Optimization of BMP Selection for Distributed Stormwater Treatment Networks

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Civil Engineering

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June 21, 2016
Blacksburg, Virginia

Keywords: Stormwater, best management practices (BMPs), selection optimization

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ABSTRACT

Current site scale stormwater management designs typically include multiple distributed stormwater best management practices (BMPs), necessary to meet regulatory objectives for nutrient removal and groundwater recharge. Selection of the appropriate BMPs for a particular site requires consideration of contributing drainage area characteristics, such as soil type, area, and land cover. Other physical constraints such as karst topography, areas of highly concentrated pollutant runoff, etc. as well as economics, such as installation and operation and maintenance cost must be considered. Due to these multiple competing selection criteria and regulatory requirements, selection of optimal configurations of BMPs by manual iteration using conventional design tools is not tenable, and the resulting sub-optimal solutions are often biased. This dissertation addresses the need for an objective BMP selection optimization tool through definition of an objective function, selection of an optimization algorithm based on defined selection criteria, development of cost functions related to installation cost and operation and maintenance cost, and ultimately creation and evaluation of a new software tool that enables multi-objective user weighted selection of optimal BMP configurations.

A software tool is developed using the nutrient and pollutant removal logic found in the Virginia Runoff Reduction Method (VRRM) spreadsheets. The resulting tool is tested by a group of stormwater professionals from the Commonwealth of Virginia for two case studies. Responses from case study participants indicate that use of the tool has a significant impact on the current engineering design process for selection of stormwater BMPs. They further indicate that resulting selection of stormwater BMPs through use of the optimization tool is more objective than conventional methods of design, and allows designers to spend more time evaluating solutions, rather than attempting to meet regulatory objectives.

DEDICATION

To my wife, Kacie, my sons, Elijah and Joel, and my parents, Allen and Peggy.

ACKNOWLEDGEMENTS

The author would like to express gratitude to his advisor, Dr. Randel (Randy) Dymond, for the opportunity to pursue a long time goal, and for his invaluable input on this and other research. Adjusting back to an academic lifestyle after nearly two decades working in industry was daunting, but Dr. Dymond's guidance made it so much easier. Dr. Dymond's background in the software industry has proven invaluable over the course of this dissertation in discussions concerning user interface, algorithmic selection, and even nuances regarding the psychology of the learning process.

The author would also like to thank Dr. Hancock for her introduction and tutelage in Geographic Information Systems (GIS). The skills that I have acquired from her courses have given me new insight on manipulation of geographic data for scientific study. Dr. Hancock also has a great ability to evaluate papers and determine issues with context and gaps in coverage, even for articles that are somewhat out of her field of expertise. Comments that I have received from Dr. Hancock on several papers have aided me in modifying and improving my technical writing style.

Thanks is also given to Dr. Grizzard and Dr. Sample for serving on my committee. I've had the opportunity to go to presentations with each several times over the last couple of years. There have been many conversations regarding the current state of the science behind stormwater BMP treatment technology. Both have a passion for improving water quality for future generations.

The author would like to thank Kevin D. Young for his support through this process. His guidance in review of articles, discussions regarding the theoretical aspects of the topic, and friendship through this process has been invaluable.

The author especially wants to thank his wife and sons for making adjustments in their lives and schedules to allow time for this pursuit. I want to thank my wife, sons, and parents for their love and support through this process. I have missed soccer games, track and cross country events, and weekend visits, and hope that I can repay their patience with my own love and support in the future.

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Chapter 1: LITERATURE REVIEW

1.1 BACKGROUND

After enactment of the Clean Water Act (33 U.S.C §1251 et seq., 1972), the creation of the National Pollutant Discharge Elimination System (NPDES) as administered by the United States Environmental Protection Agency (USEPA) began a paradigm shift in stormwater management as it relates to urban development projects. Conventional methods of stormwater management, at the time, dealt primarily with peak flow and erosion control. Large surface storage facilities that shaved peak flows and promoted gravitational settling of suspended solids through extended detention of the treatment volume were the norm. Though the treatment volume was detained, it was not reduced, which resulted in accelerated degradation of downstream channels as development proceeded.

Amendments to the Clean Water Act (CWA) were enacted in 1977, 1981, and 1987 to clarify the scope (Clarke, 2003) and applicability on a national level, with the Water Quality Act of 1987 (CWA Section 319) becoming a cornerstone of today's stormwater management regulations. Roll-out of the regulations took place in two phases, with larger Phase I Municipal Separate Storm Sewer Systems (MS4s) required to comply first, in the early 1990's. Smaller Phase II MS4s were required to comply with the new standards that placed limitations on pollutant discharges in the early 2000's. A new wave of stormwater best management practices (BMPs) resulted from these new water quality discharge requirements, resulting in the implementation of measures such as bioretention (rain gardens), sand filters, constructed wetlands, and others, in an effort to reduce the impact of pollutant loads on the nation's waters.

Later, research by Shuster et al. (2007), Li et al. (2009), Balascio and Lucas (2009), and many others, focused on stormwater management through replication of a site's predevelopment hydrologic response. Burns et al. (2012) stated that focus should be placed on development of sites using low impact development (LID) strategies. LID techniques integrated in development focus on 1) minimization of disturbance, 2) limiting large connected impervious areas, and 3) promoting runoff reduction through groundwater recharge or evapotranspiration, which combined can have a huge impact on the quality of effluent from a developed site to a receiving channel/stream. As described by Elliott and Trowsdale (2007), LID strategies have ushered in the use of distributed small scale stormwater management BMPs throughout a developed site.

1.2 LITERATURE REVIEW

Below is an abbreviated literature review related to the major research components that are part of this dissertation. More extensive background on each topic can be found in comparable sections of Chapters 2-4.

1.2.1 Selection of BMPs

The USEPA first released a 'National Menu of Best Management Practices (BMPs) for Stormwater' (USEPA, 2016) in October 2000, which forms the basis of BMP standards in most states. The standards include non-structural BMPs such as minimization strategies, and structural practices, such as permeable pavement, grassed swales, infiltration basins, bioretention, etc. The resulting list of strategies provides many viable options to a stormwater management designer for treating effluent prior to discharge from developed sites. Ellis et al. (2004) note that there are many factors that must be considered during selection of BMPs, including technical requirements, social benefits, costs, and environmental impacts.

Technical requirements in BMP selection includes choosing the appropriate BMP to meet regulatory pollutant objectives. In some jurisdictions, a mandatory reduction in postdevelopment runoff volume is also required. Physical constraints can include the properties of the contributing drainage area (CDA), including size, land cover, slope, soil properties, (Young et al., 2010), and subsurface properties such as karst, high groundwater, etc. Selection may also be affected by a desire to add social incentives, such as the aesthetic benefits associated with some BMPs. As with most components in urban development, the effect of cost during the BMP selection process usually plays a major role in stormwater management. Due to the number of available BMPs, competing selection strategies, and physical siting constraints, more efficient strategies and tools are required to ensure that the most appropriate BMP(s) are selected after weighing these criteria.

Initial attempts at guiding BMP selection can be found in government publications including BMP specifications which defined individual BMP recommendations. Most states include selection tables or matrices in their BMP design handbooks, including North Carolina (NCDENR, 2007), Maryland (MDE, 2009), West Virginia (WVDEP, 2012), Virginia (VDEQ, 2013), and others. Later, there were attempts by university groups, government agencies, and other third party sources to attempt to develop BMP selection tools to streamline the selection and/or life cycle cost evaluation of specific BMP installations. Those addressing BMP selection include the Ohio DOT BMP selection tool (ORIL, 2015), the Colorado Urban Drainage and Flood Control District UD-BMP (UDFCD, 2010), the White River Alliance (WRA, 2016) BMP Selection Tool, and several others. Most of these tools are simple web-based or spreadsheet based tools that allow the user to indicate if various site features and/or constraints are present on the project site. From this user input, many BMPs are eliminated from consideration, leaving the user with a candidate list of BMPs that may be suitable for the project. Other tools also integrate regulatory removal requirements into the selection strategy, and eliminate practices that cannot meet the required removals. The net result from either strategy is the generation of a refined list of candidate BMPs that are suitable for the site. At this point, it is the designer's responsibility to use their 'best judgement' in selecting the most appropriate BMPs for the site from this list.

Other efforts have focused not only on performance, but cost analysis related to BMP selection. Some of these tools include BMP-REALCOST (UDFCD, 2010), the National Cooperative Highway Research Program life cycle spreadsheets (Taylor et al. 2014), and the WERF SELECT tool (Pomeroy and Rowney, 2013). BMP-REALCOST was developed as a planning level tool that uses input to estimate how many single type BMP installations would be necessary to treat a region, and from that prediction provide life cycle cost estimates for those installations. The National Cooperative Highway Research Program [NCHRP] (Taylor et al., 2014) attempts to address the issue of calculation of capital cost and life cycle cost associated with retrofit of highway BMPs in its Report 792. The purpose of the report is to provide a framework and tools for the user to perform cost analysis for particular BMP installations. The database used for costs in the report is a consolidation of data from the International Stormwater BMP Database (ISBMPD, 2014) and various other cost studies. The WERF SELECT model (Pomeroy and Rowney, 2013) is also a regional planning tool that allows life cycle cost analysis for a specified region. In addition to cost estimates, the WERF model also has built-in functionality to estimate various water quality treatment parameters such as load reduction and runoff reduction based on specified installations within the region.

The cost tools previously described use different methods to generate cost estimates for BMP comparison. Capital (installation) costs are typically either estimated based on statistical analysis of past installations, or through the integration of engineering cost opinions which take into account more local unit costs for BMP components. WERF (2005) concluded that it is not likely that computation of construction costs would benefit from a national cost database. This is due to difficulties in standardizing reporting of costs, and the inability to take into account all of the regional variations associated with costs. Despite this assertion, the International Stormwater BMP Database (ISBMPD, 2014), does provide records regarding BMP performance and cost. An analysis of ISBMPD (2014), however, yields only a small sample (145) of records that indicate cost data of any kind, of which, only 49 records include initial construction cost, spread over multiple BMP types. Lack of sample size and unknown consistency and variability related to these entries make it difficult to rely on this data for accurate estimations of BMP installation cost.

Initial construction cost may not be the most important cost factor in BMP selection, since operating and maintenance (O&M) costs can also be significant. USEPA (1999) reported O&M cost as a percentage of initial construction cost, based on a statistical analysis of the work by Wiegand et al. (1986), Schueler (1987), SWRPC (1991), Livingston et al. (1997), and Brown and Schueler (1997). Weiss et al. (2007) and King and Hagan (2011) support the estimation of O&M costs as a percentage of initial construction costs. Others, such as Taylor et al. (2015) and WERF (2005) attempt to estimate common maintenance activities and material and labor costs in order to compute a net present values (NPV) cost associated with long term maintenance.

1.2.2 Selection of BMPs in Series

Increasing use of smaller distributed BMPs throughout development sites has resulted in interconnection of these practices in many instances, which can allow for additional treatment in downstream BMPs. Hathaway and Hunt (2010) discuss the use of wetland cells in series in treating stormwater runoff. Villarreal et al. (2004) examine a series of stormwater treatment cells at reducing runoff in an urban environment. Cascading treatment of stormwater runoff requires a method of tracking pollutant and runoff reduction through each node. Pennsylvania (PADEP, 2006), published equations for tracking effluent loads through BMPs installed in parallel or in series. Hirschman et al. (2008) published a method known as the Runoff Reduction Method (RRM), which was used in the development of the Virginia Runoff Reduction Method spreadsheets (VDEQ, 2016), that enables the user to input and track pollutants and runoff reduction through connected BMP configuration, also called ‘treatment trains’ (Wong et al., 2006). Commercial software packages, such as SWMSoftVA (Ensoftec, 2013) have recently been produced which integrate the runoff and pollutant tracking capability of the VRRM Spreadsheets (VDEQ, 2016), with constraint input, which allows elimination of BMPs based on physical constraints, while performing calculations to determine if regulatory thresholds have been met.

Integration of treatment trains in computation methods for stormwater management has allowed for additional effluent treatment prior to discharge from the site, but has also shed light on several issues related to BMP treatment strategies. Work by Hathaway and Hunt (2010) was performed to confirm that 1) treatment efficiencies are related to the event mean concentration (EMC) of incoming runoff, and 2) secondary mechanical treatment becomes ineffective as the EMC approaches an irreducible concentration value, which varies between pollutants. Published methods of computation for most states ignore both of these items, opting instead to recommend use of static removal efficiencies, and not address the irreducible concentration of pollutants. The state of Delaware (DNREC, 2008) does address the issue of irreducible concentrations, and has developed a simplified method of restricting additional mechanical treatment beyond this level. DNREC (2008) lists the irreducible concentration of phosphorus as 0.11 mg/l, and that of nitrogen as 1.2 mg/l, while work by Schueler and Holland (2000) indicates that irreducible concentrations for total phosphorus are between 0.15 mg/L and 0.20 mg/L, for total nitrogen, 1.9 mg/L, and for total suspended solids, between 20 mg/L to 40 mg/L. Note that the irreducible concentrations listed above are related to physical removal of further concentration from stormwater runoff; however, additional removal beyond this irreducible concentration can be achieved on a mass load basis through runoff reduction.

1.2.3 Optimization Software related to BMP Selection

Sections 1.2.1 and 1.2.2 discuss BMP selection tools that aid the user by decreasing the number of viable BMP candidates through input of various constraints. Other more advanced tools have gone a step further and integrate algorithms to automate the BMP selection process based on a variety of criteria. These include the Virginia Tech BMP Decision Support Software (Young et al. 2009), the SUSTAIN tool by EPA (U.S. EPA, 2011), Prince George's County, Maryland's BMP-DSS tool (Cheng et al., 2009), and a multi-objective BMP siting tool by Liu et al. (2016). Both the SUSTAIN tool and BMP-DSS are built on top of a Storm Water Management Model (SWMM) v. 5.0 platform, are integrated into ESRI ArcMap 9.3, and use a variety of selection factors to ultimately select optimal BMP installations through implementation of scatter search [BMP-DSS and SUSTAIN] or the Non-Dominated Sorting Genetic Algorithm II (NSGA II) [SUSTAIN]. BMP-DSS and SUSTAIN are tailored to be regional watershed planning tools and are used to provide feedback on a watershed scale of the most efficient strategies for meeting various implementation goals, including projected cost. Use of the SWMM platform allows analysis of BMP treatment trains, and in the case of the SUSTAIN model, allows optimization algorithms to evaluate various predefined BMP configurations within the train. BMP-DSS, SUSTAIN, and the tool by Liu et al. are targeted at regional watershed planning. Individual small-scale project development and BMP optimization on a site scale is not targeted by these tools.

The decision support software tool developed by Virginia Tech (Young et al. 2009) focuses on BMP selection at the site development scale. The program uses a list of user selected project constraints and criteria weightings to provide inputs for Analytic Hierarchy Process (AHP) algorithms, which are then used to select the highest ranked BMP. Although this decision support software (DSS) provides a significant step forward in the goal of unbiased selection based on specific project constraints, it does not allow integration of the selection procedures with treatment train networks nor allow optimization based on actual load reduction or runoff reduction requirements which are typically drivers in BMP selection for project sites.

1.2.3.1 Optimization Algorithms

Recently, there has been a surge of engineering optimization problems that have been solved using genetic algorithms (GAs). These algorithms were first proposed by Holland (1975) and operate using rules and techniques borrowed from the natural world. Many fall under a category known as evolutionary algorithms in which the population is based on candidate solutions, with each successive generation [hopefully] approaching the optimal solution based on predefined fitness functions. This method uses principles such as genetic crossover, random mutation of a portion of the population, and other techniques for ‘breeding’ new generations closer to the optimal solution. There are also other genetic algorithms, such as firefly optimization (Sayadi et al., 2010), ant colony optimization (Di Caro and Gambardella, 1999), and others that have been successfully employed on past problems.

Behera and Teegavarapu (2015) employed GAs for cost minimization associated with detention pond installation on single or multiple parallel watersheds using multi-objective constraints. USEPA (2009) integrated NSGA II and Scatter Search algorithms for minimization of cost based on sizing of upstream BMPs at candidate locations and tied to specified land uses. While scatter search is not really a genetic algorithm, according to Lee et al. (2012) it shares several character traits that are found in genetic algorithms. As employed by USEPA (2009), the scatter search algorithm is directed to single-objective problems, while the NSGA II is used for multi-objective solutions. Perez-Pedini (2005) integrated GAs to find the optimal numbers and locations of infiltration facilities throughout a watershed. Though often used for optimization problems, genetic algorithms typically do not find the optimal solution, instead settling for near-optimal solutions based on the defined fitness function. GAs have been shown to be much better at solving continuous versus discrete engineering problems.

The AHP, as used by Young et al. (2009, 2010) was first proposed by Saaty (1980). Use by Young et al. (2009) of the AHP was for creation of a DSS, and not an optimization tool since the AHP, by default, is not typically used for system optimization. However, Javanbarg et al. (2012) demonstrated that it is possible to expand the capabilities of the AHP to create an optimization tool through creation of a hybrid system using particle swarm optimization. At its essence, the AHP operates by generating a solution vector through comparison of static paired comparison matrices. When used for mutli-objective decision support, the method typically embeds a pairwise comparison matrix defining comparison of all selection weights against others, in addition to matrices relating parameters for each candidate solution set (Young, 2009).

Exhaustive search (ES) algorithms are known by several other names, including direct search, and brute force algorithms. They fall under a category of algorithms called 'combinatorial search', which operate through iteration of all possible solution combinations. Due to the potential for large solution sets, ES algorithms are rarely used without some form of preprocessing, which is used to eliminate invalid solutions prior to iteration. This step can significantly decrease the run time of these algorithms. Although ES algorithms are easy to understand conceptually, Nievergelt (2000) states that they are underused because of their simplicity, which makes them appear inelegant. Nievergelt (2000) goes on to state that for many discrete, problems that require the optimal solution, that the ES approach is more likely to isolate the correct answer than use of other algorithms. In the past, use of ES algorithms was restricted due to long run-times associated with attempting all possible solutions; however, with the integration of intelligent elimination strategies and faster processors, use of ES versus other pseudo-optimal techniques is viable. Although ES is not used as frequently today since the development of Quasi-Newton and genetic functions, in many non-linear (discrete) optimization applications, ES performs as well—if not better—than more sophisticated algorithms (Lewis et. al. 2000).

1.3 RESEARCH OBJECTIVES

The goal of this research is to develop a multiple criteria optimization algorithm that can be used to facilitate BMP selection in distributed stormwater networks based on objective evaluation of user ranked parameters and simultaneous analysis of required pollutant reduction goals and site constraints. Specific objectives addressed by this research are the following:

1. Perform a literature review to determine the most effective computational algorithm for multiple criterion BMP selection.
2. Download and review/analyze the most recent International BMP Database for nutrient/pollutant removal efficiencies and cost data, as applicable, based on data records.
3. Conduct a literature review to compile and evaluate data and methods used in computation of BMP cost evaluation.
4. Determine a normalization procedure that allows for unit cost comparison between various BMP candidate installations.
5. Create BMP selection vectors for each BMP type. Each vector will consist of various parameters related to BMP selection such as applicable drainage area, nutrient removal efficiencies, ability to allow hotspot runoff, etc.
6. Integrate the selection algorithm in a user-friendly software tool that incorporates the Virginia RRM spreadsheet treatment train methodology.
7. Incorporate testing comments by industry experts (VDOT, consultants, reviewers, etc.) to refine software.
8. Apply integrated software optimization algorithms to various case study projects to determine its effectiveness in BMP selection.

1.4 ORGANIZATION OF DISSERTATION

The remainder of this dissertation is organized as follows:

CHAPTER 2: ***Selection of an Optimization Algorithm for Selection of Site Scale Best Management Practices in a Distributed Network***

This paper describes the background of the problem and discusses the interconnectivity of treatment trains. It explains the development of the objective function which will be optimized using the selected algorithm. A literature review on likely candidate algorithms is performed to determine the most viable candidate based on several selection criteria.

CHAPTER 3: ***Generation of Cost Functions for use in Stormwater BMP Selection Optimization***

This paper contains a literature review related to methods of computing construction cost and operation and maintenance cost for stormwater management BMPs. After considering several candidate methods for each, strategies are selected for development of cost functions. A review for methods of cost comparison is conducted to determine the best independent variable for inclusion in developed functions.

CHAPTER 4: ***Case Study: Integration of Optimization Software into the Engineering Design Process for Stormwater BMP Selection***

This paper describes the development of the final optimization software tool. The tool is tested through development of two case study problems which are solved by volunteer stormwater engineering professionals in Virginia. The study includes solution by a group using the newly development selection optimization tool, and a second control group using the VRRM spreadsheets. Responses from post-study questionnaires are analyzed to determine the effect of the software tool on the engineering design process.

CHAPTER 5: ***Conclusions***

Final commentary on the research objectives are discussed based on the results of the research. Significance of the research to the engineering community is detailed and a discussion of needed future work concludes this chapter.

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Chapter 2: Selection of an Optimization Algorithm for Selection of Site Scale Best Management Practices in a Distributed Network

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Status: This manuscript was submitted to *Environmental Modelling & Software* in April 2016 and is in review.

2.1 ABSTRACT

Typical site scale stormwater management projects include multiple distributed stormwater best management practices (BMPs) to meet regulatory objectives for nutrient removals and groundwater recharge. Selection of the optimal configuration of BMPs by iterating through multiple candidate solutions has proven difficult for the design community. This study focuses on selection of an algorithm for use in determination of optimal BMP configurations at a site scale by meeting multi-criteria competing objectives. An objective function related to the selection of BMPs in series is developed prior to evaluation of candidate solution algorithms. Genetic algorithms (GAs), the Analytic Hierarchy Process (AHP), and exhaustive search (ES) are evaluated to determine which, if any, are well suited to meet the objectives of this study. The selected algorithm is implemented and tested over a range of candidate combinatorial solution sets to determine stability and run times for typical hardware configurations in use by design engineers.

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2.2 HIGHLIGHTS

- Development of objective function for tracking stormwater volume and pollutant loads
- Selection of candidate algorithms that can be used to develop optimization tool
- Evaluation of candidate algorithms based on defined optimization objectives

Keywords: Multi-objective optimization; stormwater; treatment trains

2.3 INTRODUCTION

The enactment of the Clean Water Act (33 U.S.C §1251 et seq., 1972) was spurred by a growing nationwide ecologic awareness and resulted in prioritization of tracking and eliminating pollution discharges to surface waters. At the outset, the National Pollutant Discharge Elimination System (NPDES) focused primarily on establishing limits for point source industrial and domestic discharges. However, amendments to the Clean Water Act (CWA) in 1977, 1981 and 1987 further defined the scope of the act (Clarke, 2003) through additional oversight of stormwater discharges. The 1987 Water Quality Act (CWA Section 319) is the foundation of many present day stormwater management regulations. Mandated regulatory compliance was enacted in phases across the 1990s and 2000s, and proceeded based on population-defined classifications, with Phase I (defined as serving populations of 100,000 or more) Municipal Separate Storm Sewer Systems (MS4s) regulations enacted first. Phase II MS4s (populations between 50,000 and 100,000, with lower thresholds depending on several designation criteria such as discharge to impaired waters, population density, etc.) were required to meet pollutant thresholds in the early 2000s.

Enactment of stormwater quality regulations has caused a paradigm shift in project level stormwater management strategies. In the mid to late-20th century, stormwater strategy mostly focused on reduction of sediment transport from disturbed land in construction zones, or flood (peak flow rate) control to protect downstream areas. This early strategy resulted in design and construction of large regional surface impoundment facilities that achieved limited pollution reduction through gravitational settling and localized peak reduction. However, increases to volume and temperature of post-construction runoff was largely unaddressed. Subsequent research, such as studies by Shuster et al. (2007), Li et al. (2009), and Balascio and Lucas (2009), and many others, have indicated that a distributed management approach which reduces runoff by promoting groundwater recharge throughout a developed site, results in a solution which more closely mimics predevelopment hydrologic response. This refined management approach has resulted in the integration small scale low impact development (LID) strategies (Elliott and Trowsdale, 2007) as well as development of smaller structural and non-structural stormwater best management practices (BMPs) installed in series to achieve stormwater discharge goals.

In response to pollution and sediment discharge thresholds mandated by the CWA, many states including North Carolina (2007), Maryland (2009), West Virginia (2012), Pennsylvania (2006) and Virginia (2013) have published design guidelines and pollution removal efficiencies usually based on statistical analysis of limited studies found in the literature. Application of the variable removal efficiencies of BMPs paired with individual installation restrictions due to site and/or drainage area constraints can make it difficult to determine the optimal BMP for a specific site design. The task becomes even more challenging for multiple BMPs, which may be installed in series, creating a network of distributed BMPs, often referred to as a treatment train (Figure 2.1). State agencies have adopted various techniques for computing and tracking both groundwater recharge and nutrient load removals through treatment train practices. Although computational methodologies vary between states, the general procedure involves computation of a nutrient load and runoff (treatment) volume entering the facility, application of load and runoff volume reduction credit due to treatment in the facility, and a subsequent discharge of remaining effluent volume and nutrient load out of the facility (Figure 2.1).

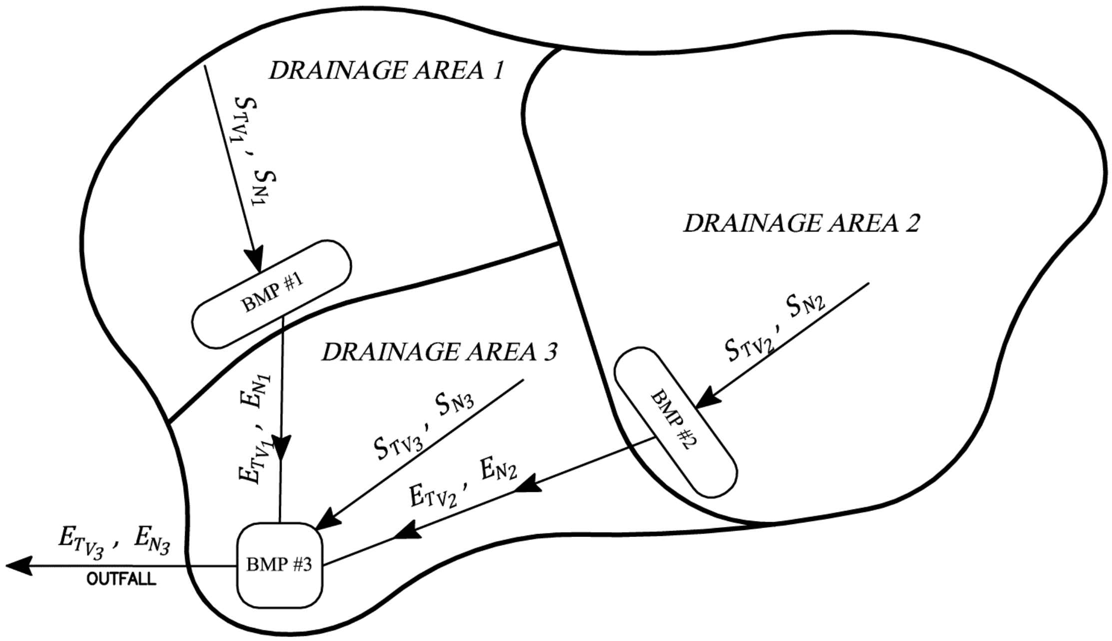

Figure 2.1. Schematic layout of treatment train demonstrating component input from surface treatment volume (S_{TV_i}) and nutrient influent loads (S_{N_i}) and incoming effluent loads from upstream BMPs (E_{TV_i} and E_{N_i}), as applicable, with i indicating component contributing drainage area, as appropriate.

