Checker Tool

Physical features of the landscape are the primary concern when initially siting BMPs. The most readily accessible source of information concerning land features is in the form of GIS layers and associated data. A siting tool is best suited to read and manipulate GIS information to quickly determine the physical characteristics of a given site. BMP siting is dependent upon comparison of those physical characteristics to the physical design constraints of each BMP. If

the physical features of that location are within applicable BMP design constraints, that BMP is deemed suitable for use in that location. This basic idea formed the framework for development of BMP Checker, visualized in Figure 2. In addition to basic BMP siting, the tool was developed to incorporate pollutant load calculations according to the RRM.

Other principles are also important in guiding development toward a suitable end product. Decision support tools often face significant adoption challenges post-development (McIntosh et al., 2011). To improve likelihood of successful adoption, GIS inputs were made to require as little preconditioning or alteration by the user as possible to enhance accessibility for those unfamiliar with GIS. The input “database” containing BMP design constraints was designed as a Microsoft Excel® workbook (.xlsx), allowing the table to be readily viewed and altered by the user. This feature improves tool lifespan and expands the potential audience; thus updated BMP standards will not render the existing program useless, furthering likelihood of adoption. Similarly, output tables were coded as a Microsoft Excel® workbook for easy access, utilization, and sharing by the user. Brief information on expected relative costs and maintenance of each BMP type, a list of rejected BMPs with reasons for rejection, and a summary of the locations’ physical characteristics were included as outputs for the convenience of the user. The program was developed with 32-bit Python 2.7.10 and utilizes the functions available in ArcGIS 10.3 (Esri, 2016), but was made to run independently of ArcGIS, eliminating processing overhead and improving processing speed. Because the program utilizes ArcGIS functions, it must be used on a computer with a licensed and functioning copy of ArcGIS 10.3 installed. With end-user comfort and the goal of making the existing task of BMP siting and RRM compliance easier, chances of successful adoption may be increased (McIntosh et al., 2011).

The program requires a minimum of four GIS inputs and a single Microsoft Excel® workbook. The GIS inputs required to run the tool include two raster files and two polygon shapefiles. Up to two additional shapefiles are needed when calculating the pretreatment loading and estimated load removed by the BMPs in each drainage area (DA). The two required raster inputs include a DEM and a SHWT depth grid, while the two shapefile inputs include DA boundaries and soil data, including HSG attributes. To calculate RRM loadings and credits, an impervious cover shapefile is required while an undisturbed cover shapefile is optional. The DEM determines output projection and resolution (cell size) of raster calculations, including the conversion of shapefiles to rasters. Because the RRM was designed using U.S. customary units, all spatial inputs should be in these units.

The DAs are the unit of analysis for program functions and act primarily as BMP siting areas. The user determines DA boundaries. DAs can be any size and created via any method, though the program is most suited for DAs less than 25 acres (10 ha). The minimum DEM resolution is related to DA size and requires judgement by the user. For example, a 0.2 ha (0.5 ac) DA used in conjunction with a 30 m DEM will result in under 3 cells used for analysis, which will not yield meaningful results. Number of DAs for analysis ranges between 1 and 500. Average land characteristics within the boundary of each DA are used to determine BMP suitability within the DA boundary. In this way, the program functions as a semi-distributed model to arrive at results. This is in contrast to the cell-by-cell or fully distributed approach taken by the SUSTAIN BMP Siting Tool (Tetra Tech, 2013). The advantages of a semi-distributed approach include avoiding BMP selections that are applicable on just a few isolated cells, improving processing time, and enhancing readability of output. DA size and DEM resolution are related. Small DAs are only suitable when the DEM is of adequate resolution, and low

resolution DEMs require larger DAs, for example. The highest available DEM resolution is preferred. For best results, SHWT data should be the same resolution as the DEM, otherwise automatic resampling will occur.

The BMP constraint table used to compare the physical characteristics of a site and determine suitable BMPs was developed in the form of a Microsoft Excel® workbook. A default version of this table was built using information obtained from the 2011 edition of the Virginia Stormwater Management Handbook BMP Standards & Specifications for post-construction, non-proprietary BMPs (Virginia Department of Environmental Quality, 2011). Of the 15 post-construction, non-proprietary BMPs, default constraints were not found for rainwater harvesting or green roofs because those BMPs are not dependent on land features. Soil restoration was not included as a standalone BMP, but was included as an option with other BMPs to enhance performance. The remaining 12 BMPs were separated into design levels according to the RRM BMP specifications (Virginia Department of Environmental Quality, 2011). The BMP constraint table includes measures for maintenance preferences and relative annual cost. Neither maintenance preference nor costs are used within the program to site BMPs; these measures were provided for the convenience of the user when viewing output tables. Maintenance preference was provided by the Virginia Beach Department of Public Works Operations Management. Costs were estimated using a procedure detailed in the program documentation, included with download of the application. Costs do not represent the absolute costs expected in Virginia Beach. A significant portion of BMP cost depends on site-specific factors (Sample et al., 2003), thus cost information was provided only to gauge BMP costs relative to each other. Maintenance preferences and cost can be altered by the user to fit their knowledge and experience.

Though the tool was developed using Virginia BMP standards with special attention to coastal application, the customizable nature of the BMP constraint table and the limited restrictions on inputs allows the basic BMP siting functionality to be used in most environments. The constraint table can be set to ignore water table limitations and other coastal- and Virginia-specific siting options. BMP Checker can be used to save time summarizing drainage area characteristics and to identify the most likely BMP options in non-coastal Virginia and beyond.

2.3 Program Structure and Function

The program was named BMP Checker, after its primary purpose of checking whether the basic physical characteristics of a site are suitable for any of the Virginia-approved BMPs. First, the user determines whether they are interested in calculating areas and loadings for total phosphorus (TP) and total nitrogen (TN), then the user specifies file paths for the GIS raster and shapefile inputs, names the project, and identifies a file path for the project outputs. After that, the user's involvement is over and the remainder of the program proceeds automatically until BMP Checker completes successfully or encounters an error. An example of a successful run as it appears in the program's user interface is given in Figure 3.

The logic of the main program is summarized in Figure 4. First, soil data is checked for the presence of dual-group soils. The water table depth raster is used to convert dual-group to single-group soils based on water table proximity to the land surface (USDA, 2009). If nutrient loading is desired, the areas for each DA, soil, and land use combination are used to calculate the untreated pollutant load from each DA and the total site area. If the total area of a single HSG covers less than 46.5 m² (500 ft²) in a single DA, that HSG is not considered by BMP Checker in further calculations. The slope, median slope, and median water table depth in each DA is found

and combined with the DA and HSG information to create a summary table of physical features in each identified DA.

The features of each DA are then compared to BMP features in the constraint table. This process, illustrated in Figure 5, occurs in a nested loop: the program iterates through each BMP listed in the constraint table for each DA. Note that cost and maintenance preferences are not used to determine BMP suitability. Users have the option of utilizing impervious and undisturbed (forested) cover amounts as a constraint. Optionally, BMPs requiring the presence of undisturbed area can be removed if the undisturbed area in the DA is less than 46.5 m² (500 ft²), and BMPs are removed if the impervious cover in the DA is less than that needed by the BMP. Next, the soil types in the DA are compared to the recommended BMP soil types. Median slopes are calculated and compared, along with the water table, to the constraint table. The water table constraint specifies the distance between the BMP invert elevation and the water table. If the BMP is allowed to intersect the water table, then this step is skipped and the program moves on to the DA size constraint. If the BMP is not allowed to intersect the water table, the program sums the minimum BMP depth and the default water table separation distance. Unlike the previous constraints, if the DA's median water table depth is less than the combined BMP depth and minimum water table separation, that BMP does not automatically fail the criteria check. Virginia's BMP standards allow for some coastal design modifications related to minimum BMP depths and water table separation distance. If the BMP has approved coastal modifications, the modified values are combined and compared to the median water table depth again. If the median water table depth is still higher than the combined depth for the modified conditions, or if there are no coastal modifications for the BMP, then the BMP fails and is removed from consideration. If the adjusted depths or separation cause the water table depth to fall below the

combined BMP values, then the BMP is preserved and marked as allowable if special modifications are implemented.

As a last step, DA size is compared to the minimum contributing drainage area for each remaining BMP. If the DA size is smaller than necessary for the BMP, that BMP is removed. Maximum DA size is not used to eliminate BMPs, but is accounted for by including the minimum number of equivalent-sized BMPs needed to treat the entire DA. For example, a 4 ha (10 ac) site is suitable for grass channels, which have a maximum contributing drainage area of 2 ha (5 ac). A minimum of 2 grass channel BMPs would be required to treat runoff from the entire 4 ha (10 ac) site.

If nutrient loading is desired, the program calculates TP and TN removed by each BMP using the Virginia RRM (Battiata et al., 2010; Hirschman et al., 2008). RRM uses the NRCS TR-55 method (USDA, 1986) to estimate runoff for a water quality storm event, which is defined as 25.4 mm (1 in) in depth across the subject watershed. RRM modifies the TR-55 method by subtracting retention storage provided on site, then back calculates a modified curve number for use in estimating runoff from each DA on the site. Pollutant loads are calculated by:

$$L = P \cdot P_j \cdot \left(\frac{T_v(S)}{R_d} \right) \cdot C \cdot 0.001 \quad (1)$$

where L is the post-development pollutant load for the site in kg/year of pollutant, in this case, phosphorus, P is the average annual precipitation in mm (1,092 mm for Virginia), P_j is the ratio of rainfall events that produce runoff (0.9), $T_v(S)$ is the post development treatment volume in m^3 , R_d is the rainfall depth for the water quality storm (25.4 mm), and C is the event mean concentration of that pollutant in mg/L, which for phosphorus in Virginia, is approximately 0.26 mg/L. The post development treatment volume, $T_v(S)$ is calculated as:

$$T_v(S) = R_d/1000 (R_v(S) \cdot SA - R_v(F) \cdot A_f) \quad (2)$$

Where $R_v(S)$ = runoff coefficient for the site, SA = total site area (m^2), $R_v(F)$ = weighted forest runoff coefficient, and A_f = total area of forest and open space on the site (m^2).

The BMP Checker then ranks the BMPs by TP load removed. Otherwise, the BMPs are ranked by TP removal percentage. In both cases, an output table of suitable BMPs is generated, along with several secondary tables. Intermediate GIS layers are saved and are viewable in ArcGIS 10.3, but the output tables summarize physical characteristics of each DA, eliminating the need to view the GIS files to obtain the values.

2.4 Validation

Eleven sites located throughout the developed portion of the City of Virginia Beach were used to validate BMP Checker. The name, size, purpose, and BMP types of all eleven sites are displayed in Table 1. Results were considered validated if the existing BMPs on the sites were included in BMP Checker output. All other BMPs selected for the various sites were manually verified to ensure they could work in their respective areas based on site conditions, but had no bearing on whether the results were considered validated.

DA boundary and land cover information was digitized manually for each of the 11 sites. The DA boundaries were digitized based on georeferenced site plans, or best professional judgement when drainage plans were unavailable. Land cover information was created based on April 2013 aerial imagery. The 1.5 m (5.0 ft) resolution DEM was derived from Lidar data taken in November 2012.

Soil information was obtained from the USDA NRCS Web Soil Survey (Soil Survey Staff et al., 2015) and modified to include HSG based on information contained in the Soil Survey Geographic Database (SSURGO). Soils associated with development, such as Udorthent and Urban soils, are not associated with a HSG in SSURGO. Both soil types are associated with disturbance from urban development; while Udorthent are fill soils. Urban complex soils were assigned the HSG for the non-Urban soil portion. If the soil was Udorthent, fully Urban, or water, the soil was assigned a “---” designation. The “---” designation was converted to a D-type soil in the BMP Checker algorithm.