Despite differences in treatment volume, nutrient load, and runoff reduction goals between states, typical equations for tracking loads through treatment trains are given in Equations 1 and 2. These equations indicate properties of effluent exiting BMP nodes as shown in Figure 2.1.

$$\boldsymbol{E_{TV_i} = (1 - C_{v_i})\left(S_{TV_i} + \sum_{u=0}^{j} E_{TV_u}\right)} \tag{1}$$

$$\boldsymbol{E_{N_i} = (1 - C_{N_i})(1 - C_{v_i})\left(S_{N_i} + \sum_{u=0}^{j} E_{N_u}\right)} \tag{2}$$

where:

i = numeric designation of stormwater BMP node

E_{TV_i} = effluent treatment volume leaving BMP (m^3)

E_{TV_u} = treatment volume entering BMP i from upstream BMPs (m^3)

E_{N_i} = effluent nutrient load leaving BMP (kg/year)

E_{N_u} = nutrient load entering BMP i from upstream BMPs (kg/year)

C_{v_i} = credit ratio for reduced volume (static ratio or compute from infiltration rate)

C_{N_i} = credit ratio for nutrient load removals (typically nitrogen or phosphorus)

S_{TV_i} = surface component treatment volume entering BMP (m^3)

S_{N_i} = surface component nutrient load entering BMP (kg/year)

$\sum S_{TV_u}$ = sum of upstream BMP effluent treatment volume entering BMP (m^3)

$\sum S_{N_u}$ = sum of upstream BMP effluent nutrient load entering BMP (kg/year)

j = number of BMPs upstream from a BMP treatment node

Connectivity and preliminary locations of individual BMP nodes in a treatment train are typically identified relatively early in the site design process. After logical locations for BMP nodes are identified, the next step in the design process is compilation of characteristics related to the contributing drainage area (CDA) of each BMP node. These characteristics include parameters such as drainage area, land cover conditions, and soil conditions in addition to design constraints such as the presence of karst features, high groundwater, limited infiltration, and other constraints that may affect candidate BMP selection by the designer.

Available BMPs can generally be divided into two major categories: proprietary and non-proprietary BMPs. Proprietary installations can often be the only viable means of treatment in site re-developments and/or retrofits due to space limitations. Methods of treatment in proprietary BMPs is through hydrodynamic separation of sediment particles in the runoff, removal of sediment and pollutants through mechanical filtration, and several others. Non-proprietary BMPs are also divided into categories by unit treatment processes. Four major categories are: Surface Vegetal Stripping, Media Filtration, Infiltration, and Gravitational Settling. Segregation of individual non-proprietary BMPs into these categories can often be challenging due to the overlapping characteristics of several common BMPs (Figure 2.2).

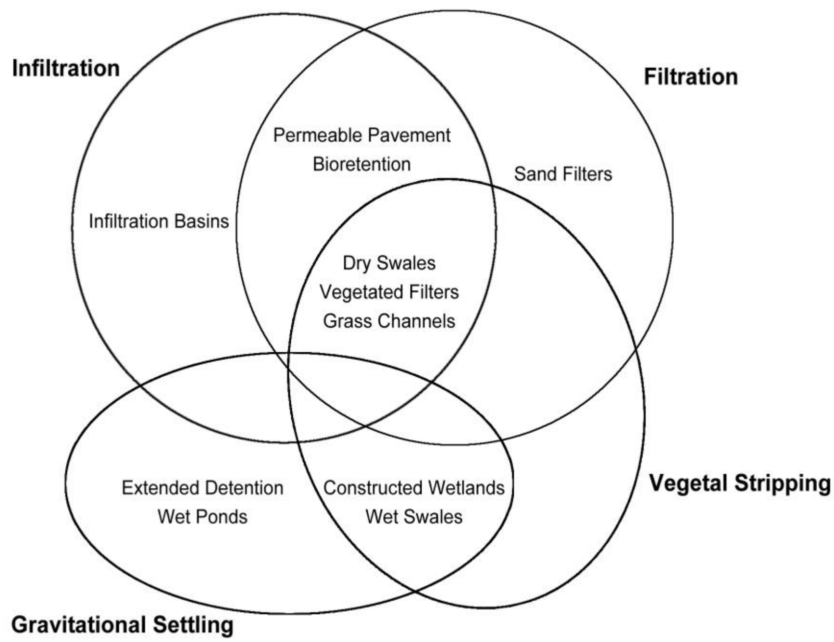

Figure 2.2. Categorized classifications of non-proprietary stormwater BMPs

At a site scale, the designer's goal is to reconcile the large number of candidate BMPs and siting constraints previously discussed, through optimizing a host of competing selection criteria for each specific project. These selection criteria may include minimization of installation and maintenance costs, total suspended solids (TSS) load removals above required reduction, and maximization of parameters such as groundwater recharge, aesthetics, and others, as warranted by particular project goals. Although the design engineer may be able to rectify these competing goals on sites where only one or two BMP locations are necessary, larger sites may require multiple treatment trains consisting of several interconnected BMPs discharging to multiple drainage outfalls. The number of possible combinations of BMPs can be computed using standard combinatorial equations. Consider an example site that has ten viable candidate BMP choices after consideration of physical site constraints (to simplify, it will be assumed that all CDAs to BMP locations have ten candidates, although on actual projects this number will likely vary). Table 2.1 summarizes the number of possible combinations to be considered by the designer for a variety of treatment train scenarios.

Table 2.1. Example calculations showing possible candidate solutions based on candidate BMPs per CDA, CDAs per outfall, and number of outfalls using standard combinatorial equations.

# BMPs/CDA	#CDAs/Outfall	# Outfalls	Combinatorial Equation	Candidate Solutions
10	1	1	10^1	10
10	2	1	10^2	100
10	2	2	$10^2 \cdot 10^2$	10,000
10	3	2	$10^3 \cdot 10^3$	1,000,000
…	…	…	…	…
n	a	o	$\prod_{i=0}^{o} n^a{}_i$	$n^a{}_1 \times n^a{}_2 \cdots n^a{}_o$

2.4 OBJECTIVE AND BACKGROUND RESEARCH

As demonstrated in Table 2.1, stormwater management analysis for many sites can be very complicated due to the presence of multiple outfalls, each with contributing drainage areas (CDAs) containing BMP networks. It is difficult for even veteran engineers to select the optimal solution that takes into account all of the parameters related to the multi-criterion selection discussed above on small sites. Due to the number of BMP combinations possible in most treatment train scenarios, optimization of multiple target criteria through iteration becomes more difficult with an increasing number of potential treatment train components. Therefore, manual iteration to determine differences in treatment train installations is ineffective. The result of these difficulties is often engineering bias in the BMP selection process, causing a reliance on 'known' BMP combinations by the design engineer, which can derail the process of selecting optimal BMPs based on unique project constraints (Young et al. 2009b). In order to achieve a goal of un-biased optimal selection of BMPs in meeting reductions for specific sites, selection of a computational algorithm becomes necessary to optimize a variety of potentially conflicting user-defined secondary selection characteristics. The selected algorithm must also simultaneously meet required water quality goals and eliminate candidate BMPs based on physical site constraints.

State agencies have recognized the complexity in attempting to select the best single or multiple isolated or interconnected BMP treatment strategies on sites. Maryland (2009) has published selection matrices that guide the user through various site constraints to narrow the list of possible candidate BMPs for use in the stormwater management strategy. Virginia's Department of Conservation and Recreation (DCR) attempted to address the issue by commissioning the Center for Watershed Protection (CWP, 2008) to create a methodology for estimating the impact of BMPs installed in a distributed network on the site's runoff characteristics. The resulting computational process is known as the Virginia Runoff Reduction Method (VRRM) was adopted May 24, 2011 by the Virginia Soil and Water Conservation Board. VRRM spreadsheets have provided a compliance tool to aid design engineers in determining pollutant removal requirements and selecting appropriate BMPs to meet target removal rates. While this tool does provide a means to determine removal requirements and methods for compliance, its complexity—especially in the number of entry cells and input methodology—for testing multiple combinations of BMPs in series, make it prone to input error and difficult to use iteratively for selecting the best single or group of BMPs based on individual site characteristics and/or constraints. In addition, the VRRM method requires the user to have innate knowledge of physical site constraints for each BMP type and provides no avenue for the user to optimize the solution other than through trial and error. As a compliance tool, the VRRM spreadsheets, and the VRRM method itself, are limited in scope and do not address stormwater quantity control regulations, nor do they provide guidance related to final design and sizing of selected BMPs.

Some jurisdictions have developed software-based tools that generally focus on narrowing the list of candidate BMPs considered as part of the solution set, but again, do not focus on an optimized solution. These include the Ohio DOT BMP selection tool (ORIL, 2015), the Colorado Urban Drainage and Flood Control District UD-BMP (UDFCD, 2010), the White River Alliance BMP Selection Tool (http://www.ecologik.net/bmpTool/), SWMSoftVA by Ensoftec (Ensoftec, 2013), BMPSELECT (Pomeroy and Rowney, 2013) and many others.

Other more advanced tools have gone a step further and utilize heuristic algorithms in order to select and rank BMP selection based on a variety of selection criteria. These include the Virginia Tech BMP Decision Support Software (Young et al. 2009a), the EPA's SUSTAIN tool (U.S. EPA, 2009), and Prince George's County, Maryland's BMP-DSS tool (Cheng et al., 2009). Both the SUSTAIN tool and BMP-DSS (developed by Tetra Tech) are built on top of a Storm Water Management Model (SWMM) v. 5.0 platform and use a variety of selection factors to ultimately select optimal BMP installations through implementation of scatter search [BMP-DSS and SUSTAIN] or the Non-dominated Sorting Genetic Algorithm II (NSGA II) [SUSTAIN]. These SWMM oriented tools are tailored to provide feedback on a watershed scale of the most efficient strategies for meeting various implementation goals, including projected cost. Use of the SWMM platform allows analysis of BMP treatment trains, and in the case of the SUSTAIN model, allows optimization algorithms to evaluate various BMP installations within the train. Both the BMP-DSS and SUSTAIN tools are generally targeted at regional watershed planning. Individual small-scale project development and BMP optimization on a site scale is not typically targeted by these tools and use of these tools for such applications is hindered by the large amount of data and calibration required to get these tools operational. Conversely, the software tool developed by Virginia Tech (Young et al. 2009a) focuses on BMP selection at the site development scale. The program uses a list of user selected project constraints and criteria weightings to provide inputs for Analytic Hierarchy Process (AHP) algorithms, which are then used to select the highest ranked BMP. Although this provided a significant step forward in the goal of unbiased selection based on specific project constraints, it does not allow integration of the selection procedures with distributed treatment train networks nor allow optimization based on actual nutrient load reduction requirements or runoff reduction which are typically drivers in BMP selection for project sites.

Liu, et al. (2016) also developed a decision support tool optimally locate stormwater BMPs and low impact development (LID) practices. The model employs the Multi-Algorithm Genetically Adaptive Multiobjective (AMALGAM) method to perform multiple parameter optimization to determine the best locations of various LID and BMP practices at a watershed scale, with optimization occurring in two stages. The first is within discrete hydrologic response units (HRUs), and the second is at the watershed scale. Liu et al. (2016) found that optimized placement of LID and BMP strategies throughout a watershed, rather than random placement, achieved 3.9 to 7.7 times the runoff and pollutant load reductions at a much lower cost.

Perez-Pedini et al. (2005) and Srivastava et al. (2002) demonstrated that genetic algorithms can be used when choosing the optimal location of single type infiltration based BMPs. Integration of NSGA II genetic algorithms in the SUSTAIN tool (U.S. EPA, 2009) has shown that employing algorithms greatly aids in the selection of candidate BMPs on a watershed scale. While genetic algorithms have been increasingly used for many engineering optimization problems over the last two decades, selection of the optimal BMP solutions for site scale development requires reconsideration of viable algorithms for quickly achieving an optimal solution, which will aid in removing designer bias from the selection process.

2.5 DEVELOPMENT OF OBJECTIVE FUNCTION

Any optimization analysis requires the development of an objective function for maximization or minimization. The first step in algorithmic implementation includes the application of rules to narrow the list of candidate BMPs considered during computations. The logic rules for this pre-processing step are applied regardless of the final optimization algorithm selected. These rules can include example strategies such as those described in Tables 2.2 and 2.3; however, these are not an exhaustive list of weeding methods that may be applied.

Table 2.2. Example of elimination strategies based on physical constraints in the CDA to each BMP location.

Physical Constraint	Eliminated BMPs
Karst	Infiltration type or wetland type BMPs
High Groundwater	Any BMP with hampered functionality due to the presence of high groundwater: Drywells, bioretention, permeable pavement, grass channels infiltration, extended dry detention
Hotspot Runoff	Any BMP which promotes infiltration or direct interaction with groundwater table: Drywells, bioretention, permeable pavement, grass channels infiltration, extended dry detention, wet swales (high groundwater)
Limited/No Infiltration	Infiltration type BMPs

Table 2.3. Examples of elimination strategies based on characteristics of CDA to BMP location.

Parameter	Description
Soil Type	Eliminates BMP based on specified soil properties.
Contributing Drainage Area	Eliminates BMPs that are less than the suggested minimum CDA, or greater than the suggested maximum CDA
Impervious/Turf Ratio	Eliminate BMPs that are have a CDA with an impervious to turf ratio less than the suggested minimum or greater than the suggested maximum

Once weeding methods have been applied, the selected algorithm will iterate through remaining candidate solutions in order to determine the optimal, or an acceptable solution (depending on algorithm used). It is the method used to reach the solution in the iterative process that differentiates the various algorithms that may be applied.

The objective function is created in a step-wise fashion through consideration of computations necessary to evaluate each candidate against other viable solutions. First, one must consider the computations necessary at each BMP location to compute influent and effluent requirements. Computations in this step will use the procedures described in Equations 1 and 2 to determine and track treated and discharged loads for BMPs at individual treatment train nodes for each iteration. Computation of the runoff reduction, which has component reductions such as groundwater recharge, adsorption of water to BMP media, or evapotranspirative processes is defined through redefinition of Equation 1 as shown in Equation 3.

$$R_{TV_i} = C_{v_i}\left(S_{TV_i} + \sum_{u=0}^{j} E_{TV_u}\right) \tag{3}$$

where:

i	=	numeric designation of stormwater BMP node
R_{TV_i}	=	runoff reduction component of the total treatment volume
C_{v_i}	=	credit ratio for reduced volume (static ratio or compute from infiltration rate)
S_{TV_i}	=	surface component treatment volume entering BMP (m^3)
$\sum E_{TV_u}$	=	sum of upstream BMP effluent treatment volume entering BMP (m^3)
j	=	number of BMPs upstream from a BMP treatment node

Likewise, calculation of the nutrient reduction at a specific node is computed using Equation 4.

$$R_{N_i} = \left(S_{N_i} + \sum_{u=0}^{j} E_{N_u}\right)\left(1 - \left(1 - C_{N_i}\right)\left(1 - C_{v_i}\right)\right) \tag{4}$$

where:

i	=	numeric designation of stormwater BMP node
R_{N_i}	=	effluent nutrient load removed by BMP (kg/year)
C_{N_i}	=	credit ratio for nutrient load removals (typically nitrogen or phosphorus)
C_{v_i}	=	credit ratio for reduced volume (static ratio or compute from infiltration rate)
S_{N_i}	=	surface component nutrient load entering BMP (kg/year)

$\sum E_{N_u}$ = sum of upstream BMP effluent nutrient load entering BMP (kg/year)

j = number of BMPs upstream from a BMP treatment node

A determination of BMP cost must now be made for each node in a candidate solution. A common method of tracking BMP costs when comparing multiple BMP types is to relate cost to treatment volume or nutrient removal (usually phosphorus or nitrogen) as found in CWP (2013) and Taylor et al. (2014). Additional methods exist for establishing relational comparisons to cost such as by BMP surface area or CDA. Historically, the use of water quality volume (WQV) or treatment volume has been found to related well with cost. A broader discussion related to the development of cost functions is beyond the scope of this study; however, for the remainder of this analysis, treatment volume will be the assumed relational parameter. Based on this assumption, the cost associated with each BMP node can be described using Equation 5.

$$M_{N_i} = F(T_{V_i}) \tag{5}$$

where:

i = numeric designation of stormwater BMP node

M_{N_i} = installation and operating cost of BMP ($)

$F(T_{V_i})$ = cost function with inflow treatment volume as independent variable

T_{V_i} = treatment volume entering by BMP (m^3)

The cost function, $F(T_{V_i})$, presented in Equation 5 may be a constant, a linear, or a power equation, and is usually a function of the amount of historic cost data available. In addition, this cost function may be broken into component parts for optimization of each individually; for instance, the installation cost and the annual maintenance cost may be evaluated separately as independent parameters. However, to simplify development of the objective function as discussed in this paper, the cost function is assumed to capture all present day cost associated with the installation and life cycle of a BMP; therefore, further cost components are not discussed.

Additional more subjective parameters may be included in the optimization process such as factors like aesthetics or public safety, for example. While several of these parameters could be used during determination of the objective function, here, only aesthetic benefit is addressed as an additional selection criterion to explain the procedure. Like cost, there can exist many methods related to the normalization of aesthetic benefit for comparison against other BMPs. The aesthetic benefit associated with each BMP node, normalized using the total number of BMP nodes, can be described using Equation 6.

$$A_i = \frac{F\left(C_{A_i}\right)}{n} \tag{6}$$

where:

i	=	numeric designation of stormwater BMP node
A_i	=	normalized aesthetics score for BMP i
$F(C_{A_i})$	=	aesthetics score related to a constant value between 0 and 10
n	=	number of BMPs in solution (across all outfalls)

Equations 3-6 result in raw scores for each candidate BMP node. In order to compare the full solution which includes all BMPs across all CDAs and outfalls, the parameter values yielded from Equations 3-6 may simply be summed, giving total solution raw scores as shown in Equation 7.

$$\sum_{i=1}^{n} R_{TV_i} \quad , \quad \sum_{i=1}^{n} R_{N_i} \quad , \quad \sum_{i=1}^{n} M_{N_i} \quad , \quad \sum_{i=1}^{n} A_i \quad \ldots \quad \sum_{i=1}^{n} P_i \tag{7}$$

where:

i	=	numeric designation of stormwater BMP node
R_{TV_i}	=	runoff reduction component of the total treatment volume (m^3)
R_{N_i}	=	effluent nutrient load removed by BMP (kg/year)
M_{N_i}	=	installation and operating cost of BMP ($)
A_i	=	normalized aesthetics score for BMP i
P_i	=	additional parameter(s) for BMP i
n	=	number of BMPs in solution (across all outfalls)

In the engineering design process, it is typical for differing weights to be applied to various design considerations, with the weights varying between individual projects. For instance, on a commercial site design the engineer may prioritize the minimization of initial installation cost, while maximizing runoff reduction and aesthetics. On other project types, the engineer may place a lower weight on installation cost or aesthetics, while placing the highest weight on minimizing additional nutrient reduction (beyond minimums required by regulations). The point here is not to say that these parameters should be weighted in a specific manner on certain project types, but instead to demonstrate that the designer will likely need to consider variable parameter weighting based on project type or location. Weightings for runoff reduction, nutrient removal, cost, and aesthetics will be denoted by W_r, W_n, W_c, and W_a, respectively. General equations for the feature scaling normalization of minimization and maximization procedures to be used in development of the objective function are given by Equations 8 and 9.

Minimization
$$X'_{p_i} = W_p \frac{X_{p_i} - X_{p_{max}}}{X_{p_{max}} - X_{p_{min}}} \tag{8}$$

Maximization
$$X'_{p_i} = W_p - W_p \frac{X_{p_i} - X_{p_{max}}}{X_{p_{max}} - X_{p_{min}}} \tag{9}$$

where:

p	=	parameter being normalized (i.e. runoff reduction, nutrient removal, cost, or aesthetics)
X'_{p_i}	=	normalized value of subject parameter for candidate solution (i)
W_p	=	user weighted ranking for target parameter (W_r, W_n, W_c, or W_a)
X_{p_i}	=	raw score of subject parameter for candidate solution ($\sum_{i=1}^{n} R_{T_{V_i}}$, $\sum_{i=1}^{n} R_{N_i}$, $\sum_{i=1}^{n} M_{N_i}$, $\sum_{i=1}^{n} A_i$ ... $\sum_{i=1}^{n} P_i$)
$X_{p_{max}}$	=	maximum raw score of subject parameter across all candidate solutions
$X_{p_{min}}$	=	minimum raw score of subject parameter across all candidate solutions

Once the chosen normalization procedure (minimization with Equation 8 or maximization with Equation 9) has been applied to each of the weighting criteria, the scores for each parameter are summed to yield the total score (Equation 10), which is also the final objective function that must be maximized to yield the optimal BMP treatment train solution.

$$Z_i = X'_{N_i} + X'_{RR_i} + X'_{C_i} + X'_{A_i} \ldots X'_{p_i} \qquad (10)$$

where:

X'_{N_i} = Normalized nutrient score for candidate solution (i)

X'_{RR_i} = Normalized runoff reduction score for candidate solution (i)

X'_{C_i} = Normalized cost score for candidate solution (i)

X'_{A_i} = Normalized aesthetics score for candidate solution (i)

X'_{p_i} = Normalized additional parameter(s) score(s) for candidate solution (i)

Z_i = Total raw score for candidate solution (i)

2.6 EVALUATION OF CANDIDATE ALGORITHMS

The optimization problem described above is a discrete nonlinear problem with finite candidate solutions. In discrete optimization, finite solution combinations are evaluated to determine the maximum (or minimum) value of the objective function. As described above, with treatment train connectivity and related CDA geometry draining to each node being static for all possible solutions, candidate solutions are evaluated by logically iterating through all possible valid BMP combinations. Because each BMP node type being substituted is defined by discrete values of runoff and nutrient reduction, all subsequent computations up to development of the optimization objective function are necessarily discrete.

The selected algorithm to be used for solving this optimization problem, like the objective function described herein, should meet several potentially conflicting requirements.

1. The algorithm must be able to consistently meet the objective of yielding an optimal solution.
2. The algorithm must be readily understandable in order to be adopted by a wide array of practitioners.
3. The algorithm must not be so computationally intensive that normal run times are excessive.
4. The algorithm must achieve consistently repeatable results between multiple runs.

To achieve these goals, several candidate algorithms were evaluated for use in the optimization problem based on their past use on problems related to BMP selection and their ability to meet the criteria listed above.

2.6.1 Genetic Algorithms

Genetic algorithms (GA) have been increasingly used in the solution of engineering optimization problems since proposed by Holland (1975) and brought into the mainstream by Goldberg (1989). The premise behind GAs is that initial candidate solutions in any generation (i.e. parents) cross-over with other candidate solutions (mates), generating children solutions (i.e. offspring) that survive and have the ability to 'breed' the next generation based on 'fitness'. Additionally, mutations may occur which send computations down new evolutionary branches that would not be otherwise investigated. Behera and Teegavarapu (2015) used GA based algorithms to minimize cost associated with installation of detention ponds on single or multiple parallel watersheds while meeting multi-objective stormwater quality and quantity constraints. Their dynamic programming (DP) solution through discretization (a simplifying assumption) was abandoned in favor of genetic algorithms since many of the design variables (e.g. dimensions of ponds) have solution sets that operate across a continuous range. As described by Behera and Teegavarapu, using the DP solution for their study would have one of two possible effects: 1) use of coarse discretization in candidate pond dimensions would potentially yield results that were not optimal, or 2) decreasing discretization steps would result in increasing processor time to find the near optimal solution.

U.S. EPA's (2009) SUSTAIN system attempts to minimize cost against BMP aggregate sizes based on predefined BMP train options that are tied to upstream land use. The model has two optimization modes which each use GAs for achieving near optimal solutions (Lee et al., 2012). The first uses Scatter Search, as described by Lee et al. as sharing some similar characteristics with GAs. The Scatter Search method is used to solve single-objective problems, while the second method, NSGA II, is a GA that can be used to solve multi-objective problems. U.S. EPA (2009) contains a full discussion of the theory behind the two algorithms used for the SUSTAIN software. The software allows input of predefined BMP train scenarios based on land use, and then iterates across a continuous range of size and treatment volume scenarios in order to optimize cost at a watershed scale. Lee et al. (2012) describe two cost optimization functions that can be chosen within the program, once of which is a cost minimization function providing near optimal solutions, and the other, a formulation of a cost effectiveness curve.

Perez-Pedini et al. (2005) used GAs to determine the optimal number and location of infiltration BMPs on a watershed scale. This study focused on the optimization of a single BMP type (infiltration BMPs) throughout the watershed. Since the optimization function used for this study operates in continuous space (unknown number of BMPs required to meet objective), GA algorithms are used to find a near optimal solution. Perez-Pedini et al. (2005) discusses restrictions that were implemented in the decision space to reduce computational time, which seems to indicate excessive run times for at least some simulations.