Groundwater data from construction documents was not available for all eleven sites. In lieu of specific groundwater measurements, the validation runs used a citywide SHWT depth grid derived from water surface elevations found in the DEM and adjusted to the seasonal high by a factor calculated from U.S. Geological Survey groundwater monitoring data. Johnson (2016b) details the creation and validity of the grid. All spatial data was projected in NAD1983 HARN (US Feet) Virginia State Plane South.

The program was run using the default BMP constraint table, given in Table 2 and the column headings are decoded in Table 3. Land cover constraints, including impervious percentage, were not included in the analysis. The land cover information generated for the validation runs was used to determine RRM TP and TN loadings using the process described in section 2.2.

2.5 Citywide Application

The BMP Checker algorithm was used to investigate BMP implementation patterns in the City of Virginia Beach with respect to coastal conditions. Computational limitations prevented

the use of property parcels as DA boundary input for the analysis. To compensate, a vector net of 30.5 x 30.5 m (100 x 100 ft) cells was generated to cover the city area. Cells were removed from the net if they did not have a centroid located within the city boundary. Similarly, if a cell centroid was located within a body of water, that cell was removed from analysis. The final net is composed of 680,160 individual cells. The cell shapefile was used as DA input in the program. Each cell represented a BMP siting area rather than a traditional drainage area. This did not affect program function. The DEM, SHWT depth data, and soil shapefile were the same as those used in the validation runs. Land cover information was not generated or utilized for citywide application.

Computational limitations prevented the citywide analysis from using the complete algorithm tested in the validation procedure. Because each cell in the vector net did not represent a true drainage area and all cells were the same size, the contributing drainage area size was discarded as a BMP checking constraint. Each cell therefore represented a siting location rather than a true drainage area. The HSGs, median slope, and median SHWT depth were found for every cell. If a cell contained less than 46.5 m² (500 ft²) of a single type of HSG, that HSG was not used for BMP constraint comparison purposes in that cell. Additional alterations to the BMP Checker algorithm included a revised BMP constraint table and a revised output format that reduced processing and post-processing time. Neither change had an impact on the program results. The modified BMP constraint table is given in Table 4. Contributing drainage area size was removed from consideration. BMPs with design levels that did not differ in slope, BMP depth, water table separation, or HSG requirements were consolidated into a single entry. BMPs that make use of soil amendments for additional credit were not considered because soil amendments only affect credited performance, not siting requirements.

Because land cover constraints were not considered, additional manual post-processing was needed to approximate the true applicability of the sheet flow to conservation area (SFCA) BMP in Virginia Beach. SFCA is only usable in cells that contain undisturbed, vegetated area. Undisturbed, vegetated areas were defined using soil type, land use, and vegetation location. Vegetation and parcel data were obtained from the City of Virginia Beach Open GIS Data website (City of Virginia Beach, 2016). Parcels with land use types shown in Table 5 were considered the most likely to be undisturbed. Areas with Udorthent, Urban, or Urban-complex soils were considered disturbed area. The vegetation layer was clipped to areas of both appropriate land use and soil type. SFCA cells in the vector net containing more than 46.5 m² (500 ft²) of vegetation after clipping were preserved.

3.0 Results and Discussion

Information on obtaining BMP Checker is included in the Software Availability section at the end of this paper. Output samples for the BMP Checker program are provided in the program documentation and as a supplement to this article in Appendix B.

3.1 Validation Results

Results from the validation runs are given in Table 6. Of the 28 BMPs tested, 5 were not given in the BMP Checker results. This appears to indicate failure of the program to work as desired and expected, but the BMP Checker results make sense when they are considered in the context of actual site conditions.

At one of the linear sites, Nimmo Parkway, there currently is an extended detention (ED) pond that is meant to accept runoff from the street, sidewalks, and medians. BMP Checker did

not list ED ponds as an acceptable practice in the drainage area because the SHWT proximity was too near the minimum ED pond invert. Though the actual pond was designed to be a dry ED pond, it is seldom dry. The pond can be seen in Figure 6; the photograph was taken April 3, 2016, more than 24 hours after a small 1.4 cm storm event. The presence of algae indicates prolonged inundation. In essence, BMP Checker failed ED ponds because they would fill with water from the water table, and the actual BMP is regularly filled with water. Because of this, the BMP Checker result was considered valid. Another potential failure of the tool was at the site of a school bus facility on Harpers Road. This site was designed to have multiple bioretention cells. BMP Checker failed to approve the bioretention cells due to the SHWT proximity. Similar to the ED pond at Nimmo parkway, several of the bioretention cells at Harpers Road appear to be more pond than bioretention due to persistent water levels in most of the cells. Figure 7 shows a photograph of the inundation of one bioretention cell at the site. The photograph was taken in October 2014, outside of the seasonal high window. Because the actual BMPs are regularly inundated, the BMP Checker result was considered valid. New Kellam High School, was constructed with several BMP types, including infiltration basins, permeable pavement, bioretention, and wet ponds (see Appendix A for descriptions of these BMPs). Of those four, only wet ponds were included in the BMP Checker results. Infiltration was chosen in B-type soils in the drainage area, but not in the C-type soil where the BMPs were actually constructed. Permeable pavement and bioretention failed due to SHWT proximity. The construction documentation indicated that the New Kellam infiltration units were built to a depth of at least 0.9 m below the surface. At that depth, the soil was sandier than predicted by the USDA NRCS Web Soil Survey(USDA, 2015) and had a hydraulic conductivity sufficiently high for infiltration. Though the geotechnical report was unavailable, the construction document

mentioned that the water table was 1.8 - 2.1 m below the land surface at the time of testing and the groundwater depth used in design was 1.7 m. Replacing the groundwater data in the simulation with a constant 1.7 m (5.5 ft) depth allowed BMP Checker to select both permeable pavement and bioretention for the New Kellam High School site. In all three cases of initial validation failure, refining the input data allowed BMP Checker to select those BMPs. Though the default input data could use some refinement, the underlying logic of the program was found to be sound and the results provided were deemed valid.

Overall, the underlying logic of BMP Checker appears sound and the provided soil and SHWT depth information is in agreement with expectations on 10 of the 11 tested sites. Like all models, BMP Checker is limited by the quality and accuracy of its input data. BMP Checker includes pre-built soil and SHWT depth information for the City of Virginia Beach, but that data should only be used when more accurate or specific information is unavailable.

3.2 Citywide Application

The final cell net represents the total study area, visualized in Figure 8. After the BMP siting analysis was completed, the spreadsheet output was joined with the vector net in GIS in order to show the results graphically. The results for all BMP types are viewable in Appendix C, a provided supplement to this article, in Figures C-1 through C-17. The most and least applicable BMPs can be seen in Figures 9 and 10, respectively. Tabular results, as a percentage of tested land area, are given in Table 7.

As expected, the most widely applicable BMPs in Virginia Beach were wet ponds that intercept the water table and constructed wetlands. Both BMPs lack a groundwater proximity constraint and have a high maximum contributing drainage area slope of 25%. Both BMPs were

applicable on 74% of the city land area. Though wet ponds that intercept groundwater are highly applicable, they receive less credit than wet ponds that do not intercept the water table.

Conversely, the least applicable BMP was sheet flow to conservation area due to the limited amount of conservation area in the city. Otherwise, the least applicable BMP type is infiltration at 24%. A- and B-type soils occupy a minority of the area in Virginia Beach, and a water table depth requirement of 1.14 m below land surface is difficult to accommodate in the coastal landscape.

At 25%, wet swales follow infiltration as the next least applicable BMP. This is a somewhat surprising result, considering there is no water table depth constraint for wet swales. The lower-than-expected result is likely due to the contributing drainage area slope requirement of 2%. The slope calculation is very sensitive to manmade changes in elevation, like at the edge of curbs or ditches. Smaller drainage areas effectively give more weight to the high slopes of these manmade features when calculating the median, resulting in a higher median slope than would be expected based on the overall grade of the land. The same issue likely affected the results for Level 2 dry swales, which have a 9% applicability and the same contributing drainage area slope requirement.

Level 2 infiltration, the most effective BMP for total phosphorous removal (TPR), is applicable on 8% of the tested land area in Virginia Beach. Level 2 bioretention is the next most effective BMP for TPR and is applicable on 30% of the land area when coastal modifications are included, and 16% when they are not. After Level 2 permeable pavement with a 21% applicability, Level 2 dry swales are the next most effective practice and are usable on just 9% of the land area when coastal modifications are included. Without coastal modifications, applicability is just 7%. It would appear that the most effective runoff reduction BMPs from a

crediting and performance standpoint are not widely applicable in Virginia Beach. As previously stated, this is consistent with local experience (Greg Johnson, City of Virginia Beach Public Works, personal communication, 2016).

Though the approved modifications permit BMP use on more area in the Coastal Plain, the actual performance of BMPs with these modifications is unverified, with the exception of wet ponds that intercept groundwater. BMP types were ranked according to their total land applicability when coastal modifications were and were not included in analysis. The rankings and Level 1 TPR efficiency are found in Table 8 and Table 9 for analysis with and without coastal modifications, respectively. Coastal modifications improved the usability of wet ponds the most, followed by filters and bioretention units. Dry swales and grass channels showed modest improvement in applicability when coastal modifications were used. With the coastal modifications, just one of the top five most usable BMP types received a 25% or less TPR credit. Without coastal modifications, three of the five most applicable BMP types received a TPR credit of 25% or less. Coastal modifications appear to make effective BMPs more applicable, but the true performance of modified BMPs remains unknown regardless of the credit assigned to them.

Applicability percentages from this analysis are based on minimum BMP requirements and available planning-level data. Results are meant to provide perspective on BMP usage in a coastal area and provide a basic guideline for where BMPs may or may not be investigated for design purposes. True applicability of BMPs depends on site-specific factors that cannot be quantified in this analysis. For example, the existence of structures, roadways, or protected areas will significantly reduce viable BMP locations as a percentage of total land area. Ultimately, the

city-wide analysis identifies general areas of BMP applicability. Without a non-coastal location to compare BMP applicability, these percentages are best viewed relative to one another.

4.0 Conclusion

In summary, the BMP Checker tool presented in this paper can identify which BMPs are likely suitable for a location based upon basic constraint criteria. The tool efficiently summarizes physical characteristics of individual drainage areas and matches those characteristics with compatible BMP types.

Like the VT BMP DSS, the BMP Checker was created to address Virginia BMP standards, but BMP Checker's flexible BMP constraint table allows it to be used outside of Virginia. The BMP Checker also uses the RRM for hydrologic and water quality calculations; which has limitations as previously noted and may or may not be accepted in a given location. While many available tools leave the physical constraints optional, BMP Checker prioritizes physical constraints over subjective measures and reduces the need to manually verify usability in a particular location. BMP Checker's input files are easy to obtain or create and exist in formats that are familiar to most stormwater engineers, in contrast to awkward databases or unusual input formats requiring specific information that often goes beyond a preliminary planning level. Finally, BMP Checker explicitly accounts for high water table conditions, making the tool more usable in coastal or low-lying areas than available tools currently offer.

The tool was validated using 11 developed sites and was employed to characterize the extent of BMP applicability in the coastal study area. BMP Checker can reduce time spent summarizing physical characteristics of drainage areas, including finding the area of different land cover types and hydrologic soil groups (HSGs) for use with the RRM compliance

spreadsheet. BMP Checker also identified BMPs that were predicted to function well based on the spatial inputs, potentially saving resources in the initial planning stages of a development. When possible, site-specific data should be used as tool input. The default BMP constraints did not account for some design interventions. For example, BMPs with a permanent pool are not suggested for A- and B-type soils, but a wet BMP may be usable on A- and B-type soils through the use of an impermeable liner. Swales of both kinds can be used in areas of steeper slope if check dams are installed, but the default constraint table was set to ignore steeper areas. The user may need to alter the constraint table in order for BMP Checker to consider more advanced designs.