As described above, GA solutions have been implemented across a wide range of engineering problems related to stormwater analysis. Unfortunately, based on analysis of the predefined algorithmic objectives for this study, implementation of a GA solution does not appear practical. Behera and Teegavarapu (2015), U.S. EPA (2009) and Perez-Pedini et al. (2005), discuss that GAs are well suited at finding near optimal solutions in a continuous search space. The problem described in this study does not exist in a continuous space which would make application of GAs difficult and hamper the ability to achieve a near-optimal solution that is reasonably close to the absolute optimal solution. The inability to consistently produce an optimal solution would also likely impede wide-scale adoption by design professionals. In addition, GAs can exhibit excessive run times when searching for a near-optimal solution unless modifications are found that can adjust the run-time as mentioned in Perez-Pedini et al. (2005). As stated in U.S. EPA (2009), both algorithms used in SUSTAIN incorporate compromises that result in a near optimal solution by solving across a partially continuous solution set defined by ranges in sizes of BMPs. This approach is justified by stating that computation of a truly optimal solution would be extremely time intensive, if at all possible. Excessive run times can be due to an exponential increase based on input of a large candidate solution pool, or due to the GA becoming so focused within local maxima (or minima) that genetic cross-over or mutation cannot dislodge to force movement toward a global optimum.

2.6.2 Analytic Hierarchy Process (AHP)

The AHP is a multi-criteria decision support algorithm that has been used by many researchers since it was originally proposed by Saaty (1980). Young (2009a, 2009b) integrated the AHP into a BMP selection decision support tool, and Jato-Espino et al. (2014) integrated the AHP algorithm in a multi-criteria decision tool to aid in the selection of the appropriate pervious pavement type for specific projects based on user defined parameters. By default, the AHP is not an optimization algorithm; however, Javanbarg et al. (2012) extended the abilities of the AHP through integration of particle swarm optimization (PSO). This PSO extension allows the maximization of the objective function, which pushes the AHP from a support tool to an integrated optimization tool.

The AHP algorithm operates by deriving a solution vector from evaluation of paired comparison matrices. For multi-decision optimization, there is typically a pairwise comparison matrix defining a comparison in weights of selection criteria against all others. In addition, there is a secondary set of comparison matrices relating distinct parameters for each candidate solution set. In the case of Young (2009a, 2009b), the candidate matrices compared each candidate BMP against others at single locations (a single BMP node). For the problem defined in this study, the comparison matrices would need to describe the relative comparison of one full candidate solution against another, which can be a single node, but is likely a multi-outfall, multi-node train configuration. In order to perform these comparisons, static matrices are needed for each candidate solution. Creation of the comparison matrices, however, requires computation of all valid solutions prior to generating the pair-wise comparisons. Since all valid solutions must be computed to create pairwise matrices, use of the AHP process is ultimately unnecessary, because solution rankings can be computed directly using the candidate configurations in tandem with the objective function. Therefore, the AHP procedure does not appear to be a good fit for the optimization problem described in this study since it is tailored to finite decision support models with a static candidate solution set.

2.6.3 Exhaustive Search

Exhaustive Search (ES) is known by several other names including combinatorial search and brute force. Fundamentally, the method requires iteration through all possible valid solutions of the objective function in order to find the optimal solution, although intelligence functions can be added to logically decrease the candidate solution set. These adaptations provide the key to addressing excessive run times, a common issue that can hamper use of this algorithm on many optimization problems. Rao (2009), notes that exhaustive search is well-suited for finding the optimal solution for an objective function that operates in a finite solution space. Several key characteristics that sets the ES algorithm apart from the GA algorithms is that given enough time, the ES algorithm will find the optimal solution, it is understandable, and run times can be kept to minimal levels if enough pre-processing (weeding) takes place.

Although the validity of solutions produced by ES are above reproach since all solutions are explored, Nievergelt (2000) states that in many academic circles, use of the ES algorithm is considered ‘inelegant’. Nievergelt (2000) also explains that due to dramatic increases in processing power that interest in the ES approach has been renewed and the technique has been applied to ‘messy’ problems that are difficult to solve using more ‘elegant’ approaches, such as with genetic algorithms. Use of an ES algorithm appears to be well adapted to maximizing the objective function described in this study; however, prior to selection, the primary weakness plaguing ES algorithms must be addressed—computational run times.

To definitively quantify run times, an ES algorithm using the Virginia Runoff Reduction Method (VRRM) was implemented to iterate through BMP solutions over multiple outfalls and multi-level treatment trains in order to validate the approximate time necessary for various levels of computation. Since the algorithm is being applied at the site scale and not the watershed or regional scale as with other studies such as U.S. EPA (2009) and Perez-Pedeni (2005), the total number of combinatorial outcomes is expected to be less than 1,000,000, similar to scenario four in Table 2.1, on projects with small land disturbances, which would likely keep runtimes to manageable levels (1 second – 5 minutes). This expectation is based on analysis of representative ranges in size of land disturbance projects in Virginia by computing representative statistics for active Virginia Stormwater Management Permit (VSMP) holders (VDEQ, 2016) across the Commonwealth of Virginia. Figure 2.3 provides a statistical distribution of the 5,187 active development projects in Virginia in March 2016. As shown in Figure 2.3, 95% of all development projects within the Commonwealth are 30 hectares or less, with 75% being 6 hectares or less. Based on this data, it can be assumed that the majority of projects will have limited numbers outfalls, CDAs, and treatment train configurations, and are likely to fall within the combinatorial example ranges that are presented in Table 2.1, with few exceptions.

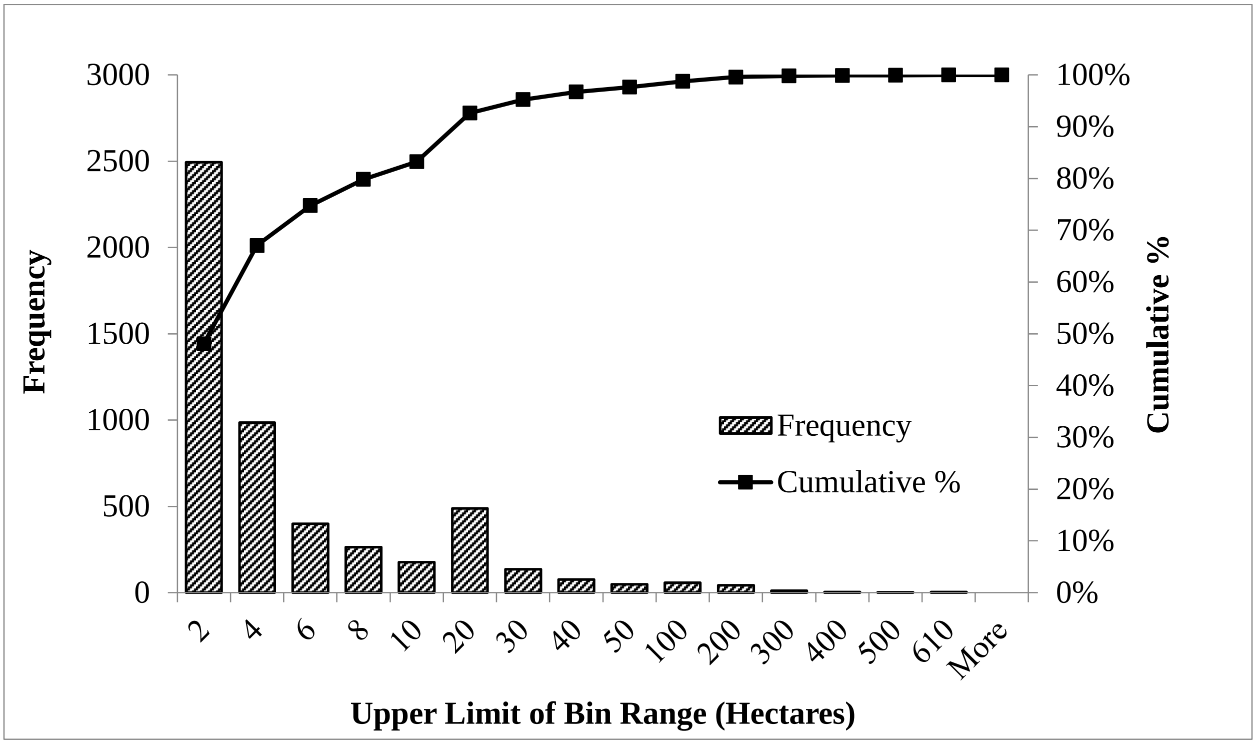

Figure 2.3. Frequency and cumulative distribution of active projects (March 2016) in the Commonwealth of Virginia from permit holder composite list, data from (VDEQ, 2016).

Resulting sample ES optimization runs across a variety of combinatorial solution sets were performed to determine approximate operating times. A laptop computer with an Intel Core i7-4650u Haswell processor, with 8 GB of RAM, and a desktop computer with on Intel Core i5-2500K, 3.30 GHz, with 4 GB RAM were used to determine representative runtime results, which are reported in Figure 2.4. These results do not appear to be excessive for combinatorial ranges expected in most site development projects. However, the progression of the processing curve indicates large increases to processing times when leaving the site scale range that is targeted by this project. This indicates that the ES algorithm would not be well suited if applied to projects at the watershed or regional level without significant adaptations for reducing combinations, which in turn would decrease computational time.

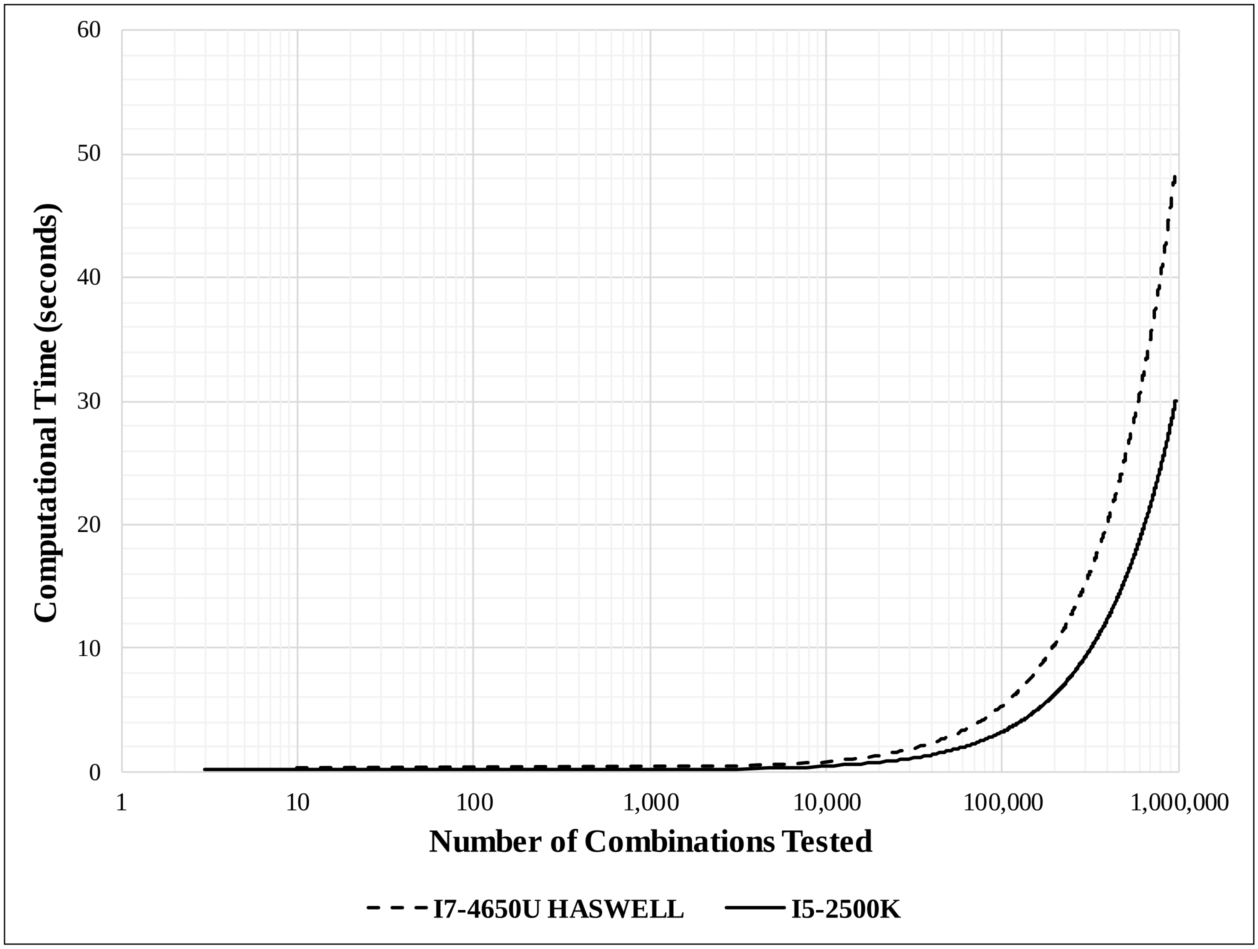

Figure 2.4. Semi-log plot depicting computational time to iterate through candidate solutions for two test processors.

In essence, these results indicate that based on current processing power, smaller site scale analysis, as defined by this study, can be performed that yield the optimal result. However, there is a threshold beyond which a tradeoff must occur between processing time and the need for an optimal vs. a near optimal result, as provided by many optimization methods, including GAs.

2.7 CONCLUSIONS

This paper has stepped through the development of an objective function related to the optimal selection of BMP nodes in a treatment train configuration at a site scale. Due to the large number of potential combinations in BMP selection, engineering bias typically affects the ultimate selection of BMPs. Testing all valid combinations would be impossible for design engineers without an algorithmic selection tool to iterate through valid combinations to reach an optimal solution for many sites. Based on a review of the literature, three possible candidate algorithms were considered for implementation in a tool used to optimally evaluate the objective function defined in this study.

Of the three evaluated algorithms in this study, based on analysis of solution space, the objective function, and defined algorithmic selection goals, the exhaustive search method is the only candidate solution algorithm that meets all of the stated objectives. For discrete optimization problems, ES algorithms will find the optimal solution, are easy to understand, and results are identical between successive program runs since all valid solutions are evaluated. Ultimately, processing speed is specific to computer hardware and is difficult to evaluate without application of the ES algorithm to the objective function described by this study. However, preprocessing by weeding illogical candidates, user defined constraints, and designer based omission of illogical BMPs at each BMP node will reduce the possibility of an excessive candidate solution set, and thus, run times. Tests using two computers that are representative of those used by design engineers indicate similar processing times throughout the range of combinatorial solutions tested. Those tests also indicate that the algorithm discussed in this paper should only be applied to projects at a site scale due to the likelihood of dramatically increased run times at a regional level. For watershed level or regional analysis, it is likely that GAs or other non-optimal solutions, such as those methods proposed in Behera and Teegavarapu (2015), Lee et al. (2012), Perez-Pedini et al. (2005), or Liu et al. (2016) would be necessary to determine an acceptable non-optimal solution in order to reduce computational time.

The problem described in this study exists in a finite (discrete) search space and seeks to find the optimal solution, which does not promote the use of GAs or similar algorithms that are more effective for continuous solution sets. Though the AHP process has been applied to decision support tools related to BMP selection in the past, its use of comparison matrices does not promote rapid integration or viability for use for optimization of the objective function described herein. It is believed that a tool developed using the ES algorithm for BMP selection will be a tremendous benefit to the design community at large by providing and easy to understand, reproducible, and rapid method for determining the optimal layout of BMPs in a treatment train configuration.

2.8 ACKNOWLEDGEMENTS

Author contributions: C. Hodges and R. Dymond wrote the journal article, formulated the objective function, and evaluated advantages/disadvantages of potential algorithms. C. Hodges developed a computational model to evaluate the ES algorithm and computed run times for various scenarios. Other contributions: Kevin D. Young, Virginia Tech provided peer reviews of algorithm selection and evaluation of results, which was invaluable due to his previous work in the field.

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Chapter 3: Generation of Cost Functions for use in Stormwater BMP Selection Optimization

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Status: This manuscript was submitted to *ASCE Journal of Sustainable Water in the Built Environment* in May 2016 and is in review.

3.1 ABSTRACT

During selection of optimal series of stormwater BMPs for a development site, designers must simultaneously consider multiple competing criteria for final selection, one of which is typically cost. A review of previous studies related to capital and O&M costs for various stormwater BMPs is conducted with the goal of developing a methodology for creating cost functions for integration in a BMP selection optimization algorithm. Four methods for relating cost to various BMP parameters are considered prior to selecting treatment volume as the best alternative. The selected method is applied to a wide array of non-proprietary structural BMP practices within the Commonwealth of Virginia to produce capital cost functions for all BMPs as related to treatment volume. The selected method for estimation of maintenance cost is based on a percentage of construction cost, with recommended values established from an analysis of previous studies.

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3.2 INTRODUCTION

During the middle to late 20th century, stormwater management related to site development projects generally focused on prevention of flooding downstream, and to a more limited extent, erosion control. Historically, flood control has been managed using impoundments which temporarily store an excessive volume of runoff to release to the receiving stream at a controlled rate. In addition to decreasing the peak runoff rate into receiving streams, temporary impoundment promotes partial settling of the suspended sediment load within the treatment volume. This method of management may be cost effective to implement on a site; however, since it does not address higher runoff volumes generated by land development activities, downstream degradation can occur which can cause regional economic and environmental impacts.

After passage of the Clean Water Act (33 U.S.C §1251 et seq., 1972) and its amendments, including the Water Quality Act (1987), the United States Environment Protection Agency (USEPA) was tasked with oversight of the National Pollutant Discharge Elimination System (NPDES) program and resulting permits in an effort to improve the quality of the nation's waters through the establishment of various allowable target thresholds of sediment, nutrients, and environmental toxins. The 1990 NPDES Stormwater Permit program hinged on redefinition of stormwater discharges from Municipal Separate Storm Sewer Systems (MS4s) as point source discharges (USEPA, 2016), causing them to fall under the purview of the NPDES permit program. Roll out of the NPDES stormwater permit program was phased, with permits required first in 1990 by Phase I communities (populations exceeding 100,000), and later, starting in 1999, by Phase II (USEPA, 2005) communities (populations between 50,000 and 100,000, with lower thresholds depending on several designation criteria such as discharge to impaired waters, population density, etc.).

Integration of water quality requirements through the NPDES program resulted in a paradigm shift in site scale stormwater management. It is now accepted that the most effective way to reduce degradation in receiving streams is by mimicking predevelopment hydrologic characteristics on the developed site. Because traditional stormwater impoundments are not effective at replicating predevelopment hydrologic characteristics, stormwater runoff is now commonly treated in relatively small scale stormwater BMPs distributed throughout the site in an attempt to maximize volume, nutrient, and sediment load reductions. Often, these distributed

BMPs are interconnected to allow secondary and tertiary treatment, in networks colloquially referred to as ‘treatment trains’. Treatment through these BMPs has benefits to receiving waters, including, reduction in downstream erosion, nutrient and toxin loads to receiving streams (Schueler and Youngk, 2015), and partial mitigation of thermal impacts caused by development (Long and Dymond, 2013).

In practice, manual optimization when integrating treatment trains in the design process can be difficult due to the need to simultaneously consider regulatory requirements against competing physical site constraints (Young et al., 2011) and cost. This is compounded with increasing site size and number of outfalls, where the number of viable solution combinations can be in the thousands. Due to the inability to test every viable candidate train for determination of the optimal solution, bias can creep into the design process. To maintain objectivity in the selection process, software based optimization can be employed for optimal treatment train selection. Past stormwater BMP optimization efforts on a regional or watershed scale have maximized nutrient removal and/or volume reduction, while minimizing cost (Cheng et al., 2006, USEPA, 2011). For land development projects, the regulatory requirements for pollutant or volume load computation, as well as efficiencies related to discharge efficiencies are typically established by state or local legislation, including a regulatory method for computation. Therefore, inclusion of pollutant/nutrient loadings and removal efficiencies in the maximization (load/volume reduction) portion of the selection algorithm must be employed based on local/state standards without regard to efficacy.

Cost functions, however, are dynamic and based largely on market conditions, and unlike regulatory pollutant removals, are not mandated values. Creation of functions for cost minimization initially seems to be a relatively easy task; however, reliable estimates of stormwater BMP costs are difficult to produce due to regional variation in labor and material costs, inflation, seasonal variation in material costs, lack of consistency in design standards and construction practices in historic BMP cost databases, the large variety of stormwater BMPs, and many other factors. Although many states (North Carolina, 2007; Maryland, 2009; West Virginia, 2012; Pennsylvania, 2006; Virginia, 2013) have defined specific efficiencies related to pollutant, nutrient, and volume reductions to BMP types, few have provided specific guidance on cost implications of the various practices, instead relying heavily on studies such as that by USEPA (1999) to provide an indication of cost.

This study focuses on development of a standard methodology to provide expected construction and maintenance cost functions, for integration in an optimization algorithm for optimal selection of BMP treatment train components against competing alternatives. A complete BMP cost is determined through compilation of various component costs. These can include design costs, construction (capital) costs, operating and maintenance (O&M) costs, and end of life disposal and replacement costs. Design costs are not considered for this study, as it is assumed that the magnitude of design costs is similar between all BMP categories for a specific site. Construction cost, though the focus of most engineering cost opinions, may not be the primary cost consideration in the life cycle of treatment BMPs, since O&M costs are high for many practices. Various studies have attempted to define construction and O&M costs as described in later sections. Although disposal and end of life replacement costs rival initial installation costs, there is little present data on the life expectancy of most BMPs, which hampers integration of end of life costs in net present value (NPV) or annualized estimations of cost; therefore, these costs are not included in this study.

3.3 REVIEW OF LITERATURE

USEPA (1999) was, at the time, a pivotal report on the state of the practice of BMP technology. This report consolidated nutrient efficiency, runoff reduction, cost data, etc. related to stormwater BMPs, which included the newer BMP implemented in Phase I communities over the previous decade. The construction cost data summarized in the report was based on studies by Brown and Schueler (1997) or SWRPC (1991). Construction cost functions provided for BMPs investigated by USEPA (1999) are related to volume for storage type BMPs (detention, retention, and infiltration) and surface treatment area for porous pavements, filter strips, and grassed channels. Sand filters were separately correlated to the impervious component of the contributing drainage area (CDA). USEPA (1999) was groundbreaking in providing direction for creation of BMP cost estimates; however, the varying normalization parameters used for developing construction cost functions between BMP categories hampers rapid comparison between competing BMP types during selection. Annual maintenance cost, as reported by USEPA (1999) was generally reported as a percentage of BMP construction cost, and based on a consolidation of various studies by Wiegand et al. (1986), Schueler (1987), SWRPC (1991), Livingston et al. (1997), and Brown and Schueler (1997).

Water Environment Research Foundation (WERF, 2005) produced a report summarizing performance and whole life cost of stormwater BMPS. The study was undertaken in an effort to overcome several deficiencies related to cost analysis of BMPs, including lack of historic cost and operational data and little understanding of long-term liabilities associated with BMP installations. Authors of the study noted significant regional discrepancies in cost and maintenance between similar BMP types that were largely attributed to local perceptions or regulations regarding aesthetics of installed practices. The WERF model evaluates various installation and operational costs (capital, operating and maintenance (O&M), monitoring, disposal, residual, and others) related to BMPs to determine a NPV whole life cost. WERF (2005) noted several deficiencies with its developed methodology, including limited data availability for generation of costs and the extreme sensitivity of whole life cost to the associated maintenance cost component.

The authors of WERF (2005) noted that computation of installation costs would not benefit from a national effort in compiling installation costs by BMP types. Instead, capital cost functions should be generated locally based either on local installation cost data, or local engineering cost opinions that effectively take into account regional variations in labor and material costs. Capital cost functions generated by WERF (2005) are related to physical size of the facility and vary by type, with ponding categories related to volume (m^3), infiltration/filtration beds related to area (m^2), and linear practices such as grass swales related to distance (m). Operation and maintenance costs in the study are defined as a percentage of the capital construction cost, similar to USEPA (1999). The data and cost curves generated from WERF (2005) are the basis for the cost analysis that is included in the WERF SELECT BMP selection spreadsheet tool (WERF, 2013).

Weiss et al. (2007) performed an analysis of six types of stormwater BMPs to determine both construction and O&M costs with the goal of developing a tool for comparison of stormwater BMPS. The study defined the total present cost as capital cost plus the NPV of an additional twenty years of O&M costs. Regional cost adjustment factors as published by the USEPA (1999) were used to convert national cost data to a common basis. Weiss et al. (2007) determined that data compared using the water quality volume (WQV) of BMPs produces less scatter when plotted than that related to CDA. A review of current data at the time of the study was performed in an attempt to statistically analyze O&M costs for various BMPs; however, no historical O&M data was found for any of the BMP types. Due to the reported lack of historic O&M cost data, Weiss et al. recommend estimating the costs as a percentage of construction cost, and reference those reported in USEPA (1999) as well as reporting values from additional studies in the literature (SWRPC,1991; Landphair et al., 2000; Caltrans, 2004; Moran and Hunt, 2004).

USEPA SUSTAIN (Shoemaker et al., 2009) was developed as a decision support tool to aid planners in developing and optimizing regional stormwater management plans. Subsequent updates have been performed, resulting in the most recent version, released June 2014 (USEPA, 2014). The software uses genetic algorithms to select locations and estimate costs by attempting to simultaneously maximize pollutant and volume removal, while minimizing cost. The authors note extreme sensitivity in model results to BMP cost data. Construction cost data used for computations in SUSTAIN come from a variety of sources including wholesale retail costs, EPA Stormwater Fact Sheets (932-F-99-001 to 048), the California Department of Transportation (CALTRANS), Fairfax County, Virginia, BMP Fact sheets, Natural Resources Conservation Service (NRCS) Cost Share Data, and several others. SUSTAIN (USEPA, 2014), relies heavily on NRCS cost share data for development of cost curves, which the authors state is focused primarily on agricultural or rural projects, with few costs based on urban applications.

The Minnesota Pollution Control Agency (MPCA, 2011) commissioned a report detailing construction and maintenance costs for stormwater BMPs. Capital costs were consolidated from actual construction cost data, converted to NPV 2010, and related to the treatment WQV of each BMP. The treatment WQV, as defined in the report, is not a design volume based on characteristics of the CDA and precipitation data. Instead, it is defined as the storage volume below the overflow for some filtration/infiltration practices, eighteen inches over the surface area for wetland type BMPs or the dead storage volume for extended detention facilities. Linear grass swales were omitted from analysis due to insufficient data available to estimate an as-constructed WQV.

Colorado State University, the Urban Watersheds Research Institute, and the Colorado Urban Drainage Flood Control District have developed a spreadsheet tool, Best Management Practices – Rational Estimation of Actual Likely Costs of Stormwater Treatment (BMP – REALCOST) to aid in the estimation of construction costs of stormwater BMPs in the Denver metropolitan area (Olson et al., 2013). As reported by Olson et al. (2013), the tool uses data from engineering cost opinions created and statistically analyzed for creation of cost curves related to various BMP categories. Resulting cost functions relate probable construction cost to the contributing impervious area. The basis of the analysis was development of conceptual designs of the various BMP types across the expected operational range (i.e., contributing drainage areas, impervious cover, etc.) for each. The designers note that the developed curves are "approximate and intended primarily for comparative purposes" (Olson et al., 2013). Additionally, the authors warn that since the curves were developed across operational contributing drainage area (CDA) ranges, and not nutrient/pollutant removal ranges, that each cost function does not "in itself reveal the relative treatment costs per pound of pollutant removed."

The Center for Watershed Protection (CWP, 2013) prepared a study at the request of the James River Foundation (JRF, Virginia) to evaluate cost-effectiveness of various urban stormwater BMPs. The study defines cost-effectiveness in terms of annualized life cycle costs per pound of pollutant removed. This study is novel in that it suggests normalization using nutrient removal as a standard metric across all BMP categories, which addressed a shortcoming in the study by Olson et al. (2013). Although the study did not focus on selection of BMPs, a variation of the standard employed for comparing cost to nutrient removal appears well suited to the task.

The International Stormwater BMP Database [ISBMPD] (2014) is a compendium of studies related to BMP installation, performance, and cost. Started in 1996 as a joint project by the American Society of Civil Engineers (ASCE) and USEPA, the project more recently added new partners including WERF, the Federal Highway Administration (FHWA), the American Public Works Association (APWA) and the Environmental and Water Resources Institute (EWRI). Updated every several years, the 2014 version of the database holds 145 records related to BMP cost. The data reported by ISBMPD (2014) related to cost is often inconsistent, and contains incomplete records. For instance, of the 145 records related to cost, only 49 list the initial construction cost, with only 9 of those records occurring after year 2000, around the time Phase II MS4s began installation of water quality BMPs. With little information given by ISBMPD (2014) related to construction and design specifications for BMPs, and the small number of recent construction cost records overall, there is insufficient data related to construction costs for the newer generation of stormwater BMPs to provide a statistically valid sample for analysis in the determination of cost. In addition, ISBMPD (2014) has no records related to the O&M costs of reported installations.

The National Cooperative Highway Research Program (NCHRP) published a 2014 report (Taylor et al., 2014) aimed at aiding the designer in optimization of the stormwater BMP design and maintenance, primarily for Department of Transportation (DOT) programs. To date, it is one of the most comprehensive studies of the type, using not only data from past studies, but also collecting cost and performance data directly from transportation programs in all states. The study produced a report as well as spreadsheets for various BMP types to aid in computation of whole life cycle costs. Like CWP (2013), costs between BMP types were related to removal of various nutrients and pollutants, including E. Coli, fecal coliform, total copper, total lead, total zinc, nitrate, total Kjeldahl nitrogen, total nitrogen, dissolved phosphorus, total phosphorus, and total suspended solids. Construction cost data was developed using unit costs (RS Means publications) along with estimated units of materials as input by the user. O&M cost estimates, unlike most previous studies, do not correlate maintenance costs as a percentage of construction cost, but instead uses results from statistical analysis of collected data regarding maintenance hours (labor) and equipment and material cost from various DOT project studies. Taylor et al. (2014) also expands on previous work by attempting to provide a whole life cycle cost calculation by predicting full future replacement of BMPs based on likely life expectancy of major BMP components. A shortcoming of the study, as related to new site development projects, as explained in Taylor et al. (2014), is that the cost information is specifically tied to retrofit of existing stormwater infrastructure on highway projects. The authors suggest that designers using the developed spreadsheets on new projects would need to override supplied unit cost data and local performance metrics prior to utilizing the tool.

3.4 METHODOLOGY

The goal of this project is to develop a consistent method for development of cost functions for both construction and maintenance costs that may be used in a site scale BMP selection optimization tool. Because the primary focus of the tool will be comparison between BMP treatment train solutions, and not as a cost estimation tool, the absolute accuracy of the determined cost is less important than a realistic relative cost between candidate solutions. A review of the literature has indicated generalized guidance in the development of both construction and maintenance cost functions. As indicated by Taylor et al. (2014), Olson et al. (2013), Shoemaker et al. (2009), and WERF (2005), regional variations in initial construction costs of stormwater BMPs should be addressed through the creation of cost functions either by using historic local materials and labor data, or locally created engineering cost opinions. Most studies found in the literature (USEPA, 1999; Weiss et al., 2007; MPCA, 2011; King and Hagan, 2011) define operating and maintenance cost as a percentage of initial installation cost. Therefore, this study follows recommendations in the literature and bases initial construction cost functions on locally based unit component costs for stormwater BMPs. O&M cost is computed as a percentage of initial construction cost, as indicated by a review of the literature.

3.4.1 Evaluation of BMP Design Parameters vs. Cost

Attempts to provide objective relative cost comparisons between BMPs has resulted in a variety of relational methods that can be used to estimate BMP construction and maintenance costs. Past studies have indicated four distinct parameters typically relating construction and/or maintenance costs of stormwater BMPs. These include costs related to:

- Water quality volume (WQV)
- Contributing Drainage Area (or impervious portion of CDA)
- BMP size (length, area, or volume)
- Nutrient or pollutant removal

Each of these parameters were evaluated for integration in cost functions to be used in an algorithm for selection of the optimal layout of distributed stormwater BMPs at the site scale.

3.4.1.1 Water Quality Volume

WQV, is a standard metric that is commonly used to determine sizing for selected stormwater BMPs. The volume is sometimes based on a rainfall depth over the impervious portion of the CDA, but also can be based on a depth over the entire CDA with adjustments to account for pervious portions of the drainage area. The most common method for computing WQV is based on capturing and treating the rainfall represented as the 90th percentile of annual events, as presented in Equation 1 (NYDEC, 2015).

$$WQV = P \times R_v \times A \quad (1)$$

where,

WQV	=	Water quality volume [m^3]
P	=	Precipitation [m]; typically taken as the 90th percentile of annual storms
R_v	=	Runoff coefficient based on land use
A	=	Contributing drainage area (m^2)

Although some states use a standard precipitation value statewide (ex. Virginia = 2.54 cm), other states publish isohyets of 90th percent rainfalls across the state (NYDEC, 2015) for the precipitation parameter of the equation. The result related to BMP design is that both inter- and intrastate designs in different regions are not based on comparable volumes. Although these volumes may be different throughout a state, this should not affect use for cost normalization because the sizing of the BMP is tied to the water quality volume; therefore, areas with lower 90th percentile precipitation depths will have smaller BMPs at proportionally lower costs than areas with higher depths. When BMPs are arranged in a treatment train, a more complicated scenario arises because downstream BMPs receive treatment volume inflow from two components. The first is the direct surface inflow from the CDA of the BMP node (WQV as calculated in Equation 1). The second is remaining effluent treatment volume from an upstream node. The two components are combined into a BMP 'treatment volume' for sizing the BMP. Because this combined treatment volume takes into account both contributing loads necessary for design, it is considered a more relevant metric for development of BMP cost functions.

3.4.1.2 Contributing Drainage Area

The contributing drainage area of a BMP is easily defined. Delineation of component land uses within the CDA (i.e. impervious, turf, forest, etc.) is also easily achieved. Previous studies have indicated that resulting pollutant load is highly correlated with the impervious cover in the CDA, resulting in the 'Simple Method' equation for pollutant load estimation (Schueler, 1987). The Simple Method has been widely accepted and is in use by many state level environmental agencies (Virginia DEQ, Maryland Department of the Environment, New York State Department of Environmental Conservation, etc.), which infers acceptance that land cover within a CDA predominantly dictates pollutant load to discharge locations.

There is no doubt that land cover in the CDA directly affects the pollutant load, design size, and ultimately cost of BMPs used to treat stormwater runoff. However, issues arise when attempting to relate cost to the CDA for comparison of competing BMP treatment trains. Volume reducing stormwater BMPs installed in treatment trains (such as bioretention, grass channels, dry swales, etc.) only remove a portion of the treatment volume and pollutant load. The remaining volume and load is discharged downstream to the next BMP node. Although the direct CDA treatment volume contribution to a single BMP node remains constant between candidate solutions, any volume or pollutant load contribution from upstream BMPs can change as various upstream trial solutions are tested, due to BMPs varying pollutant and volume reduction efficiencies. Without significant mathematical manipulation to take into account load reductions from upstream treatment nodes, the addition of remaining upstream treatment volume at a downstream node that is not tied to the direct surface inflow CDA of a BMP node makes comparison of cost to CDA impractical for comparison of BMP treatment train solutions. Note that this is not the case for single (non-train) BMP installations where the CDA remains constant across all candidate solutions. However, even in these instances, Weiss et al. (2007) indicated that significant scatter occurred when relating cost data to CDA, which implies that used of this metric is, at best, inconsistent.

3.4.1.3 BMP Size

Relationships of cost to BMP size are normally broken into three potential categories, including volume (m^3), surface area (m^2), or longitudinal distance (m). These relationships are suitable for creating a database of individual BMP costs; however, the goal of this study is selection of a procedure to be used for optimizing the selection of BMPs that are potentially in treatment trains and spanning multiple outfalls. Since the selection algorithm will not fully design candidate solutions (yielding length, width and depth geometry), there is no way to generate an associated cost for comparison of candidate solutions. Based on this limitation, no further consideration was given to this method of comparison.

3.4.1.4 Nutrient or Pollutant Removal

As described above, typically regulatory requirements are based on meeting required removals of nutrients (typically phosphorus or nitrogen) or total suspended solids (TSS). Meeting the regulatory objective at the lowest cost (if only required pollutant reduction and cost are considered) is the goal of a design optimization. The common goal of a total computed load reduction is shared across all site outfalls. Individual direct BMP node loads are typically computed through use of the Simple method (Schueler, 1987) and based largely on impervious fraction of the CDA. Indirect loads occur in BMP trains when effluent treatment volume from an upstream node is directed to a downstream node. This influent volume is partially treated by the upstream BMP and enters the downstream node with a diminished pollutant concentration.

Effluent pollutant concentrations from BMPs are often computed through application of assigned removal efficiencies that have been statistically derived and enacted as regulatory standards. Because the ultimate goal of stormwater BMPs is volume and pollutant (including TSS and nutrients) reduction, it seems logical to tie cost to those parameters. However, the interaction between the mass load removal (through volume reduction and BMP physical treatment processes) and distribution of loading throughout a treatment train calls this into question. Unlike single BMP installations, downstream nodes in a treatment train are subject to both partially treated effluent from upstream practices, as well as direct inflows from the adjacent CDA. The result is variable pollutant/nutrient loads entering downstream practices. Because design standards are based on the incoming treatment volume regardless of pollutant/nutrient concentration, and it is likely that the concentration is lower due to upstream treatment, cost functions should not be tied to pollutant/nutrient loads or load removals.

3.4.2 Development of Cost Functions for Predicting Relative BMP Cost

Construction cost as defined in this study is similar to the 'base construction cost' parameter used in spreadsheets by Taylor et al. (2014) and does not include design fees, legal fees, bidding, property acquisition and remediation, or contingencies. Typically, for engineering design projects, BMP selection takes place after a contract is executed for design services; therefore, those fees exist regardless of the selected BMP solution. This logic also holds true for legal fees related to recording of maintenance covenants as well as recording of plats of easement related to long term BMP operation. Costs associated with property acquisition varies greatly between projects, even within the same economic region, due to fluctuations in cost based on zoning, proximity to established commercial areas or attractions, etc. These costs can have a large effect on overall BMP cost if additional land is necessary for the construction of the selected design. However, when used in a selection algorithm comparing efficiencies and costs between BMP categories, omission of this cost item should have little effect due to the nature of the established operating ranges and rules related to comparison of the practices. For instance, rooftop practices are only compared against other rooftop practices, which would have the same land acquisition cost. Filtration/infiltration practices such as bioretention, dry swales, surface sand filters, infiltration basins, etc. have similar footprints across their expected operating ranges; therefore, land acquisition for comparison would be similar. The largest discrepancies would occur when comparing smaller filtration/infiltration practices with the ponding category (extended detention, wet ponds, or constructed wetlands); however, due to established non-overlapping CDA operating ranges (maximum of 2.023 hectares CDA for filtration/infiltration and minimum of 4.047 hectares CDA for ponding classification) comparisons between these categories by the selection routines does not take place. This means that if a ponding practice is required for the project, comparisons in a selection algorithm would only be between competing ponding practices, which infers a comparable land acquisition cost since these practices have similar operating footprints.

Statistical analysis of a large pool of as-built construction cost data for BMPs designed using consistent designed standards would be the ideal method for developing cost functions. Unfortunately, due to the lack of documented as-built costs at this time, development of these cost estimates appears to be the best option (WERF, 2005). Opinions of probable cost were created using methods similar to those found in Olson et al. (2013) and Taylor et al. (2014) where unit costs for various construction items were generated as an opinion of likely cost. As discussed above, cost functions will vary regionally, and should be generated using local cost data accounting for those variations in material and labor costs. For this study, cost opinions have been created using expected engineering unit costs for projects located in southwest Virginia. Construction cost estimates were generated for multiple designs across the recommended operating CDA ranges of each BMP. Impervious cover percentages were also varied for each CDA, with cost estimates generated for each. The number of cost estimates generated for statistical analysis varied between BMP types. Practices requiring 100% impervious cover (e.g. rooftop practices) were evaluated using 50 automated cost estimates based on varying CDA (rooftop) size. Practices that may have a large variation in CDA impervious cover (i.e. bioretention, dry swales, etc.) were analyzed using up to 1000 estimates for each.

Although Raghavan et al. (2002) indicated that cost functions for capital cost are best fit using a power equation, plots of the generated cost data in this analysis did not support that determination. An examination of the data, instead, show strong linear correlations; therefore, results for each BMP were linearly regressed, using water quality treatment volume as the independent variable. BMP types evaluated in the study and recommended operating ranges, based on recommended values established by the Virginia Department of Environmental Quality (VDEQ), are reported in Table 3.1. Virginia has two levels of design for many of these practices, with the second (higher) level requiring increases in required treatment volume and level of pretreatment (Battiata et al., 2010). Analysis ranges reported in Table 3.1 combine the ranges of the Level 1 and Level 2 analyses, which were conducted separately.

Table 3.1. BMP types evaluated in study with Contributing Drainage Area (CDA) range evaluated for creation of cost functions.

BMP Type	CDA Range Evaluated (hectares)	Impervious Cover % Range Evaluated	Treatment Volume Range Evaluated (m^3)
Vegetated Roof (Extensive)	0.017 – 0.186	100%	2.2 – 49.3
Rooftop Disconnection (RD)	0.005 – 0.009	100%	1.1 – 2.2
RD to Dry Well	0.002 – 0.023	100%	0.6 – 6.2
RD to Rain Garden	0.009 – 0.023	100%	2.2 – 7.0
RD to Stormwater Planter	0.009 – 0.023	100%	2.2 – 5.6
Bioretention	0.202 – 1.012	20% – 100%	49 – 305
Sand Filters (Surface)	0.202 – 2.023	80% – 100%	49 – 610
Infiltration	0.202 – 0.809	80% – 100%	49 – 215
Grass Swale	0.121 – 2.023	20% – 100%	24 – 288
Wet Swale	0.121 – 2.023	20% – 100%	24 – 610
Dry Swale	0.202 – 2.023	20% – 100%	49 – 537
Permeable Pavement	0.040 – 0.304	100%	20 - 103
Sheetflow (Filter Strips)	0.019 – 0.047	100%	4 – 11
Constructed Wetlands	4.047 – 12.141	20% – 100%	635 – 2856
Wet Ponds	4.047 – 12.141	20% – 100%	977 – 4394
Extended Detention Basins	4.047 – 12.141	20% – 100%	977 – 3662

Resulting ranges of cost functions from the analysis are shown in Figure 3.1. The linear relationship for construction costs found is similar to those reported by Olson et al. (2013). While cost functions for all practices and design levels have been plotted on Figure 3.1, due to the number of practices and significant function overlap, the figure was simplified to show logical groupings of the various practices. The resulting linear functions yielded by regression for each BMP type and level, as applicable, are listed in Table 3.2.

Level 2 practices in Virginia are required to treat a larger volume than their Level 1 counterparts. While the Level 1 BMPs are designed based on a treatment volume related to the 90th percentile rainfall in Virginia (2.54 cm adopted state-wide), the Level 2 treatment volumes are increased to values between 110% and 150% of that standard. Cost functions were adjusted, as necessary, to accommodate these differences in design treatment volume.

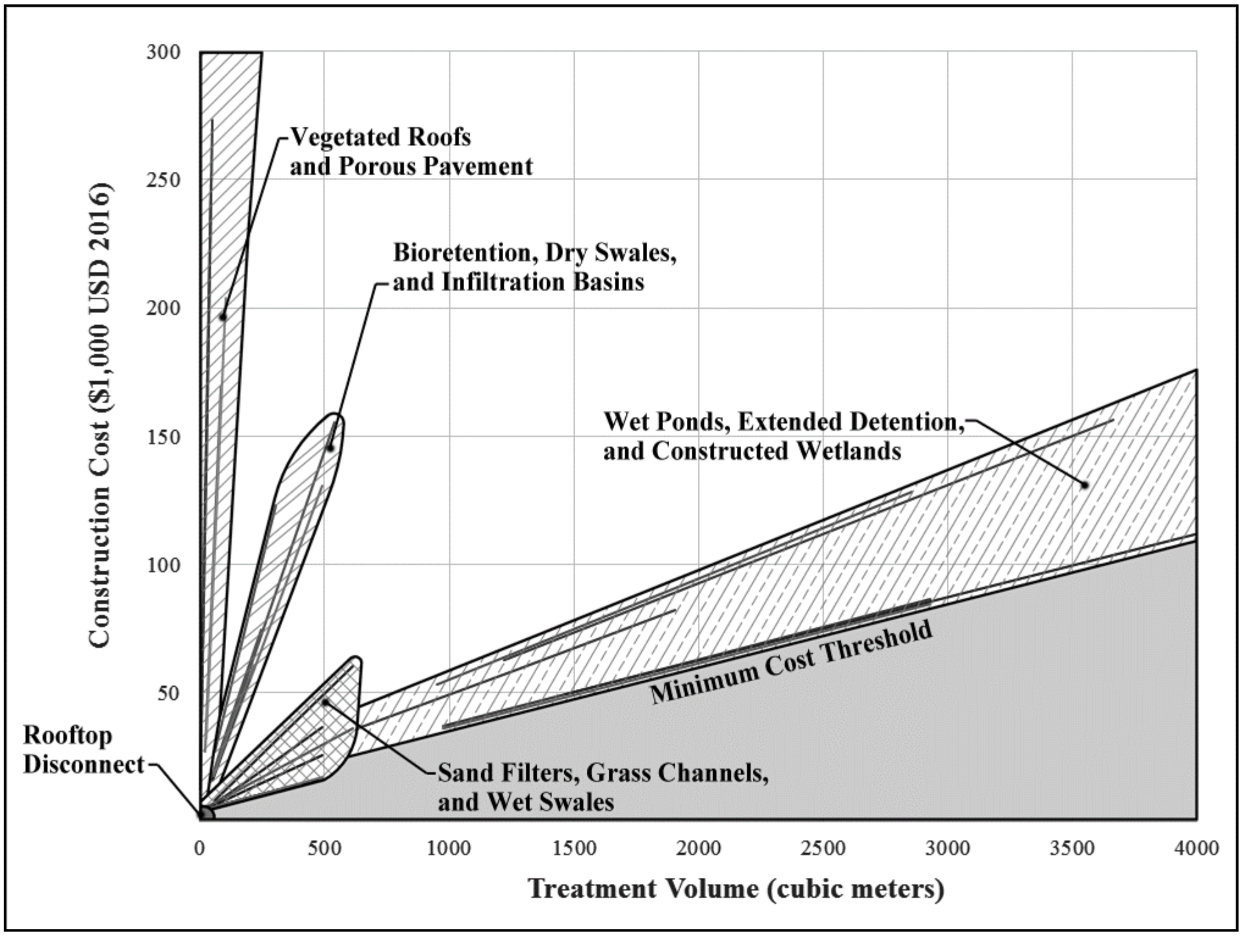

Figure 3.1. Construction cost vs. treatment volume. Resulting cost functions are in grayscale behind hatched cost regions for each BMP group.

Table 3.2. Initial construction cost (C_i) vs. Treatment Volume (T_v, m^3) [modified from VDOT, 2016]

BMP Type	Level 1	Level 2
Vegetated Roof	$C_i = 5602.77T_v$	$C_i = 5539.71T_v$
Rooftop Disconnect (RD)	$C_i = 180.32$, $C_i = 550.32$[1]	N/A
RD to Dry Well	$C_i = 300.30T_v + 478.73$	$C_i = 299.63T_v + 483.61$
RD to Rain Garden	$C_i = 453.24T_v + 671.46$	$C_i = 411.69T_v + 683.29$
RD to Stormwater Planter	$C_i = 935.72T_v + 1613.99$	N/A
Bioretention	$C_i = 293.13T_v + 3307.69$	$C_i = 392.92T_v + 3019.84$
Sand Filters (Surface)	$C_i = 69.58T_v + 2697.69$	$C_i = 94.66T_v + 2569.87$
Infiltration	$C_i = 268.82T_v + 3278.45$	$C_i = 268.45T_v + 3316.38$
Grass Swale	$C_i = 25.98T_v + 3979.50$[2]	N/A[2]
Wet Swale	$C_i = 26.41T_v + 4287.60$	$C_i = 52.12T_v + 4287.60$
Dry Swale	$C_i = 261.53T_v + 2934.08$	$C_i = 283.33T_v + 3120.75$
Permeable Pavement	$C_i = 2231.95T_v + -16200.84$	$C_i = 2164.27T_v + -20654.31$
Sheetflow (Filter Strips)	$C_i = 315.73T_v$, $C_i = 547.03T_v$[3]	N/A[3]
Constructed Wetlands	$C_i = 36.19T_v + 13143.95$	$C_i = 39.63T_v + 15399.33$
Wet Ponds	$C_i = 25.12T_v + 12854.45$	$C_i = 24.58T_v + 13552.16$
Extended Detention	$C_i = 24.91T_v + 11750.00$	$C_i = 38.29T_v + 16236.86$

[1] First equation is for A/B/C/D soils without amendments. Second equation for compost amended soils.
[2] Equation in table is for A/B soils. Level 1 Eqn. for C/D soils is $C_i=25.98T_v + 3979.50$; Level 1 Eqn. for compost amended C/D soils is $C_i=44.30T_v + 3979.50$.
[3] First equation is for A soils. Second equation is for B/C/D compost amended soils.

3.4.2.1 Evaluation of Results

Regressed equations were evaluated using the coefficient of determination (R^2) and the correlation coefficient. For all practices, both values were greater than 0.99, which indicate a linear trend with excellent fit; however, this high degree of fit is not unexpected with generated data. A closer examination of the Level 1 and Level 2 cost function curves for Bioretention (Figure 3.2) graphically reinforces the linearity of the data. This high level of linearity in the data can be explained since all designs are based on the water quality treatment volume; therefore, all component units generally increase in cost proportionally with treatment volume. Some variation in the linear trend results as BMP design size increases due to the addition of BMP components added at specific dimensional thresholds, such as additional underdrains on filtration BMPs after a maximum width is exceeded. However, these deviations in the data tend to be almost negligible when compared to the overall cost trend; therefore, the linear model holds.

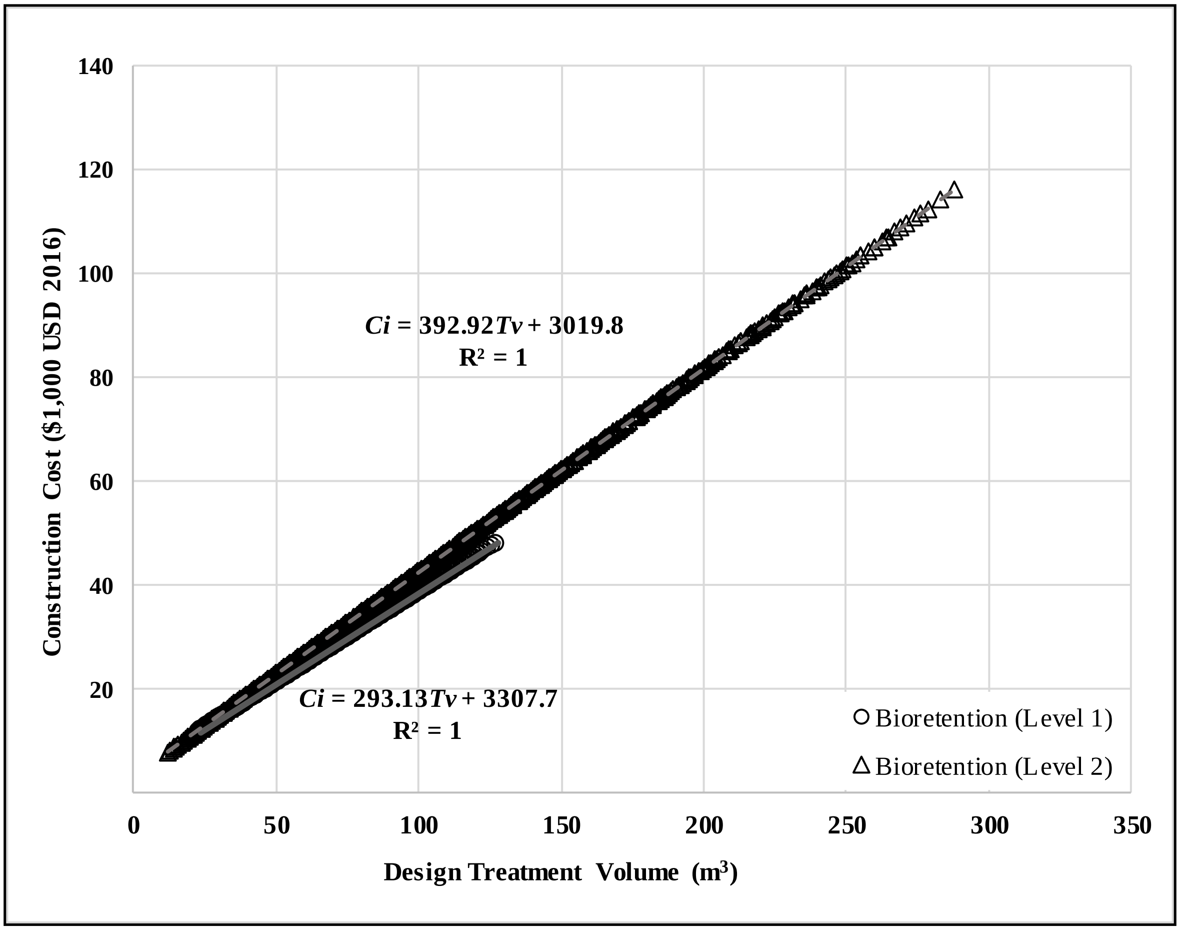

Figure 3.2. Linear functions fit through cost estimate points for Level 1 and 2 bioretention

The high degree of linearity shown by resulting data points (Figure 3.2) does not translate into a high degree of confidence in the resulting function. As is true for most cost estimation exercises, the model is extremely sensitive to error in unit costs of major components. For instance, the major cost component of a bioretention facility (excluding land acquisition costs, etc.) is the media. Variations in media unit costs have a large influence on overall cost with increasing cost spread over increasing treatment volume (Figure 3.3).