Use of BMP Checker's algorithm showed that application of runoff reduction BMPs in the City of Virginia Beach is limited by coastal physiography, including low soil permeability, flat terrain, and SHWT depth. Of these, SHWT depth is the most limiting constraint in Virginia Beach with regards to BMP siting. As expected, wet ponds and constructed wetlands are the most widely applicable BMPs in Virginia Beach because they are allowed to intercept the water table, albeit with a reduction in removal credit. BMPs that receive the most credit in the RRM framework are usable at a reduced frequency, comparatively, due to scarcity of A- and B-type soils and water table proximity. Flat terrain appears to be the least limiting standalone constraint for individual BMP siting. It is recommended to conduct a citywide analysis on a county of similar size located within the Piedmont region using the current version of the BMP Checker tool or algorithm, in order to have a comparison measure of BMP applicability in the Coastal Plain. Additionally, improved functionality of the tool and algorithm should incorporate the addition of physical constraints, such as building setbacks, and the ability for the user to specify where in the drainage area the BMP(s) will reside.

Software Availability

Attribute	Information
Name of software or data set	BMP Checker
Developer and contact address	Rachael D. Johnson
Telephone	757-681-1136
Fax	None
Email	RDJohnson@vt.edu
Year first available	2016
Hardware required	2.2 GHz CPU speed (minimum), 2 GB memory RAM (minimum), 64 MB video RAM (minimum), 2.4 GB available disk space (minimum), networking hardware for the ArcGIS license manager
Software required	Windows 10 (recommended) or Windows 8.1, ArcGIS 10.3 (recommended) or ArcGIS 10.2 with Spatial Analyst extension
Availability	https://drive.google.com/open?id=0B2LcuSknDCX5SDdodXhjUTA5TnM
Cost	Free
Program language	Python 2.7.10
Program size	90 KB
Data: form of repository (database, files, spreadsheet)	Files
Size of archive	< 3 GB
Access form	FTP

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reflect no endorsement by the City. Funding for this research was also was provided in part by the Virginia Agricultural Experiment Station and the Hatch program of the National Institute of Food and Agriculture, U.S. Department of Agriculture, which also does not imply endorsement of opinions contained herein.

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(VDEQ, 2012).

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Figure Captions

Figure 1. (a) Soil hydrologic classification in the City of Virginia Beach, and (b) Land Use in the City of Virginia Beach.

Figure 2. The guiding methodology for tool development, wherein the program reads GIS information, computes average characteristics of a catchment, compares those characteristics to a BMP design criteria table, and outputs feasible BMPs for the catchment in order from most efficient to least efficient.

Figure 3. An example of the BMP Checker user interface after a successful run, inclusive of optional inputs.

Figure 4. An overview of the logic and workflow used in the main program. The "BMP Criteria Loop" process is detailed in Figure 4.

Figure 5. The "BMP Criteria Loop" process. This logic runs in a nested loop for every entry given in the BMP constraint table for each DA.

Figure 6. The extended detention pond at Nimmo Parkway. The photograph was taken April 3, 2016, more than 24 hours after the last storm event. Algae in the pond is evidence of prolonged inundation.

Figure 7. An October 2014 photograph of one bioretention unit located at the Harper's Bus Garage site. Prolific algae on the water surface indicates inundation has persisted for some time.

Figure 8. Total land area included in the citywide application of the BMP Checker algorithm. Each square cell is 929 m² (10,000 ft²) and there are a total of 680,160 cells in the tested land area. The figure is divided into natural watersheds, label with the number designation of each watershed.

Figure 9. Graphical citywide results for wet ponds that intersect the water table. With 74% land applicability, wet ponds that intercept groundwater were tied with constructed wetlands for the most applicable BMP in the City of Virginia Beach. The figure is divided into natural watersheds, labeled with the number designation of each watershed.

Figure 10. Graphical citywide results for sheet flow to conservation areas. Due to the limited amount of undisturbed area in Virginia Beach, sheet flow to conservation area was the least applicable BMP with just 11% land applicability. The figure is divided into natural watersheds, labeled with the number designation of each watershed.

Table 1. The 11 sites in Virginia Beach used for validation of the BMP Checker algorithm and default inputs.

[illegible]

Table 2. The default BMP constraint table used to validate BMP Checker's algorithm. BMP Checker uses imperial units; the values here have been converted to metric from imperial units. The column headings are decoded in Table 3. Impervious percentage was not used in the validation runs.