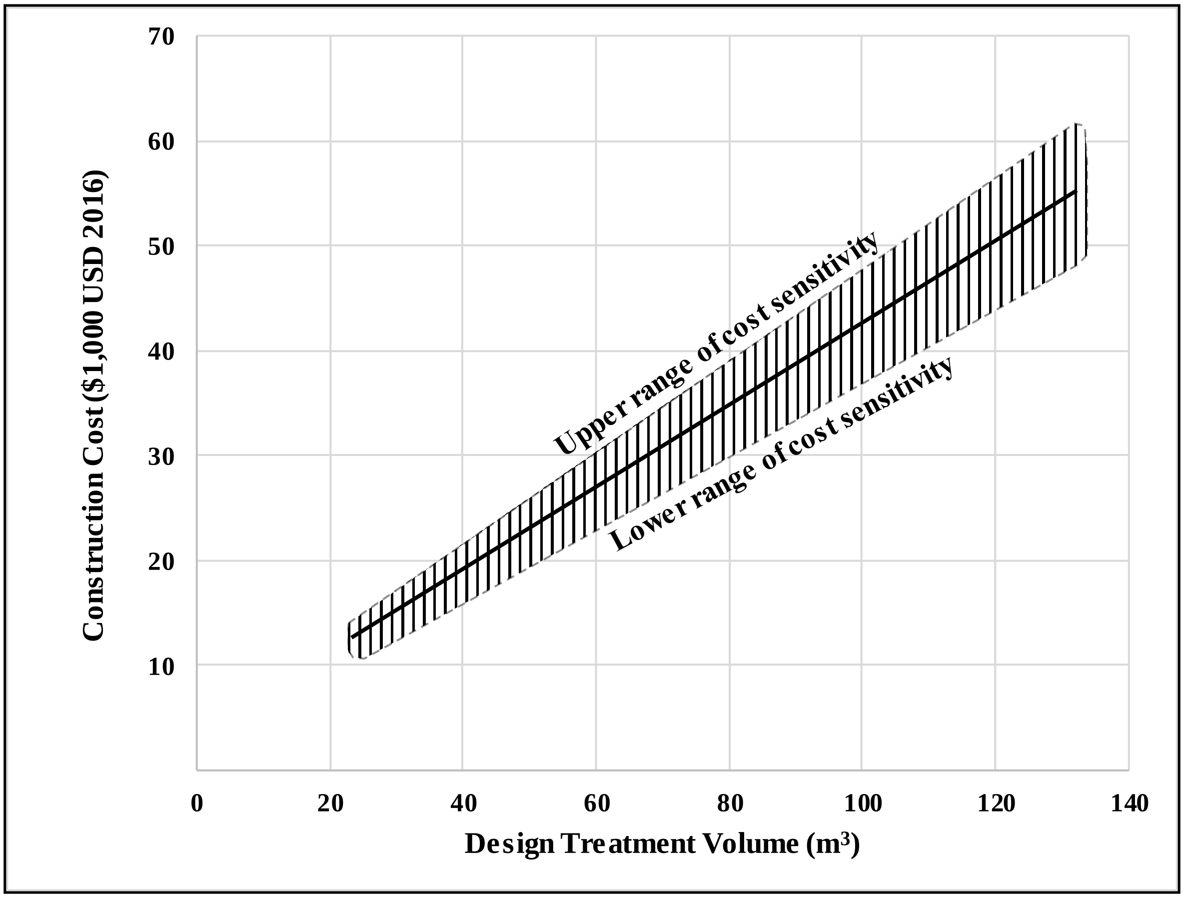

Figure 3.3. Sensitivity of Bioretention Level 1 to fluctuations in estimated soil media unit cost (85% - 115% of average unit cost used in estimates).

This sensitivity does not have a strong effect when comparing practices with similar design components, such as bioretention and dry swales. However, relative comparison can be significantly affected by unit cost variation in single components between non-similar BMPs, such as fluctuation in the asphalt index causing variations in the cost of permeable pavement, but having no effect on other BMP types. To combat this sensitivity to market conditions, cost functions developed for the purpose of BMP selection should be reviewed and updated regularly to remain current with market conditions.

3.4.3 Estimation of Annual Maintenance Cost

Several viable methods for estimation of annual maintenance cost for stormwater BMPs were found in the literature. The ideal method for estimation of maintenance cost, as discussed with capital costs, is statistical analysis of a large sampling of historic maintenance cost data for each BMP type. Unfortunately, due to the recent emergence of many of these BMP types, sufficient data does not exist for this analysis. Again, analyzed data needs to be compiled for similarly designed practices, which often means that database consolidation at a national level has limited merit due to regional variation between BMP design standards. To combat this limitation, two other methods have been suggested in the literature.

The first is a more time intensive method that includes estimating tasks, materials, and labor for ‘normal’ years and ‘extensive upkeep’ years, and averaging those costs. Conceptually, this method is similar to that explained above for generation of opinions of expected costs. Taylor et al. (2014) uses this method in the development of spreadsheets for estimating the whole life cycle cost of various highway related stormwater BMP retrofits. WERF (2005) also integrates this methodology in its analysis of O&M costs. WERF reported that factors, such as proximity of closest disposal site, rather than labor, materials, and tasks at the BMP location often have a larger effect on overall maintenance cost.

A second, more commonly used method found in the literature, is estimation of O&M costs as a percentage of construction cost (USEPA, 1999; Weiss et al., 2007; MPCA, 2011; King and Hagan, 2011). King and Hagan (2011) describe a general trend among O&M costs related to construction cost where the O&M percentage cost for stormwater BMPs decreases with increasing initial installation cost. Weiss et al. (2007) performed an updated analysis of O&M costs for comparison to USEPA (1999). That data, in addition to values derived from component costs computed from an analysis by King and Hagan (2011) and evaluation of BMPs using Taylor et al. (2014) spreadsheets over those ranges found in Table 3.1, are shown in Table 3.3.

Table 3.3. Summary of operation and maintenance costs as percentage of BMP construction cost for various studies in the literature.

	O&M Costs as Percentage of Construction Cost			
BMP Type	**EPA** (1999)	**Weiss et al.** (2007)	**King and Hagan** (2011)[1]	**NCHRP** (2014)[2]
Retention Basin	3%-6%	Not Reported (NR)	4%	CNE[3]
Constructed Wetland	3%-6%	4%-14.1%	4%	NR
Infiltration Trench	5%-20%	5.1%-126%	NR	NR
Infiltration Basin	1%-10%	2.8%-4.9%	2%	NR
Porous Pavement	NR	NR	1%	NR (PFC)[4]
Sand Filters	11%-13%	0.9%-9.5%	4%	1%-5%
Bioretention	5%-7%	0.7%-10.9%	4%	4%-32%[5]
Swales	5%-7%	4.0%-178%	3%	1%-3%
Filter Strips	$320/acre	NR	NR	25%-50%
Detention Basin	NR	NR	NR	0.4%-3%

[1]Percentage values for King and Hagan (2011) were computed from reported values of maintenance cost vs. installation cost normalized by areas of impervious drainage area.

[2]Percentage values for Taylor et al. (2014) were computed through an analysis using the tool developed by that study of various ranges (Table 3.1) of operation to established estimated O&M vs. construction base costs.

[3]Could not evaluate using the Taylor et al. (2014) tool due to an error causing an infinite loop in evaluation, which could not be resolved.

[4]NCHRP (2014) utilized a permeable friction course (PFC) overlay which is not similar to permeable pavement as defined by this study; therefore, costing for this item is not evaluated for this study.

[5]Maintenance costs for this item are depicted in the Taylor et al. (2014) spreadsheet tool as static across the entire design range evaluated.

For this study, values reported in Table 3.3 were analyzed to determine an average percentage value for use in creation of a cost function that can be used in a BMP selection algorithm. A single value was computed by averaging both the low and high ranges across studies to determine a unified range in values across studies. It was assumed that values reported by each study have equal weight. Regional or annual variations in costs between studies should have little impact in this analysis since the costs are evaluated as a percentage of construction cost, which for each study, individually, had been transformed to provide a consistent cost basis. Excessively high ranges for infiltration trenches and swales for Weiss et al. (2007) were assumed in this study to be outliers caused by either major replacement of BMP components, increased maintenance due to improper installation, or other factors that would not normally be expected to occur for BMPs of those types. Therefore, high ranges for those BMPs were ignored during the consolidation process.

Values for several BMP types as listed in Tables 3.1 and 3.2 were not mentioned in the four studies discussed above. These BMPs, in general, fall into a category related to treatment of stormwater falling directly on rooftops. Based on the trend related to maintenance vs. installation cost discussed by King and Hagan (2011), O&M cost for vegetative roofs is expected to be small since the installation cost is typically high. A study published by the U.S. General Services Administration (GSA, 2011) indicates that annual maintenance for green roofs is typically rated at 4 man-hours per 93 m^2 of roof. Based on the construction costs ranges evaluated in this study, this relates to 1% or less of the expected construction cost. This low value is supported by Carter and Keeler (2008) who indicate that the expected maintenance cost of green roofs is very low, and primarily related only to visual inspections a couple of times per year. Due to the lack of data in the literature, other rooftop disconnection practices were assigned values as computed for their 'parent practices'. For example, dry wells are micro-infiltration basins, while rain gardens are micro-bioretention facilities. The trend presented by King and Hagan (2011) would predict that smaller rooftop related practices, due to lower installation costs, would have higher maintenance cost percentages than their larger 'parent' practices. Although this distinction does have an effect on a whole life cost of these BMP categories, it should not affect relative BMP comparisons as required by this study since rooftop practices are compared only against competing rooftop practices, and 'child' practices should follow the same comparative trend as the 'parents'. Permeable pavement maintenance costs are primarily related to sweeping or vacuuming the surface several times per year. This, like green roofs, results in a low expected O&M cost relative to installation cost. Evaluation for relatively small scale permeable pavement applications results in approximately a 1% O&M cost for use in the selection algorithm. Using averages of cost ranges reported in Table 3.3, and data discussed above for those practices not considered in Table 3.3, a consolidated list of proposed maintenance cost percentages (of initial construction cost) was generated (Table 3.4).

Table 3.4. Maintenance cost as a percentage of construction cost

BMP Type	Percentage of Construction Cost
Vegetated Roof	1.0%
Rooftop Disconnect (RD)	11.0%
RD to Dry Well	3.8%
RD to Rain Garden	8.5%
RD to Stormwater Planter	8.5%
Bioretention	8.5%
Sand Filters (Surface)	6.1%
Infiltration	3.8%
Grass Swale	3.8%
Wet Swale	3.8%
Dry Swale	3.8%
Permeable Pavement	1.0%
Sheetflow (Filter Strips)	37.5%
Constructed Wetlands	5.9%
Wet Ponds	4.3%
Extended Detention	1.7%

A third maintenance cost alternative, not found in the literature, but considered by the authors for integration in the BMP selection algorithm, is the use of relative ranks for comparison of alternative solutions. For example, some BMP categories may have low (1) expected annual maintenance, while other types are expected to have high (5) expected annual maintenance. Unlike other methods, this would not produce an actual O&M cost for the candidate; however, since an actual cost estimate is not necessary for comparison of candidate BMP solutions, this is a viable method. Mathematically, this method is conceptually similar to the percentage of construction cost method, having a range of low to high, instead of 1% to 37.5% (Table 3.4) with the alternative method. Due to this similarity, this method was abandoned in favor of the method estimating O&M cost as a percentage of construction cost described above.

3.5 CONCLUSIONS AND RECOMMENDATIONS

After evaluation of stormwater BMP cost studies found in the literature, a method relating BMP treatment volume to initial construction cost was determined to be the best metric for use in an algorithm aimed at optimization of BMP selection in treatment trains. Treatment volume, as defined in this article, includes the WQV as computed with Equation 1 and any additional contributions arising as effluent from upstream BMPs. The methods outlined in this paper for construction of cost estimates using a unit cost data approach were applied to BMP types used in the Commonwealth of Virginia. Cost functions relating construction cost to treatment volume that resulted from these data points were shown to have a high linear correlation. Despite this high correlation of resulting functions, a sensitivity analysis was performed to verify the expected high degree of sensitivity of the cost function data to fluctuations in unit costs of BMP components. Use in a comparison algorithm limits the sensitivity to unit cost variation since absolute cost is not as important as relative cost between candidate solutions.

A review of O&M cost studies revealed several methods for computation of annual maintenance cost for stormwater BMPs. Of these methods, the method that reports O&M cost as a percentage of construction cost is the most prevalent. Summaries of maintenance cost ranges from various studies were collected and analyzed to determine an average percent maintenance cost for this study. Papers detailing these percent ranges contained little or no commentary regarding data used to establish the published ranges, therefore, the efficacy of the data is unknown. Several suspected outliers were omitted when computing average cost percentages for final values reported in this study.

Resulting functions listed in Table 3.2 are applicable to BMPs designed and installed in the Commonwealth of Virginia; however, the unit cost method for determining these functions can be applied universally. Further, if used for cost estimation, functions listed in Table 3.2 were specifically determined for the southwest Virginia region and should be adjusted for regional variation if used in other areas of the state. However, when using for comparison and selection between BMPs, which is the focus of this study, adjustment should not be necessary, since comparative and not absolute cost is the determining factor. Percent values of O&M costs (Table 3.4) should be applicable nationally, since data originally used to create ranges found in various studies was adjusted to provide a consistent cost basis.

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Chapter 4: Case Study: Integration of Optimization Software into the Engineering Design Process for Stormwater BMP Selection

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Status: This manuscript will be submitted for peer review and publication after completion of the dissertation defense.

4.1 ABSTRACT

Low impact development (LID) strategies are being increasingly employed to provide for a holistic treatment of stormwater runoff from developed sites. Designers are required to simultaneously consider pollutant load reductions, physical site constraints, and selection criteria, including cost when making selections. Due to the large number of constraints, selection priorities, and best management practice (BMP) configurations, designers frequently resort to choosing known solutions strategies that are excessive is reduction of pollutant loads and costlier than an optimal configuration. This manuscript describes development of a software model for optimal selection of stormwater treatment BMPs. A release version of the software is developed incorporating the Virginia Runoff Reduction Method (VRRM) in development of the objective function. Two case studies are developed and applied to a group of consulting engineers to determine the effect that use of the selection optimization tool has on the engineering design process. Results of the case study indicate that use of a selection optimization algorithm for stormwater BMP selection significantly alters the engineering design process by removing bias and allowing designers to spend more time evaluating solutions rather than attempting to meet regulatory objectives.

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4.2 INTRODUCTION

Increasing urbanization, and the resulting increase in impervious cover has led to a degradation in the quality of the Nation's waters (Dietz and Clausen, 2008). Impacts to surface waters include increased volume, pollutant loads, temperature, and potential decreases to base flow (Elliott and Trowsdale, 2007). Prior to enactment of the Clean Water Act (CWA, 1972) stormwater management focused primarily on flood and erosion control. Recently, with adoption of the CWA and its amendments, a paradigm shift has spurred state level regulations that address additional stormwater runoff components, including volume and quality. This development has resulted in less reliance on impounding/detention facilities and more on low impact development (LID) strategies distributed throughout a development site. LID strategies are employed with the goal of mimicking pre-development hydrologic response in post-development sites (USEPA, 2000). Techniques employed by such practices can include both non-structural strategies, such as disturbance minimization, and structural practices such as bioretention, permeable pavement, grass swales, etc. (Dietz, 2007; Battiata et al., 2010). Integration of these LID best management practices (BMPs) may have a higher implementation cost than regional basins; however, they can be more cost effective on a long term pollutant reduction and volume retention and abatement basis (Dietz, 2007; Montalto et al., 2007). Despite cost concerns, in order to meet pollutant reduction mandates for discharges to surface waters, most states have now published stormwater BMP manuals (NCDENR, 2007; MDE, 2009; West Virginia (WVDEP), 2012; VDEQ, 2013b; and others) that provide BMP types and specifications which promote the use of LID strategies similar to practices described by the United States Environmental Protection Agency (USEPA, 2000).

There has been increasing recognition that runoff volume reduction is necessary to effectively reach pollutant reduction goals (Battiata et al., 2010). Battiata describes a compliance strategy called the Runoff Reduction Method (RRM) (Hirschman et al., 2008) which uses a three-tiered approach for treatment that sequentially addresses reduction goals through 1) minimization measures, 2) runoff reduction measures, and, if necessary, 3) pollutant reduction measures. Since it is uncommon for development projects to reach goals solely through minimization strategies, engineers increasingly are tasked with providing designs and computations employing runoff and pollutant reduction strategies. Attempting to provide the necessary tools to aid design engineers in the compliance of both runoff and pollutant reduction through BMPs, the Center for Watershed Protection (CWP), in cooperation with the Virginia Department of Conservation and Recreation (VDCR) developed a Virginia RRM (VRRM) spreadsheet tool (VDEQ, 2016a) based on the RRM methods first introduced by Hirschman et al. (2008). Battiata et al. (2010) describe the RRM method as transferable to a wide array of state and local stormwater planning operations, with the Commonwealth of Virginia being one of the first states to employ this method.

Although LID strategies are becoming more common, engineers today are often using design tools that are not specifically tailored for tracking runoff reduction (Dietz, 2007) and nutrient removal. The need for new, more intelligent tools to aid engineers has become more pressing due to distributed BMP designs, often linked to form a sequence of BMPs in series called a 'treatment train' (Wong et al., 2006). Tracking pollutant and volume reductions through treatment train components requires the ability to evaluate partially treated effluent entering a downstream BMP from upstream BMP(s), in addition to untreated surface influent. This need was addressed in Virginia through distribution of the VRRM spreadsheets (VDEQ, 2016a), which were established to provide a tool that aids designers with application of the VRRM.

Though early tools have provided the ability to track pollutant and runoff reduction through treatment trains, they do not identify the optimal BMP configuration. Most tools, such as the VRRM spreadsheets, have simple interfaces that allow single configuration input and testing, but are not targeted at yielding the optimized solution. Engineers, increasingly, need a unified stormwater BMP selection tool that simultaneously considers siting constraints with user specified selection criteria, while allowing rapid iteration through all valid BMP configurations. The goal of this study is to create and implement a stormwater BMP selection tool that meets this need. To quantify the effect that this tool has on the engineering design process, two BMP selection case studies were presented to a group of stormwater design professionals in Virginia to provide a comparison of solutions using the selection optimization tool versus the VRRM spreadsheets (VDEQ, 2016a), as the control.

4.3 VRRM SPREADSHEET TOOL

The VRRM (VDEQ, 2016a) spreadsheets provide designers with a tool that allows computation of required nutrient (phosphorus) reductions, and methods for inputting and tracking pollutant loads and runoff reduction for single BMP or treatment train configurations.

Required phosphorus load reductions are computed for new or re-development projects based on user input of pre-development and post-development land cover and drainage area data, as applicable. ‘Drainage area tabs’ allow input and tracking of runoff reduction and phosphorus removal based on total mass removal according to methods outlined in Hirschman et al. (2008). Finally, the tool provides adjusted curve numbers, which Hirschman et al. (2008) describe as a means to approximate the hydrologic impact of the BMP to downstream runoff. While the tool is effective in providing support for design engineers for single BMP installations, applicability for designs employing treatment trains becomes more cumbersome since it is not intended to provide engineers with the ability to rapidly consider multiple BMP combinations.

The VRRM method and spreadsheets are limited in nature, and were designed as a compliance tool for computing and meeting required nutrient reductions on development sites. The method does not enable a full hydrologic analysis of the site for complying with required quantity control in the developed state. It also provides no direction related to the design of the selected BMPs, including required pretreatment measures, which must be performed by engineers using other guidance documents.

4.4 CANDIDATE BMPS USED IN VRRM

Battiata et al. (2010) describes BMP runoff reduction and pollutant removal practices that can be employed as part of the RRM. Battiata et al. further describes ranges of runoff reduction and pollutant removal values for each BMP, with the lower value in the range representing the median runoff/pollutant removal values based on a CWP literature review. These lower range values are assigned the designation ‘Level 1’ treatment devices by Battiata et al. (2010). Likewise, the upper value in the range is assigned the designation of ‘Level 2’ treatment device based on the 75th percentile value resulting from the statistical analysis of studies from the literature as analyzed by Battiata et al. (2010). Accounting for BMP treatment strategies that employ a Level 1 and Level 2 designation, as applicable, and those that have a single ‘level’, there are 37 unique non-proprietary BMP types that are currently employed as part of the VRRM computational methodology (Table 4.1).

Table 4.1. List of stormwater treatment BMPs allowed by Virginia State Code (9VAC25-870-65)

Stormwater Treatment BMPs with Levels 1 and 2	**Stormwater Treatment BMPs without Two Levels**
Vegetated Roof	Rooftop Disconnect – A/B Soils
Rooftop Disconnect – Dry Well	Rooftop Disconnect – C/D Soils
Rooftop Disconnect – Rain Garden	Rooftop Disconnect – Amended Soils
Permeable Pavement	Rooftop Disconnect – Rainwater Harvesting
Dry Swale	Rooftop Disconnect – Stormwater Planter
Bioretention	Grass Channel – A/B Soils
Infiltration	Grass Channel – C/D Soils
Wet Swale	Grass Channel – Amended Soils
Extended Detention	Sheetflow to Conservation Area – A/B Soils
Wet Swale	Sheetflow to Conservation Area – B/C Soils
Filtering Practice	Sheetflow to Vegetated Filter
Constructed Wetland	
Wet Pond	

4.5 DIFFICULTIES ENCOUNTERED IN OPTIMAL BMP SELECTION

Engineers evaluate alternatives and specify these non-proprietary and other proprietary BMPs, as necessary, to meet regulatory objectives. Often, site development projects require consideration of multiple outfalls and/or multiple BMPs distributed throughout a site at logical treatment locations in order to fully meet nutrient reduction goals. Addressing the large number of viable BMP combinations used to treat stormwater runoff can be a challenge for designers. As described by Hodges and Dymond (2016), consideration of just 10 unique BMP choices at each candidate BMP location can yield hundreds of thousands of unique BMP combinations across development projects. The large number of combinations of BMPs that are possible on many development sites makes manual iteration through even a small fraction of unique candidate solutions for selection optimization untenable for most design engineers.

In addition to the large number of unique solutions, further difficulties arise for designers due to additional selection and/or physical site constraints. When selecting the best BMP configuration, engineers must simultaneously consider physical site constraints, such as presence of high groundwater, bedrock, hotspot runoff, etc., while also meeting selection priorities, such as pollutant removal, runoff reduction, cost minimization or aesthetics. With an overwhelming numbers of choices, multiple competing criteria, and marginal tools to aid in selection, bias often creeps into the selection process. Jacob et al. (2007) describe how memory of past decisions can cause designers to choose solutions similar to past designs regardless of applicability current needs. Tools such as the VRRM spreadsheets (VDEQ, 2016a) only partially address the difficulty associated with compliance computations for design of distributed BMP networks. Although they do afford designers the ability to track volume and nutrient reduction through BMP networks for candidate solutions, they do not allow for rapid iteration through potentially thousands of viable solutions. The end result is that for complicated sites, to save time, designers often steer to non-optimized conservative solutions which meet regulatory load reduction objectives, but often provide excess pollutant removal at higher cost than the optimal solution. In order to eliminate this selection bias, a multiple criteria optimization algorithm is required to facilitate BMP selection in distributed stormwater networks based on objective evaluation of user ranked parameters, consideration of site constraints, and simultaneous analysis of required pollutant reduction goals.

4.6 MODEL DEVELOPMENT AND DESIGN

The optimization model was designed to operate as a standalone software tool with relatively low data input requirements and processor overhead. This more streamlined design was implemented in part to address an apparent disconnect between many software tools that are developed to fill a niche need and require extensive datasets and user input for operation. Typically, these systems are so data intensive that they cannot be considered for everyday use by most engineering consultants. This software’s interface is presented to the user as a simple tabbed interface, which allows rapid guided navigation by the user when developing solutions for computing and meeting required phosphorus load reduction goals.

Treatment train input is similar to that found in many other hydrologic software products (USACE, 2015) and generally implements the node and link graphical model, which allows the user to add and link BMPs in a treatment train configuration, as required (Figure 4.1).

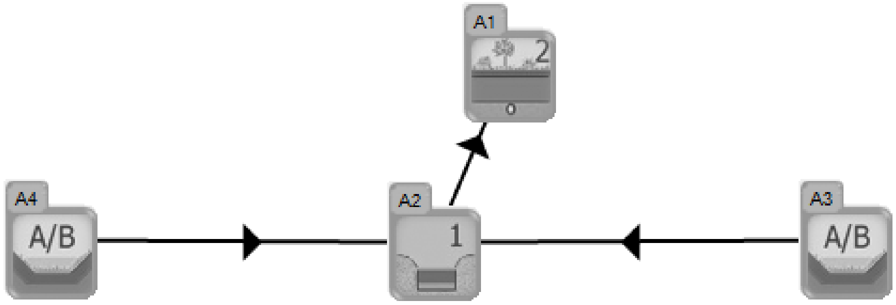

Figure 4.1. Example of node and link input model integrated as part of BMP layout functionality of tool.

The software can be operated in 'manual mode' which allows manual iteration of solutions, similar to VRRM spreadsheets (DEQ 2016a). However, if the user desires optimization, automatic iteration can be used to rapidly iterate through potentially millions of solutions after the user has defined the contributing drainage area (CDA) connectivity and land cover data for candidate BMP locations.

4.6.1 Definition of Site Constraints

Physical site constraints that exist at single, or multiple, candidate BMP locations can be defined by the user. These constraints, in general, follow recommendations found in the Virginia DEQ Stormwater Design Specifications (VDEQ, 2013b). Constraints available include:

1. **Karst Terrain** – The presence of karst terrain, which can be prevalent in the western region of Virginia, typically indicates that BMPs which promote rapid infiltration should not be used due to the risk of sinkhole formation or the potential of introduction of surface pollutants into the groundwater table.
2. **High Groundwater** – High groundwater contraindicates the choice of some BMP types (or levels) relying on infiltration as a major treatment component. However, other practices such as wet swales and constructed wetlands are designed to integrate a high groundwater table for efficient operation.
3. **Limited or no Infiltrative Capacity** – Areas with hydrologic soil group (HSG) B, C, and D soils, or areas that have been excessively compacted or have shallow bedrock, may not allow sufficient infiltration for proper operation of some BMP types, or levels.

4. **CDA Subject to Hotspot Runoff** – Hotspot areas are those that exhibit higher than normal concentrations of surface pollutants. Areas that are subject to hotspot runoff, typically have parking or high traffic areas as part of the CDA which indicates the presence of hydrocarbons or toxic metals in surface runoff. BMPs that promote rapid infiltration or integrate a high water table are contraindicated in these areas.
5. **Coastal Plain** – Several BMPs are not recommended for use in the coastal plain area due to the presence of high groundwater. Modifications to other BMPs, such as wet ponds, are required when they are designed and implemented in these areas.

4.6.2 Elimination of BMPs Prior to Optimization

To reduce computational time during the optimization process, BMPs that cannot be used due to physical site constraints, or other connectivity issues should be eliminated. These strategies are not unique to this tool, and in fact form the basis of several other publications or software tools that aid in the selection of BMPs. Maryland (MDE, 2009) provides matrices to aid in BMP selection, but provides little guidance in computation of load reductions through treatment trains. Selection tools addressing BMP selection include the Colorado Urban Drainage and Flood Control District UD-BMP (UDFCD, 2010), Ohio DOT BMP selection tool (ORIL, 2015), the White River Alliance (WRA) BMP Selection Tool (WRA, 2016), BMPSELECT (Pomeroy and Rowney, 2013) and several others. Most of these tools are simple web-based or spreadsheet based tools that allow the user to indicate if various site features and/or constraints are present on the project site. From this user input, many BMPs are eliminated from consideration, leaving the user with a candidate list of BMPs that may be suitable for the project. At this point, it is the designer's responsibility to use 'best judgement' in selecting the appropriate BMP for the site from the remaining list. Although these programs are useful in eliminating candidates that do not meet project constraints, the programs do not rank the list of candidate BMPs based on additional user input and cannot deal with large numbers of candidate BMP combinations expected in treatment train configurations; therefore, the danger of bias in selecting BMPs when using these tools still remains.

Depending on the number of outfalls and BMPs, elimination of a single BMP choice could eliminate hundreds to thousands of candidate combinations. Hodges and Dymond (2016) discuss several weeding techniques that have been implemented in the development of the optimization algorithm. The first elimination pass is based on definition of physical site constraints, as discussed in the preceding section. Other strategies have been employed for subsequent weeding passes that follow logic rules as indicated in BMP design specifications by VDEQ (2013b). An example of some of the rules applied are listed in Table 4.2. Once elimination strategies have been exhausted, the remaining candidate configuration list is passed to the software optimization engine.

Table 4.2. Sample of logic rules used for elimination that are dependent on candidate treatment train linkage configuration

Rule used for Elimination
Sheetflow to Conservation Areas or Vegetated Filters should be the most downstream control in a candidate treatment train
Vegetated Roof (all levels) and Permeable Pavement Level 2 must be the first (most upstream) control in a treatment train—note that Permeable Pavement Level 1 is not listed because Vegetated Roof is allowed to discharge into a Level 1 (but not Level 2) configuration
Vegetated Roof (all levels) is the **only** BMP allowed to flow into Permeable Pavement Level 1
Vegetated Roof (all levels) is the **only** BMP allowed to flow into any of the other Rooftop related BMP practices
Rooftop practices cannot flow into other rooftop practices (with the exception of Vegetated Roof listed above)
Pond Class BMPs should be the terminal (most downstream) BMP in a train (e.g. Wet Ponds [all], Extended Detention [all], and Constructed Wetlands [all])

4.6.3 Optimization Engine

Several algorithms were considered for integration in the model based on review of past studies that have applied algorithms to stormwater related optimization efforts. These include genetic algorithms (Perez-Pedini et al., 2005; Behera and Teegavarapu, 2015; USEPA, 2009), the analytic hierarchy process (AHP) (Saaty, 1980; Young et al., 2009a; Young et al., 2009b; Javanbarg et al., 2012; Jato-Espino et al., 2014), and exhaustive search (brute force) approaches. Acceptance of the selected algorithm by the engineering design community is paramount, and should meet several requirements as described by Hodges and Dymond (2016). These include the ability to produce the optimal solution, be understandable by users, require low to moderate run-times, and provide repeatable solutions.

Despite previous use on many stormwater optimization problems, genetic algorithms do not necessarily achieve the optimal solution, and can be difficult to implement for discrete non-continuous optimization problem. In addition, genetic algorithms are not guaranteed to yield the same solution during alternate runs due to the randomness associated with 'mutation' which is integrated in the solution. The AHP has been used by Young et al. (2009a) for a decision support tool related to BMP selection; however, the AHP requires the generation of static matrices for evaluation which would be dependent on each trial configuration of BMP solutions. This requirement adds an additional step to the computational procedure beyond what is required by the exhaustive search method, which would only act to reduce optimization speed. Exhaustive search (ES) can be easily understood since at its essence, all possible solutions are attempted through iteration, with the optimal candidate being selected from the final solution set. After evaluating the ability of each of the algorithms to meet the four criteria listed above, Hodges and Dymond (2016) concluded that an exhaustive search algorithm was the best choice for meeting selection objectives.

Optimization is defined as the maximization or minimization of a model's objective function. The objective function for this study is based on maximization of a solution score which has five major components. These selection criteria include minimization of excess nutrient removal, minimization of installation cost, minimization of maintenance cost, maximization of runoff reduction, and maximization of aesthetic benefit (if any). The nutrient removal and runoff reduction functions used in model development is based on the VRRM; although, development of an objective function derived from other standards can be developed and applied. Full descriptions of the nutrient removal, runoff reduction, and aesthetics functions are found in Hodges and Dymond (2016), while a complete discussion of the installation and maintenance cost functions are found in Hodges et al. (2016). Solutions are optimized based on user weights applied to each of the selection criteria listed above, in addition to physical site constraints and CDA descriptive parameters.

Prioritization is based on a zero (0) to ten (10) scale, with a value of zero giving no weight to the associated parameter, while a value of ten, conversely, yields the highest weight. Prior to optimization, the user can modify these values, as desired, including setting parameter weights to equivalent values. Final solution scores and configuration ranking are directly dependent on this user weighting.

4.7 CASE STUDIES

The release version of the selection optimization tool was applied to two case studies at a site scale to determine its impact on BMP selection by design engineers. A group of land development/water resources engineers with at least one year of design experience were recruited from various consulting firms in throughout Virginia and asked to volunteer for a design charrette where approximately one half of the participants were to select BMP configurations using the VRRM spreadsheets (VDEQ, 2016a) as a control group, with the remaining participants using the selection optimization tool described in this study. In total, eleven volunteers responded to the request, with six being assigned to develop solutions through use of the new software tool, and five assigned to generate solutions using the VRRM spreadsheets (VDEQ, 2016a).

4.7.1 Case Study 1

The first case study was based on development of a 0.66 hectare (1.64 acre) commercial site at an undisclosed location in the Commonwealth of Virginia. Participants were provided with a problem statement that outlined the hydrologic soil group (HSG) and land cover data for both pre and post-development conditions. The post-development scenario was broken into separate CDAs to provide logical candidate locations for stormwater BMPs (Figure 4.2). Land cover summaries for CDAs draining to each candidate BMP location are summarized in Table 4.3. Participants were further instructed that BMP B2 can drain to the location of BMP B1 as part of a treatment train, or may also discharge directly to the receiving underground detention system. Ultimately this decision in configuration was up to the participants and one of the variables in the experiment. Each group was instructed that due to the presence of rock outcroppings, karst conditions may be present in area P1. Additionally, the use of proprietary treatment devices was prohibited by either group.

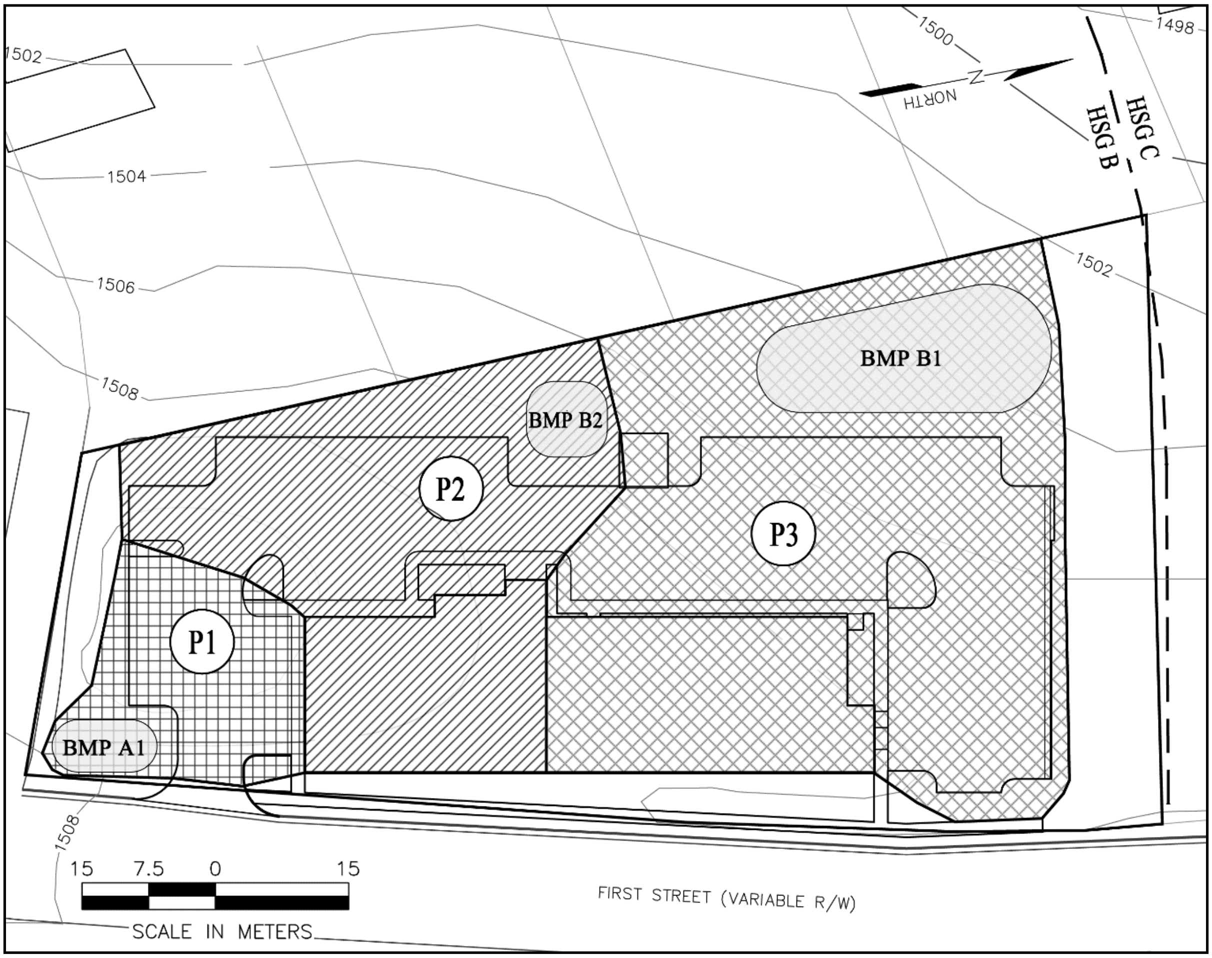

Figure 4.2. Post-development CDAs to candidate BMP locations for Case Study 1.

Table 4.3. Land cover for post-development CDAs to candidate BMPs, Case Study 1.

Area Designation	Turf Cover (hectares)	Impervious Cover (hectares)	Hydrologic Soil Group
P1	0.02	0.04	B
P2	0.05	0.13	B
P3	0.11	0.19	B
Uncaptured	0.11	0.02	B
Site Totals	**0.29**	**0.38**	

Participants in the control and test group were physically divided into separate testing areas and each group was given approximately 20 minutes to complete a solution. For this problem, each group was required to compute and meet regulatory requirements by choosing appropriate BMPs for each location, as required. Note that valid solutions could include having no BMPs installed at one or more of the candidate BMP locations.

At the cessation of the allowed work time, participants in each group were given identical questionnaires related to their solution for case study 1 (CS1). The questionnaire was designed to have close-ended questions (multiple choice with check boxes), with several following the Likert scale format. Use of close-ended questions facilitates statistical analysis of data within and between groups. Questions were designed to provide data from several general categories:

- Stormwater design experience level of participating engineers
- Perceived usability of the tool (spreadsheet or optimization software)
- Perceived constraint consideration when solving the problem
- Time used for meeting compliance vs. consideration of multiple valid solution alternatives
- Number of valid solutions considered
- Effect that the tool has on the perceived ability of the engineer to provide the best services to clients

4.7.1.1 Case Study 1 Survey Results

CS1 was specifically designed to limit the number of viable candidate solutions, with the aim of minimizing deviation in the time or difficulty in achieving compliance by either group. Although candidate BMPs (out of the 37 possible non-proprietary choices) employed by participants is not fully known, likely candidate BMPs for consideration at each location due to the size of the CDAs and land cover are Levels 1 and 2 of bioretention, dry swales, sand filters, infiltration, or no BMP. If these choices were used by participants, the number of unique combinations available for solution with or without treatment trains is 9^3, or 729 configurations. Execution of the BMP optimization selection tool using this assumed BMP candidate set indicates that of these 729 candidate configurations, with the application of a karst constraint in area P1 and other elimination strategies, that only 28 solutions are viable for the treatment train solution, while 8 solutions are viable for the no train solution. For purposes of this analysis (CS1), a solution is considered viable if it meets or exceeds the required phosphorus reduction goal for the site (1.87 kg/ha/year).

4.7.1.1.1 Case Study 1 Qualitative Results

All participants obtained solutions that achieved compliance goals; however, there were prominent differences between the two groups with regards to how the allotted time was used in achieving solutions. Generally, the spreadsheet group initially implemented BMPs with known high phosphorus reduction capabilities and then tested other viable candidates with lower phosphorus removal efficiencies to obtain, first, a valid solution, and then a more site specific solution, as time allowed. The software optimization group, instead, entered all viable CDA land cover data and viewed the optimized solutions, spending more time on testing the treatment train/no treatment train scenarios, or adjusting optimization ranks to determine differences in optimization solutions when runoff reduction, nutrient removal, or cost parameters were given higher weight. Although the software optimization group had never used the software previously, the participants appeared to embrace the optimized results offered by the tool.

4.7.1.1.2 Case Study 1 Quantitative Results

Frequency analysis was performed on collected data from post solution questionnaires to determine the percentage of respondents that fell within each response category. Median values were also determined for each individual question to provide indication of central tendency. Based on responses, all participants had greater than 2 years of experience in stormwater site design, with the median value of both groups, as assessed both separately and combined, falling in the '5 – 10 year' range. Overall, the combined groups indicated that they had used the VRRM spreadsheets (DEQ, 2016a) on '10 – 20' projects; however, the software group had a median that fell within the '5 – 10' project range, while the control had slightly more experience, falling in the '10 – 20' project bin.

Participants were asked to assess the assigned tool's usability related to several general categories, including:

- Data entry
- Treatment train connectivity and visualization
- Consideration of site constraints
- Rapid iteration through additional treatment scenarios
- Tool's ability to reduce repetitive design tasks

Frequency analysis of consolidated usability data indicates that the optimization software solution was viewed much more favorably than the spreadsheet tool (Figure 4.3a). Of respondents, 72.9% indicated that they strongly agreed with the optimization software's ease of use, versus only 7.5% of the spreadsheet group.

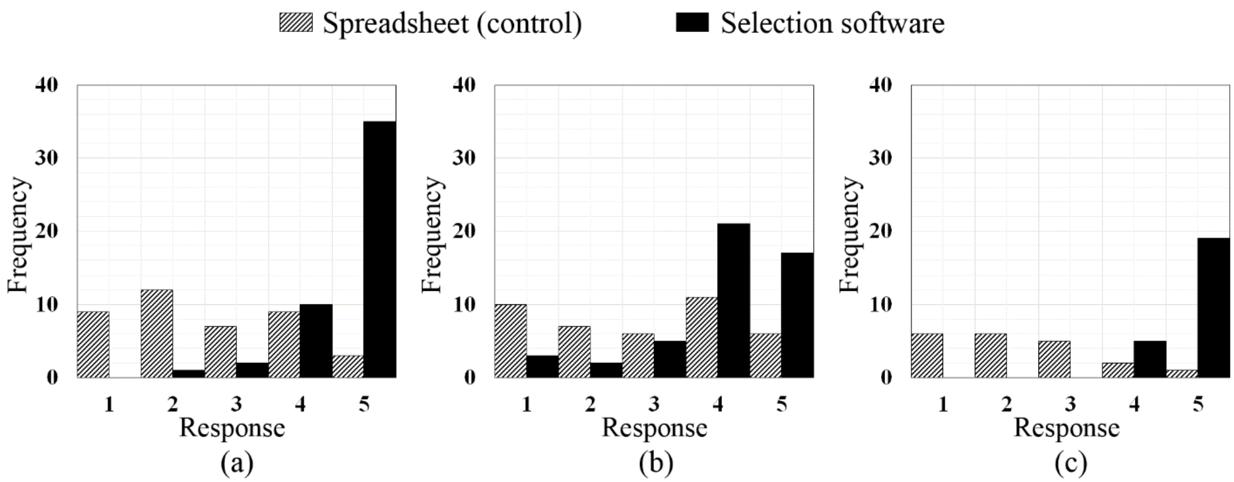

Figure 4.3. Frequency histograms indicating (a) usability (b) constraint consideration, and (c) perception of improved design capabilities for CS1. Bin values are based on a Likert scale with (1) strongly disagree, (2) somewhat agree, (3) neither agree or disagree, (4) somewhat agree, and (5) strongly agree.

Analysis of the constraint consideration category was performed to determine the relative comparisons between the spreadsheet and optimization software groups. Constraint consideration is not a built in function of the spreadsheet tool, and the median value of responses indicate that the control group was neutral (median value of 3) concerning consideration of physical site constraints, costs, runoff reduction volumes, and aesthetics. The median response of the software optimization group indicated that the group somewhat agreed that constraint consideration was part of their solutions. Consolidated results for this category are shown in Figure 4.3(b).

Comparisons of the median time spent on meeting phosphorus reduction goals were the same for both groups, at '< 10 minutes'. However, the optimization software group indicated that more alternatives were considered ('2 – 5' solutions) in that same amount of time. The median value of solutions considered for the spreadsheet group was '< 2'. Based on the median of responses, the optimization software group also indicated that both maintenance and installation costs were considered as part of the solution, while the control group indicated that only installation cost was considered.

The final major evaluation category dealt with the effect that tool has on the designer's normal method of selection and evaluation. Questions in this set of data were meant to determine 1) if integration of intelligent selection algorithms could impact the way engineers assess BMPs for integration in site development and 2) if bias could be addressed by consideration of unexpected alternatives. Median values of consolidated responses for this set of questions was a 5 ('strongly agree') for the software optimization group, while median values for the control group was a 2 ('somewhat disagree'). A consolidated frequency analysis for this data group is presented in Figure 4.3(c).

Of particular note is that optimization software participants felt overwhelmingly that:

1. The software optimization tool affected the way they typically approached BMP design
2. The tool allowed more time to be spent on evaluation of results rather than on data input
3. The tool allowed them to consider alternatives that they would not have otherwise considered
4. The tool would enhance their effectiveness in providing services to their clients

Items 1 and 3 in the above list indicate that the implementation of optimization algorithms can fundamentally change the engineering design process by allowing rapid generation and consideration of alternative optimal solutions. This shift in stormwater management design acts to remove bias by reducing time necessary to develop 'a solution'; instead, allocating time to evaluation of the optimal solution. Results from quantitative analysis of respondent answers were in line with the qualitative assessment by the authors, discussed previously, and indicates that use of the optimization tool significantly impacts the engineering design process.

4.7.2 Case Study 2

Case study 2 (CS2) is a more complicated design scenario building off of CS1, and expanding the development site to 3.91 hectares. This case study involves a mixed use development with commercial development on the eastern side of the site, and residential development (townhomes) to the west. Multiple candidate BMP locations were provided to participants, as well as information regarding potential treatment train connectivity between BMPs C2 to C1, D2 to D1, and E2 to E1 (Figure 4.4) and CDA land cover data (Table 4.4).

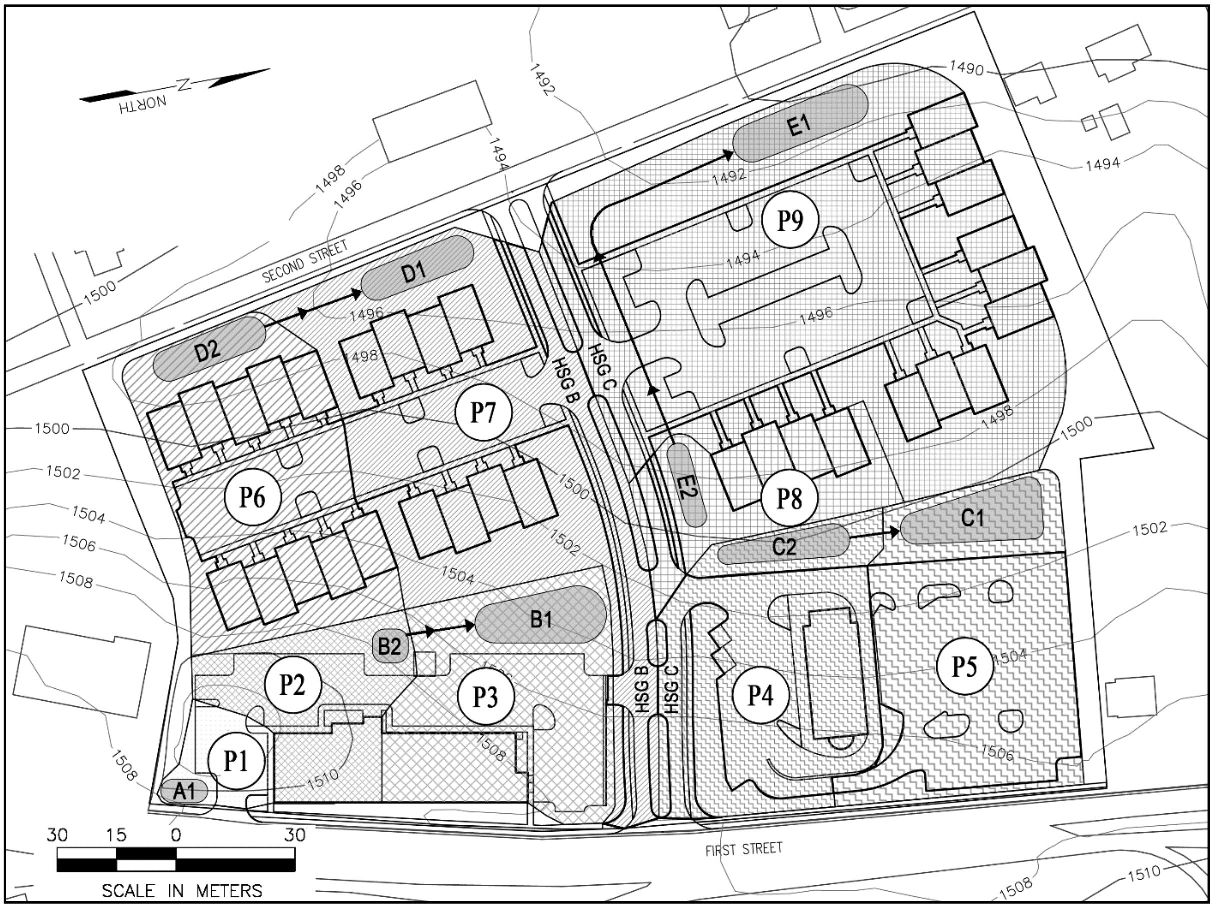

Figure 4.4. Post-development CDAs to candidate BMP locations for Case Study 2. Arrows indicate direction of flow if BMPs are linked in a treatment train configuration.

Table 4.4. Land cover for post-development CDAs to candidate BMPs, Case Study 2.

Area Designation	Turf Cover (hectares)	Impervious Cover (hectares)	Hydrologic Soil Group
P1	0.02	0.04	B
P2	0.05	0.13	B
P3	0.11	0.19	B
P4	0.12	0.25	C
P5	0.13	0.26	C
P6	0.24	0.15	B
P7	0.32	0.32	B
P8	0.1	0.08	C
P9	0.53	0.47	C
Uncaptured	0.13	0.01	B
Uncaptured	0.25	0.01	C
Site Totals	**2.00**	**1.91**	

Participants were instructed that BMPs A1, B2, and B1 from CS1 were already under construction and could not be modified as part of CS2; however, they were to be included as part of the solution in order to integrate any excess phosphorus removal from the CS1 configuration as part of the CS2 solution. As with CS1, participants in the control and test group were physically divided and each group was given approximately 40 minutes to complete a solution. Each group was required to once again compute required post-development phosphorus reduction and develop a solution using given supplied land cover data.

At the cessation of the design time, participants in each group were given questionnaires matching those supplied after CS1. Due to the complexity of CS2, it was expected that responses in several categories may be different that after completion of the simpler CS1.

4.7.2.1 Case Study 2 Survey Results

CS2 was designed provide a substantially larger number of viable candidate solutions than CS1. Again, although exact candidate BMPs considered by participants is unknown, likely candidates at each location due to the size of the CDAs and land cover are similar to those described for CS1. Based on the problem statement, BMPs A1, B1, and B2, as designed during CS1 would remain the same during all trial solutions of CS2. Due to this restriction, and assuming similar BMP choices were used as described for CS1, the total number of unique BMP configurations (if 8 BMPs and the no BMP option are assumed to be viable) is calculated as 9^6, or 531,441 combinations (Scenario 1).

Participants were given the latitude to aggregate some areas to limit the number of unique combinations of trial solutions. For instance, for areas P4 and P5, which flow to BMPs C1 and C2, respectively, participants could aggregate land cover data, eliminate a candidate BMP at location C1, and instead use a larger single BMP at location C2. If BMPs C1, D1, and E1 were all eliminated by employing this strategy, the total number of unique BMP combinations is reduced to 9^3, or 729 candidate configurations (Scenario 2).