CODE	BMP	RR	PR	TPR	NR	TNR	SOIL	MAX SLOPE	MIN CDA	MAX CDA	IC PCT	WT SEP	WT RELAX	COAST SEP	MIN DEPTH	DEPTH RELAX	COAST MIN DEPTH	MAINT	REL YEAR COST
SDAB	Simple Disconnection A&B	50	0	50	0	50	A,B	5	0.06	405	0	0.6	0	0.6	0.0	0	0.0	Unavailable	\$----
SDCD	Simple Disconnection C&D	25	0	25	0	25	C,D	5	0.06	405	0	0.6	0	0.6	0.0	0	0.0	Unavailable	\$----
SDSA	Simple Disconnection C&D with Soil Amendments	50	0	50	0	50	C,D	5	0.06	405	0	0.6	0	0.6	0.0	0	0.0	Unavailable	\$----
CAAB	Sheet Flow Conservation Area A&B	75	0	75	0	75	A,B	6	0.00	1.21	0	0.6	0	0.6	0.1	0	0.1	Allowed	\$3,100
CACD	Sheet Flow Conservation Area C&D	50	0	50	0	50	C,D	6	0.00	1.21	0	0.6	0	0.6	0.1	0	0.1	Allowed	\$3,100
VFA	Sheet Flow Veg Filter A	50	0	50	0	50	A	8	0.00	1.21	0	0.6	0	0.6	0.1	0	0.1	Allowed	\$2,200
VFSA	Sheet Flow Veg Filter B,C&D with Soil Amendments	50	0	50	0	50	B,C,D	8	0.00	1.21	0	0.6	0	0.6	0.1	0	0.0	Allowed	\$4,100
GCAB	Grass Channel A&B	20	15	32	20	36	A,B	5	0.00	2.02	0	0.6	1	0.3	0.5	0	0.5	Allowed	\$2,000
GCCD	Grass Channel C&D	10	15	24	20	28	C,D	5	0.00	2.02	0	0.6	1	0.3	0.5	0	0.5	Allowed	\$2,000
GCSA	Grass Channel C&D with Soil Amendments	20	15	32	20	36	C,D	5	0.00	2.02	0	0.6	1	0.3	0.3	0	0.3	Allowed	\$2,200
PP1	Permeable Pavement- Level 1	45	25	59	25	59	A,B,C,D	5	0.00	405	75	0.6	0	0.6	0.7	0	0.7	Allowed	\$22,000
PP2	Permeable Pavement- Level 2	75	25	81	25	81	A,B	5	0.00	405	95	0.6	0	0.6	0.5	0	0.5	Allowed	\$23,000
MI1	Infiltration- Level 1	50	25	63	15	57	A,B	15	0.00	0.81	95	0.6	0	0.6	0.5	0	0.5	Intensive, not preferred	\$4,500
MI2	Infiltration- Level 2	90	25	93	15	92	A	15	0.00	0.81	95	0.6	0	0.6	0.5	0	0.5	Intensive, not preferred	\$4,900
BRE1	Bioretention Basin- Level 1	40	25	55	40	64	A,B,C,D	5	0.00	1.01	0	0.6	1	0.3	1.1	1	1.0	Intensive, not preferred	\$4,300
BRE2	Bioretention Basin- Level 2	80	50	90	60	90	A,B,C,D	5	0.00	1.01	0	0.6	1	0.3	1.5	1	1.2	Intensive, not preferred	\$5,200
DS1	Dry Swale- Level 1	40	20	52	25	55	A,B,C,D	4	0.00	2.02	0	0.6	1	0.3	0.8	0	0.8	Allowed	\$3,400
DS2	Dry Swale- Level 2	60	40	76	35	74	A,B,C,D	2	0.00	2.02	0	0.6	1	0.3	1.4	0	1.4	Allowed	\$3,600
WS1	Wet Swale- Level 1	0	20	20	25	25	C,D	2	0.00	2.02	0	0.0	0	0.0	0.0	0	0.0	Allowed	\$2,000
WS2	Wet Swale- Level 2	0	40	40	35	35	C,D	2	0.00	2.02	0	0.0	0	0.0	0.0	0	0.0	Allowed	\$2,300
F1	Filter- Level 1	0	60	60	30	30	A,B,C,D	15	0.00	2.02	75	0.6	1	0.3	0.8	1	0.6	Intensive, not preferred	\$4,400
F2	Filter- Level 2	0	65	65	45	45	A,B,C,D	15	0.00	2.02	95	0.6	1	0.3	0.8	1	0.6	Intensive, not preferred	\$5,000
CW1	Constructed Wetland- Level 1	0	50	50	25	25	C,D	25	0.00	405	0	0.0	0	0.0	0.0	0	0.0	Intensive, not preferred	\$2,200

CODE	BMP	RR	PR	TPR	NR	TNR	SOIL	MAX SLOPE	MIN CDA	MAX CDA	IC PCT	WT SEP	WT RELAX	COAST SEP	MIN DEPTH	DEPTH RELAX	COAST MIN DEPTH	MAINT	REL YEAR COST
CW2	Constructed Wetland- Level 2	0	75	75	55	55	C,D	25	0.00	405	0	0.0	0	0.0	0.0	0	0.0	Intensive, not preferred	\$2,800
WP1	Wet Pond- Level 1	0	50	50	30	30	C,D	25	4.05	405	0	0.6	0	0.6	1.8	0	1.8	Allowed	\$2,200
WP2	Wet Pond- Level 2	0	75	75	40	40	C,D	25	4.05	405	0	0.6	0	0.6	1.8	0	1.8	Allowed	\$2,700
WPGW1	Wet Pond with GW- Level 1	0	45	45	20	20	C,D	25	4.05	405	0	0.0	0	0.6	1.8	0	1.8	Allowed	\$2,200
WPGW2	Wet Pond with GW- Level 2	0	65	65	30	30	C,D	25	4.05	405	0	0.0	0	0.6	1.8	0	1.8	Allowed	\$2,700
EDP1	ED Pond- Level 1	0	15	15	10	10	A,B,C,D	25	0.00	4.05	0	0.6	0	0.6	0.6	0	0.6	Allowed	\$3,700
EDP2	ED Pond- Level 2	15	15	31	10	24	A,B,C,D	25	4.05	405	0	0.6	0	0.6	0.6	0	0.6	Allowed	\$4,200

Table 3. Column headings decoded for the BMP constraint table given in Table 2.

CODE	Unique string ID that the program uses to identify different BMPs; may be altered as long as each is unique.
BMP	The full BMP name and design level according to the 2011 Virginia Stormwater Management Handbook (VSWMH).
RR	Runoff reduction. The percent of annual runoff removed from the storm sewer system. The default value is from the 2011 VSWMH.
PR	Phosphorous removal. The percent of phosphorous event mean concentration (EMC) reduced on an annual basis. The default value is from the 2011 VSWMH.
TPR	Total phosphorous removal. The percentage of annual EMC and mass load phosphorous removal. The default value is from the 2011 VSWMH.
NR	Nitrogen removal. The percent of Nitrogen EMC reduced on an annual basis. The default value is from the 2011 VSWMH.
TNR	Total nitrogen removal. The percentage of annual EMC and mass load nitrogen removal. The default value is from the 2011 VSWMH.
SOIL	Hydrologic soil groups (HSG).
MAX SLOPE	Maximum slope (%) of the contributing drainage area or longitudinal slope for linear practices. Each BMP has its own internal slopes that are separate from this slope value. Consult the BMP design specifications for internal slope guidance.
MIN CDA	Minimum contributing drainage area (CDA) in hectares.
MAX CDA	Maximum contributing drainage area (CDA) in hectares.
IC PCT	The minimum amount of impervious cover in the drainage area, as a percent (%), needed for proper BMP function.
WT SEP	Water table separation (m). Separation between the BMP invert and the high water table elevation.
WT RELAX	Water table relaxation. A Boolean value indicating whether the 2011 VSWMH allows for a relaxed water table separation constraint.
COAST SEP	Coastal water table separation (m). The relaxed separation between the BMP invert and the high water table elevation in a coastal setting, as allowed by the VSWMH.
MIN DEPTH	Minimum BMP depth (m).
DEPTH RELAX	BMP depth relaxation. A Boolean value indicating whether the 2011 VSWMH allows for a relaxed BMP depth constraint.