The BMP optimization selection tool indicates that of the unique configurations available in Scenario 1, 10,003 solutions are viable. In Scenario 2, the number of viable solutions is dropped to 59 viable solutions. Differences between the number of viable configurations from Scenarios 1 and 2 illustrate the large effect that initial CDA assumptions made by the designer can have on the final solution set.

4.7.2.1.1 Case Study 2 Qualitative Results

As with CS1, all participants obtained solutions that achieved compliance goals, but again, there were prominent differences between the two groups with regards to how the allotted time was used in achieving solutions. It was even more apparent with CS2 that the tendency of the control group was to implement BMPs with known high phosphorus reduction capabilities to find a solution, and then refine the solution as time allowed. The software optimization group, as with CS1, entered all viable CDA land cover data and viewed the initial optimized solutions. The optimization software group appeared to spend more time determining if various optimization criteria affected their results, but in general appeared to quickly achieve a solution to the problem. For purposes of this analysis (CS2), a solution is considered viable if it meets or exceeds the required phosphorus reduction goal for the site (8.31 kg/ha/year).

4.7.2.1.2 Case Study 2 Quantitative Results

Frequency analysis consistent with that used in CS1 was performed on collected data from post solution questionnaires. Analysis of consolidated usability data again indicates that the optimization software solution is much more favorable than the spreadsheet tool (Figure 4.5). Of respondents, 81.3% indicated that they strongly agreed with the optimization software's ease of use, versus only 7.5% in the control group.

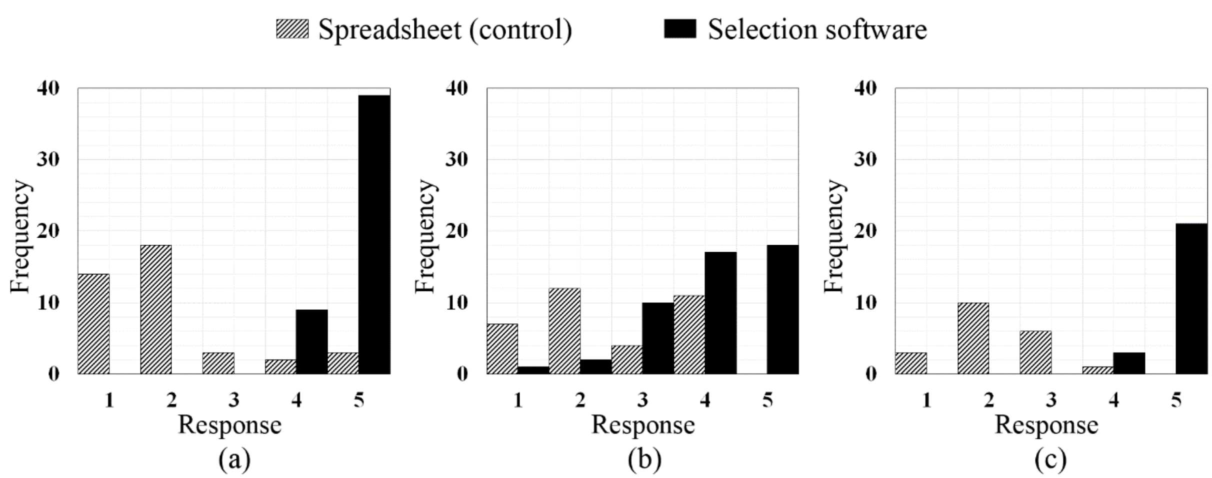

Figure 4.5. Frequency histograms indicating (a) usability (b) constraint consideration, and (c) perception of improved design capabilities for CS2. Bin values are based on a Likert scale with (1) strongly disagree, (2) somewhat agree, (3) neither agree or disagree, (4) somewhat agree, and (5) strongly agree.

There were minor differences in the results from the questions concerning constraint consideration in solutions between CS1 and CS2 [Figures 4.2(b) and 4.4(b)]. Although several control participants strongly agreed that various constraints were considered during CS1, none strongly agreed that any of the constraints were considered during CS2. This result may be due to the time required for control participants to obtain a valid nutrient removal solution. It is suspected from observation of the group that so much time was spent on achieving a valid solution, that little time was available for consideration of site constraints. Results for the software group were similar between CS2 and CS1; although, there were some marginal improvements in the 'strongly agree' category for the CS2 solution.

Comparisons of the median time spent on meeting phosphorus reduction goals was '10 - 20 minutes' for the control group, and "< 10 minutes" for the software group. Both groups indicated that a similar number of alternatives were considered. However, due to the ambiguity of the question, it is unknown if respondents believed this to mean full solutions, or modifications to BMP types at individual locations. The perceived ability of the tool used by each group to modify/improve the design process for engineers was similar to CS1. Median values of consolidated responses for this set of questions was, again, a 5 ('strongly agree') for the software optimization group, while median values for the control group was a 2 ('somewhat disagree') [Figure 4.2(c)].

4.7.3 General Results

In general, quantitative results from CS1 and CS2 are similar. This implies that complexity of design problem does not have a significant impact on comparison of the software tool to the control group. Based on this result, it is inferred that improvements to the engineering design process imparted through use of the software tool is scalable to designs of varying magnitude. Overwhelmingly, respondents utilizing the software optimization tool believed that use of the tool allowed consideration of alternatives that would not have otherwise been considered, enhanced their efficiency in design, and most strikingly, affected the way that they typically approach BMP design. Based on these case study results, it appears that the tool was successful in reducing bias in stormwater BMP selection. Although the sample size of volunteers for this study was not large enough to constitute a full representative sample for extension to the full population of design engineers in the Commonwealth of Virginia, it is believed that based on the consistency of responses that results are translatable to the larger population.

4.8 CONCLUSIONS

Based on the prevalence of distributed LID techniques in stormwater designs, it is imperative that tools are developed to assist designers in selecting the optimal BMP configuration that takes into account constraints and selection criteria in an unbiased manner. The goal of this study was to test an optimization algorithm that was developed by the authors through implementation of a proof of concept model based on the VRRM nutrient and runoff reduction tracking procedures that was evaluated by practicing engineers. Based on results of CS1 and CS2, it is apparent that development of such tools can boost efficiency and help to minimize bias from the BMP selection process. Although the model was well received by the participants, as related to the evaluation of CS1 and CS2, there is future work that needs to be performed to improve the functioning or expand the scope of the model.

For large sites with multiple outfalls and treatment train configurations, long run times may be required to achieve an optimal solution. As discussed in Hodges and Dymond (2016), based on Virginia Stormwater Management Permit (VSMP) data (VDEQ, 2016b), most projects requiring water quality improvements are expected to have a relatively small number of outfalls and treatment train components. However, for those that fall outside the range, run times can be excessive, which complicates use by designers. One solution to combat excessive run times is application of an intra-outfall optimization where a percentage of the overall load removal for the site is distributed across outfalls based on the weighted percentage of generated post-development load in each. Although this method would significantly decrease run times for generation of results, it is unlikely to produce the optimal configuration of BMPs across outfalls. This trade off, however, may be acceptable to designers due to time constraints and the large number of combinatorial solutions.

This study has applied the VRRM with the regulatory runoff reduction and phosphorus removal efficiencies as determined and published by DEQ (2013b). In addition, event mean concentrations (EMCs), 90th percentile rainfalls, and all other data used by the method to generate pollutant loads to BMPs are based on the regulatory standards in Virginia. It is expected that these values and methods will vary over time as researchers continue to improve the science related to surface water treatment through BMP practices. As these improvements occur, adjustments will need to be made to the objective function which drives selection optimization. While the objective function and elimination strategies in this study are based on current regulations in the Commonwealth of Virginia, similar techniques can be applied based on regulatory standards in other states.

The accepted removal efficiencies used by the VRRM are based on statistical analysis of relatively few studies (Batiatta et al., 2010), by inconsistent methods, and with different construction standards for many of the practices than those adopted by the Commonwealth of Virginia. Extensive future work needs to be performed in a controlled manner to determine both initial and long term operational efficiencies of these BMPs in order to refine selection. This work should also include a determination of associated irreducible concentrations of pollutants which make installation of downstream BMPs ineffective in removing additional pollutant load from partially treated effluent (Schueler, 2000). Currently the methodology presented as the RRM (Batiatta et al., 2010) does not account for irreducible concentrations after partial treatment; although Hirschman et al. (2008) do discuss this phenomenon. If an accepted standard based on a controlled experiment is defined as irreducible incoming EMC concentration, the algorithm can be adjusted to make associated treatment recommendations to the user.

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Chapter 5: Conclusions

Chapter 2 – 4 of this dissertation provide insight on the development of a multi-objective selection optimization algorithm for optimal selection of stormwater BMPs. Following is a summary of the major findings of each chapter and a discussion of the engineering significance imparted by application of the methods described herein. Finally, the need and possible direction of future research is discussed.

5.1 OBJECTIVES AND RESULTS

Additional information regarding assessment of the final completion of tasks or results related to the objectives outlined in Chapter 1 are found below.

5.1.1 Selection of Optimization Algorithm

Chapter 2 outlines the development of an objective function aimed at the selection of optimal BMPs in distributed networks. The function specifically mentions use of the VRRM (Hirschman, 2008) method, but the strategy suggested would be applicable for other nutrient and runoff reduction strategies, including the consideration of infiltration rates at each BMP location. Results of a review of the literature indicated three primary algorithmic types that either have been used historically, or were considered viable based on four stated algorithm selection criteria. These were 1) genetic algorithms (Perez-Pedini et al., 2005; Behera and Teegavarapu, 2015; USEPA, 2009), 2) the AHP (Saaty, 1980; Young et al., 2009a; Young et al., 2009b; Javanbarg et al., 2012; Jato-Espino et al., 2014), and 3) exhaustive search algorithms. Consideration of characteristics of each resulted in selection of an exhaustive search algorithm for continued development and application in this study. This result was due to the properties of this particular algorithm, in that it is 1) easily understandable, 2) finds ***the*** optimal solution, 3) is repeatable, and 4) has relatively low run-times for the expected solution size.

5.1.2 Analysis of Data in International BMP Database

The most recent version of the International Stormwater BMP Database [ISBMPD] was evaluated to determine if removal efficiencies, cost, or other unknown data records were suitable for statistical analysis and inclusion in the study. Performance summaries have been published based on the ISBMPD (2014a) data for various pollutants (ISBMPD, 2014b). Application of the objective function defined in Chapter 2 focused on total phosphorus as the targeted pollutant, which is the pollutant/nutrient on which load based reductions are computed in the Commonwealth of Virginia. Since case studies in Chapter 4 were to be targeted at stormwater professionals practicing in the Commonwealth of Virginia, ultimately the decision was made not to consider modification of regulatory removal efficiencies, and instead integrate those adopted by the Commonwealth of Virginia. However, these efficiencies have been integrated in the software in such a way that modification of the assigned efficiency per BMP category can be modified, if required, by the user. Hirschman et al. (2008) admitted that many of the efficiencies recommended for use with the RRM were best guesses by the author due to the relative scarcity of available data, and would change once better data is available.

Cost data included in the study was discussed in Chapter 3. As described, though 145 data records in ISBMPD do contain cost data, the data is presented in an inconsistent format, with insufficient supporting data or sample sizes per BMP category to consider statistical analysis and inclusion for creation of construction cost functions in this study. In addition, no data was found related to operation and maintenance cost, as discussed in Chapter 3.

5.1.3 Selection of Cost Integration Procedure

Chapter 3 outlines the selection of a cost integration procedure. A review of the literature indicated that regional fluctuations in cost can best be captured if construction costs are based on local engineering cost opinions (WERF, 2005). In addition, a literature review was conducted to determine the best parameter to use as a comparison variable against construction cost. After consideration, the variable chosen for implementation by this study is water quality treatment volume. In order to determine regressed functions of cost versus water quality treatment volume for each BMP type, a procedure for rapidly generating thousands of simulated BMP designs and cost opinions for a range of BMP CDA impervious cover and size was implemented. Resulting plots were regressed using linear functions relating initial construction cost to water quality treatment volume for inclusion in the software tool (Chapter 4). Although the resulting functions are specific to southwest Virginia, the tool selects BMPs by considering relative costs between BMP configurations. It is expected that use of the selection tool in other geographic areas, such as northern Virginia, or the eastern seaboard, with a higher cost of living would result in increased construction costs across all BMP categories. If this is the case, relative comparisons without modification of functions are valid. If instead, there are incremental increases across only some BMP categories or component parts, new engineering cost opinions for those geographic areas should be generated and updated in the selection vectors for each BMP category.

A literature review of methods for estimated operating and maintenance (O&M) cost is fully discussed in Chapter 3. After consideration of several methods of computation, the method chosen for inclusion in this study is based on estimation of O&M costs is as a percentage of initial construction cost. Values found in the literature were compiled and averaged, with several new categories for BMPs not found elsewhere in the literature generated from sources of data discussed in Chapter 3. As with construction cost, the user can update values in the BMP selection vectors, as necessary, to account for fluctuations in costs over time. Software test groups indicated that these methods of cost function development and integration were understandable and suitable for integration into the tool.

5.1.4 Creation of Selection Vectors for Candidate BMPs

Selection vectors for candidate BMPs were created for each BMP type using parameters taken from or extrapolated from VDEQ (2013b), as discussed in Chapter 1. In addition to parameters related to removal efficiencies, applicability of BMPs based on constraints, and applicability of BMPs based on characteristics of the contributing drainage area (CDA), values related to aesthetic appeal and cost functions were also added to each vector. The implementation of parameters in vectors allows modification by the user to account for 1) variability in requirements across jurisdictions, 2) variability in application of subjective criteria between consultants or localities, and 3) modification of constraint criteria or regulatory efficiencies over time. Implementation of the vector based approach allows for rapid integration of new future BMP categories. For instance, integration of new proprietary BMPs, as they are approved, or addition of new sub-classifications of existing non-proprietary types, can be implemented as additional vectors in the tool's BMP selection decision matrix. Software test groups indicated that the ability to modify the functioning of the selection and optimization engine by the end user, as necessary, is a desirable quality of the software.

5.1.5 Creation of Software Tool for BMP Selection/Optimization

A software tool based on the algorithmic selection discussed in Chapter 2 and the development of cost functions discussed in Chapter 3 was created, tested, refined, and implemented as part of the case studies in Chapter 4. The software tool was based on the runoff reduction method (RRM) as outlined by Hirschman et al. (2008) and Batiatta et al. (2010). The tool incorporates selection vectors discussed in 5.1.4. Programming was performed in VB.net with Microsoft Visual Studio 2010. Additional functions not directly related to the stormwater BMP selection discussed in this dissertation were added to support stormwater designers in the Commonwealth of Virginia including 1) built in mapping functionality to locate the longitude and latitude of the project site, 2) built in shape files incorporating the 6^{th} order HUCs for the Commonwealth (VDCR, 2015), and 3) built in raster grids to allow integration of NOAA 24-hour rainfall depths for the 1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events (NOAA, 2016).

The software tool was compared against the VRRM Spreadsheets (VDEQ, 2016) to verify consistent results between both tools. Due to the graphical input of treatment trains using the node and link system discussed in Chapter 4, configurations not possible in the VRRM Spreadsheets (DEQ, 2016) can be designed with the developed tool; therefore, some test configurations implemented by the software tool could not be verified in the spreadsheet. However, in all cases where replication is possible, the software tool matches those solutions found via direct input into the VRRM spreadsheets (VDEQ, 2016).

5.1.6 Incorporation of Testing Comments from Peer Review of Software

Testing of the software took place in 3 phases. First, the software interface was presented to a group consisting of Virginia Department of Transportation (VDOT) hydraulic engineers, Virginia Department of Environmental Quality (VDEQ) staff, and various expert consultants in the field in a teleconference on September 29, 2015. Results from that meeting were integrated in the graphical user interface (GUI) of the software tool and presented to a group of VDOT hydraulic engineers on October 21, 2015 for further comment. Once all interface refinements were integrated in the GUI, functions related to the VRRM computations, as well as initial versions of the selection vectors (5.1.4) and optimization engine were integrated into the software for alpha testing by a group of VDOT hydraulic engineers for the period of December 10, 2015 – December 31, 2015. Note that at this stage final cost functions had not been developed for integration in the software tool.

The tool was further refined in early 2016 based on comments received during alpha testing. A beta version of the software was prepared for deployment and testing, then presented and distributed to a VDOT test group on March 4, 2016. The beta software was subsequently distributed to a consultant test group on March 10, 2016 for additional testing involving a wider range of project types. Comments from beta testing were required to be completed by March 31,

2016. Refinements to the software from beta testing were integrated, with a final release version of the software tool compiled and presented for case study evaluation as discussed in Chapter 4, and 5.1.7, below.

5.1.7 Application of Software Integrated Optimization Algorithms to Case Studies for Evaluation

Application of the software to controlled case studies for evaluation against more conventional methods of BMP selection is discussed in detail in Chapter 4. During testing periods discussed in section 5.1.6, consultants and VDOT engineers subjected the software tool to a wide array of linear, new, and re-development projects across the Commonwealth. Although specifics of many of these evaluations are not known since they were not performed in a controlled environment, any applicable comments generated from these isolated case studies by individual testers were included in tool development. Based on review of comments from all case study testing, it appears that bias related to the selection of stormwater BMPs has been substantially decreased (see additional discussion in Chapter 4), in favor of objective selection.

5.2 ENGINEERING SIGNIFICANCE

Based on results of testing, it appears that integration of the tool has significant impacts on the BMP selection process by improving design time efficiency, allowing selection of the most cost effective (short or long term) solutions, and through fundamental impacts to the engineering design process which acts to increase objectivity and decrease selection bias. As discussed throughout this document, optimal BMP selection requires an ability to consider multiple physical constraints, properties of the CDA, and selection criteria simultaneously, across potentially thousands of candidate BMP configurations. Due to the inability to effectively meet all of these competing objectives with today's tools, engineers often resort to selection of BMPs with which they are familiar and that they know will meet regulatory requirements. This selection bias can often result in choosing sub-optimal solutions with larger footprints or increased installation and/or operating and maintenance costs. While some consultants have created procedures to improve their selections, the sheer number of iterations renders the goal of finding the optimal solution untenable by manual calculations.

The tool described herein is significant, first due to targeting development at a site scale. Several studies have been discussed in Chapters 2 and 4 aimed at BMP optimization on a regional scale for watershed planning. Other tools, as discussed in Chapters 2 and 4 have been aimed at BMP selection by elimination of candidates based on physical constraints. The algorithm described in this dissertation has been developed to specifically address issues related to selection bias in BMP selection and provide a means to provide multi-objective selection optimization at a site scale. The impacts to consultancy, based on perceptions of the case study group from Chapter 4, includes increased efficiency in design times, achieving optimal cost effective solutions for clients, and consideration of solutions that would not have been considered without employment of the tool. Also, based on results discussed in Chapter 4, use of the tool imparts a significant shift in the use of design time by decreasing time used to input data for the purpose of meeting nutrient load reduction requirements, and increasing the time spent on consideration of the optimal or near-optimal solutions. Finally, the tool is effective in reducing inefficiencies in design caused by designers with less experience, which will decrease training time for new entrants into the field.

5.3 FUTURE RESEARCH

Design and implementation of distributed networked stormwater quality BMPs is still in its infancy, and has not yet become a mature science. Although the objectives that were outlined in the introduction have been achieved, there is still much research that needs to be performed. Potential future research related to this topic has been consolidated into several categories below.

5.3.1 Research Related to Selection Vectors

5.3.1.1 Removal Efficiencies

The standard value of the EMC associated with phosphorus concentrations for stormwater runoff on urban lands was 0.266 mg/L as first established by the Nationwide Urban Runoff Program (NURP) (USEPA, 1983), and later refined by Smullen et al. (1999) through statistical analysis of the NURP data and additional studies to be 0.26 mg/l, which has been adopted by the Commonwealth of Virginia. Removal efficiencies embedded in the selection optimization tool created as part of this dissertation are those accepted as the approved standards in the Commonwealth of Virginia, as reported by Hirschman et al. (2008) and later by Battiata et al. (2010). Due to the limited number of studies used by Hirshman et al. (2008) in developing these values, the authors of the studies admit that the values will change over time as new, better, information becomes available and that efficiencies presented are based on the authors best judgement. Extensive future research needs to be performed to determine actual removal efficiencies based on influent event mean concentrations (EMC) for both newly installed practices, and aged installations. This research needs to be performed with scientific rigor in order to provide consistent collection and cataloguing of data over time.

Smullen et al. (1999) also reported updated median EMC concentrations for a variety of other pollutants, including total suspended solids (TSS), total Kjeldhal nitrogen, copper, lead, and zinc. Future extensibility of the tool can include tracking and removal of other pollutants through treatment trains; however, ongoing future work needs to be performed to determine pollutant removal efficiencies of these additional pollutants prior to integration into the optimization tool. Additional controlled studies need to be performed for multiple BMP installations to enable statistical determination of removal efficiencies for each pollutant category as related to incoming EMC.

Results by Hathaway and Hunt (2010) support the idea that pollutant removal efficiencies are not static, but instead are related to incoming EMC. Current computational methods in most states follow the static removal method, now known to be incorrect. Future work needs to be performed to develop efficiency curves that predict removal rates based on incoming EMC.

5.3.1.1.1 Irreducible Concentrations

Based on past research, it has been proposed that as pollutant concentrations reach moderate to low levels through treatment, that the concentrations approach a level at which they cannot be reduced by further treatment. Hathaway and Hunt (2010) performed a study of wetland cells installed in series to determine the effect of irreducible concentrations for stormwater BMPs installed in treatment trains. Hathaway and Hunt (2010) concluded that installation of similar type BMPs in trains does not result in similar performance for each BMP node. Based on this conclusion, future research and modification of stage 3 of the RRM (removal by physical processes) is necessary to prevent the method from over-predicting total performance of the treatment train system.

5.3.1.2 Constraints

Several of the elimination strategies integrated in the tool deal with the size of the CDA, or the breakdown of land uses in the CDA. VDEQ (2013b) recommends upper and lower limits of CDA for many BMPs; however, due to the lack of consistent research performed on each type of BMP, it is unknown if these limits have merit. In addition, VDEQ (2013b) recommends additional limitations in using certain BMP types based on the presence of physical constraints such as karst terrain, non-infiltrative soils, shallow groundwater, and hotspot runoff. Research on integration of BMPs promoting groundwater recharge is required to improve adjustments to BMP design in areas with karst topography, non-infiltrative soils, and shallow groundwater. Physiography in the Commonwealth is not homogenous; however, the BMP design specifications mandated for use throughout the state are uniform. As the science matures, there may be other constraints that are found which have a bearing on the design and/or long term maintenance of these BMPs. If so, additional constraints can be added to the BMP selection vectors for incorporation into the optimization decision matrix.

5.3.1.3 Cost Functions

As described in Chapter 3, it is desirable to base cost functions from actual installation and maintenance cost data from a statistically valid sample size of installations for each type of BMP. Currently, sufficient data does not exist for implementation of these techniques; however, this is expected to change over time. As more data becomes available for both installation and O&M cost, the methodology defined by this dissertation using engineering cost opinions should be reevaluated. Unit costs for the methods outlined in this study and integrated into engineering cost opinions, will need to be updated frequently to maintain accurate relative cost functions between BMP types. Regardless of the dataset used for development functions, the independent variable used for linear regression should be water quality treatment volume, as discussed in Chapter 3.

5.3.2 Optimization Engine

5.3.2.1 Additional Improvements to Logic Rules to Reduce Candidates

Additional more complex logic rules should be investigated to determine if improvements can be made to operational speed. Although impacts to speed for small sites would be negligible, it is believed that additional logic implementation could result in significant speed improvements for larger sites.

5.3.2.2 Investigate Use of Multi-Threading to Increase Speed

Central processing units (CPUs) with multiple cores allow the ability for software to take advantage of the architecture by running multiple parallel computational threads is each core. This can have the advantage of significant boosts to speeds since the architecture is being used more efficiently. To use multithreading, iterative loop structures must be split into groups based on the number of desired threads, and are then evaluated separately, but in parallel. Integration of multi-threading would require replacement of the recursive functions currently driving the optimization engine; however, improvements to solution speeds on sites with larger numbers of BMP nodes and/or outfalls could be significant.

5.3.3 Extensibility of Software Tool

5.3.3.1 Channel and Flood Protection

Currently, the optimization algorithms are focused on the water quality aspects of stormwater management. However, the objective function discussed in Chapter 2, as shown, allows the integration of future selection criteria, which could include channel and/or flood protection rankings. The tool as presented to the case study group already integrates the adjusted curve number functionality as described in VDEQ (2013a). Additional future hydraulic functionality can be added to integrate ‘energy balance’ techniques (VDEQ, 2013a), or others, as applicable per jurisdictional requirements, to allow optimization to consider both water quality and quantity compliance.

5.3.3.2 Extensibility to other States/Jurisdictions

The selection optimization tool as described in Chapters 2-4 was created using the Commonwealth of Virginia’s VRRM as to test implementation of the technique. However, the methods described in Chapters 2-4 can be widely applied to other states through modifications of the requisite components of the objective function, the selection vectors, and the elimination logic criteria. Collins et al. (2009) report that Virginia currently integrates the RRM, Georgia is integrating a modified version for coastal areas of the state, and Maryland, Delaware, and the District of Columbia are working to integrate the concept of runoff reduction into new handbooks. The methods described in this dissertation can easily be modified to provide a BMP selection optimization tool for stormwater designers in other states similar to the tool used as a case study platform, described in Chapter 4.

5.4 REFERENCES

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APPENDIX A: Unit Costs for Development of Engineering Cost Opinions

Table A-1. Unit costs used for formulation of engineering cost opinions in Chapter 3.