COAST MIN DEPTH	Coastal minimum BMP depth (m). The relaxed minimum BMP depth in a coastal setting, as allowed by the VSWMH.
MAINT	Public Works Operations preference. The City of Virginia Beach Public Works Operations designated preference for maintenance. "Allowed" includes maintenance that is manageable and the BMP is able to be used in a Right-of-Way (ROW). Intensive inspection and maintenance is not preferred.
REL YEAR COST	Relative average annual cost (USD) over 20 years per acre of impervious area treated (King & Hagan, 2011; Weiss, Gulliver, & Erickson, 2007). These data were developed for Maryland and require additional adjustment for use in Virginia. 2011 dollar values have been converted to 2015 dollar values and alterations have been made for different design levels, but the values are otherwise unadjusted. These numbers are provided only for comparison to one another. Costs are not used to locate or rank BMPs.

Table 4. The modified default BMP constraint table used in the citywide analysis. Values have been converted to metric from imperial units.

CODE	BMP	SOIL	MAX SLOPE	WT SEP	WT RELAX	COAST SEP	MIN DEPTH	DEPTH RELAX	COAST MIN DEPTH
SDAB	Simple Disconnection A&B	A,B	5	0.6	0	0.6	0.00	0	0.00
SDCD	Simple Disconnection C&D	C,D	5	0.6	0	0.6	0.00	0	0.00
CAAB	Sheet Flow Conservation Area A&B	A,B	6	0.6	0	0.6	0.05	0	0.05
CACD	Sheet Flow Conservation Area C&D	C,D	6	0.6	0	0.6	0.05	0	0.05
VFA	Sheet Flow Veg Filter A	A	8	0.6	0	0.6	0.11	0	0.11
VFSA	Sheet Flow Veg Filter B,C,D	B,C,D	8	0.6	0	0.6	0.11	0	0.11
GCAB	Grass Channel A&B	A,B	5	0.6	1	0.3	0.46	0	0.46
GCCD	Grass Channel C&D	C,D	5	0.6	1	0.3	0.46	0	0.46
PP1	Permeable Pavement- Level 1	A,B,C,D	5	0.6	0	0.6	0.69	0	0.69
PP2	Permeable Pavement- Level 2	A,B	5	0.6	0	0.6	0.48	0	0.48
MI1	Infiltration- Level 1	A,B	15	0.6	0	0.6	0.53	0	0.53
MI2	Infiltration- Level 2	A	15	0.6	0	0.6	0.53	0	0.53
BRE1	Bioretention Basin- Level 1	A,B,C,D	5	0.6	1	0.3	1.14	1	0.99
BRE2	Bioretention Basin- Level 2	A,B,C,D	5	0.6	1	0.3	1.52	1	1.22
DS1	Dry Swale- Level 1	A,B,C,D	4	0.6	1	0.3	0.84	0	0.84
DS2	Dry Swale- Level 2	A,B,C,D	2	0.6	1	0.3	1.37	0	1.37
WS	Wet Swale	C,D	2	0.0	0	0.0	0.00	0	0.00
F	Filter	A,B,C,D	15	0.6	1	0.3	0.76	1	0.61
CW	Constructed Wetland	C,D	25	0.0	0	0.0	0.00	0	0.00
WP	Wet Pond	C,D	25	0.6	0	0.6	1.83	0	1.83
WPGW	Wet Pond with GW	C,D	25	0.0	0	0.6	1.83	0	1.83
EDP	ED Pond	A,B,C,D	25	0.6	0	0.6	0.61	0	0.61

Table 5. List of land use types given in the Virginia Beach parcel shapefile that were most likely to have undisturbed soil. “Military base” was included because much of the vegetated portion of the military bases are undisturbed.

Parcel Land Use
Forest
Marsh
Military Base
Park
Public/Semi-Public
Undeveloped
Water

Table 6. Validation results for the eleven Virginia Beach sites. No BMPs outright failed validation when accounting for actual site conditions and specific input data. Soil restoration, vegetated roofs, and rainwater harvesting were excluded from analysis. Columns are greyed out because those BMPs were not testable by BMP Checker.

Site	Scale	Land Use	BMPs														
			Rooftop Disconnection	Sheetflow to Open Space	Grass Channels	Soil Restoration	Vegetated Roofs	Rainwater Harvesting	Permeable Pavement	Infiltrative Practices	Bioretention	Dry Swale	Wet Swale	Filtering Practices	Constructed Wetland	Wet Pond	Extended Detention/ Dry Pond
Bow Creek Rec Center and Golf Course	Large	Multipurpose			✓										✓		
College Park Elementary	Small	Schools	✓	✓	✓		•	•		✓	✓						
Harpers Rd. School Bus Facility	Medium	Commercial/industrial					•				○						
Independence Rd.	Medium	Linear project													✓	✓	
Joint Use Library	Medium	Schools	✓	✓										✓			
New Kellam High School	Large	Schools	✓	✓				•	Δ	Δ	Δ				✓		
Little Neck Fire Station	Small	Commercial/industrial	✓							✓						✓	
Lynnhaven Mall Ponds	Large	Commercial/industrial													✓		
Nimmo Rd.	Large	Linear project														○	
Seatack Recreation Center	Small	Multipurpose									✓						
Williams Farm	Medium	Multipurpose	✓	✓											✓		

✓ - BMP built on site and approved by BMP Checker

X - BMP built on site and not approved by BMP Checker

○ - BMP built on site and not approved by BMP Checker, but site condition suggests BMP is failing

Δ - BMP built on site and approved by BMP Checker using site-specific inputs

Table 7. Tabular results of the city-wide analysis, given as a percentage of tested land area, rounded to the nearest whole percent. The proportion of unique cells for each BMP level (level total) and all levels (unique cells by BMP type) is also reported. Given totals are inclusive of coastal modifications.

BMP	Level	Mods	City-wide Applicability	City-wide Applicability (level total)	City-wide Applicability (by BMP type)
Simple Disconnection	AB		28%	28%	56%
	CD		34%	34%	
Sheet Flow to Conservation Area	AB		6%	6%	11%
	CD		6%	6%	
Sheet Flow to Vegetated Filter	A		9%	9%	57%
	BCD		52%	52%	
Grass Channels	AB	Standard	22%	26%	52%
		Coastal Mods	4%		
	CD	Standard	25%	31%	
		Coastal Mods	6%		
Permeable Pavement	1		36%	36%	39%
	2		21%	21%	
Infiltration	1		24%	24%	24%
	2		8%	8%	
Bioretention	1	Standard	24%	36%	36%
		Coastal Mods	12%		
	2	Standard	16%	30%	
		Coastal Mods	13%		
Dry Swale	1	Standard	30%	38%	38%
		Coastal Mods	8%		
	2	Standard	7%	9%	
		Coastal Mods	3%		
Wet Swales	Both		25%	25%	25%
Filters	Both	Standard	39%	54%	54%
		Coastal Mods	15%		
Constructed Wetland	Both		74%	74%	74%
Wet Pond	Both	Standard	7%	74%	74%
		W/Groundwater	74%		
Extended Detention Pond	Both		45%	45%	45%

Table 8. Ranking of BMPs by land applicability when coastal modifications were included in analysis. Credited TPR from the 2011 Virginia BMP Design Standards & Specifications was included for comparison.

Approved Coastal Modifications			
Rank	BMP Type	Land Applicability	TPR
1	Constructed Wetland	74%	50%
2	Wet Pond	74%	45%
3	Sheet Flow to Vegetated Filter	57%	50%
4	Simple Disconnection	56%	25%
5	Filters	54%	60%
6	Grass Channels	52%	24%
7	Extended Detention Pond	45%	15%
8	Permeable Pavement	39%	59%
9	Dry Swale	38%	52%
10	Bioretention	36%	55%
11	Wet Swales	25%	20%
12	Infiltration	24%	63%
13	Sheet Flow to Conservation Area	11%	50%

Table 9. Ranking of BMPs by land applicability when coastal modifications were excluded from analysis. Credited TPR from the 2011 Virginia BMP Design Standards & Specifications was included for comparison.

No Coastal Modifications			
Rank	BMP Type	Land Applicability	TPR
1	Constructed Wetland	74%	50%
2	Sheet Flow to Vegetated Filter	57%	50%
3	Simple Disconnection	56%	25%
4	Extended Detention Pond	45%	15%
5	Grass Channels	43%	24%
6	Permeable Pavement	39%	59%
7	Filters	39%	60%
8	Dry Swale	30%	52%
9	Wet Swales	25%	20%
10	Infiltration	24%	63%
11	Bioretention	24%	55%
12	Sheet Flow to Conservation Area	11%	50%
13	Wet Pond	7%	50%

Figure 1a

Figure 1b

Figure 2

Figure 3

BMP Checker :: File Inputs and Program Settings

Project Name
No spaces, less than 13 characters
Park-RRM

Project Location
C:/Users/Rachael/Documents/Python/Res... [Select Location](#)

☒ Calculate RRM loads and areas
☐ Calculate loads with no BMP checking
☐ Use land cover constraints

Rasters
Digital Elevation Model (DEM) ☐ .GDB
C:/Users/Rachael/Documents/City-1 [Find File](#)
Water Table Depth ☐ .GDB
C:/Users/Rachael/Documents/City-1 [Find File](#)

Shapefiles
Drainage Area Boundaries ☐ .GDB
C:/Users/Rachael/Documents/Si... [Find File](#)
DAstr [Populate Field List](#)
Soil Data ☐ .GDB
C:/Users/Rachael/Documents/Ci... [Find File](#)

Runoff Reduction Method
Average Annual Rainfall: 43.0 inches
Impervious Cover ☐ .GDB
C:/Users/Rachael/Documer... [Find File](#)
Undisturbed Cover (optional) ☐ .GDB
C:/Users/Rachael/Documer... [Find File](#)

[Save Inputs](#) [Load Inputs](#) [Check Input Validity](#) [OK](#)

Results

```

Creating an environment mask from the site outline shapefile...
Setting raster mask and snap raster for project...
Converting dual group soils to single groups...
Adding necessary fields to land cover shapefiles...
Limiting land cover shapefiles to the site boundary...
Combining land cover shapefiles with the soil shapefile...
Deleting unnecessary fields in the land cover/HSG shapefile...
Identifying sections of turf on the site...
Calculating areas for the VRRM spreadsheet Site Area tab...
Splitting site into drainage areas...
Calculating area of drainage polygons...
Summing areas of each drainage basin, soil type, and land use...
Summarizing DA characteristics...
Calculating RRM TP and TN loading for each drainage area...
Loading BMP constraint database...
Comparing site values to BMP constraints...
Calculating approximate TP and TN removed from the drainage areas by each BMP...
Reducing result redundancy...
Creating blank Excel workbook with headers...
Writing BMPs to the Excel document...
Ranking BMPs and organizing other outputs...
Saving formatted Excel file...
***Save completed!***

```

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Tested Cells

Figure 9

Wet Pond - Both Levels

Figure 10

Sheet Flow to Conservation Area