Item	Units	Unit Cost
#57 Stone	CY	$38.00
#8 Stone	CY	$32.00
12" Inlet Piping	LF	$25.00
18" Outlet Piping	LF	$40.00
6" SCH 40 PVC	LF	$20.00
6" Underdrain	LF	$20.00
Bottom Sand Layer	CY	$170.00
Clay Liner	CY	$25.00
Compost Amendment	CY	$30.00
Drainage Membrane	SF	$1.00
Excavation	CY	$15.00
Excavation/Preparatory Grading	CY	$15.00
Filter Fabric (2 Layers)	SF	$0.50
Geotextile	SF	$2.00
Impermeable Membrane	SF	$1.50
Media (Bioretention)	CY	$140.00
Mulch	CY	$30.00
Overflow	EA	$2,500.00
Overflow Structure-Small	EA	$500.00
PAM 19.0	TON	$70.00
PAM 9.5	TON	$65.00
Planter Walls	SF-FACE	$15.00
Pre-Treatment Excavation	CY	$15.00
Pre-Treatment Seeding	SF	$0.10
Pre-Treatment Topsoil	CY	$20.00
Riser	EA	$5,000.00
Root Barrier	SF	$1.00
Sand	CY	$170.00
Seeding	AC	$3,500.00
Stone	CY	$38.00
Stone Cap	CY	$32.00
Surface Plantings	SY	$12.00
Topsoil	CY	$20.00
Wetlands Seeding	AC	$5,000.00
Pretreatment Diaphragm	CY	$38.00

APPENDIX B: Case Study 1 (used in Chapter 4)

Case Study 1 – Small Scale Commercial Development

As part of a conceptual design package, you have been tasked with developing a preliminary stormwater management plan for a development project located in Loddi, Virginia (fictional). The parcel area totals 1.64 acres and fronts on First Street. It is expected that any quantity control required to meet the erosion and channel protection discharge requirements will take place in an underground detention facility; therefore, the goal for this conceptual design is to meet stormwater quality compliance only, with additional quantity design being performed later, during the final design process. The developer is attempting to acquire additional adjacent acreage for an expanded Phase II, but has been unsuccessful in reaching agreements with the owners of neighboring parcels at this time.

Table B-1.SCS 24 Hour Rainfall Totals

	1 Year	2 Year	10 Year	100 Year
24 Hour Rainfall (in)	2.28	2.76	4.11	6.51

Existing Conditions

The site, totaling 1.64 acres (Figure B-1), is covered primarily with turf and a couple of sparse trees. Phase I is entirely underlain by HSG B soils. Access into the site will be from First Street to the east.

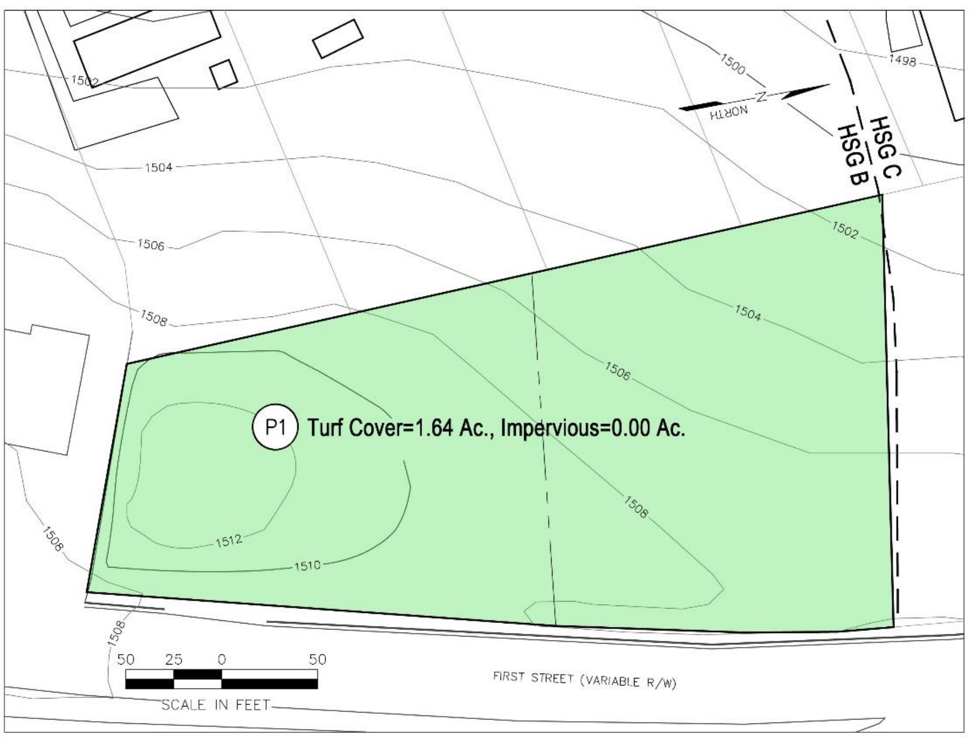

Figure B-1. CS-1 – Existing Conditions

Proposed Conditions

After discussions with the client, a conceptual layout has been created that meets programming requirements for a commercial office/retail building, and has left several candidate locations for stormwater BMPs (Figure B-2). Grades shown in Figure B-2 are existing grades, which give a rough idea of likely postdevelopment drainage patterns; however, proposed grading will not be generated until the concept stormwater plan is complete. You have been tasked with preparation of a concept stormwater management plan (quality only) that meets targeted phosphorus removal for this new development project. The location of BMP A1 discharges into a storm sewer structure running along First Street. BMP B2 can drain to the location of BMP B1 as part of a treatment train, or may discharge directly into an underground conveyance (or extended detention) system.

Although you are not designing the quantity control components at this time, relatively high weight should be placed on runoff reduction in selected BMPs in order to minimize the cost associated with underground storage. However, consideration should also be given to both installation and maintenance cost of the selected treatment strategy. For this exercise, no proprietary BMPs will be used as part of the management strategy.

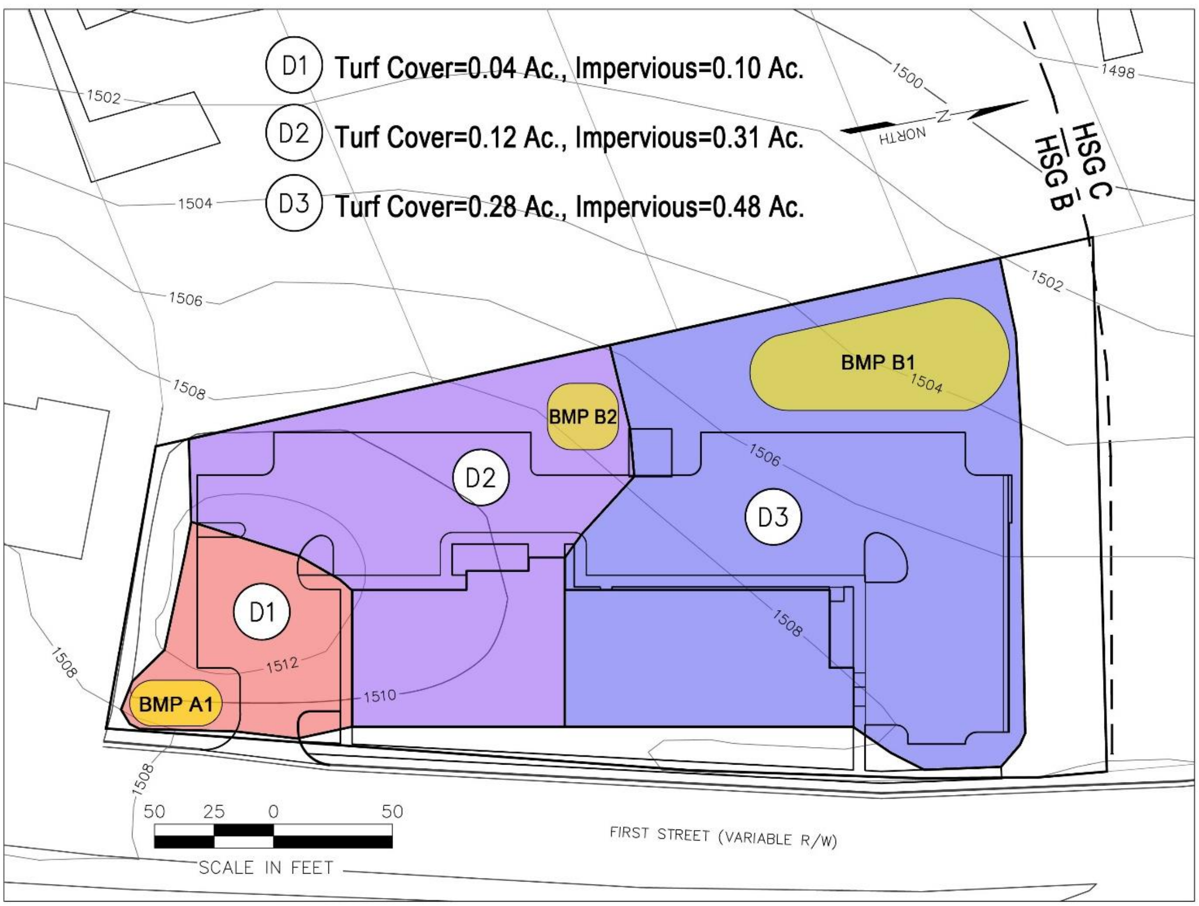

Figure B-2. CS-1 – Concept Layout with Potential BMP Locations

Table B-2. Overall Land Cover (including areas not flowing to BMPs) for CS-1 Proposed Conditions

Land Cover (acres)	B Soils
Managed Turf	0.71
Impervious Cover	0.93

Table B-3. Land Cover for CS-1 Proposed Conditions Flowing to Candidate BMP Locations

Area Designation	Turf Cover (acres)	Impervious Cover (acres)	Hydrologic Soil Group
D1	0.04	0.10	B
D2	0.12	0.31	B
D3	0.28	0.48	B
Totals	0.44	0.89	**(1.33 acres total)**

APPENDIX C: Case Study 2 (used in Chapter 4)

Case Study 2 – Phase II – Mixed Use Development

During construction of Phase I, the developer is finally successful in obtaining additional adjacent lots, and is ready to move forward with Phase II development. As part of the Phase II conceptual design package, you have been tasked with developing a preliminary stormwater management plan for the full build-out of the development, which will include the improvements you have already designed for Phase I. The locality is requiring a reanalysis of the entire site area (including Phase I) as a redevelopment scenario, assuming that existing conditions were those prior to the start of construction on Phase I. Site characteristics for the entire predevelopment parcel are shown in Figure C-1. It is assumed that virtually all of the 9.65 acres will be disturbed during construction.

Existing Conditions

As seen in Figure C-1, there are several existing dwellings to the west and one existing small commercial lot to the north that must be accounted for in the re-development stormwater quality calculations. There are no forested areas within the boundary of the site. Land coverage data for existing conditions is summarized in Table C-1.

Figure C-1. CS-2 – Existing Conditions (Prior to Phase I Construction)

Table C-1.Composite Land Cover for CS-2 Existing Conditions

Land Cover (acres)	B Soils	C Soils
Managed Turf	3.92	4.69
Impervious Cover	0.29	0.75

Proposed Conditions

After discussions with the client, a conceptual layout has been created that meets programming requirements, and has produced several candidate locations for stormwater BMPs (Figure C-2). Grades shown in Figure C-2 are existing grades, which are indicative of postdevelopment drainage patterns; however, proposed grading will not be generated until the concept stormwater plan is complete. You have been tasked with preparation of a concept stormwater management plan (quality only) that meets targeted phosphorus removal for this new development project. **Because construction has already begun on BMPs in Phase I, those BMPs (designed as part of Case Study 1) should not be modified as part of this expanded design**; however, those BMPs should be included in the overall quality analysis to take advantage of any extra phosphorus removal that may have been achieved as part of the Phase I design.

As seen in Figure C-2, there are several logical locations for proposed BMPs within the proposed development; however, it is not expected that BMPs will be required at all of these locations. As a designer, you will need to determine the most effective layout of BMPs at the candidate locations. You will not be performing a full analysis for quantity control requirements as part of this analysis; however, a high weight should be placed on runoff reduction in chosen BMPs. Assume that any additional quantity control required to reduce the 2-year storm to below predevelopment levels (the receiving storm sewer system is adequate to the 1% point) can be met through the design of an underground storage system that does not impact the candidate BMP locations.

For this exercise, **no proprietary BMPs should be used** as part of the management strategy. A summary of land cover data for the proposed conditions for the entire parcel is found in Table C-2, while data relating to areas flowing to proposed BMP locations as shown in Figure C-2 is found in Table C-3.

Figure C-2. CS-2 – Proposed Development Conditions with Preliminary Locations of Stormwater BMPs

Table C-2. Overall Land Cover (including areas not flowing to BMPs) for CS-2 Proposed Conditions

Land Cover (acres)	B Soils	C Soils
Managed Turf	2.13	2.79
Impervious Cover	2.08	2.65

Table C-3. Land Cover for CS-2 Proposed Conditions Flowing to Candidate BMP Locations

Area Designation	Turf Cover (acres)	Impervious Cover (acres)	Hydrologic Soil Group
D1	0.04	0.10	B
D2	0.12	0.31	B
D3	0.28	0.48	B
D4	0.30	0.62	C
D5	0.32	0.65	C
D6	0.59	0.37	B
D7	0.78	0.79	B
D8	0.25	0.19	C
D9	1.31	1.16	C
Totals	3.99	4.67	**(8.66 acres total)**

APPENDIX D: Case Study Sample Questionnaire

Participant Questionnaire (common questions for either tool)

1. **How many years of experience do you have performing stormwater computations related to land development projects?**
   - ☐ < 2 years
   - ☐ 2 – 4 years
   - ☐ 5 – 10 years
   - ☐ > 10 years

2. **Approximate the number of projects for which you have used the VRRM spreadsheets to determine water quality compliance?**
   - ☐ < 4
   - ☐ 5 - 10
   - ☐ 10 - 20
   - ☐ > 20

3. **Consider your use of the drainage area tab(s) on the tool you used today. Based on that experience rate your level of agreement with the following items:**

	1 Strongly Disagree	2 Somewhat Disagree	3 Neither Agree or Disagree	4 Somewhat Agree	5 Strongly Agree
Data entry is easy	☐	☐	☐	☐	☐
Adding treatment train connectivity is easy	☐	☐	☐	☐	☐
Tool allows visualization of treatment train connectivity	☐	☐	☐	☐	☐
Tool provides ability to take into account constraints at BMP location	☐	☐	☐	☐	☐
Changing entry to an alternate BMP is easy	☐	☐	☐	☐	☐
Iterating through multiple treatment train test solutions is easy and time efficient	☐	☐	☐	☐	☐

4. **Consider your analysis for the case study today. Based on your analysis, rate your level of agreement with whether or not you actively considered the following criteria during development of your final solution(s):**

	1 Strongly Disagree	2 Somewhat Disagree	3 Neither Agree or Disagree	4 Somewhat Agree	5 Strongly Agree
Consideration of contributing drainage area to BMP location	☐	☐	☐	☐	☐
Consideration of physical site constraints	☐	☐	☐	☐	☐
BMP installation cost	☐	☐	☐	☐	☐
BMP maintenance cost	☐	☐	☐	☐	☐
Consideration of total volume (runoff) reduction provided	☐	☐	☐	☐	☐
Consideration of aesthetics	☐	☐	☐	☐	☐

5. **What percentage of your time today did you spend on manipulating entries in the drainage area tab(s) to meet the phosphorus reduction goals?**
   ☐ < 10 minutes
   ☐ 10 – 20 minutes
   ☐ 21 – 30 minutes
   ☐ 31– 45 minutes
   ☐ > 45 minutes

6. **What percentage of your time today did you spend on evaluating results from solution alternatives?**
   ☐ < 10 minutes
   ☐ 10 – 20 minutes
   ☐ 21 – 30 minutes
   ☐ 31– 45 minutes
   ☐ > 45 minutes

7. **How many alternative solutions were considered?**
   ☐ < 2
   ☐ 2 - 5
   ☐ 6 - 10
   ☐ > 10

8. **When developing alternate solutions, which cost factors were considered?**
   - ☐ Installation cost
   - ☐ Maintenance cost
   - ☐ Both installation and maintenance cost
   - ☐ Cost was not considered

9. **Consider your use of the assigned tool (spreadsheets or VT software today). Indicate level of agreement with the following statements:**

	1 Strongly Disagree	2 Somewhat Disagree	3 Neither Agree or Disagree	4 Somewhat Agree	5 Strongly Agree
The assigned tool affected the way I typically approach BMP design	☐	☐	☐	☐	☐
The tool enhanced my efficiency in design by simplifying repetitive tasks	☐	☐	☐	☐	☐
The tool allows me to spend more time on evaluation of results rather than on input of data	☐	☐	☐	☐	☐
The tool allowed me to quickly consider siting constraints	☐	☐	☐	☐	☐
The tool allowed me to consider alternatives that I would not have otherwise considered	☐	☐	☐	☐	☐
The tool allows me to take cost into account when selecting the best alternatives	☐	☐	☐	☐	☐
The tool was easy to use	☐	☐	☐	☐	☐
The tool will enhance my effectiveness in providing services to my clients	☐	☐	☐	☐	☐
The tool is visually appealing	☐	☐	☐	☐	☐

APPENDIX E: Raw Data from Case Studies

Case Study 1

			Optimization Software Tool							
			1	**2**	**3**	**4**	**5**	**6**	**Avg.**	**Median**
Usability	3a	Data entry is easy	4	2	5	3	5	5	4.0	4.5
	3b	Adding treatment train connectivity is easy	5	4	5	4	5	5	4.7	5
	3c	Tool allows visualization of train connectivity	5	5	5	5	5	5	5.0	5
	3d	Tool provides ability to take into account constraints at BMP	4	5	5	4	5	5	4.7	5
	3e	Changing entry to an alternate BMP is easy	5	5	5	5	5	5	5.0	5
	3f	Iterating through multiple test solutions is time efficient	5	4	5	5	5	5	4.8	5
	9b	Tool enhanced efficiency by simplifying repetitive tasks	5	4	5	5	5	5	4.8	5
	9g	Tool was easy to use	4	4	5	3	5	4	4.2	4
Constraint consideration	4a	Consideration of CDA to BMP	5	5	5	2	3	5	4.2	5
	4b	Consideration of physical site constraints	5	5	5	4	4	2	4.2	4.5
	4c	Consideration BMP installation cost	3	5	4	4	4	4	4.0	4
	4d	Consideration of BMP maintenance cost	4	5	3	4	4	4	4.0	4
	4e	Consideration of runoff reduction volume	4	5	4	5	3	5	4.3	4.5
	4f	Consideration of aesthetics	3	5	1	1	1	4	2.5	2
	9d	Tool allows quick consideration of siting constraints	4	4	5	4	5	5	4.5	4.5
	9f	Tool allows me to take cost into account when selecting best alternatives	4	4	4	4	4	5	4.2	4
Affects Engineering Design Process	9a	Tool affected the way BMP design is approached	5	4	5	5	5	5	4.8	5
	9c	Tool allows more time to be spent on evaluation rather than data entry	4	4	5	5	5	5	4.7	5
	9e	Allows consideration of alternatives that wouldn't have been considered	5	5	4	5	5	5	4.8	5
	9h	Tool will enhance my effectiveness in providing services to my clients	5	4	5	5	5	5	4.8	5
	1	Years of experience	3	3	4	2	4	3	3.2	3
	2	Number of VRRM Spreadsheet projects	2	3	2	3	2	2	2.3	2
	5	Time spent on meeting phosphorus reduction	1	1	1	1	1	3	1.3	1
	6	Time spent evaluating alternatives	2	2	2	2	1	4	2.2	2
	7	Number of alternatives considered	2	2	2	2	2	3	2.2	2
	8	Cost factors considered in solution	2	3	3	3	3	3	2.8	3
	9i	Tool is visually appealing	4	5	5	5	5	5	4.8	5

Case Study 1

			VRRM Spreadsheets						
			1	**2**	**3**	**4**	**5**	**Avg.**	**Median**
Usability	3a	Data entry is easy	2	5	3	4	4	3.6	4
	3b	Adding treatment train connectivity is easy	4	4	3	4	4	3.8	4
	3c	Tool allows visualization of train connectivity	2	1	1	4	2	2	2
	3d	Tool provides ability to take into account constraints at BMP	1	1	1	2	2	1.4	1
	3e	Changing entry to an alternate BMP is easy	2	5	2	3	3	3	3
	3f	Iterating through multiple test solutions is time efficient	1	1	2	1	3	1.6	1
	9b	Tool enhanced efficiency by simplifying repetitive tasks	2	1	2	2	2	1.8	2
	9g	Tool was easy to use	4	5	3	4	3	3.8	4
Constraint consideration	4a	Consideration of CDA to BMP	5	5	2	4	3	3.8	4
	4b	Consideration of physical site constraints	4	5	4	4	4	4.2	4
	4c	Consideration BMP installation cost	3	4	4	1	2	2.8	3
	4d	Consideration of BMP maintenance cost	3	4	3	1	2	2.6	3
	4e	Consideration of runoff reduction volume	4	5	5	1	4	3.8	4
	4f	Consideration of aesthetics	3	5	4	1	3	3.2	3
	9d	Tool allows quick consideration of siting constraints	1	1	2	2	2	1.6	2
	9f	Tool allows me to take cost into account when selecting best alternatives	1	1	1	1	2	1.2	1
Affects Engineering Design Process	9a	Tool affected the way BMP design is approached	2	5	4	3	4	3.6	4
	9c	Tool allows more time to be spent on evaluation rather than data entry	1	1	2	2	3	1.8	2
	9e	Allows consideration of alternatives that wouldn't have been considered	1	1	1	2	1	1.2	1
	9h	Tool will enhance my effectiveness in providing services to my clients	2	3	3	2	3	2.6	3
	1	Years of experience	2	2	4	4	3	3	2.5
	2	Number of VRRM Spreadsheet projects	2	4	3	3	3	3	3
	5	Time spent on meeting phosphorus reduction	2	1	1	1	1	1.2	1
	6	Time spent evaluating alternatives	1	2	1	1	1	1.2	1
	7	Number of alternatives considered	2	1	2	2	2	1.8	2
	8	Cost factors considered in solution	1	3	1	4	1	2	2
	9i	Tool is visually appealing	1	3	2	3	4	2.6	3

Case Study 2

			Optimization Software Tool							
			1	**2**	**3**	**4**	**5**	**6**	**Avg.**	**Median**
Usability	3a	Data entry is easy	4	5	5	5	4	4	4.5	4.5
	3b	Adding treatment train connectivity is easy	5	5	5	5	5	5	5.0	5
	3c	Tool allows visualization of train connectivity	5	5	5	5	5	5	5.0	5
	3d	Tool provides ability to take into account constraints at BMP	4	5	4	5	5	4	4.5	4.5
	3e	Changing entry to an alternate BMP is easy	4	5	5	5	5	5	4.8	5
	3f	Iterating through multiple test solutions is time efficient	5	5	5	5	5	5	5.0	5
	9b	Tool enhanced efficiency by simplifying repetitive tasks	5	5	5	5	5	5	5.0	5
	9g	Tool was easy to use	4	5	5	4	5	5	4.7	5
Constraint consideration	4a	Consideration of CDA to BMP	3	2	4	5	3	4	3.5	3.5
	4b	Consideration of physical site constraints	4	4	4	5	4	4	4.2	4
	4c	Consideration BMP installation cost	5	3	5	5	4	3	4.2	4.5
	4d	Consideration of BMP maintenance cost	5	3	5	5	4	3	4.2	4.5
	4e	Consideration of runoff reduction volume	4	5	5	5	5	3	4.5	5
	4f	Consideration of aesthetics	2	1	5	5	3	3	3.2	3
	9d	Tool allows quick consideration of siting constraints	4	4	4	5	5	4	4.3	4
	9f	Tool allows me to take cost into account when selecting best alternatives	4	3	5	4	5	4	4.2	4
Affects Engineering Design Process	9a	Tool affected the way BMP design is approached	5	5	5	4	5	5	4.8	5
	9c	Tool allows more time to be spent on evaluation rather than data entry	5	5	5	5	5	5	5.0	5
	9e	Allows consideration of alternatives that wouldn't have been considered	4	5	5	5	5	4	4.7	5
	9h	Tool will enhance my effectiveness in providing services to my clients	5	5	5	5	5	5	5.0	5
	1	Years of experience	2	4	3	3	4	3	3.2	3
	2	Number of VRRM Spreadsheet projects	3	2	3	2	2	2	2.3	2
	5	Time spent on meeting phosphorus reduction	1	1	1	2	2	1	1.3	1
	6	Time spent evaluating alternatives	2	2	1	5	2	2	2.3	2
	7	Number of alternatives considered	1	4	2	4	3	2	2.7	2.5
	8	Cost factors considered in solution	3	3	3	3	3	2	2.8	3
	9i	Tool is visually appealing	5	5	5	4	5	4	4.7	5

Case Study 2

			VRRM Spreadsheets						
			1	**2**	**3**	**4**	**5**	**Avg.**	**Median**
Usability	3a	Data entry is easy	5	2	1	2	2	2.4	2
	3b	Adding treatment train connectivity is easy	4	2	4	3	2	3	3
	3c	Tool allows visualization of train connectivity	1	2	1	2	1	1.4	1
	3d	Tool provides ability to take into account constraints at BMP	1	2	1	2	1	1.4	1
	3e	Changing entry to an alternate BMP is easy	5	2	1	1	2	2.2	2
	3f	Iterating through multiple test solutions is time efficient	1	2	1	2	1	1.4	1
	9b	Tool enhanced efficiency by simplifying repetitive tasks	1	2	1	2	2	1.6	2
	9g	Tool was easy to use	5	3	2	3	2	3	3
Constraint consideration	4a	Consideration of CDA to BMP	--	4	4	2	4	3.5	4
	4b	Consideration of physical site constraints	--	4	4	2	4	3.5	4
	4c	Consideration BMP installation cost	--	2	2	3	4	2.75	2.5
	4d	Consideration of BMP maintenance cost	--	2	2	3	4	2.75	2.5
	4e	Consideration of runoff reduction volume	--	4	4	4	2	3.5	4
	4f	Consideration of aesthetics	--	2	2	3	3	2.5	2.5
	9d	Tool allows quick consideration of siting constraints	1	2	1	2	1	1.4	1
	9f	Tool allows me to take cost into account when selecting best alternatives	1	1	1	2	1	1.2	1
Affects Engineering Design Process	9a	Tool affected the way BMP design is approached	3	2	2	4	2	2.6	2
	9c	Tool allows more time to be spent on evaluation rather than data entry	3	2	1	2	2	2	2
	9e	Allows consideration of alternatives that wouldn't have been considered	1	2	3	2	2	2	2
	9h	Tool will enhance my effectiveness in providing services to my clients	1	3	3	3	2	2.4	3
	1	Years of experience	2	4	3	3	4	3.2	3
	2	Number of VRRM Spreadsheet projects	4	3	2	3	3	3	3
	5	Time spent on meeting phosphorus reduction	1	2	2	2	1	1.6	2
	6	Time spent evaluating alternatives	4	1	2	3	2	2.4	2.5
	7	Number of alternatives considered	2	3	2	4	2	2.6	2.5
	8	Cost factors considered in solution	3	4	4	4	3	3.6	4
	9i	Tool is visually appealing	3	3	1	3	2	2.4	3